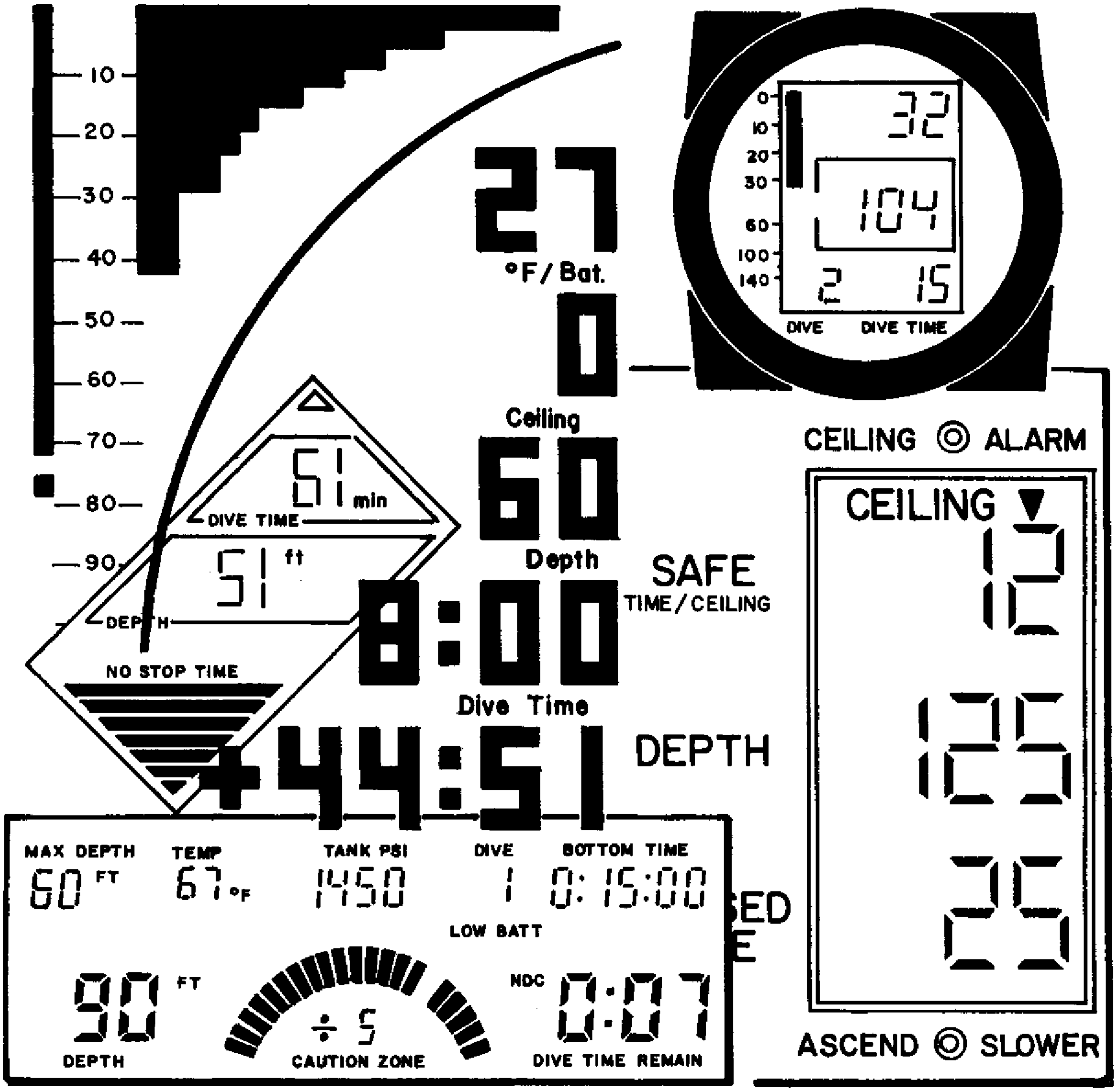
PROCEEDINGS OF DIVE COMPUTER WORKSHOP



THE AMERICAN ACADEMY OF UNDERWATER SCIENCES

SEPTEMBER 26 TO 28, 1988

USC CATALINA MARINE SCIENCE CENTER
SANTA CATALINA ISLAND, CALIFORNIA

PROCEEDINGS OF THE

AMERICAN ACADEMY OF UNDERWATER SCIENCES DIVE COMPUTER WORKSHOP

September 26-28, 1988

U.S.C. Catalina Marine Science Center
Santa Catalina Island, California

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PREFACE

These proceedings contain twenty-three invited papers, presented at the American Academy of Underwater Sciences Dive Computer Workshop, September 26 -28, 1988, at the U.S.C. Catalina Marine Science Center. This workshop was one of several held in conjunction with the 8th Annual AAUS Scientific Diving Symposium *"Advances in Underwater Science...1988"*. In addition to the invited papers, personal experiences and perspectives were presented, dive computer manufacturers offered a hands-on opportunity to acquaint the workshop with the various units, and the discussions and recommendations throughout the workshop were recorded, transcribed and edited. It was the goal of the Academy, with support from the California Sea Grant College Program and the U.S.C. Sea Grant Institutional Program, to bring together scientists, manufacturers and knowledgeable members of the various sectors of the international diving community, to provide the opportunity for sharing objective information and scientific data on dive computers and their use.

The need for an objective, scientific examination on the applicability of these dive computers to the scientific diving community's needs was met by this panel of experts and knowledgeable participants. This workshop came at the very opportune point in time when the proliferation of dive tables and decompression devices left the entire diving community with several fundamental questions regarding the issues of diving, physiology and decompression.

The invited speakers were requested to provide their papers by the time of the Workshop. In addition to a hard copy, the papers were to be on computer disk. This was complied with reasonably well, and the remaining few were obtained after the workshop. We then edited and printed the papers in a uniform format. We did not have access to a court reporter to transcribe the proceedings, so we elected to do the best we could to summarize the important parts of the discussions, with as much rationale and opinion as we could reasonably include. The discussions are inserted at the end of each session. This method means that we have no doubt overdone the matter of condensing, and because much of this had to be taken from a remote microphone in a noisy room we have no doubt attributed some comments to the wrong people, have missed some gems, and have misinterpreted others. We take full blame for this, and apologize to any that may be offended and to the readers for any minor inaccuracies. We do feel that what we have here reflects the mood, if not always the consensus, of the participants.

For consistency throughout this document, the workshop participants agreed to refer to these electronic devices as "Dive Computers" or DC's, which was then substituted in these transcripts in lieu of the myriad of other existing acronyms and terms.

Though it was the scientific diving community that took the initiative and formulated the questions regarding the use of dive computers for the diving scientist's safety, the results presented here prove to be applicable to the recreational, commercial and cave diving communities as well.

Michael A. Lang
R.W. Hamilton
Editors

AMERICAN ACADEMY OF UNDERWATER SCIENCES

Dedicated to the advancement and practice of scientific diving

ABOUT AAUS

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

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

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

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

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

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

EXECUTIVE SUMMARY

Historically, the diving community has depended on the United States Navy Air Decompression tables to accomplish safe time and depth limits. These tables have served the military and civilian sector well for over four decades. Today, in the quest of safely extending bottom time, industry has developed the *in situ* dive computer. Utilizing mathematical models of human tissue compartments and gas exchange dive computers allow the constant computation of the "decompression status" during the dive.

At present there are a number of dive computers on the market and they all vary in the assumptions utilized in the model and in their capabilities. Since these tools have the potential for widespread use in the scientific diving sector, this workshop was planned and implemented by the American Academy of Underwater Sciences.

Technical representatives of the leading dive computer manufacturers, authors of the most widely used decompression algorithms, diving physiologists and knowledgeable users were invited to a two-day workshop. After intense information exchange, discussions, and evaluations of each of the dive computers, it was concluded that they are presently in the second generation of development. After evaluating the available database on pressure related injuries to examine the effectiveness of dive computers, it was the consensus that such devices have demonstrable potential for use in the entire diving community. The usefulness of specific dive computers varied among manufacturers and as a result guidelines for their use within the scientific diving community were formulated.

In addition, recommendations for future uniformity or standardization in data displays and capabilities were discussed as well as dive profile recall capabilities.

It is clear that neither tables nor dive computers can eliminate all decompression problems. It is also clear that this second generation of technology, if utilized conservatively, represents an important tool for improving diver safety.

Dive computers are expanding rapidly and will doubtlessly form an important element of the safety equipment for the scientific diver. In the future, exposure data must continue to be collected from users to provide a proper statistical base with which to monitor their effectiveness.

ACKNOWLEDGEMENTS

The organization of this workshop and the production and assembly of a document of this size and diversity would not have been possible without the assistance of a number of people. I thank the workshop organizing committee Bill Hamilton (Program Chair), Glen Egstrom (AAUS President-Elect), Chuck Mitchell (AAUS Workshops Chair), Andy Pilmanis and Jack Engle (Local coordinators and Workshop hosts at the Catalina Marine Science Center) for a job well done. I extend my personal thanks to the contributing authors, participants and manufacturers for working so cooperatively in the pursuit of safe diving. I appreciate the distances people had to travel, many at their own or their organization's expense and the time they invested in preparing their presentations for this workshop.

In the initial stages of workshop organization, Ann Muscat, Andy Pilmanis, Jim Fawcett and Lindy Nagata were of great support and encouragement. Thanks also to Capt. Ed Thalmann, Dr. Paul Weathersby and Prof. A.A. Bühlmann for their support and supplying information on dive profiles, maximum likelihood analysis and decompression models. I thank my co-editor Bill Hamilton, who is credited with the division of topics and questions that were addressed by the speakers.

Special thanks to Bill Morris and Jim Varnell of the SDSU Life Sciences Computer Center for the transcription of the various floppy disks.

This workshop was sponsored in part by NOAA, National Sea Grant College Program, Department of Commerce, under grant number NA85AA-D-SG140, project number R/NP-1-17M, through the California Sea Grant College Program, and in part by the University of Southern California Sea Grant Institutional Program (Project AP-1-3) under grant #NA86AA-D-SG119, and in part by the American Academy of Underwater Sciences.

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INTRODUCTION TO THE AAUS DIVE COMPUTER WORKSHOP

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I thank all of you for coming to participate in this workshop. We've put a considerable amount of time and effort into the organization and planning of it, so I feel confident that we will be able to work together very well and get some good results. The workshop should prove interesting because we have a nice cross-section of participants here: scientists, manufacturers, training agency representatives, scientific diving officers, cave divers, professional divers, hyperbaric chamber directors and decompression experts. Everyone will contribute to the workshop to some degree, which is why you're here. We've had a good start coming over on the Sea Watch, which proved fairly uneventful. Please refer to your program and notice how full it really is. We'll be keeping a tight schedule, so that we may accomplish what we set out to do.

Next, I will introduce the speakers and briefly outline the program. I also acknowledge the speakers who delivered their papers as requested, following author's instructions and with a floppy disk. [This was followed by a self-introduction of participants].

The AAUS is a group that was formed in the late 1970's with a specific purpose. At the time, it was to make sure that the scientific diving community, which had been operating under the model originating from Scripps Institution of Oceanography, would gain exemption from the OSHA commercial diving standards. In addition, the scientific diving community wished to continue its self-regulating procedures. We did not feel those standards represented the safety and scientific needs of the scientific diver. After about eight years of hearings and meetings, the exemption was granted.

The AAUS holds annual scientific diving meetings, the first through fourth of which were held at Scripps Institution of Oceanography. In 1985, also at S.I.O., a Joint International Scientific Diving Symposium was held with the Scientific Committee of CMAS (World Underwater Federation). As a national organization, the AAUS held its annual meeting at Florida State University in Tallahassee in 1986, at the University of Washington in Seattle in 1987, at Scripps Institution of Oceanography this week, and at Woods Hole Oceanographic Institution in 1989. The Academy publishes yearly pre-symposium proceedings. The symposia provide an excellent forum for the dissemination of information between different sectors of the diving and science communities.

The guidelines for the management of diving programs is one of the main efforts of the AAUS. This results in a national, consensually derived, diving safety manual: Standards for diving certification and operation of scientific diving programs.

Every scientific diving program has two major components: the Diving Control Board and the Diving Safety Manual. The major scientific institutions across the U.S. with a scientific diving program have been able to standardize this diving manual, so that we're actually all diving the same way. We need this reciprocity because of the many projects which simultaneously involve scientists from various governmental, state or university programs. It makes sense for a diver trained at Woods Hole Oceanographic Institution to come to the West Coast and not have to jump through the hoops again at Scripps Institution of Oceanography. What we are basically accepting is the training and experience scientific divers bring with them from their home institution. The manual is a living document, has been revised twice to reflect state-of-the-art equipment, procedures and training concepts, and is now slated for another revision.

The types of diving we do is typically no-decompression diving. We've been looking at several alternate modes of diving, to be used as tools by the underwater scientist, such as nitrox diving, tether diving and the use of dive computers. The practice of scientific diving is really a continuously evolving process.

The current guidelines, and part of the reason we are here, were discussed at our last Diving Officer's Meeting in Seattle. We felt dive computers left many questions to be addressed. Examples are: Should each buddy have one? What do you do when the unit floods? Can you go back to the tables? Several answers to many of our questions resulted in tentative guidelines for the use of DC's, which we'll be able to use as a starting point to develop a thorough set of guidelines on how to use these dive computers. Are they applicable to scientific diving? As you look through the program, several papers are directly addressing these questions, so I hope we will produce some objective, valid information which we can then disseminate to all sectors of the diving community. I'll leave the presentation of the issues up to Andy, since he's speaking next. I trust we'll have a successful workshop.

PRESENTATION OF THE ISSUES

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During the last five years, small diver-carried decompression computers (dive computers) have become popular and widely used. Logically, their evolution is a natural progression from decompression tables. This evolution is in its infancy, and a workshop such as this is very timely in influencing the direction of this process.

Operationally, these devices offer to the diver a number of advantages over the tables:

1. They can replace the diver's watch and depth gauge and provide greater accuracy;
2. They provide computerized, real-time, at-depth, continuous dive profile data, eliminating the need for the working diver to remember tables and make decompression decisions while underwater - it takes the decompression decision making process out of the diver's hands;
3. While multi-level diving, they allow for longer working bottom times than permitted by tables.

Dive computers are especially appealing to the scientific diver. These divers are usually highly motivated in their work and are interested in maximizing underwater time and efficiency. They view decompression requirements as a hindrance and distraction from this work. However, they are generally concerned about safety and try to stay current with respect to new developments such as dive computers. Although there are exceptions, scientific diving can be characterized by:

1. Air diving
2. Use of SCUBA
3. Relatively shallow exposures (0 to 60 fsw)
4. Relatively long bottom times
5. Working in remote locations
6. Multi-level diving
7. Repetitive diving
8. Multi-day diving

9. A population at risk of approximately 3,000 to 5,000 in the U.S.
10. Low budget operations
11. Part of an organized diving program

The dive computer experience in scientific diving from the past 5+ years appears to be generally good. However, isolated reports of decompression sickness resulting from use of dive computers exists, primarily from the recreational diving community. This experience is difficult to assess because very few scientific diving programs permit the use of dive computers as the primary decompression tool. More commonly, diving programs allow these devices as back-up for the tables. In addition, more recently, a proliferation of these computers has occurred. For a diving program to determine the acceptance of none, some, or all of these devices for use by its divers has become a perplexing problem. Most diving officers and diving control boards of scientific diving programs do not have the expertise to make such determinations.

The purpose of this workshop is to provide guidance to the AAUS and other interested parties as to:

1. The safety of dive computers
2. Evaluation procedures for these devices
3. Guidelines for their use

Some specific areas of concern are listed below. This is not an exclusive list, nor is it in order of priority.

1. **Decompression models** - What models are these dive computers programmed with? Does it matter? Should the manufacturers specify the model in their brochures? Which models are "acceptable"? Which models are not "acceptable"?

2. **Validation and human testing** - What comprises an acceptable validation process? Should all devices be tested on human subjects with Doppler monitoring? If so, what type of dive profiles should be used? Should comparisons with existing decompression tables be made? Should the manufacturer publish these data? Should they be evaluated by an independent agency?

3. **Acceptable risk** - What levels of "bends" risk are acceptable in scientific diving?

4. **Limitations** - Should depth and time limitations be imposed on these computers? If so, how is this determined? Specifically, what is the applicability of these devices to:

   - long shallow dives
   - short deep dives
   - stage decompression dives
   - repetitive dives
   - multi-level dives

- multi-day dives
- deep dive following a shallow dive
- ascent rates
- diving at altitude
- flying after diving

5. **Dive computer failure** - What does a diver do with his/her decompression during or after a dive when the computer fails? Can there be contingency plans for continued diving after a computer failure?

6. **Operational reliability** - What is the operational experience? Are there specific equipment failures? Should the manufacturer provide reliability data?

In the final analysis, the most important factor in the evaluation of dive computers for use in safe diving operations is the incidence of decompression sickness from dives controlled by these devices. Such data is extremely difficult to obtain. Since 1974, the University of Southern California Catalina Hyperbaric Chamber has been treating diving accidents from the southern California region. During the past two years, the number of patients reporting the use of dive computers has been steadily increasing. However, after reviewing the chamber files, it is impossible to compile any meaningful data on the effectiveness or safety of dive computers. The reason is that the patient's reports are so incomplete and vague that no confidence can be attached to them. Some patients report wearing a device but not looking at it during the dive; others can't recall even the brand name; others monitored it during the dive, but not during the ascent. During this workshop, such data should be scrutinized for accuracy. Second-hand anecdotes may be of some interest, but should not form the basis of the workshop recommendations.

It is apparent that dive computers "are here to stay" but are still in the early stages of development. From this perspective, this workshop can begin the process of establishing standard evaluation procedures for assuring safe and effective utilization of dive computers in scientific diving.

THE HISTORY OF DECOMPRESSION DEVICES AND COMPUTERS

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Since the introduction of SCUBA in the 1950's, devices have been made which determine a diver's decompression status in real time. These devices, which met with varying levels of success, included mechanical and electrical analog computers and more recently microprocessor-based digital computers. Today, with the availability of inexpensive microprocessor technology, we have the largest variety of dive computers (DC's) ever available to divers at a single time. However, these DC's only use the variables depth and time to compute decompression status. Safety factors based on individual and environmental variations should still be incorporated while diving with a DC. I expect that future devices will incorporate additional variables that play a role in decompression sickness susceptibility, with the ultimate DC monitoring actual inert gas levels in the diver.

INTRODUCTION

During World War II, the concept of deep sea diving changed with the introduction of SCUBA. Up to this time diving operations were carried out using surface supplied air to hardhat divers who would spend their entire dive at one depth for as long as they needed to complete a task. Decompression status computations and execution were performed by tenders at the surface.

With the advent of SCUBA came some logistical problems which had to be considered:

A. Divers were now separated from surface contact and had to be responsible for their own decompression computations. This produced the need for some means to determine their decompression status underwater.

B. The divers no longer had an unlimited surface supplied source of air. They had to return to the surface occasionally for a fresh tank of air. Therefore, some mechanism was needed to compute repetitive dives, an operation that had not often been required prior to the introduction of SCUBA.

C. Divers now had three-dimensional freedom during a dive. All the previous tables assumed the divers spent their entire dive at a single depth with no 3-D movement.

The following quote, from a Navy Experimental Diving Unit (NEDU) report (Searle, 1956), indicates the need for some type of decompression device:

> *"With the ever widening fields of both civilian and military free-swimming and diving using self contained breathing apparatus, and particularly when such diving is untended from the surface, there arises a very pressing need for a small portable indicating apparatus to be used to indicate proper decompression in ascent."*

In the early 1950's, the U.S. Navy formed the Committee for Undersea Warfare and Underwater Swimmers to identify improvements required in diving equipment to fit scuba operations. The committee met in 1951 at Scripps Institution of Oceanography. One of the topics addressed was how to control the decompression of a non-tethered, free-swimming scuba diver. The committee report dealing with this problem, (Groves & Monk, 1953), stated:

> *"In ordinary diving [hard hat] the tender aboard the ship keeps a log of the depth-time history of the dive and then computes the decompression requirements from some simple table. For a diver using self-contained equipment, three possibilities present themselves: (a) the diver keeps a log of depth and time and then computes the decompression requirement while under water (this involves a depth gauge, watch, and wits); (b) the diver follows a prearranged schedule (how dull); (c) by guess and by God. None of these alternatives is entirely satisfactory."*

This report presented a preliminary design for a diver-carried decompression device. It was a pneumatic analog computer which simulated nitrogen uptake and elimination in two theoretical tissue groups. The potential benefit of such a device was summarized by the following statement:

> *"The gauge automatically takes into account the depth-time history of the entire dive. The resulting continuous "optimum ascent" should be somewhat more efficient than the usual step-wise ascent, the latter being used only because of its greater simplicity of presentation in tabular form."*
>
> *"There are two other situations for which the gauge is conceivably an improvement over the table. For repeated dives the gauge automatically takes into account the residual elevation of nitrogen pressure in the body from the preceding dives. (Divers are known to be more subject to bends on subsequent dives.) In the case of an emergency ascent, such as may be required by an exhaustion of breathing air, the gauge gives some indication of the desirable re-compression procedure."*

This report also included a basic design for the "Ultimate Gauge," an electrical analog computer. The envisioned device would show both decompression and air consumption status so that the diver would know if the remaining air supply would be sufficient to perform the required decompression schedule.

This report established the foundation for most of the early designs for decompression devices. Since its publication, a variety of both analog and digital decompression computers have been designed, built, and have met with various levels of success.

ANALOG DEVICES

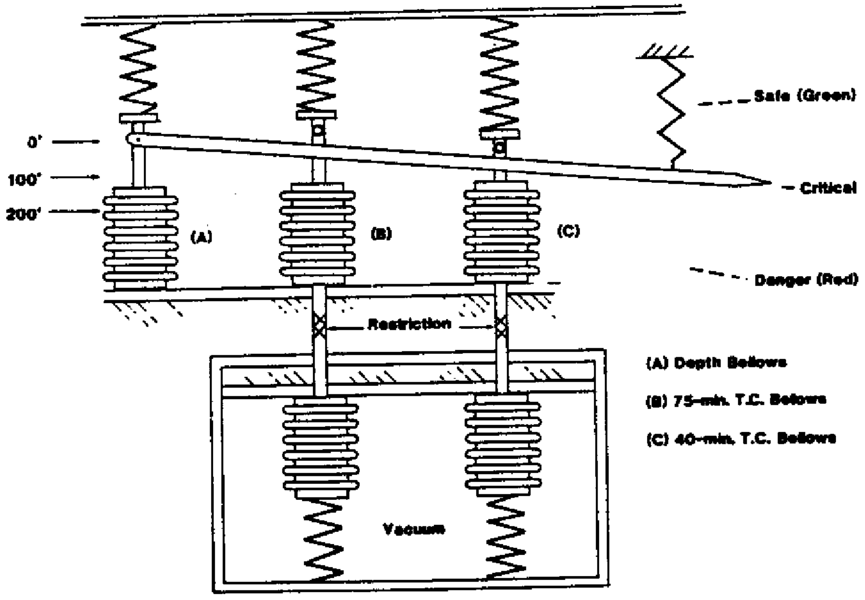
Prior to the advent of microprocessors, mechanical and electrical analog computers were used to simulate decompression models in various decompression devices.

Foxboro Decomputer Mark I

An analog decompression computer built by the Foxboro Company in Foxboro, Massachusetts, was submitted to NEDU in October, 1955. Its two compartment pneumatic design was based on the Groves and Munk report. The two compartments to be simulated had half-times of 40 and 75 minutes and surfacing ratios (compartment nitrogen pressure to ambient pressure) of 1.75:1 for both compartments (Frederickson, 1956). The computer used five bellows to determine decompression status (Figure 1).

Nitrogen absorption and elimination from the compartments was simulated by the flow of gas through porous resistors between bellows, which were exposed to the ambient pressure, and bellows sealed in a vacuum, kept under a constant pressure by a spring.

This device (Figure 2) was the result of communications between two brothers, Dr. Hugh Bradner (member of the Committee of Undersea Warfare) and Mead Bradner (head of Research and Development at Foxboro). The operation of the unit involved balancing the colors on a disk viewed through a window on the right side of the device. The disk was divided into three sections. One-half was white, one-quarter was red, and one-quarter was green. If the dial showed any green through the half-disk window, the diver was safe. If any red was showing, the diver had exceeded the safe ascent depth and would have to descend. Optimal decompression was achieved by keeping just the white half of the disk visible through the window.



Bellows A, B, C, are exposed to pressure of sea water during dive.

Figure 1. Foxboro Decomputer Mark I Schematic (from Fredrickson, 1956).

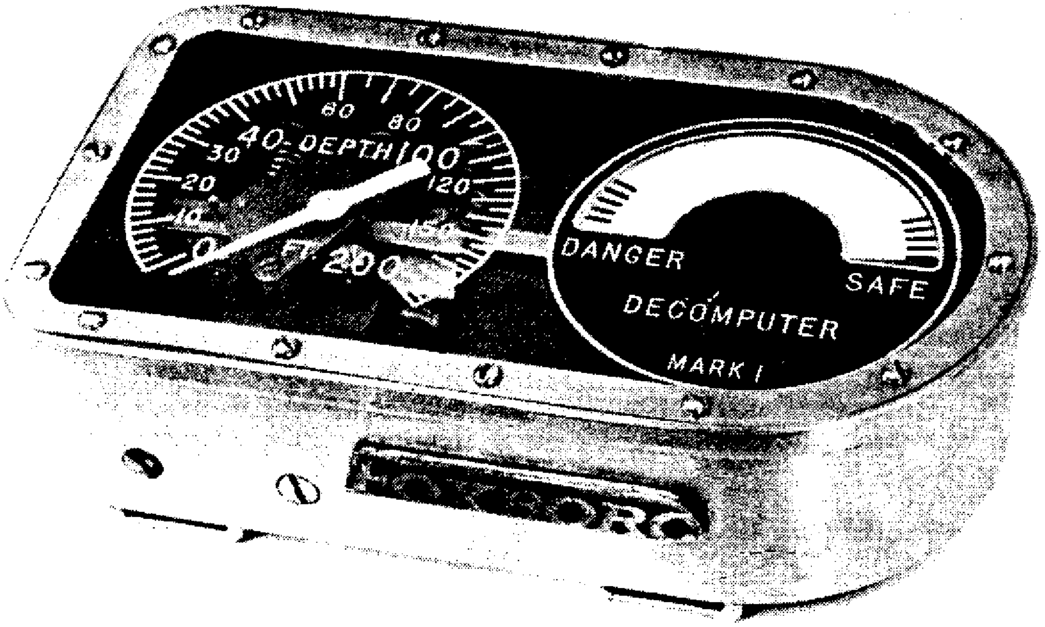


Figure 2. Foxboro Decomputer Mark I (photograph courtesy of Mead Bradner).

Results of the evaluation by the NEDU (Searle, 1956) stated that the device gave readings within the U.S. Navy Table decompression ranges for some dives and outside the ranges for others. The major reason for this was that compartment half-time values were mistaken for the time constants of the bellows. The actual compartment half-times simulated by the device were 27.7 and 52 minutes, causing deviations from tables.

The device was returned to Foxboro for re-evaluation and modification but was never resubmitted to the Navy. In 1957 the Navy published new air no-decompression/decompression tables, and repetitive dive tables. The Navy apparently rejected the idea of a decompression computer and accepted option "a" of the Groves and Monk report (i.e., depth gauge, watch, tables, and wits).

SOS Decompression Meter

The SOS decompression meter has, until recently, been the most well known decompression device. It was designed in 1959 by Carlo Alinari and manufactured by an Italian firm, SOS Diving Equipment Limited (Gordon, 1978). The SOS Meter or DCP (Decompression Computer) is still manufactured and available. The DCP is a one-compartment, pneumatic device which "is purported to be an analog to a 'general' body tissue" (Kuehn, 1981). Due to the design of the DCP, the compartment half-time varies with the pressure differential across the ceramic resistor.

Figure 3. Schematic diagram of SOS Decompression Meter (from Gordon, 1978).

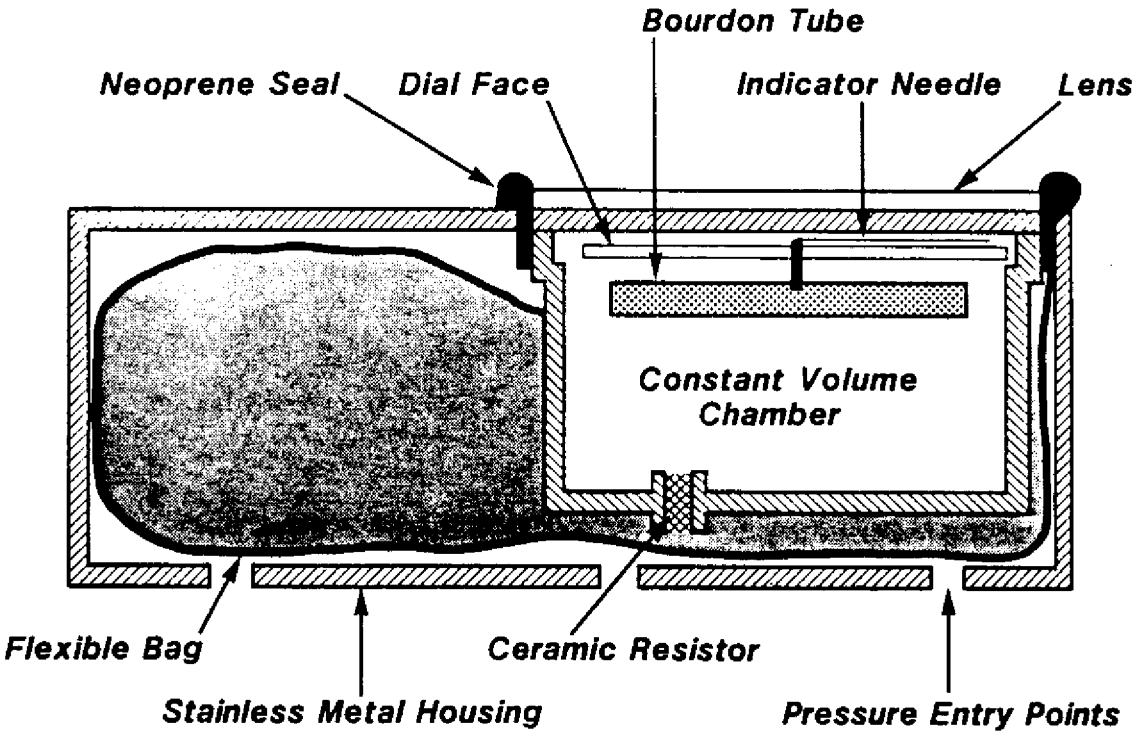


TABLE 1
Comparison of DCP and U.S. Navy no-decompression limits (from Howard, 1975a)

Depth (fsw)	DCP Time (min:sec)	U.S. Navy Table (min.)
40	140:11	200
50	72:34 - 77:57	100
60	60:00	60
70	47:11 - 54:07	50
80	38:40 - 39:54	40
90	30:15 - 32:52	30
100	28:09 - 29:35	25
110	25:35 - 26:43	20
120	21:24 - 22:29	15
130	19:18 - 21:14	10
140	16:11 - 17:13	10
150	14:56 - 16:05	5
160	12:56 - 13:42	5

(from Howard, 1975a)

Figure 3 shows the construction of the DCP. As the diver descends with the device, the ambient pressure increases on the flexible bag, forcing gas through the ceramic resistor into the constant volume chamber. The role of the ceramic resistor is to simulate nitrogen uptake and elimination in the body. The pressure increase in the constant volume chamber is indicated by the bourdon tube gauge. The gauge face indicates the safe ascent depth for the diver. As the diver ascends, the gas pressure in the constant volume chamber will become greater than the external pressure and the gas flow will be reversed.

A major problem with the DCP is its deviation from the U.S. Navy no-decompression limits at deeper depths. Howard (1975a) evaluated ten DCP's and determined that the no-decompression limits allowed by the DCP's were more conservative than the U.S. Navy limits at depths shallower than 60 fsw (feet of seawater), but less conservative at depths deeper than 60 fsw (Table 1).

TRACOR Electrical Analog Computer

The first electrical analog decompression device was developed in 1963 by Texas Research Associates Inc. and was known as the TRACOR computer. The device employed a 10-section ladder network of series resistors and parallel capacitors to simulate nitrogen diffusion within the body. Ambient pressure measurement was supplied by a depth sensor which varied the voltage supplied to the network. Two sets of batteries powered the device. Two 1/2D alkaline cells powered an oven which housed the electronics and kept them at a constant 90 °F. Four small mercury batteries were used as the computer network power source. The display was a micro-ammeter which was calibrated in fsw. The meter would display how many fsw the diver could safely ascend. To obtain the most efficient decompression the diver would ascend at a rate which kept the meter reading zero throughout decompression.

An evaluation of the computer by NEDU, (Workman, 1963), found:

> *"The decompression meter predicted minimal decompression requirements adequately for schedules throughout the depth range tested from 40 through 190 feet for ascent rates of 20 and 60 fpm. Longer and deeper exposures were not provided adequate depth and total decompression time at stops compared to the present U.S. Navy air decompression tables. Continuous ascent decompression predicted by the instrument was inadequate both in depth and duration of total decompression time. Temperature dependency of the instrument was excessive, particularly for cold exposures, and resulted in widely varying decompression requirements for the same dive schedule."*

Workman further suggested that a mechanical analog computer could be used to avoid the instability and breakdowns which occurred in the electrical circuitry.

DCIEM Analog Computer Series

In 1962, the Defense and Civil Institute of Environmental Medicine (DCIEM) began to develop a series of pneumatic analog decompression computers under the direction of D.J. Kidd and R.A. Stubbs. The device had four compartments to simulate the nitrogen absorption and elimination in the diver. Initial versions arranged the compartments in parallel. The final design arranged the compartments in series, resulting in the Kidd-Stubbs decompression model (Kidd and Stubbs, 1966). Table 2 shows test results for the various versions of the device (Flynn, 1978).

TABLE 2
Incidence of DCS produced with versions of the Pneumatic analog decompression computer

	DECOMPRESSION COMPUTER		
	MARK II P	MARK III P	MARK V S
CONFIGURATION	PARALLEL	PARALLEL	SERIAL
HALF-TIMES (min)	10 20 40 80	20 40 80 160	21 common
SUPERSATURATION RATIO (PTN2/PA)	2.65, 2.15 1.85, 1.65	1.6 common	1.44 common
NUMBER OF DIVES	526	478	3775
DCS INCIDENCE	5.0%	1.5%	0.6%

The MARK VS was the first thoroughly tested, successful decompression computer. The four compartments in series gave effective half-times of 5 minutes to over 300 minutes (Nishi, 1978). The display consisted of a depth gauge face with two needles: one to indicate the diver's present depth, and the other to indicate the depth to which the diver could safely ascend.

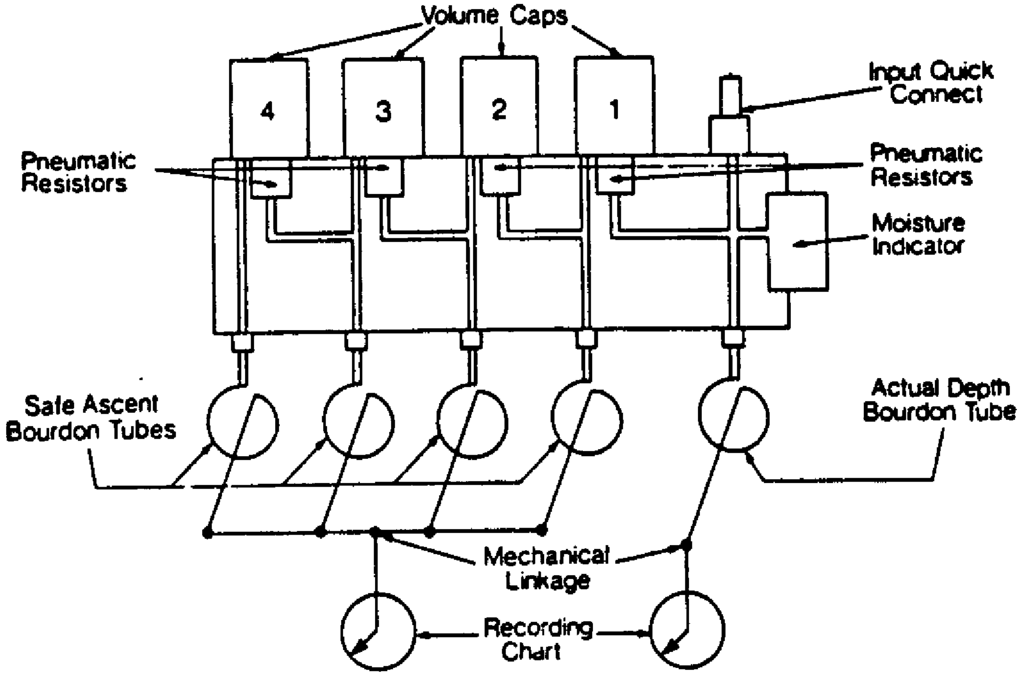
The unit was small enough to fit into a housing 9 cm in diameter and 18 cm long, which could be easily carried by a scuba diver. Another version of the device, called the MARK VIS, was designed utilizing the same algorithm for hyperbaric chamber use. Figure 4 gives the schematic diagram for both the MARK VS & VIS.

The MARK VS was produced by Spar Aerospace in the late 1960's for sale to industrial and military agencies with operational depth limits to 200 fsw. In 1970, Spar developed a smaller and lighter version operational to 300 fsw. Due to the complexity of construction, high manufacturing costs, and extensive maintenance and calibration requirements, the MARK VS computer was not a commercially viable product for sport divers.

GE Decompression Meter

General Electric designed a decompression meter in 1973 which utilized semipermeable silicon membranes to simulate nitrogen diffusion (Borom & Johnson, 1973). These membranes operate better than porous resistors since the simulated half-time of a compartment does not vary with depth (as in the SOS meter). A four-chamber device was built to simulate the U.S. Navy air decompression tables using compartment half-times of 24, 39, 90, and 144 minutes. Initial evaluations by GE showed that the membrane-based decompression meter concept was sound. The size of the unit could be reduced and temperature dependence was "well within satisfactory limits." However, no information on any subsequent development and testing is available.

Figure 4. Schematic of the Mark VS & VIS Pneumatic Analog Decompression Computers (from Nishi, 1978).



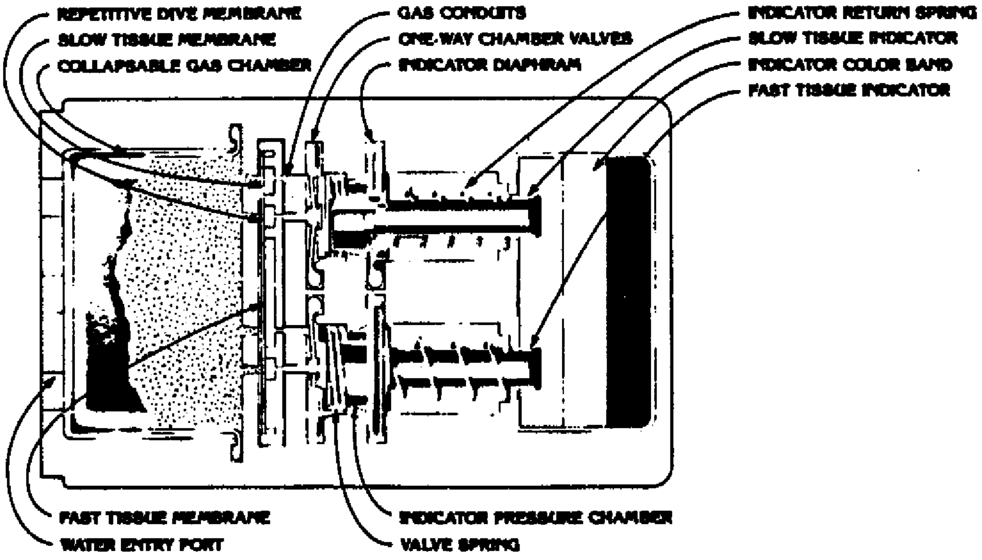


Figure 5. Farallon Decomputer (from Farallon, 1975).

Farallon Decomputer

As scuba diving entered the mid 1970's, the only commercially viable decompression computer available was still the SOS Meter. All other attempts to develop a reliable and safe decompression meter did not succeed or resulted in a product too expensive for the average sport diver. In 1975, Farallon Industries in California released a device called the Decomputer. The device was a pneumatic analog computer which used semipermeable membrane technology. It had four membranes which simulated two theoretical tissue groups. Two of the membranes were used for gas uptake and the other two for elimination. Figure 5 shows the schematic of this device.

Air from the collapsible gas chamber flows through the "fast tissue" (large) and "slow tissue" (small) membranes when exposed to elevated pressures. The increased pressure within the mechanism causes the pistons to move along the display. The display, color-coded green, yellow, and red, indicates the diver's decompression status. The object was to never surface with the pistons in the red, or upper yellow, portion of the display. When the ambient pressure is reduced to less than the pressure inside the tissue simulator, the air flows out through the "repetitive dive membrane". Both compartments had off-gassing membranes which simulated a slow off-gassing rate.

Testing at Scripps Institution of Oceanography indicated that the device failed to "approximate" the U.S. Navy air decompression limits and tables (Howard, 1975). Some allowable no-decompression limits were: 60 fsw for 75.5 minutes; 80 fsw for 51 minutes; 150 fsw for 12.5 minutes, and; 190 fsw for 7 minutes. Tests using the device for repetitive dives proved even less acceptable. The Royal Australian Navy also evaluated the Decomputer, and found that it was too permissive and it developed too much mechanical deterioration with use (Flynn, 1978).

DIGITAL DEVICES

By the mid-1970's the microprocessor revolution was well underway. Now it was possible to construct a small digital computer dedicated to the specific task of decompression computation. Digital computers are more accurate than mechanical analog computers and have fewer calibration problems than electronic analog computers. However, a major drawback with these early digital computers was the lack of an adequate power supply.

DCIEM XDC Digital Decompression Computer Series

DCIEM began work on the XDC Digital Decompression Computer Series in the mid-1970's. Due to their previous success with pneumatic decompression computers, they elected to use the Kidd-Stubbs decompression model with their digital computers.

DCIEM's first computer, the XDC-1 (Figure 6), is a desk-top model. It is used to analyze dive profiles or plan upcoming dive operations by accepting dive profile information through the keyboard. It can also be used in a real-time mode where the diver's depth information is supplied via a pressure transducer and an A/D converter. The decompression status is determined by computing the nitrogen pressure accumulated in the four compartments of the Kidd-Stubbs model.

During the dive, the operator can extrapolate the dive profile and determine required decompression debt based on numerous dive options (Lomnes, 1975). The XDC-1 was manufactured by Canadian Thin Films Systems Inc. in British Columbia and successfully used in laboratory hyperbaric facilities. However, the design was not practical for open water diving situations.

To handle the rigors of diving operations, DCIEM designed the XDC-2 (Figure 7). This computer is a dedicated real-time decompression computer used with surface supplied diving operations. The unit can be connected to a pressure transducer carried by the diver or connected to the pneumo hose on the diver's umbilical. The decompression model in the XDC-2 was the same Kidd-Stubbs model used in the XDC-1. The output information of the XDC-2 consists of four large LED displays and two arrays of LED indicator lamps. The main information supplied by the four large LED displays is:

A. Depth.

B. Elapsed Dive Time.

C. Safe Depth (depth to which the diver can ascend safely without violating the model).

D. No-Decompression Time/Ascent Time Display. When the diver is within the no-decompression limits this display will show the no-decompression time remaining if the diver stays at that depth (negative number). If the diver goes into a decompression dive this display will give the optimum ascent/ decompression time (positive number).

One array of LED lamps presents a bar graph showing the safe ascent depth and the other array is composed of warning lights that indicate the system's status. The unit runs off a standard 110V AC line and has internal rechargeable NiCd batteries that power the unit for two hours if the AC power fails. The unit can also run off an external 12V DC power supply. The XDC-2 is still used in the Canadian Navy, with slight modifications to the Kidd-Stubbs decompression model software. The main limitation with the XDC-2 is that it requires the diver to be tended from the surface because the computer cannot be carried by the diver.

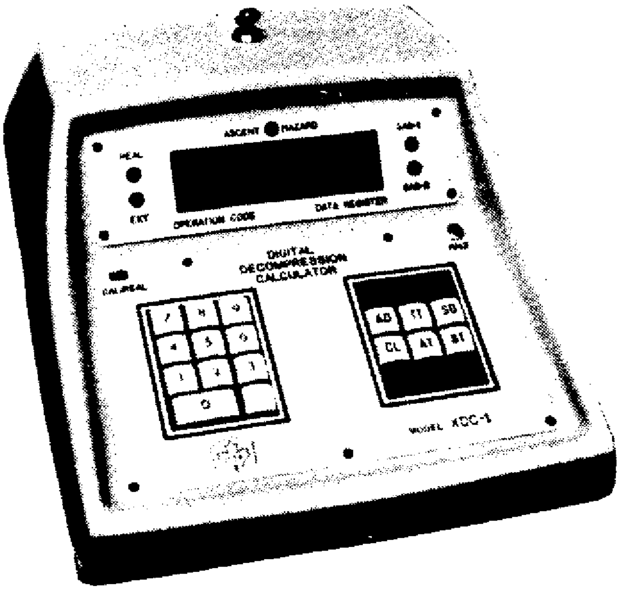
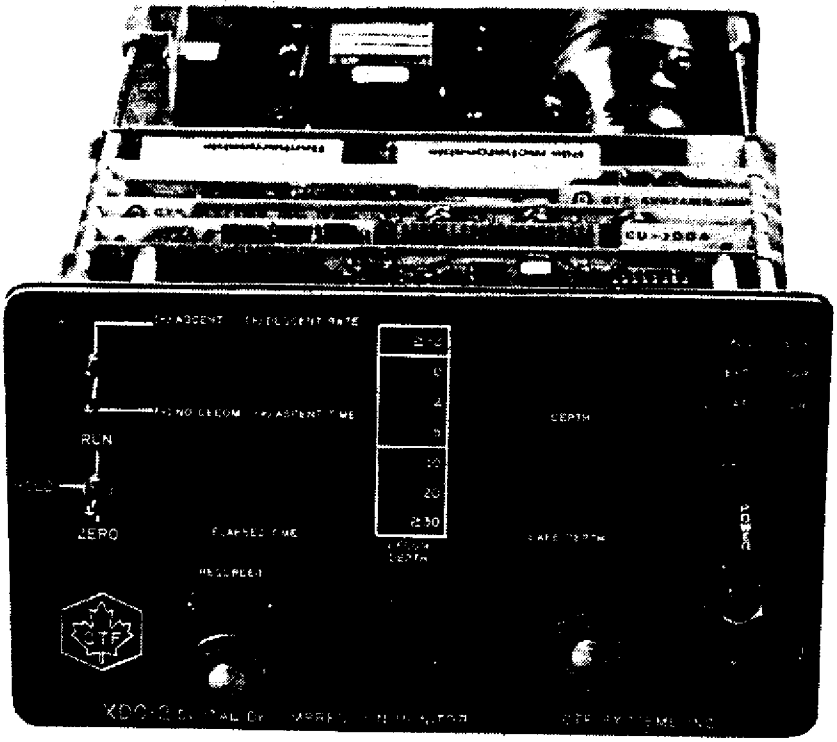


Figure 6. XDC-1 Decompression Computer (from CTF Systems, Inc).

Figure 7. XDC-2 Decompression Computer (from CTF Systems, Inc).



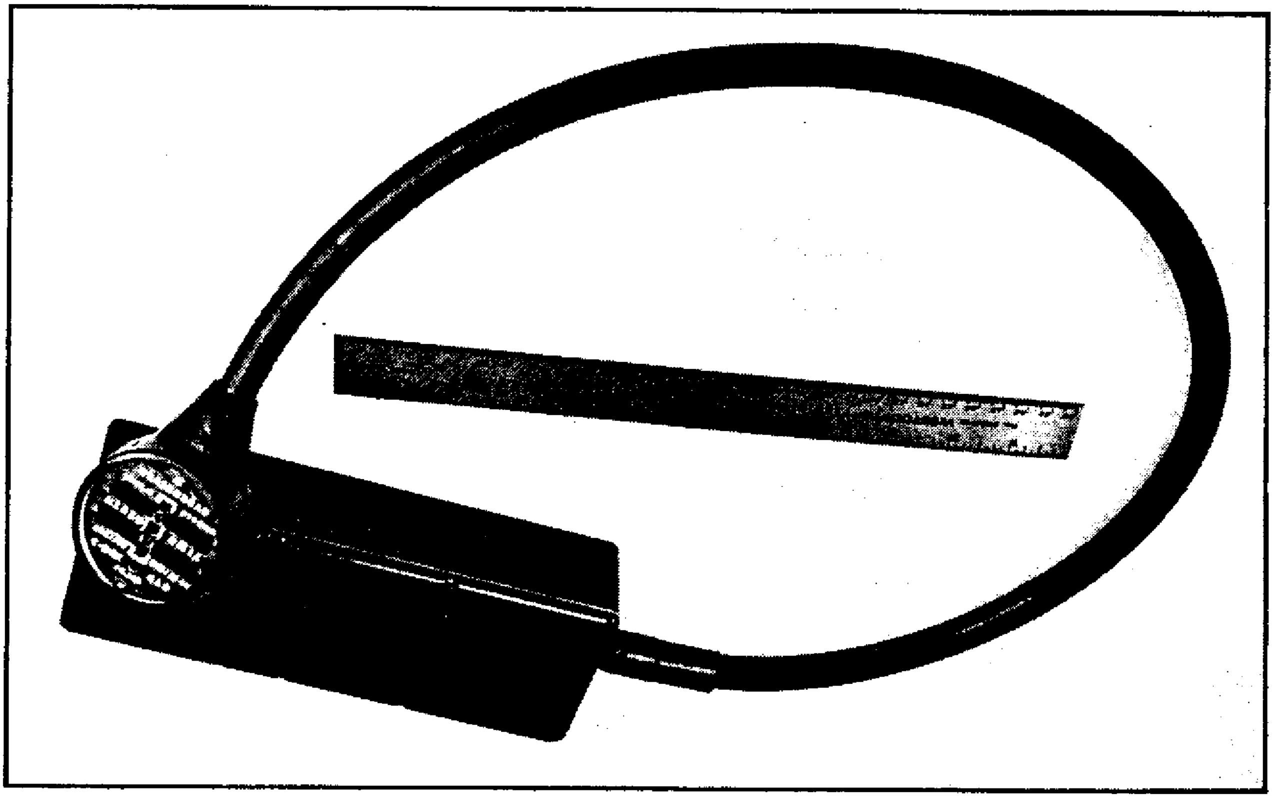


Figure 8. XDC-3 Decompression Computer/Cyberdiver (from CTF Systems, Inc).

To accommodate the free-swimming scuba diver, the XDC-3, or Cyberdiver, was developed. The Cyberdiver was the first diver-carried microprocessor-based underwater decompression computer (Figure 8).

The device, attached to the diver's tank, and the small hand-held display presented the same information as the XDC-2. The unit was powered by four 9V batteries with a lifetime of about four hours. The batteries could be replaced without losing the existing decompression information. To conserve power, since the display LED's had a large current drain, the display was equipped with an inertial switch that would turn the LED's on for six seconds for reading. The XDC-3 met with limited success since its initial cost and the cost of four 9V batteries every four hours on a diving excursion were too high for the average sport diver.

DACOR Dive Computer

The most effective way to use microprocessor technology in dive computers is to program the decompression model into the microprocessor software program, as in the XDC series. Another less efficient way to use microprocessors in a dive computer is to store established tables in the memory, and design the software to read those tables. In this configuration any advantage obtained by integrating the decompression status over the entire dive is lost.

The Dacor Corporation was interested in designing and producing an underwater decompression computer during the late 1970's. They decided, due to liability reasons, to design a diver-carried computer which would read the U.S. Navy air decompression tables for the diver (Foley, 1979). In the first section of this paper, choice "a" in the Groves and Monk report stated that a diver would need a table, depth gauge, watch, and wits. Dacor's solution combined the first three items and eliminated the diver's need for wits.

Dacor was prepared to market the unit, but the power consumption in the device was so high that it required a special battery to allow it to continuously run for at least twelve hours. According to the company, two-thousand units were ready to ship as soon as the batteries arrived, but the factory that produced the batteries was destroyed by fire and the project was shelved.

Cyberdiver II

Kybertec (now Newtec) in British Columbia which worked on the XDC-3, or Cyberdiver, entered the sport diving market with Cyberdiver II in 1980. Like the Dacor computer, it read the U.S. Navy air decompression tables. It also connected to the high pressure hose of the regulator and displayed the diver's tank pressure. Its power supply was one 9V battery which provided six-to-twelve hours of continuous operation, depending on water temperature. However, there was a way to save previous dive information if the battery was changed. The unit had an audio warning system to indicate hazardous decompression situations. The Cyberdiver II met with some marketing success, but the primary complaints were that it was too bulky and the calibration system was too complex.

Cyberdiver III

Newtec returned to a decompression model instead of a table to determine decompression status with the Cyberdiver III in 1981. The Cyberdiver III uses the Kidd-Stubbs model like the original Cyberdiver. The decompression status is displayed in graphical form using five LED's which indicate the diver's safe ascent depth and safe ascent altitude for flying after diving. Like the Cyberdiver II, the Cyberdiver III attaches to the high-pressure hose of the regulator, and the size of the two units is almost identical. Even though Newtec is not advertising the unit, it is still available.

U.S. Navy UDC

Since 1980, NEDU has been developing a decompression model and algorithm to program into an UDC. It is to be used with their constant partial pressure of oxygen closed-circuit mixed gas system (Thalmann, 1980, 1983, 1984). The decompression model that they have decided upon uses the "E-L Algorithm." This model assumes that nitrogen is absorbed by tissues at an exponential rate, as in Haldanian models. However, the nitrogen discharge is a slower linear rate. This slows the surface off-gassing rate indicating higher residual nitrogen levels for repetitive dives.

Figure 9. Prototype of U.S. Navy Underwater Decompression Computer (from Thalmann, 1980).

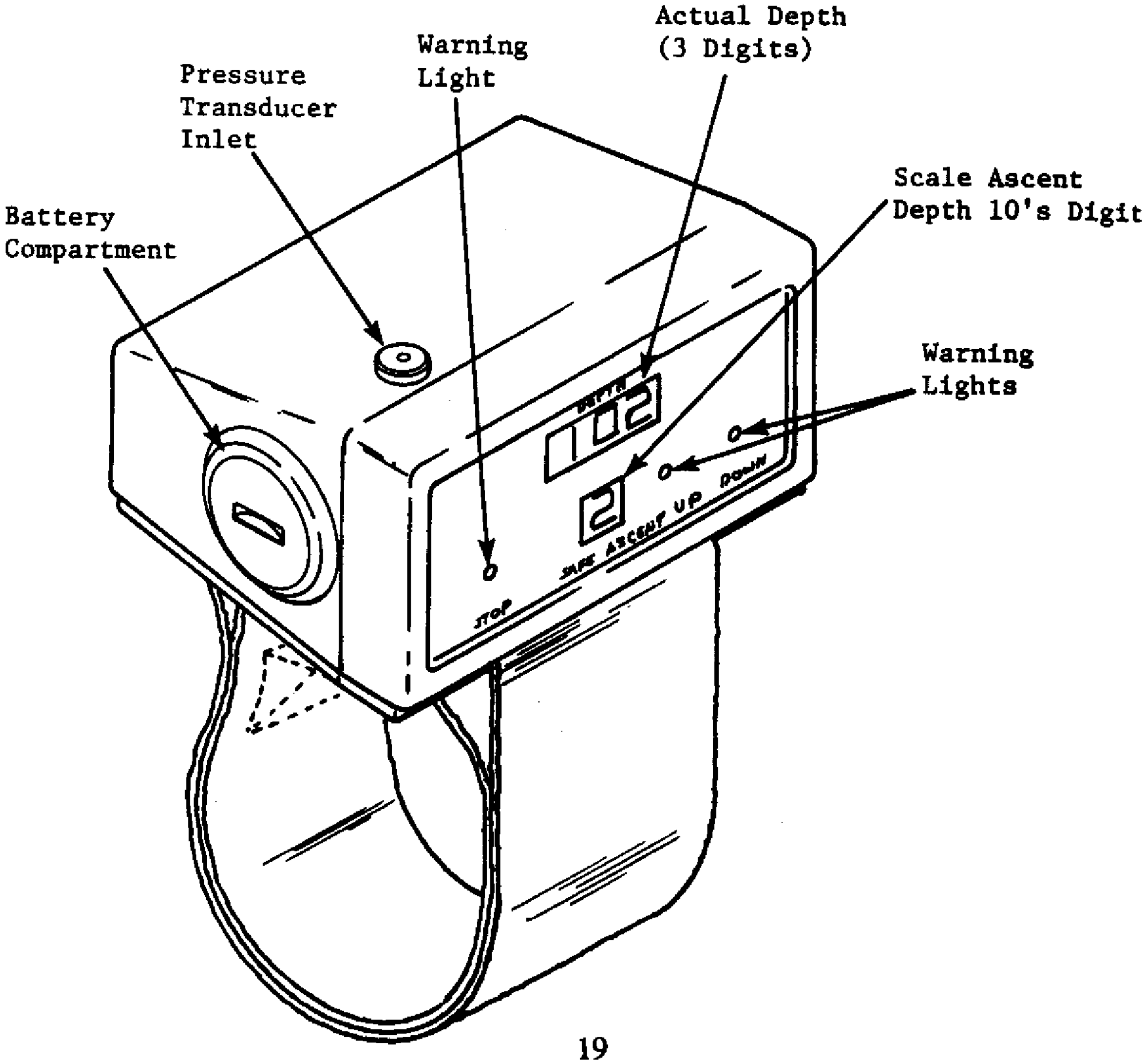


Figure 9 shows a preliminary design for the U.S. Navy UDC. This initial design incorporated only the "essential readouts for safely informing the diver of his decompression status." The display would show the present depth, a safe ascent depth (SAD), and three warning lights. The SAD display would present the first decompression stop depth as 10 fsw multiple. The "UP" light would indicate when the diver was deeper than the SAD, the "DOWN" light would illuminate when the diver was shallower than the SAD, and the "STOP" light would turn on when the diver reached the SAD. Decompression would be performed by moving up to the first decompression stop and waiting until the SAD decreases and the "UP" light comes on. At present the specifications for the unit have been modified such that the display now includes total dive time, total ascent time (total decompression time required from present depth to surface), time required at decompression stop until it is safe to move to the next decompression stop, and a battery level indicator (Presswood, 1986). Prototypes from Divetronics, Orca Industries, and Tekna have been submitted to NEDU and preliminary evaluations performed. However, at this writing it is not clear if the U.S. Navy has an operational UDC.

Decobrain I

The Decobrain I is a table-based decompression device. The tables which it uses are the five sets of Swiss tables that were available at the time it was designed. Each table is used for a different altitude range from 0 to 3500 meters above sea level. It was manufactured by a company in Liechtenstein called Divetronic. The unit (Figure 10), worn on the wrist, displays the diver's depth, bottom time, ascent time, and initial decompression stop. When the diver gets within two minutes of the no-decompression limit, two zeros blink in the decompression stop display. If a diver enters a decompression dive, the decompression stop display presents the first decompression stop depth and time. When the diver comes within 5 fsw of the stop depth, the decompression time counts down to zero and the next decompression stop is displayed. At the surface, the Decobrain displays the maximum depth and bottom time of the previous dive, the surface interval, and the desaturation time (time required to eliminate all residual nitrogen). The power source is a rechargeable NiCd pack which allows 80 hours of operation on a full charge (Hass, 1984).

Figure 10. Decobrain Decompression Computer (from Divetronics).

When the unit is turned on it reads the ambient air pressure and determines which of the five sets of tables to use. The decompression information for the subsequent dive is based on the table range that covers the ambient pressure sensed at initialization.

A unique aspect of the Decobrain I is that, even though it is table-based, it allows multi-level dives. This is done by having the computer perform multi-level computations using the table's repetitive group designators. The problem with this repetitive group technique is that only one compartment in the model is considered. In this case it is the 80-minute half-time compartment. None of the other seven compartments are considered in the computation of the Swiss table repetitive groups.

Dr. Bruce Bassett and this author separately performed tests on this device and found that the unit could easily be put into an "out of range" situation, rendering the unit useless as a decompression device. Also, *"The technical information and operating instructions supplied with the product are sorely lacking in the details needed to adequately use and interpret the device"* (Bassett, 1983).

AVAILABLE COMPUTERS

At this time there are eleven DC's available to the diving communities. However, there are, in essence, only three different decompression models that are used in these devices. Two of the models are based on no-decompression limits that have been determined by Doppler ultrasonic bubble detection (Spencer, 1976; Bassett, 1982). The other model is the Swiss decompression model developed by Dr. Bühlmann at the University of Zürich.

The EDGE:

The Edge (Figure 11) has been manufactured and distributed by Orca Industries since 1983. The model it uses is a twelve compartment Haldanian model that is based on Doppler research. The compartment half-times range from 5 to 480 minutes. Every three seconds the "nitrogen pressure" in the compartments are updated based on the new pressure that is read in through the pressure transducer. In the Haldanian based DC's the "on-gassing" and "off-gassing" of the compartments follow the same exponential rates. Any time the ambient pressure is greater than the compartment pressure on-gassing occurs and if the compartment pressure is greater than the ambient pressure nitrogen is off-gassed. The resulting pressure values in the twelve compartments are then used to compute the diver's decompression status.

The display on the EDGE is divided into graphical and digital information. The display is split into the two sections by a curve (limit-line) which represents the maximum pressure allowed in the twelve compartments (their Mo values). The display area above and to the left of the curve gives a bar graph representation of the pressures in the twelve compartments against a depth scale (running vertically down the left side of the display). As long as all the compartment bars are above the limit-line, the model is indicating a no-decompression dive and the diver can ascend directly to the surface. To the left of the depth scale is the depth bar which represents the divers actual depth and a maximum depth indicator. All the compartment bars will try to equilibrate to the same level as the depth bar. If any of the compartment bars have crossed the limit-line two "ears" start to move down the depth bar, indicating the ceiling, or minimum depth, the diver can ascend to without violating the model. To decompress the compartments that have exceeded their Mo values, the diver must ascend to a depth shallower than the value of the Mo value of the violated compartment in order for the required off-gassing to occur (Barshinger, 1984).

Figure 11. The EDGE No-Decompression/Decompression Computer

The digital section of the display presents the present depth of the diver, elapsed dive time, no-decompression/decompression time remaining, ceiling, and water temperature. The no-decompression/decompression time remaining display shows no-decompression time remaining as a positive number and decompression time remaining as a negative number. These times are based on the depth that the diver is at. If the diver is in a no-decompression dive and ascends, the no-decompression time will increase due to the reduced pressure gradient between the ambient pressure and the compartments. If the diver moves into a decompression dive and will not be able to decompress at the present depth an "up-arrow" will be displayed, indicating the diver will need to ascend in order to decompress.

At the surface, the display goes into surface mode. The graphical display will continue to indicate the compartmental pressures. The digital display however, will indicate additional information. The depth display will present the maximum depth of the last dive. The elapsed time display will alternate between the dive time of the last dive (in minutes and seconds) and the elapsed surface interval (in hours and minutes). The area which displayed the no-decompression/decompression time will scroll through the no-decompression times for repetitive dives to depths between 30 and 150 fsw.

Additional information can be displayed if the diver violates the recommended ascent rate (60 fpm at depths deeper than 100 fsw, 40 fpm for depths between 60 fsw and 100 fsw, and 20 fpm for depths shallower than 60 fsw), if the diver ascends to a depth shallower than the ceiling, or if the diver exceeds the depth range of the device (approximately 160 fsw depending on the pressure transducers' calibration). When any of these situations occur a full screen warning will be alternated with the normal display.

Skinny Dipper:

The Skinny Dipper is also a product of Orca Industries. It utilizes the same decompression model as the EDGE, but uses a simpler display scheme. The display on the Skinny Dipper consists of three numerical segments (no graphics) and two LED's. During a dive, the top number of the display is the no-decompression time remaining. If a diver passes into a decompression dive, the top number will convert to the ceiling depth. Since the Skinny Dipper was designed as a no-decompression computer, it does not display decompression time remaining. Even though it does not display decompression information other than ceiling, it blinks a message telling the diver to "go up" until a depth is reached where decompression can be achieved. The diver then waits until the ceiling reaches zero and can then surface. If the diver ascends to a depth shallower than the ceiling, the ceiling and depth displays will start to flash and the "Ceiling Alarm" LED will blink.

The middle number displays the present depth and the bottom number is the elapsed dive time. If the maximum depth of the unit is exceeded (199 fsw) an out-of-range display "or" will flash. If the diver is ascending faster than the recommended ascent rate the "Ascend Slower" LED will blink.

At the surface, the Skinny Dipper scrolls through allowable repetitive dive time for depths between 30 and 130 fsw. The no-decompression time is displayed on the top line and the depth of the repetitive dive is the center number. The elapsed surface interval is presented on the last line. After the no-decompression time for 130 fsw is displayed, the unit displays a "log" screen for nine seconds. This log screen presents the maximum depth and dive time of the last dive. On the top line a calculated time to fly is presented. This time to fly value represents the time it will take all the compartments in the model to reach a nitrogen pressure equivalent to 2 fsw or less.

Sigmatech:

The Sigmatech is distributed by Sherwood. It is a private labeling of the Skinny Dipper. Sherwood has incorporated it into a console along with a pressure gauge.

SME-ML:

The SME-ML is manufactured by Suunto of Finland and distributed by SeaQuest (Murphy, 1987a). It uses a nine compartment Haldanian model based on Doppler research. The half-time range of the compartments is 2.5 to 480 minutes. The display consists four numbers, a depth bar graph, and five warning icons. During a dive, the remaining no-decompression time is shown in the center of the screen. The depth is displayed at the top of the display and a depth bar descends along the scale on the left side and the dive time is shown at the bottom. A dive counter in the lower left corner shows how many dives have been done since the device was activated. If a diver enters a decompression dive, the ceiling is displayed by flashing the portion of the depth bar which is shallower than the ceiling and the required decompression time is shown in the center area along with an icon that indicates "Dec Time." If the ceiling is violated another icon appears indicating the diver should descend. If the diver violates the ascent rate of 33 fpm a "Slow" icon will be displayed.

At the surface, the unit scrolls through the no-decompression times for depths of 30 to 190 fsw. This will alternate with a display of the surface interval. A unique feature is that the device can be interrogated by touching its wet switches in a certain order. This produces a display of the maximum depth that was achieved every three minutes. The SME-ML stores ten hours worth of dive information that can be recalled at any time after the dive.

Datamaster II:

The Datamaster II is distributed by Oceanic. The decompression model it utilizes is pseudo-Haldanian consisting of six compartments with half-times of 5 to 120 minutes. Its Mo values are based on no-decompression limits determined by Doppler studies. The difference between this model and the previous ones is that no off-gassing from the compartments is allowed while on a dive. Once a compartment reaches its highest pressure during a dive, it will remain at that pressure even though the ambient pressure may be less. Off-gassing will begin once the device reaches the surface.

The Datamaster II also calculates air consumption. It is attached to the high pressure port of the regulator's first stage and its display is at the end of a high pressure hose. This allows the tank pressure to be displayed as well as air time remaining. The remaining air time is calculated based on the diver's average air consumption in the last minute, the air requirements for an ascent at 60 fpm to the surface, and reaching the surface with 500 psi of pressure in tank.

The remaining no-decompression time shares display space with the remaining air time at the lower right of the screen. If the remaining dive time is controlled by the decompression model then an "NDC" icon is displayed next to the time. If the remaining air time is less than the no-decompression time, an "AIR" icon is presented. To the left of the remaining dive time display is the "Caution Zone." This presents a numerical and graphical representation of the last ten minutes of no-decompression time remaining. It is recommended by the manufacturer that a diver never surface with less than +5 minutes in the caution zone. If a value of less than +5 is displayed then the diver should stop at 10 fsw until the display reaches +5. If the diver passes into a decompression dive, the caution zone number becomes negative. The diver will then need to stop at 10 fsw until a value of +5 is reached. Following a decompression dive, the unit will not display any decompression information for the next twelve hours.

Continuing around the display in a clock-wise direction is the present depth, maximum depth, water temperature, tank pressure, dive counter, and dive timer. When the diver surfaces the display will present display the surface interval time and computes a repetitive group letter based on the pressure of the 120-minute compartment. When the regulator is attached to a new tank, the display presents a scrolling display of no-decompression time from 30 to 130 fsw.

Data Scan II:

The Data Scan II (distributed by U.S. Divers) and the Datamaster II are the same unit with different display configurations (Murphy, 1987b). The Data Scan II presents the same information (except for temperature) as the Datamaster II plus a bar graph representation of the tank pressure.

Decobrain II:

In 1985, Divetronic released new software for the Decobrain package, Decobrain II. The Decobrain II (manufactured and distributed by Divetronic) is based on the 16 compartment Swiss model (ZHL-12) developed by Dr. Bühlmann at the University of Züurich. The half-times of the compartments range from 4 to 635 minutes. This unit is designed for altitude diving up to 4500 meters above sea level. It adjusts its Mo values based on the altitude it is being used at. During the dive, the unit displays the no-decompression time remaining and flashes the time when within five minutes of the no-decompression time. If a decompression dive is performed, the first decompression stop is displayed along with the shortest safe ascent time. The depth and dive time are displayed with the maximum depth displayed two times a minute for two seconds. An ascent rate LED will start to flash if an ascent rate of 33 fpm (10 mpm) is exceeded.

At the surface when the unit is turned on, it will display the atmospheric pressure in millibars and then will scroll through the no-decompression limits for 30 to 100 fsw. After a dive, it will display the maximum depth and bottom time of the dive, the surface interval required before flying, and the total time to eliminate all the residual nitrogen from the compartments.

Micro Brain:

The Micro Brain is manufactured by Divetronic and distributed by Dacor (Murphy, 1988). The model it uses has six compartments (4.5 to 395 minute half-times) that correspond to the 16 compartment Swiss model. It can be used as a decompression computer to altitudes of 1500 meters above sea level. During the dive, the no-decompression information is presented as a decreasing wedge at the bottom of the display. The wedge consists of seven bars that disappear as the no-decompression time decreases. The bars have values of "++", "30", "15", "8", "4", "2", and "0" minutes. Along with the wedge, the dive time and present depth is displayed. If a decompression dive is performed, the depth of the first decompression stop alternates with the depth display every five seconds for a second, along with a "Deco Stop" icon and an "Ascend" warning. If the diver ascends past the decompression stop a "Descend" icon is displayed.

At the surface, the no-decompression times for depths from 49 to 135 fsw are scrolled through. The maximum depth and dive time of the last five dives can be recalled using a wet switch. A "Do Not Fly" icon is presented while the model indicates that it is not safe for the diver to fly.

Uwatech:

Uwatech of Switzerland manufactures a DC for its own distribution as the Aladin (Murphy, 1987c). This DC is also distributed by Beuchat as the G.U.I.D.E. and Parkway as the Black Fox. The decompression algorithm used in this unit is a twelve compartment version of the Swiss model. The Uwatech DC utilizes four sets of Mo values based on the altitude range the dive is conducted in. These ranges are 0 - 2470, 2470 - 5100, 5100 - 8555, and 8555 - 13200 feet above sea level. During a dive, the no-decompression information is presented, in minutes, as a negative number in the lower right of the display. If a diver enters a decompression dive, it flashes "DEC" in the decompression information display, along with the depth of the first decompression stop. Once the diver reaches the first decompression stop, that depth will continue to flash until it is time to ascend to the next stop, which will be displayed. If the diver ascends past the required decompression stop, a flashing "DOWN" icon will be displayed along with a down arrow to indicate the diver needs to descend. Along with the decompression information, the diver's present depth is displayed in the upper left area of the screen and below it, the maximum depth attained during the dive. The total dive time is displayed above the decompression information area.

After the dive, the unit will present the maximum depth of the last dive and the elapsed surface interval. The Uwatech DC can be interrogated and the log entries for the last five dives can be recalled by activating two wet switches.

THEORIES AND MODELS VS. REALITY

One major misconception that is held by many divers who use DC's is that they monitor, or model, exactly what is going on in the body. A DC, like a set of decompression tables, can only be used as a guide, based on a **theoretical** decompression model. The ability of a model to produce safe profiles may or may not have anything to do with how accurately the model describes the mechanics of nitrogen on-gassing and off-gassing during those profiles.

In all decompression models the major (and in most cases the only) variables that are considered are depth and time. DC's compute their decompression status based solely on these two variables. Thus, the decompression status computed by a DC does not take into account water temperature, physical exertion, ascent rate (even though it is monitored in some cases), the divers physical condition, age, gender, hydration level, etc. These are all variables that are considered to affect the diver's susceptibility to decompression sickness. The result is that a strenuous dive to a certain depth in a cold water environment will produce the same decompression status in a DC as a low exertion dive to the same depth in a warm Caribbean environment. To counter these factors, the diver must assume the responsibility of adding safety factors to their dives while using DC's, just as they have been added in the past while using tables. DC's are not talismans that will guarantee the diver will not develop decompression sickness. They must be used with common sense and the diver must be aware of potential of developing DCS during any dive.

Another area where the dive computer may deviate from reality deals with the accuracy of the pressure transducer. As depth gauges, DC's have proven to be much more reliable than mechanical depth gauges. Their accuracy, in the worst cases, is listed at +/- 2 fsw (+/- .6 msw). During a dive, DC's perceive a depth that is 2 fsw shallower than the actual depth. If this occurs then the nitrogen pressure that is calculated will be less than the actual pressures that should have been calculated. The DC is computing a less strenuous decompression status than it should be. Preliminary calculations indicate that a reduction of the Mo values to 95% of their current values would adjust for the potential transducer error. This would have the effect of reducing the no-decompression limits as much as 20% in the shallower depth ranges.

FUTURE CONFIGURATIONS OF DIVE COMPUTERS

With the growing acceptance of DC's, the ability to incorporate additional features seems to be limited only by imagination and technology. Two functions that should be available soon are the ability of a DC to communicate with a personal computer (PC) and, full dive profile recordings. The ability to communicate with PC's will permit easy reprogramming of the dive computer if modifications are made to its software. The PC could also be used as a diagnostic tool by interrogating the various components of the DC.

Along with these functions the ability to "talk" to a PC presents an easy way to log dive information. By incorporating additional memory into the DC, the actual depth of the dive can be recorded every few seconds. After the dive, this information could be downloaded into the PC and the actual dive profile displayed along with any other recorded information from the dive. This dive profile information could be used in decompression research or in the treatment of a diver who has developed DCS.

Another feature that could easily be incorporated into a DC would be a safety factor multiplier based on various environmental and physical variables such as water temperature, diver exertion level, actual ascent rate, age, etc. Information on the diver could be entered via the PC and other information obtained from additional sensors in the DC. The major problem with the implementation of this feature would be the determination of the safety factors for these additional variables. At present, there is no quantitative correlation between these variables and their increasing or decreasing the risk of DCS.

Perhaps the ultimate DC would be one that actually monitors the gas absorption and elimination in the diver throughout the dive. This would allow decompression status to be determined by observing the diver the DC is designed to protect.

SUMMARY

The diving community is becoming more aware of the advantages dive computers offer in terms of multi-level diving credit and computation of decompression status. But, studies of multi-level diving and development of reliable and safe dive computers must make up the 30-year head start of table-based SCUBA diving techniques.

As more dive computers become available, they must be thoroughly tested to ensure operational and decompression model integrity and reliability. Although the technology of DC's is improving rapidly, and in the future we can expect to see more sophisticated devices with additional functions and features, it must be remembered that as long as the decompression status is based on a model, it does not necessarily represent the diver's actual decompression status. The final responsibility of the diver's decompression still falls upon the diver. The diver may or may not choose to use the information displayed by the DC and should make common sense decisions based on personal limitations and environmental conditions.

It is interesting to speculate about the present state of scuba diving if the Foxboro Decomputer Mark I had performed properly and had been adopted for U.S. Navy use in 1956. If so, the present U.S. Navy air decompression tables might not have been computed and the standard tool used to determine decompression status might have been a dive computer. Dive computer technology would be far more advanced, and more information and studies about the effects of multi-level diving would be available today.

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INTRODUCTORY SESSION DISCUSSION

Discussion after Andy Pilmanis

Andy notes, among other things, that the typical scientific diver keeps up with the field, is interested in the physiology of diving and asks a lot of questions. He also made the point that scientific divers try for as much time as they can get on the bottom and sometimes have rather long bottom times. They also do multiple repetitive dives. You may see a small boat pull up with eight or ten tanks in it. These divers are very dedicated. When they go out on a ship, they try to get in all of the dives that they can.

In reflecting on the experience of his treatment chamber, he has noted that over the last couple of years more and more divers arrive wearing a dive computer. He emphasized that they are wearing it, which doesn't mean that they have looked at it. Some don't look at them, some don't even turn them on, some don't know the brand. They know the color but not the brand. Whether the DC was on or not, the patients always say they "did everything right" although the story tends to change after we probe into it and after the buddy shows up. If the diver is asked, "Did you use a depth gage and a watch?", the answer is, "Oh, no". They seem to know something about the tables and may actually know how to use them, but they didn't do it. Andy is not sure that for any of the treatments they've had of people wearing these computers, that they have used them properly. This is difficult data to find and assess and the temptation is strong to listen to "sea stories." Andy encouraged the Workshop not to listen to sea stories and not to base their recommendations on them.

Carl Edmonds supports the careful use of statistics by being very critical of the facts behind bends incidences using DC's. The second type of untruthfull statistics is the opposite, such as statements which say we've documented 50,000 dives and no one got bent on our DC. The School of Underwater Medicine recorded about 200,000 dives on the US Navy tables with no bends, while we were never near the limits of the tables.

Tom Neuman comments that as another "unbender" he very much endorses what Andy says about the people arriving at the chamber. If they have a watch, they don't know what time it is, if they have a computer, they haven't looked at it. He also mentioned a profile that he used in a treatment which was recovered from a dive computer which records the dive profile (the Suunto). He made a strong statement as to how important the ability is to record and retrieve a dive profile and called for training for the treatment facilities to be able do this.

Some general comments were made by Andy on the value of hard data and the fact that if we really don't know what has happened we can't very well assess it.

Andy is asked if he is seeing more neurological "hits" than he has in the past. He is seeing fewer hits, but this is probably because there are more chambers in use now. He thinks that the total patient load is staying stable. He warns about trying to determine "incidences" without knowing what kind of diving was being done.

Glen Egstrom pointed out that the problem with the dive computers is the same as with a lot of the other equipment that recreational divers use. They are not fully trained in its use to begin with, and they use it only occasionally. This is true of every piece of equipment they use. It is imperative that the divers not only be informed but that they go through drills on how to use it. He mentioned as an example having college students run the dive computers on decompression tests that he was doing in the lab. They screwed them up in about every way that could be done.

Andy noted that it is possible nowadays to take a diving course without being trained in how to use a dive computer. It is up to the individual to learn it. Divers should be able to receive instruction on the DC use.

Dennis Graver asked us to think about what training should the divers get on the dive computers and who should be providing it.

Ralph Osterhout makes the point that we need standardization of several aspects of the computers:

Standardization of information that is displayed;
The manner in which it is displayed;
The manner in which it is recalled;
Standardization of the computational model;
Uniform means of telling when a computer is in a "fault" mode

Ralph made some good points about spatial integration, where the same spot on the display is used to show different pieces of information at different times. He feels that the evidence is good from other fields (such as the USAF), that for important and timely data the best way to go is to use shape or color or something more to sort out the nature of the information. He makes a strong statement for absolute standardization at any cost, even if manufacturers have to make changes in their equipment and software, his company is willing.

There was agreement with the idea but great skepticism as to whether it might be made to happen. It might be a higher hurdle than anyone expects. Ralph responds we might not have complete standardization of cars, but at least it is not necessary to look in the glove box for the speedometer.

Discussion after Karl Huggins

Someone mentioned another new DC called "Monitor", which is a Bühlmann table-based device that Carl did not cover in his talk. Mike Lang mentioned the Black Fox is apparently no longer being marketed. Karl responded that the slides were over a month old. He mentioned that the computer only reads depth and time and not the individual factors or environmental factors that affect decompression.

Parker Turner asked why the manufacturers insist on forcing slower ascent rates when the divers can't even maintain 60 fsw/min. Karl Huggins responded if the instruments call for slower rates, say 20 or 30 fsw/min, then maybe divers will slow down to 60 fsw/min. He said somebody had checked the ascent rates and found them to be 120 fsw/min, or even faster than that. Ralph Osterhout mentions tests that asked divers to ascend at their normal rate and when actually measured their average rate was 112 fsw/min.

There was further discussion about the role of ascent rate. Bill Hamilton mentioned slower ascent rates to be beneficial. While it may have some effect on gas loadings, a more important effect of a rapid rate may be that it can induce bubble formation. Glen Egstrom asked Karl Huggins if we should be promoting a 30 fsw/min ascent rate and not allowing the 100+ fsw/min ascent; Karl agreed. Dick Vann said there is no experimental proof that the ascent rate is a significant factor as far as risk of decompression sickness is concerned. However, the faster ascent rates definitely increase the possibility of pulmonary barotrauma, and this is the cause of many cases attributed to DCS. Karl also pointed out still another benefit of restricted ascent rate in that it ensures that the diver will have good buoyancy control and this will pay off in overall safety. They tend to lose control at about 20 feet and just pop to the surface. It was generally agreed that the divers seemed to lack common sense and that the instructors were "delighted that they have the little black boxes so they do not have to think". This is a large part of the problem.

The discussion swung around to the matter of being able to recall a dive profile. Chuck Mitchell asked if "in a treatment, don't you just put a diver down until he doesn't hurt anymore?". Tom Neuman said that wasn't quite the case, in fact, you use an arbitrary depth that is almost totally independent of the depth of the dive. He also mentioned a case where he was able to recover a dive profile from a Suunto unit. The diver had told him his profile and he didn't believe it until he saw the data come out of the dive computer. Tom pointed out that having the profile could be a help in treatment, but its greatest potential value will come from the retrospective analysis of the data. Some units allow recall of the times, depths, and intervals of the last few dives. In another DC this information can be recalled only be the manufacturer (See Appendix).

In another discussion John Lewis mentioned that the Data Scan records violations in the use of the DC, and that it coarsely records the last 3 dive profiles. This information is not available to the user, but can be accessed by the manufacturer.

ORCA INDUSTRIES' DIVE COMPUTERS

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The ORCA Industries EDGE Dive Computer was the first model based dive computer available to recreational divers. After six years in the field, and the release of the SkinnyDipper as the second in the series, over 1.5 million dives are estimated to have been made using the ORCA decompression model. Bends incidence to date has been minimal, and less than comparable rates using the U.S. Navy tables. ORCA continues to improve hardware and software, and plans to release the third computer of the series in 1989.

ORCA Industries was formed in 1982 to develop a revolutionary element of diving technology, the EDGE Dive Computer. The EDGE was unique because it was the first of the model based dive computers. With its capability for multi-level and repetitive diving, the EDGE extended dive times and increased productivity for working divers. Its graphic tissue-tracking display has helped educate many divers about the mathematics of decompression. Since it implements a ceiling depth, instead of fixed stops, for dives requiring decompression, it allows diving flexibility which was previously unavailable.

The EDGE is a large unit, with a full range of decompression functions, many of which are unnecessary for the average recreational diver. In 1987, ORCA added the SkinnyDipper as the second computer in the series. Using the time-tested ORCA model, SkinnyDipper was designed with the recreational diver in mind. It presents an instinctive display of information, consisting of remaining no-decompression time, depth, and dive time, and doesn't have the EDGE graphics. SkinnyDipper is smaller, lighter, and less expensive than EDGE, and has proven to be very popular. Although it doesn't have the EDGE's capability for decompression information display, it does display a ceiling depth and doesn't lock up or shut down in decompression mode.

ORCA remains the leader in Dive Computers, and will present the third computer in the series at DEMA 1989. The new computer, as yet unnamed, will implement strong points of both EDGE and SkinnyDipper, and should prove to be a very capable machine.

WARRANTY DATABASE

ORCA maintains a computer database of EDGE and SkinnyDipper warranty information. Included in the database are the owner's name and address, of course, but also information about the owner's diving style and frequency. Analysis of the database shows that EDGE and SkinnyDipper owners are relatively similar people, which was not expected given the different marketing targets.

EDGE owners return warranty cards for 65% of all units sold. They are, in general, older divers who can afford the more expensive computer, with 56% over 35 years of age, and only 7% younger than 25. They report an outstanding number of dives per year, the database average is 82 for those who responded. The different age groups report different averages, with the under 25 group at 101 dives/year, the 25-35 group at 91 dives/year, and the over 35 group at 75 dives/year. This is understandable, since many EDGE owners take multiple, intensive dive trips each year, and justify the expense of the instrument by the increased diving that it provides.

SkinnyDipper owners only return warranty cards representing less than 30% of all units sold. They have a similar age distribution to EDGE owners, with 7% under 25, 33% 25-35, and 60% over 35. They report a smaller number of dives per year, with a database average of 62. The averages for the different age groups is also less than the corresponding EDGE group, with the under 25 group making 65 dives/year, the 25-35 group making 75, and the over 35 group making 54.

This information on the age distribution and diving frequency of ORCA computer owners allows us to estimate the number of dives represented by the warranty database. It is assumed that each computer only makes half the normal dives during the year that it is purchased, except for SkinnyDippers in 1987, which are only given 25% of annual dives due to late release. The individuals in the database not reporting age and dive information are assumed to have a similar distribution to those who did report. Finally, the average number of dives per year for each age group is assumed to be 50 dives/year for each EDGE, and 38 dives/year for each SkinnyDipper in the field for the full year. All assumptions are chosen to be conservative, so as to underestimate the number of dives performed.

Including only warranty data, and not dives by the entire owner population, at the end of 1987 there had been 207,000 dives on EDGE, and 12,900 dives on SkinnyDipper. At the end of 1988, only within the warranty database, EDGE will have logged 430,000, and SkinnyDipper 112,600. This data is presented in spreadsheet form in the appendix.

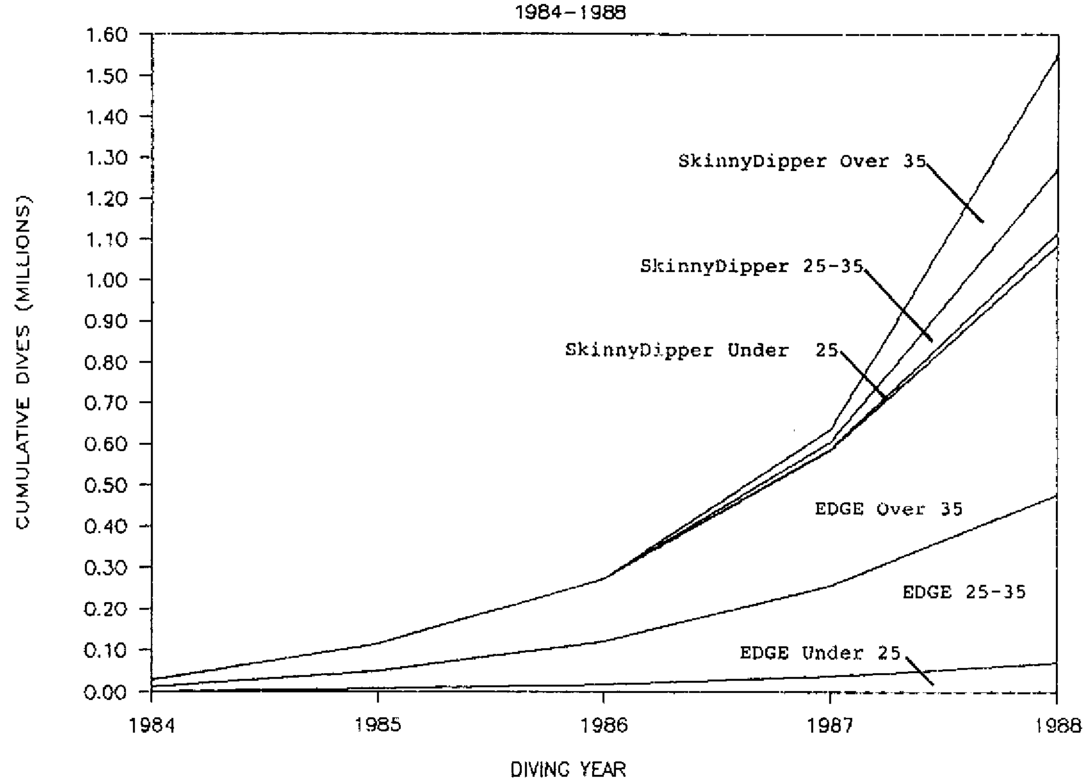
The analysis of cumulative dives can be extended to the entire ORCA computer owner population. Those owners not represented in the warranty database are assumed to be similarly distributed to those who returned warranty cards. In making this estimation, production records are used to represent the number of new computers in the field each year. Computers using the ORCA model made by other manufacturers are not included in this analysis. Other assumptions are identical to those made in the warranty database calculations.

Figure 1 shows the estimated cumulative dives for all ORCA computers from 1983 to the end of 1988. Contributions from the three different age groups and both computers are shown. The steady growth of EDGE dives can be seen, with cumulative totals of only 30,000 in 1984, 115,000 in 1985, 274,350 in 1986, and 584,725 by the end of 1987. By the end of 1988, EDGE dives will have reached over one million. The influence of SkinnyDipper is seen beginning in 1987, with 50,000 additional dives on the ORCA model, for a cumulative total of over 635,000. With 466,000 SkinnyDipper dives by the end of 1988, there will have been over 1.5 million dives made on the ORCA model.

Although Figure 1 also shows the breakdown of dives by age group, in addition to computer type, it is difficult to see the exact distribution of age group. Figure 2 displays this data directly, showing that, for the year-end 1988 data, 57% of the dives are made by the over-35 group, 36% by the 25-35 group, and only 6% by the under-25 group.

While it is not possible to place an exact number on the size of the ORCA decompression model diving exposure, these extremely conservative estimates can give us a general idea of the scale involved.

Figure 1. Cumulative dives on ORCA computers

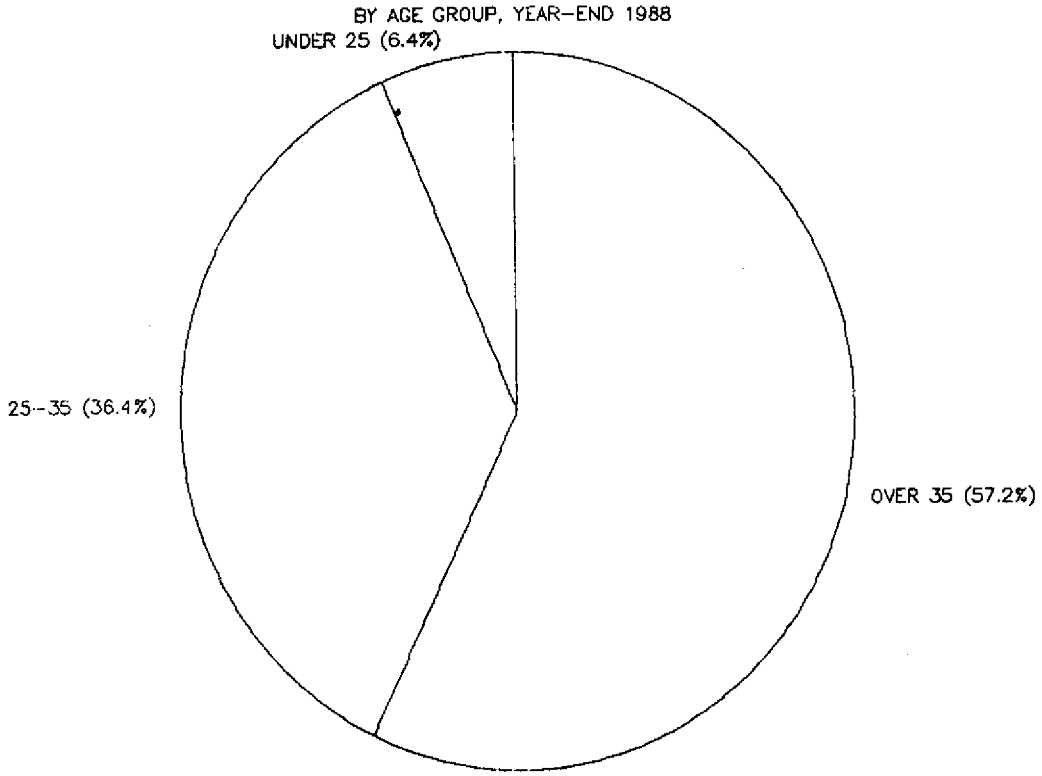


BENDS INCIDENCE

At the 1988 Annual Scientific Meeting of the Undersea and Hyperbaric Medical Society, Joel Dovenbarger presented a paper prepared by Vann, Dovenbarger, Wachholz, and Bennett, discussing dive computer bends cases. There were 38 cases, effective year-end 1987, experienced by users of dive computers. Cases of obvious user error were discarded, as were inappropriate reports such as that of the person diving with a buddy who wore an EDGE. All 38 cases were not attributable to persons wearing EDGE or SkinnyDipper, as other computers are available. For the purposes of discussion, let us assume that all cases were marks against the ORCA decompression model, or the use of model based dive computers in general.

In his February 1988 Diving Medicine Column in Skin Diver Magazine, Dr. Fred Bove cites bends incidence figures for the use of the U.S. Navy Standard Air Decompression Tables. The source of his figures and the assumptions involved is not mentioned. It is not unreasonable to assume that the figures represent the gross bends incidence attributable to the Navy tables within the Navy diving population. Furthermore, we should note that these figures are based on people diving the tables in the real world, with whatever errors and fudge factors this involves. His figures are 9 cases per 100,000 dives for dives within the no-decompression limits, and 38 cases per 100,000 dives for decompression dives. The U.S. Navy makes predominantly single no-decompression dives, with single decompression dives less common. The Navy tends not to make repetitive, multi-level, no-decompression dives over a number of consecutive diving days, which is extremely common to recreational diving vacations.

Figure 2. Distribution of cumulative ORCA dives



Using the cumulative dives on the ORCA model and the number of reported bends cases at year-end 1987, the gross bends incidence of the ORCA model is 6 cases per 100,000 dives. Since this is for all dives, not just no-decompression, it does not correspond directly with either of the U.S. Navy statistics. It compares favorably with the 9 cases/100,000 Navy no-decompression figure, and is one-sixth of the decompression dive figure. This is in spite of the typical computer vacation dive history of 3-5 multi-level dives per day, for five to fourteen day trips. These numbers can only provide a conservative rough estimate, given the errors of reporting and the uncertainty of the denominator, but they lead us to accept the ORCA decompression model for the depths and exposures typical for recreational divers.

ORCA PHILOSOPHY

ORCA is constantly alert for ways to fine-tune the hardware or the decompression model to the benefit of recreational divers. The EDGE/SkinnyDipper algorithm is not valid at altitudes above 2000 feet, as it becomes less and less conservative at increasing altitude. An altitude algorithm has been developed for use in future computers which will eliminate the problems of using ORCA computers above sea level. This algorithm will produce the time-tested ORCA model at sea level, and adjust conservatively for altitude exposures.

We listen to our computer owners, and others interested in future dive computers, and try to implement their suggestions for the improvement of the next generation of dive computers. Such features as better graphics, display lighting, dive profile logging, and more are being considered for new products.

ORCA is also seriously interested in education and training of the diving population, as we feel that the best and safest computer owner is a well educated diver and consumer. We support instructor training programs and the development of dive computer specialty courses in the scientific community, all recreational agencies, and the military. We plan on continuing as the major force in dive computers into the next decade, as well as the next millenium.

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APPENDICES

A. ORCA EDGE Warranty Database Summary Statistics

WARRANTY CARDS ON FILE

	Age Group			Age	
Year of Purchase	1	2	3	Missing	Total
1984	NA	NA	NA	166	166
1985	NA	NA	NA	225	225
1986	28	233	438	511	1210
1987	149	877	1238	97	2361
1988	76	370	533	27	1006
Year Missing	0	1	1	1584	1586
Total	253	1481	2210	2610	6554

PERCENTAGE OF WARRANTY CARDS ON FILE

	Age Group			Age	
Year of Purchase	1	2	3	Missing	Total
1984	NA	NA	NA	2.53	2.53%
1985	NA	NA	NA	3.43	3.43%
1986	0.43	3.56	6.68	7.80	18.46%
1987	2.27	13.38	18.89	1.48	36.02%
1988	1.16	5.65	8.13	0.41	15.35%
Year Missing	0.00	0.02	0.02	24.17	24.20%
Total	3.86	22.6	33.72	39.82	100.00%
Percent Response	6.41	37.55	56.03		

AVERAGE NUMBER OF DIVES PER YEAR FOR THOSE REPORTING

	Age Group			Age	
Year of Purchase	1	2	3	Missing	Total
1984	NA	NA	NA	NA	NA
1985	NA	NA	NA	NA	NA
1986	133	105	82	102	91
1987	112	92	74	72	83
1988	69	80	70	69	74
Total	101	91	75	82	

DIVES REPRESENTED BY THE WARRANTY DATABASE

	Average Number of		1984	1985	1986	1987	1988
Year of Purchase	Dives/Yr	Owners	Dives	Dives	Dives	Dives	Dives
1984	50	166	4150	8300	8300	8300	8300
1985	50	225		5625	11250	11250	11250
1986	50	1210			30250	60500	60500
1987	50	2361				59025	118050
1988	50	1006					25150
CUMULATIVE			4150	18075	67875	206950	430200
ANNUAL			4150	13925	49800	139075	223250

B. ORCA SkinnyDipper Warranty Database Summary Statistics

WARRANTY CARDS ON FILE

	Age Group			Age	
Year of Purchase	1	2	3	Missing	Total
1987	77	442	817	21	1357
1988	168	839	1477	51	2535
Year Missing	0	3	4	282	289
Total	245	1284	2298	354	4181

PERCENTAGE OF WARRANTY CARDS ON FILE

	Age Group			Age	
Year of Purchase	1	2	3	Missing	Total
1987	1.84	10.57	19.54	0.50	32.46%
1988	4.02	20.07	35.33	1.22	60.63%
Year Missing	0	0.07	0.10	6.74	6.91%
Total	5.86	30.71	54.96	8.47	100.00%
Percent Response	6.40	33.55	60.05%		

AVERAGE NUMBER OF DIVES PER YEAR FOR THOSE REPORTING

	Age Group			Age	
Year of Purchase	1	2	3	Missing	Total
1987	84	78	57	82	65
1988	56	74	52	181	60
Total	65	75	54	62	

DIVES REPRESENTED BY THE WARRANTY DATABASE

	Average Number of		1987	1988
Year of Purchase	Dives/Yr	Owners	Dives	Dives
1987	38	1357	12892	51566
1988	38	2535		48165
CUMULATIVE			12892	112623
ANNUAL			12892	99731

THE DATAMASTER II
A FUNDAMENTALLY DIFFERENT DIVE COMPUTER

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INTRODUCTION

At the present time, there are ten or more dive computers being sold within the United States. They come in a wide variety of sizes and shapes, and each displays data that is relevant to a diver. They all incorporate state-of-the-art electronics that produce exceptionally accurate and reliable measurements of depth and time. Only one uses a table calculation, and all of the rest rely on a mathematical model or algorithm to predict the decompression status of a diver. In my judgment, the most important contribution that the dive computer has made to recreational diving is the introduction of accurately monitored multi-level diving, a concept described by Graver (1979), and more recently verified by the experiments of Huggins (1983) and Powell (1987). Since the table calculation design represents no advantage beyond a table, I will not discuss it further. Instead, I shall focus on the algorithms, wherein lies the fundamental and profound difference between the Datamaster II and all of the remaining dive computers.

DECOMPRESSION THEORY

The decompression theory originally conceived by Haldane and his co-workers (Boycott *et al*, 1908) and used by Workman (1965) to produce the U.S. Navy Diving Tables predicts the nitrogen loading of six hypothetical tissues or compartments. Each compartment is assigned a "half-time" and a maximum allowable surfacing value known as an "M-value". The U.S. Navy no-decompression limits and all ten foot decompression stops are derived by calculations based on these twelve numbers.

At a constant depth, the solution to the governing equations can be expressed as an exponential function of time, and the model previously described is commonly referred to as an "E-E Model". This model predicts that the uptake and elimination of nitrogen takes place at the same rate. The algorithm used by the EDGE is an E-E Model, and the term EDGE-like refers to this model and all dive computers that use it.

The U.S. Navy Repetitive Dive Tables represent a major departure from this theoretical model. Residual nitrogen times are based on the slowest (120 min) compartment (des Granges, 1956). The algorithm designed for the Datamaster II accurately replicates the residual nitrogen time of the U.S. Navy Repetitive Dive Tables. It achieves this not by a table look up, but by allowing the 120 min compartment to control repetitive diving.

On a single dive, multi-level or not, the performance of the Datamaster II and the EDGE will be difficult to distinguish. The reason for this is that multi-level diving is governed by depth dependent compartment control and not by nitrogen elimination. Since the EDGE and the Datamaster II have similar no-decompression limits, they produce very similar multi-level profiles.

Repetitive diving is an altogether different issue. The EDGE will allow significantly more bottom time than the Datamaster II for repetitive dives, with the difference most pronounced for deep dives and short surface intervals.

Ordinarily, what works is what counts. However, when it comes to decompression sickness what does not work is the more important issue, and in the next section I shall review the data base.

DATA BASE

"Remember when discoursing about water to induce first experience, then reason"....Leonardo da Vinci

Any applied mathematician confronted with Haldane's theory, Workman's M-values, and des Granges' need to construct a single table for all repetitive diving contingencies is logically lead to the conclusion that a micro-processor programmed with an E-E Model is the proper design solution for a dive computer. Thalmann (1984, 1986), while lead to this obvious conclusion, was nevertheless prudent enough to test it. The following are quotes from Thalmann's reports:

> *"The most significant finding of this study was the failure of the E-E Model to adequately compute safe repetitive dive profiles without seriously reducing no-decompression limits"...Thalmann (1984)*
>
> *"While it appears that some increases in repetitive no-decompression times are likely, the E-L Model predicts some times that are too long"...Thalmann (1986)*

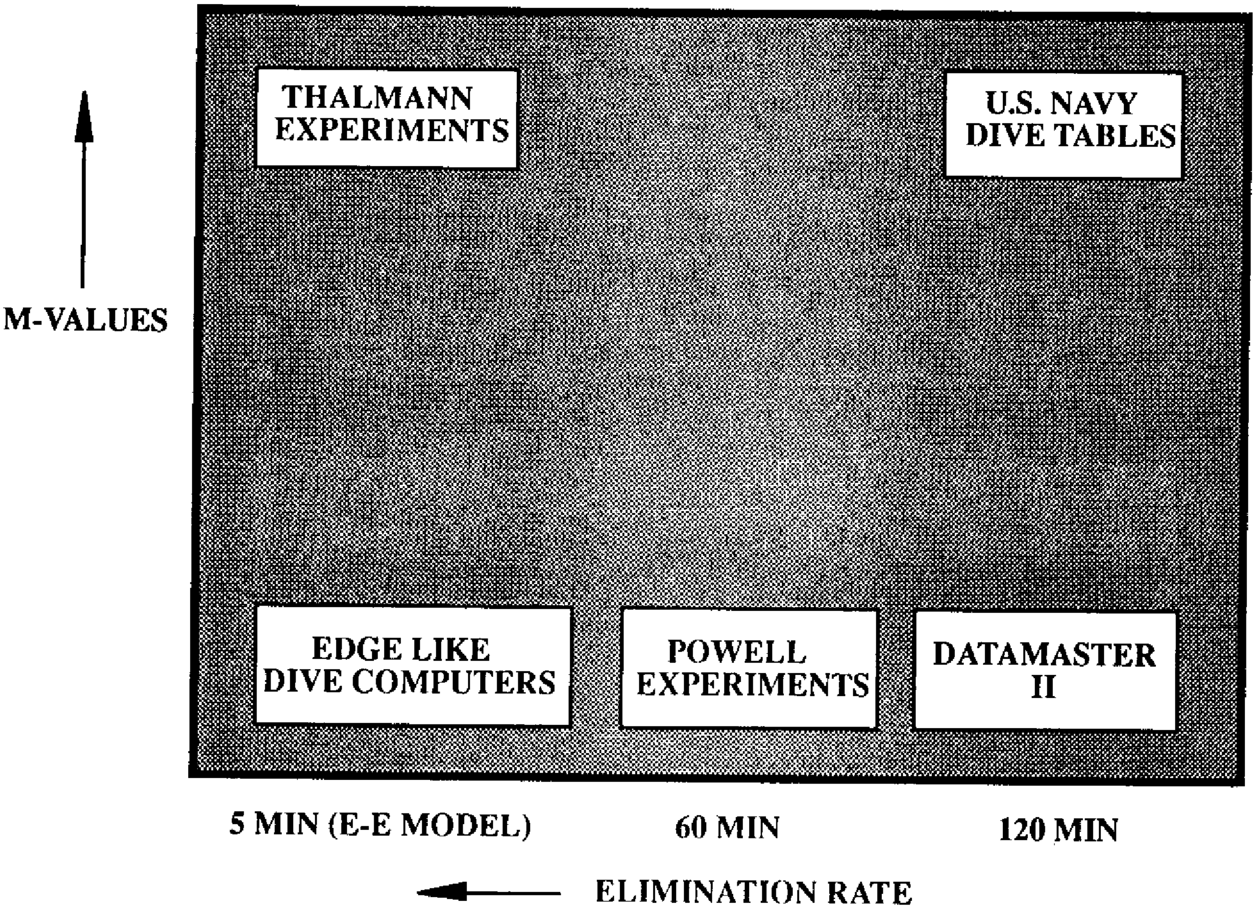
The E-L Model that Thalmann refers to in the second quote has a linear elimination that is more conservative than an E-E Model, but is less conservative than the U.S. Navy Repetitive Dive Tables.

One can only conclude that repetitive diving at the U.S. Navy no-decompression limits cannot be reliably predicted using an E-E Model. However, it is important to note that both the EDGE and the Datamaster II have reduced no-decompression limits. The ultrasonic Doppler experiments of Spencer (1976) demonstrate a substantial reduction of bubble formation for reduced no-decompression limits, and it is certainly plausible that this can be expected to lead to a reduced risk of decompression sickness. The question is whether this alone is sufficient or whether a slower elimination algorithm is also necessary for repetitive dive control.

Figure 1. is an attempt to qualitatively illustrate the design envelope, those regions that have been validated, and those that have been demonstrated to fail. The vertical axis represents M-values that are directly related to the no-decompression limits for a single dive. The horizontal axis represents elimination half-times, which control repetitive diving. The E-E Model allows the 5 min. compartment to relax with a 5 min. time scale, whereas the U.S. Navy effectively uses a 120 min. time scale for all compartments when dealing with repetitive dives.

The U.S. Navy Dive Tables fall in the upper right hand corner of Figure 1., and they represent the most extensive data base that we have, namely thirty years of demonstrated reliability. If one adds to this experience the data of Spencer, one arrives at the design of the Datamaster II that lies in the lower right hand corner. In the upper left hand corner is a region demonstrated by Thalmann to produce unacceptable DCS. In the lower left hand corner are the EDGE-like dive computers, and this is largely uncharted territory. Largely, but not entirely. Edmonds (1988) tested the EDGE against several deep (120 to 147 ft) repetitive dives that the Royal Navy had shown produced DCS after the third exposure. The EDGE not only allowed the third dive, but several thereafter.

Figure 1. Dive computer design envelope



All EDGE-like dive computers will allow repetitive dives to depths in excess of 120 ft, with surface intervals of less than 60 min., and with bottom times of the repetitive dives virtually identical to that of the first dive. These profiles are undeniably unsafe and should be avoided. Edmonds' admonition to restrict repetitive dives to 30 ft is probably overly conservative, but in the absence of further testing, it is not possible to quantify what is a safe depth for repetitive dives using these dive computers.

While the EDGE-like dive computers are unsafe for some set of repetitive dives, the Datamaster II is more conservative than is necessary for perhaps an even larger set of dives. When the Datamaster II was first designed, the U.S. Navy Dive Tables represented the only significant data base for repetitive diving. That is no longer true. In 1987, Powell presented the results of a series of experiments that were designed to produce a new set of dive tables for recreational divers (Powell, 1987). The premise was that recreational divers never reach the limits of compartments slower than 60 min, and therefore repetitive dive times could be substantially increased. Whether this hypothesis stands the test of 6 dives per day for 6 days in a row remains to be seen. Regardless, this important data set demonstrates that there is a substantial region of intermediate depths and times for which the U.S. Navy Repetitive Dive Tables, and thus the Datamaster II, are overly conservative. Unfortunately, these data do not include repetitive deep dives nor repetitive shallow dives with long exposures. The former is a direct test of fast compartment elimination, and the latter is a test of slower compartment buildup.

A dive computer should allow what has been shown to be safe, but must not allow what has been shown to be unsafe. Further, it should not allow dive profiles that are radical departures from those that have been tested. An algorithm is not magic. It is simply a means by which one can extrapolate limited experience to new circumstances, and it is only as reliable as the data base upon which it has been tested.

SUMMARY

The Datamaster II Dive Computer utilizes a decompression algorithm that is profoundly different than other presently available dive computers. The performance of the Datamaster II and any EDGE-like dive computer will be remarkably similar for a single no-decompression multi-level dive. For repetitive diving, the Datamaster II will be considerably more conservative. Arguably, the Datamaster II is too conservative for some intermediate depth repetitive dives. Demonstrably, the Edge-like dive computers are unsafe for deep repetitive dives, and at present it is not possible to define a safe depth for their use when repetitively diving deeper than 30 ft.

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THE SUUNTO SME-ML PRESENTS THE CONCEPT OF MULTI-LEVEL DIVING

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It is a warm clear day, the sky is cobalt blue and only scattered clouds off in the distance break up the horizon. The water is glassy calm. It is a perfect day for diving in the Western Caribbean. The kind of day that you would travel halfway around the world for. In fact, most of the divers on board the small dive boat had done just that.

This was their one week. The week they saved and planned and dreamed about for the last year. Dreams about this one week were often the only thing that made life in the hustle and bustle of the "day to day grind" bearable. Despite the perfectness of the Caribbean scene, the divemaster had a problem.

There were a dozen divers on board. Varying degrees of skill, physical condition, knowledge, and temperament. Almost half had some type of dive computer.

"OK, here is the plan" the divemaster started. "The top of the reef is at approximately 40 feet here, the maximum depth for this dive will be 100 feet. I don't want anyone to descend below me! Those of you diving with tables, be back on the boat in 20 minutes. The ones diving with computers must be back in an hour, no matter how much air you have left!" He raised his voice to make his point.

The faces of the "table divers" grew long. Why were they being penalized? the divemaster had seen this reaction before. It is a scene that plays itself out literally hundreds of times each day.

The diving industry is currently examining the way we dive, how we track those dives and how we teach decompression theory. Now, more than ever before, all diving professionals need to have a greater understanding of basic decompression theory. Like it or not, we are in the midst of a great technological revolution in recreational diving.

There is a desperate need to provide more information to those interested in applying this new technology to their diving activities. It will be up to the diving instructors to determine how the industry makes the transition to multi-level diving. It is now, and always has been, the instructor's job to educate divers about the proper use of new technology, advances in equipment, and changes in diving practices. Dive computers are no different. And we can all rest assured that this is not the last technological advance that will come along and affect our sport.

You will notice that we started this article by calling it "computer-assisted" multi-level diving, not computer controlled. The diver will always be in charge and any claims to the contrary are misleading and wrong. Both Sea Quest, Inc. and Suunto of Finland firmly believe that there is a "NEED TO TEACH" the principles that go into the design and proper use of dive computers. Not just ours, but all such devices. No one has come up with a way to replace common sense, diving skills and the basic concepts of decompression theory.

Instruction on the proper use of multi-level diving techniques goes far beyond the typical owner's manual of our computer, or any device, including tables of all configurations. This belief led us to develop a support program designed to assist diving instructors. The "NEED TO TEACH" program includes: Instructor guides, student work books, dive planning slates, multi-level log books, and two different instructional videos.

We sought out noted diving authorities such as Dr. George Lewbel, Dr. Bruce Bassett, Dr. Sylvia Earle, Dr. Tom Neuman, Dr. Tom Rhodes, and many other specialists, to help us present this information in a way that could be used by any qualified instructor, regardless of certifying agency.

Our instructional program is designed to allow instructors to structure and teach according to their chosen diving philosophies and their student's needs. The instructors can adapt the program's aides to their diving communities' regional differences and to the practices of their certifying agency.

WHY THE SME-ML IS THE WAY IT IS

The Suunto SME-ML is a true multi-level dive computer. It takes into account all the various depth segments of a dive and the precise amount of time spent at each depth, mathematically modeling theoretical nitrogen in-gassing and out-gassing according to appropriate pressure differentials. We modified the Haldanean model, which has been the basis for almost all decompression schedules since the early 1920's, by incorporating the Doppler meter silent bubble research done by Dr. Merrill Spencer.

In designing their standard decompression schedules, the U.S. Navy constructed a mathematical model based on 6 different "tissue" compartments. When it came time to figure repetitive dives, there were so many possible combinations of dive time, maximum depths and surface intervals that the immense number of calculations required made it impractical for them to continue using all 6 compartments. As a result, repetitive diving with the Navy tables is based on a mathematical model for a single compartment. You must remember that these tables were designed before the computer age. Use of a single compartment was the easiest and most practical way to devise a repetitive schedule that was a fairly low priority, and for an organization that had a massive roster of divers to call upon.

The Suunto SME-ML calculations are always based upon a mathematical model that contains 9 compartments, the 6 compartments found in the Navy tables plus 3 additional compartments. In addition, the SME-ML produces half times ranging from 2.5 minutes to 480 minutes, in comparison with the Navy tables' 5 to 120 minute half times. This expands the range and makes more conservative the mathematical approximation of the diver's body, and still applies both to repetitive dives and to first, or single, dives.

The SME-ML's "low bubble" no-decompression limits, by design, allow less nitrogen to build up in the compartments than the U.S. Navy tables. Each compartment has a reduced Maximum Allowable Pressure (M.A.P. or "M" value) which reflects a more conservative estimate of the body's ability to hold excess nitrogen upon surfacing. An excellent example of this is the no-decompression limit for the first dive to 60 feet: the U.S. Navy tables allow 60 minutes at 60 feet and the SME-ML allows 53 minutes at 60 feet.

More importantly, the SME-ML incorporates a slower ascent rate, 33 feet per minute, to permit a more gradual release of excess nitrogen as the diver ascends.

If a diver using the SME-ML ascends faster than 33 feet per minute, the "SLOW" warning will blink on the diving display.

The diver can slow down or stop coming up until the "SLOW" warning disappears, as long as he does not ascend above 10 feet. If "SLOW" is still flashing at 10 feet, the diver must stop there until it goes off. Should the diver surface with the "SLOW" on (definitely not a recommended practice), the "SLOW" warning will remain on until the next dive, or until the unit shuts down - a reminder for the diver to adjust ascent rates (an instructor can easily see who is having problems in this area and work with those individuals).

Our number one goal in designing the SME-ML was to present the diver with all of this valuable information in a straightforward, easy to read display. One that would only show the information that was significant at a given moment. The Suunto SME-ML features an uncluttered screen that only displays diving information while the unit is underwater, and surface/dive planning information while it is on the surface.

Next we thought that it was very important to eliminate the need for external switches. No external switches means no holes in the housing that might cause the DC to flood. Regardless of this benefit, it was the fact that we did not want the DC to be switched off (either accidentally or in uneducated attempts to prolong battery life) while it was still calculating residual nitrogen levels between dives, that lead to the development of the rubber contacts that activate and recall the dive profiles. Simply stated, the Suunto SME-ML can not be turned off during a repetitive dive series.

The surface interval display of the SME-ML automatically begins to show dive planning information to help plan the next dive at the end of the dive just completed. As the surface interval increases, so does the available dive time for the next dive, based on the residual nitrogen level in each of the 9 compartments the SME-ML uses as a model for its calculations.

The SME-ML continues to track residual nitrogen in all 9 compartments on the surface until they no longer affect no-decompression limits. It automatically shuts down when all 9 compartments are "clean" of residual nitrogen. It is not at all uncommon for an SME-ML to remain on much longer than the standard 12 hours the Navy tables call for, particularly if you have been diving heavily.

Sea Quest and Suunto saw the need for what is in essence an underwater flight recorder. A memory capable of recording precise data, an exact dive profile. We realized how quickly maximum depth and total dive time would become insufficient information when true multi-level diving techniques were applied. (How can you explain a maximum depth of 110 feet with a total dive time of an hour or more when only this simplistic information is available?)

The Suunto SME-ML features the ability to recall up to ten hours of dive time, and display it in 3 minute increments. This information can be easily organized into accurate dive profiles that graphically display a diver's true exposure at various depths.

Dive profiles are extremely helpful in post dive debriefings. Did the student execute the dive plan for this dive? Did a student exceed the maximum depth limit set for this dive? Did the student make a safety stop at the end of this dive? The many applications of the "underwater flight recorder" function of the SME-ML are just starting to be understood. It is a new tool for a new era in diving. Part of the challenge and part of the excitement of introducing these new concepts into diving instruction will be the proper application of these new tools.

At this time we all must realize the changes our sport is going through and that it is up to us, as diving professionals, to master these new tools and techniques so that we can share this information with the rest of the recreational diving community. Decompression theory has always been a complex and fascinating subject. With such a multitude of new tools and techniques, computer assisted multi-level diving is a subject that you could write a book about, and, in the process of creating our support program, we have.

The Suunto SME-ML is the state of the art in dive computers. We truly believe that. We want you to learn as much as you possibly can about decompression. We are convinced that the more you know, the better we will do in the market place. The more you teach, the safer our sport will become.

MANUFACTURER'S SESSION DISCUSSION

Discussion after John Lewis

John was asked to comment on the fact that the unit did not outgas (Lewis calls this "relaxation," in reference to the mathematical exponential "decay" at a rate proportional to the difference in gas partial pressures) at the surface. John pointed out that this function does not affect the behavior of the unit in multi-level diving, where it continues to outgas in a manner about 10 fsw more conservatively than the model of the USN tables.

Discussion in manufacturer's session

[EDITOR'S NOTE: No papers were received from Al Carpenter (Beuchat), Mark Walsh (Dacor), or Chuck Locke (U.S. Divers), but since the presentations were made, we feel some discussion should be included. Chuck Locke provided the DC comparative tables in the appendix.]

Presentation by Al Carpenter

Al Carpenter is West Coast sales representative for Beuchat USA. The dive computer sold by Beuchat in the U.S. is the same as the Aladin and Black Fox. Beuchat has no design or manufacturing function, and only distributes it in the U.S. as the G.U.I.D.E. The DC was developed in Switzerland by the Uwatech Co. This unit is based on the research of Dr. Bühlmann. It uses six compartments and has four sets of parameters for four different altitudes. First is sea level to 2470 feet altitude, 2400 to 5100, 5100 to 8555, and 8555 to 13200. The unit senses the altitude.

A big problem is that people have trouble turning the unit on. You start it by dipping it in water or by wetting your fingers and touching the two contacts. It is now ready to go into the dive mode. You have ten minutes to get it into the water or the unit will shut down. If it does shut off and then you go into the water, it will flash an error and you have to go back and start over. It displays two rows of numbers and letters and six group areas. A 3.6 lithium battery gives 5 years or 800 diving hours. It has 13 functions in the readout. The first is contact activation. It will activate at 4 feet of depth and its depth is good from 4 feet to 315 fsw. It has a maximum depth indicator. You have to come up 4 fsw shallower than the maximum depth in order to get it to lock on to the maximum depth. It shows your remaining no-d time, flashing "deco warning" on a digital display. You have to stop at 10 fsw stages to 80 fsw. As soon as you clear a depth, it clicks to the next depth.

If you pass a stop coming up, it tells you to go back to that stop and it locks into that mode. It won't outgas at the surface if a stop is missed, it will just add on to the previous dive if you do another dive. It goes into a ten minute surface interval mode after a dive in which you cannot access anything or change anything. It is waiting to see if you are going to make another dive within 10 min, in which case it will calculate it as part of the previous dive. In other words, the minimum surface interval is ten minutes.

There are two probes you can contact to access the log of the last five dives. It gives you maximum depth, total dive time and surface interval time. This surface interval would not last if you made a dive yesterday. There is a low battery indicator, and the user can change the battery. You do however lose the memory when you change the battery. It is sold as a console or as a wrist unit, at $699 and $450. There are two console models, a two-port and a three-port, which also has a compass, and there is an instructor's model.

Presentation by Mark Walsh

Mark Walsh is the project engineer for Dacor, responsible for the MicroBrain. This dive computer was developed with Divetronics, Switzerland. It uses the P3 model, a modified version of the Bühlmann-Hahn P2-3, with 6 compartments, from 4 to 397 minutes. It comes in several configurations, wrist and console, and an instructor's model with a potentiometer on it for simulating dives. There is also a simulator program that runs on an Atari available to dealers and instructors. An IBM PC version is coming out in January. They have a user's guide for dealers and instructors, but he mentioned that they are not an instructor organization and would like the input of the training agencies.

The MicroBrain runs from 0 to 330 fsw, and assumes sea level to be 0.95 bar. It is altitude adjusting, from 0 to 4920 feet and from 4920 to 6560 feet. It has a range for equilibration, and it takes less time to equilibrate if you are already partly at altitude. Above 6560 feet it does not compute no-stop times because this is not well enough known. It then becomes a precision depth gage and bottom timer. It records the most recent six dives in the last 48 hour period and is considered to be a no-decompression and multi-level computer. It scrolls no-d information before the dive from 51 to 130 fsw in 10 fsw increments. It uses depths of 51, 61, 71, 80, 90 and so on, due to rounding off of conversions from metric. It does no-d down to 250 fsw, where you get two minutes. While it is a no-decompression profiler, it does give you decompression information. Ascent rate is 33 to 40 fsw per minute. It switches from no-d time to decompression time required, with stops to as deep as 100 fsw. It is a conservative model.

If you miss a stop, it gives you a descent warning, and takes you down to where you need to go to do your decompression. If you do not go down, or if you omit a decompression stop, it goes "out of range". Another out of range condition is total elapsed time of more than 199 minutes, in which case it shuts down for 24 hours. The "bottom time" is the total dive time.

It is encased in silicone with two three-volt batteries soldered in place inside. It is supposed to be good for 10 years at 100 dives per year. If you need to send it back for a new battery, they will send you another unit and then extract the electronics from the gel of the former. It shows your diving time as bars on a triangle, which gets smaller as your available dive time is reduced. You activate the unit to get the scrolling by touching the contacts and then you activate it when you begin the dive by doing the same thing. You can zero the unit with a special magnet, allowing more than one person to use the same unit. Of course when you do this, you can't dive again until the next day because the residual gas is lost.

Presentation by Chuck Locke

Charles E. Locke is manager of R&D for U.S. Divers, who market the Data Scan II. The Data Scan II is functionally the same unit as Oceanic Datamaster II, but has a slightly different display that shows the same information. In the console version there is an algorithm for managing air usage.

Chuck mentioned development of a new unit. Their affiliate La Spirotechnique is talking to Uwatech about a Bühlmann-based unit, the "Monitor".

A great deal more information about this unit, and the others as well, is given in a comparison prepared by Chuck Locke and included in the appendix.

The next question was for more information on the air consumption algorithm which John Lewis, designer, responded to. It keeps track of the breathing rate parameter which is consumption normalized at depth. If you double the atmospheric pressure, you double the consumption. It makes that approximation so that alterations in depth, are taken into consideration. It is a running average of your particular consumption.

Flying after diving

Most of the units have a "safe to fly" mode. Someone asked what criteria are used to be able to say this. The Suunto has to outgas to a point less than 2 psi over ambient pressure. This was challenged by Mike Emmerman, who has data on a number of divers who have developed DCS in aircraft in a wide variety of gas loading statuses, even as much as 41 hours after a dive. The message is, we probably do not have enough data to make this decision. Ralph Osterhout maintained, however, that we need some sort of criterion for this function, and this was agreed.

It was further pointed out that 12 hours is considered a safe post-dive time to go flying, but that it may take 19 to 20 hours to clear the 480 minute compartment down to 2 psi over ambient. Flying as long as 5 days after extensive diving has resulted in symptoms. One opinion is that calculations of gas loadings may have little bearing on when it is safe to fly. It is probably the bubbles and how long they persist.

Dick Vann points out that we really cannot say it is "safe to fly", that all we can do is choose an acceptable degree of risk. How do we make this decision? There is no line between "safe to fly" and "not safe to fly". All we have is a gradual reduction of risk. Divers frequently, due to contingencies like bad weather, will choose to fly after a dive. They normally get away with it. Even though there is no hard line, we feel it is necessary to set some kind of limit.

Mike Emmerman has gathered 47 cases where the diver had been a "D diver" (USN repetitive status, which is the point considered safe to fly) or better, for 7 to as many as 40 hours before flying, did not show symptoms before flying, but had symptoms in the aircraft or shortly after landing. There was not enough data to reconstruct either the dive profile or even a "body" profile of the person.

Ralph asked if DEMA might sponsor data collection, perhaps through DAN, to help get a data base together. He feels sure that researchers like those in this Workshop could make something of it.

Bill Hamilton reported a workshop held by the U.K. Diving Medical Advisory Committee convened because the helicopter pilots in the North Sea were concerned about hauling divers to shore after they had been diving. When the group was asked for data, the silence was deafening. There were very few documented cases to report. The workshop was swung by a report of 15,000 diver-trips following a rule of flying no sooner than 12 hours after diving, with no reported problems. This does not mean 15,000 divers flew 12 hours after diving, but that the rule had that data base behind it. That rule was adopted. That group would not be specific about nitrox saturation diving, but felt it should be over 48 hours.

The Workshop carried on to list the values for flying after diving of the various DC's represented here.

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

The value given by Max Hahn applies to the MicroBrain. Max explained that the lowest pressure one should encounter in a commercial aircraft is 0.65 bars, and that having a ceiling of 0.58 bars should be well within this limit (this is about 8,000 feet of altitude). This is a ceiling, not the inert gas pressure in the tissue. This might take as much as 24 hours. Those DC's not mentioned do not have indicators.

John Lewis, whose DC does not have this function, suggests that to get good data this will have to be done experimentally. Glen Egstrom notes that this will take some years at best, but that it is acceptable to go on with the current criteria.

Bill Hamilton warned that this talk illustrates the hazard in making decisions of this sort, that it is easy to get narcotized by the numbers and begin to believe them.

"Lockup" mode

The discussion turned to the maximum depth allowed, with concern expressed by many that the depths allowed are too deep. The values are in the Appendix. Some of the units go "out of range" or otherwise stop working when the depth is exceeded. This led to further discussion of the matter of the DC's shutting down when they might be needed most. One reason for this is that when the diver has "violated" in certain ways, there is no good algorithm for getting him/her out of that situation with confidence. Example: When the diver omits a stop on ascent, the computer will see a faster outgassing, but what is more likely, is that the diver has provoked bubble formation and needs more time, not less, to get to the surface.

In the cases where the DC's stop computing, they usually continue to provide time and depth information and it is up to the diver to use that to get to the surface.

A number of suggestions were made about how to handle the violating diver. There seemed to be agreement that the diver in this situation cannot go unpunished. It was even suggested that the DC should shock the diver when he violates, or that it should "break" or go into a lockup mode that requires a $100 repair bill to get it going again. While there was agreement that the violation should be punished, when to do it and how to do it was not agreed upon. Another thing that was agreed by most is that we prefer the DC's to continue to compute for the diver who has violated.

There is a dilemma here, because the focus of the thinking ranged from the novice student diver to the experienced scientific diver, and the viewpoints seemed to be reflected in the part of the elephant touched by each blind man. Some wanted the units not to go deeper that 130 fsw, because that is the "limit" for recreational divers, but the realities are that the reasons they buy the units is for more aggressive diving. A major theme throughout this and other discussions is the strong belief that the recreational divers need more and better training. Whether the DC's should limit their diving was not agreed on at all.

It was pointed out that we were here with concern for the scientific diver, who may dive to as deep as 190 fsw, if qualified, and his DC should do the job. But scientific divers also operate under a much higher order of discipline and are far more diligent about obeying the rules, since there is a lot at stake. Even so, the entire diving community will note the conclusions of this Workshop.

There was of course a plea to standardize the criteria for the "lockup" mode. The Workshop did not do that, instead charged the manufacturers with providing some means of getting out of these violation situations, and to not have the DC stop computing.

Units

When the matter of units came up, Bill Hamilton pointed out that one cannot correctly use the linear conversion factors between feet and metres as units of length when pressure is the parameter involved, because the definitions are different:

One msw = 1/10 bar = 10 kPa

One fsw = 1/33 standard atmosphere = 0.030705 kPa

Therefore the conversion between the pressure units is

One msw = 3.2568 fsw

One fsw = 0.30705 msw

DIVE COMPUTERS - THE AUSTRALIAN EXPERIENCE

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Many of the current generation of dive computers, such as the ORCA EDGE, are suitable for measuring and recording various dive parameters, such as depth, time, temperature, etc. They are suitable for single fixed-depth dives, up to and including 120 feet, and probably for some single multi-level dives, if sufficient care is taken to ensure a conventional dive plan, e.g. diving from deep to shallow. Their use in a repetitive dive situation should be discouraged.

INTRODUCTION

The Royal Australian Navy School of Underwater Medicine first started testing dive computers (DC's) during 1972, because of decompression sickness cases with the SOS meter. A study of this meter showed that it needed shorter decompression times than required by the U.S. Navy decompression tables, when used for repetitive dives and for dives in excess of 60 feet (Quick, 1974).

The School continued to test computers as they produced problems in our diving population. The Farallon Multi-Tissue Decomputer was studied (West and Edmonds, 1976), but was considered unacceptable because of its unreliability. The DECO-BRAIN suffered a similar fate (LeSur, 1985).

For the same reason, in 1986, the Orca EDGE was subjected to similar trials to determine whether it was, as it claimed to be, safer than the U.S. Navy Tables (Edmonds and Anderson, 1987).

The publicity for the ORCA EDGE was accepted uncritically by commercially based Sport Diving magazines (Murphy, 1985). A report in Undercurrent (Anonymous, 1986) was complimentary to the EDGE. Like other magazines available elsewhere, the support was made without any specific testing of dive profiles.

ASSESSMENT OF DIVE COMPUTERS

In testing the performance of dive computers, the following questions must be asked.

1. Is the computer reliable, i.e. will it give repeatable results?
2. Is the computer accurate? This refers to the basic parameters that the computer is measuring, i.e. depth, time, surface interval, ascent rate, etc.

3. Are the results physiologically acceptable, i.e. will they result in relative freedom from decompression sickness if the computer or table is followed accurately?

Four ways are listed, in ascending order of practical value, to decide if a computer is physiologically acceptable.

1. Testimonials and personal experiences.
2. Compliance with decompression theories.
3. Compliance with established diving tables.
4. Comparison with hazardous diving profiles.

The diver's testimonial

In the absence of more substantial evidence, manufacturers are likely to resort to time honored techniques of testimonials from satisfied customers. Patent medicines and many DC's have been successfully marketed on this basis, supported by a veneer of scientific knowledge.

The use of a prestigious diver, in an advertising campaign to promote the computer, is really no different to the "testimonial", and should be treated accordingly.

Experience from practical divers may be of value in identifying problems with equipment. Occasionally, they report these problems, but more frequently they just make allowances for them.

The only way to determine whether a computer or a table is safe, is to repeatedly dive it to the limit allowed by the computer or the table. If this is not done, the safety of either the computer or the table is not demonstrated.

Compliance with decompression theories

Many computer, both past and present, have claimed to adhere to the principles of decompression theory. The fact that there is no agreed single theory of decompression, makes this claim questionable. During this century there have been numerous respected theories of decompression, which have eventually given way to amendments, modifications and sometimes rebuttal. Comparisons of current theories show the number of relevant "tissues" to be in dispute; as is the importance of perfusion and diffusion models; the importance, site and size of naturally or induced, nuclei and/or bubbles, etc. This does not imply a unanimity of opinion.

The theories on which the conventional decompression tables are based, have had to be subjected to empirical modifications to produce a final safe working table. One would have to be an optimist to believe that dive computers would be exonerated from a similar fate.

Compliance with conventional tables

Because the tables have been progressively modified to delete unsafe profiles, they serve as one way to assess dive computers. It is valid to compare the decompression requirements of the tables with the computer, when they are subjected to the same fixed level dive profiles, both for single and repetitive dives.

The plethora of reports emerging from Weathersby and others from the U.S. Navy on Equal-Risk Decompression Tables, and the number of amateur divers who get DCS from using them, does not suggest that comparisons with the U.S. Navy Tables are too rigorous.

Compliance with hazardous protocols

If we had enough information about what dives produce decompression sickness, then a comparison with the computer, to ascertain whether the computer permits such dangerous profiles, could indicate non-acceptability.

Practical limits of no-stop dives have been determined by Hawkins *et al.*, Van der Aue *et al.*, Berry *et al.*, and Albano, with more conservative recommendations by both Spencer and Bassett. If a computer allows greater duration than these no-decompression limits, then the computers would not be acceptable.

Less information is available on decompression dives, but these are not common in sport diving practice, and do not receive attention in this report.

Repetitive diving is more frequent, but there is little information on which repetitive dives are unsafe (Leitch and Barnard, 1982). Two sets of repetitive dives were found in the Royal Navy to be unacceptable during in-water trials, because of DCS. These were tested on Royal Navy divers who were experienced and well acclimatized prior to the trials.

1. Triple dives to depths between 120 and 140 ft. (36 - 42 m.) were performed for durations of 10 minutes with surface intervals of 120 minutes. 21 such dives were performed with 4 cases of DCS requiring treatment.

2. Triple dives to 147 ft. (45 m.) were performed, with a one hour surface interval, without problems in the chamber dives. When transferred to the open water, one diver got bent on his second dive, and the others reported transient aches at the end of the triple dives. These dives were for a maximum of 5 minutes (the mean bottom times were between 3 min.17 secs. and 4 mins. 8 secs).

Minimal information is available on the safety limits of multi-level diving (Huggins, 1983; Huggins and Somers, 1981)

METHODOLOGY

A series of trials are reported here, comparing the no-decompression dives permitted by the ORCA EDGE with RNPL/BSAC Tables, the U.S,. Navy Tables, and two hazardous dive profiles.

All the initial trials were done in the RAN.SUM small recompression chamber (Barshinger and Huggins, 1983) with 3 ORCA EDGE computers. Others were included as they became available (such as the SUUNTO ML, Aladin, SkinnyDipper) and were subjected to various trials, both at the school and elsewhere and comparisons were also made between the computers themselves and the Bühlmann tables (Lippmann, in prep.).

Tests on the SUUNTO USN dive computer are not referred to here, as the concepts and the results with this computer are substantially different to the others, which allow very similar profiles.

We decided to restrict our trials to only those dives that the computers allowed without decompression. So we're talking about non-decompression dives according to the computers. Our intent was to test the claim that the computer was safer than the U.S. Navy tables.

We found the computers to be extraordinarily reliable recording instruments of depths, durations, temperature,' etc. This technical achievement should not be underestimated.

Single dives

All the no-decompression dives to fixed depths (in 10 feet increments) were performed. Twenty others were performed at various depths.

Repetitive dives

Single depth.

The depths chosen in the first ten repetitive dive series (Tables 1-3) were constant, i.e. there was no variation in the depth between the first and subsequent dives. The 3 depths chosen for testing were midway in the metric range of the RNPL Tables, in an attempt to reduce the bias in either direction. They were 17 meters (56 feet), 31 meters (102 feet) and 43 meters (141 feet). These had the safety factors associated with "rounding up" of depths and durations that may make the tables more conservative.

Multiple depths.

The next 6 repetitive dive series (Tables 4,5) were carried out to different depths.

Two more repetitive dive series were especially selected from the U.S. Navy Tables to avoid the safety factors in "rounding up" of depths, durations and surface intervals (Table 6,7).

Hazardous dive profiles.

These two sets of repetitive dives were replicated by the dive computers:

1. Repetitive dives to 140 feet for 10 minutes each, and surface intervals of 120 minutes (Table 8).
2. Repetitive dives to 147 feet for 5 minutes each, and surface intervals of 60 minutes (Table 9).

Both these schedules were slightly more stressful than the reported in-water exposures.

RESULTS

NONE of the dives tested required decompression, according to the computer.

Accuracy and reliability of basic dive parameters

Dive parameters, including depths, maximum depths, durations, surface intervals and temperatures, were recorded accurately.

Single depth dives

The no-decompression times permitted by the computers were compared to those depicted in the manual and seen during the "scrolling" of the meter on the surface. Small discrepancies were noted.

For example, the EDGE manual (Barshinger and Huggins, 1983) stated that the "no decompression" time for 140 feet was 7 minutes. The scrolling stated 8 minutes and the actual bottom time (leaving surface to leaving bottom) on a practice dive with a descent rate of 60 feet per minute, was over 9 minutes. For most of the dives to 130 feet or more, the allowed bottom time was 1-2 minutes greater than claimed in the instruction manual.

For depths to 120 feet, the bottom time allowed by the computer was less than the U.S. Navy Tables, but often more than the Spencer or Bassett no-decompression times. Beyond 120 feet the computer was usually less conservative.

Repetitive dives to single depths (Tables 1-3)

In all the repetitive dive series performed above, decompression was omitted by the computer, compared to the U.S. Navy and RNPL/BSAC tables.

REPETITIVE DIVES TO 17m, 56ft, TABLE 1

DIVE	Bottom	Surface	Omitted Decompression Stops	
			U.S. Navy	*RNPL/BSAC**
1a	60 mins	60 mins	0 mins	10 mins
2a	45 mins	11 mins	14 mins	90 mins
3a	8 mins		26 mins	90 mins
1b	60 mins	120 mins	0 mins	10 mins
2b	56 mins		14 mins	60 mins
1c	60 mins	60 mins	0 mins	10 mins
2c	45 mins	11 mins	14 mins	90 mins
3c	8 mins	120 mins	26 mins	90 mins
4c	41 mins		14 mins	120 mins

However, in comparing the omitted decompression from the tables, 2 minutes extra decompression could be credited to the EDGE for each dive, to make allowance for the slower ascent rate at shallower depths. If this is done, the EDGE still omitted decompression, as judged by the U.S. Navy Table, in 29 of the 30 repetitive dives. The results were as follows:

In the repetitive dive series to 17 meters (56 feet), there was omitted decompression of between 10 and 46 minutes (U.S. Navy) and between 66 and 302 minutes (R.N.).

REPETITIVE DIVES TO 31m, 102ft, TABLE 2

DIVE	Bottom	Surface	Omitted Decompression Stops *U.S. Navy*	 *RNPL/BSAC**
1a	17 mins	300 mins	0 mins	0 mins
2a	17 mins		3 mins	10 mins
1b	17 mins	120 mins	0mins	0 mins
2b	17 mins	277 mins	7 mins	15 mins
3b	17 mins		7 mins	115 mins
1c	17 mins	60 mins	o mins	0 mins
2c	17 mins	37 mins	23 mins	30 mins
3c	15 mins	134 mins	54 mins	105 mins
4c *	17 mins		34 mins	155 mins
1d	18 mins	30 mins	o mins	0 mins
2d	16 mins	30 mins	23 mins	30 mins
3d	13 mins	30 mins	54 mins	105 mins
4d	11 mins	30 mins	54 mins	125 mins
5d	8 mins		54 mins	155 mins

REPETITIVE DIVES TO 43m, 141ft, TABLE 3

Dive	Bottom	Surface	Omitted Decompression Stops *U.S. Navy*	 *RNPL/BSAC**
1a	7 mins	60 mins	1 min	0 mins
2a	7 mins	105 mins	9 mins	10 mins
3a	7 mins	165 mins	9 mins	25 mins
4a	7 mins		9 mins	85 mins
1b	7 mins	30 mins	1 min	0 mins
2b	7 mins	30 mins	9 mins	10 mins
3b	7 mins	30 mins	32 mins	25 mins
4b	7 mins	30 mins	57 mins	85 mins
5b	7 mins	30 mins	57 mins	105 mins
1c	8 mins	60 mins	1 min	0 mins
2c	8 mins	60 mins	9 mins	15 mins
3c	8 mins	60 mins	21 mins	55 mins
4c	8 mins	60 mins	32 mins	105 mins
5c	8 mins	60 mins	57 mins	115 mins
6c	8 mins	60 mins	57 mins	160 mins
7c	8 mins	60 mins	57 mins	off tables
8c	8 mins		57 mins	off tables

In the repetitive dive series to 31 meters (102 feet), there was omitted decompression of between -1 and 175 minutes (U.S.N.) and between 6 and 315 minutes (R.N.).

In the repetitive dive series to 43 meters (141 feet), there was omitted decompression of between 21 and 275 minutes (U.S.N.) and between 112 minutes and "off the page" (R.N.).

Repetitive dives to different depths (Tables 4-7)

The 6 dive series to various depths (49-148 feet) had the EDGE omitting between 24 to 172 minutes (U.S.N.) and 87 minutes to "off the page" (R.N.).

The 2 series of dives especially selected to avoid the "rounding up" safety factors of the U.S. Navy Tables, resulted in an omitted decompression of 18 and 56 minutes by the computer.

REPETITIVE DIVES TO DIFFERENT DEPTHS, TABLE 4

DIVE	dive	depth	Bottom	Surface	Omitted Decompression Stops	
	Ft	*m*			*U.S. Navy*	*RNPL/BSAC**
1a	56	17	60 mins	30 mins	0 mins	10 mins
2a	108	33	12 mins	102 mins	34 mins	155 mins
3a	56	17	38 mins		14 mins	off tables
1b	102	31	16 mins	219 mins	0 mins	0 mins
2b	122	37	10 mins	14 mins	4 mins	10 mins
3b	132	40	6 mins		26 mins	85 mins
1c	62	19	50 mins	30 mins	0 mins	10 mins
2c	102	31	11 mins	180 mins	34 mins	155 mins
3c	102	31	13 mins	30 mins	23 mins	155 mins
4c	62	19	35 mins		33 mins	off tables
1d	55	17	60 mins	60 mins	0 mins	10 mins
2d	115	35	10 mins	60 mins	30 mins	155 mins
3d	55	17	45 mins	60 mins	26 mins	off tables
4d	115	35	5 mins	60 mins	30 mins	off tables
5d	115	35	10 mins	60 mins	46 mins	off tables
6d	115	35	10 mins		46 mins	off tables
1e	49	15	75 mins	180 mins	0 mins	10 mins
2e	82	25	25 mins	120 mins	18 mins	85 mins
3e	115	35	10 mins	60 mins	30 mins	off tables
4e	148	45	8 mins		57 mins	off tables

REPETITIVE DIVES TO INCREASING DEPTHS, TABLE 5

Dive No.	Depth	Depth	Bottom	Surface
	m	*Ft*		
1a	15	49	75 mins	360min
2a	25	82	25 mins	120min
3a	35	115	10 mins	60 mins
4a	45	148	8 mins	U.S.N>100 MIN DECO R.N.> 5 HOURS DECO

REPETITIVE DIVES, SELECTED, TABLE 6

Dive	Depth	Bottom	Surface	Ascent	Times
				U.S Navy	*D.C.M.*
1.a	70 ft	40 mins	67 mins	1min 10s	3min 15s
2.a	110 ft	10 mins	32 mins	8min 50s	4min 15s
3.a	70 ft	30 mins		19min 10s	3min 15s

TOTAL	DECO	29min 10s	10min 45s

REPETITIVE DIVES, SELECTED, TABLE 7

Dive		Bottom	Surface	Total Ascent	Times
				U.S. Navy	*Edge*
1.a	120 ft	15 mins	46 mins	2 mins	4min 30s
2.a	120 ft	10 mins	34 mins	8 mins	4min 30s
3.a	120 ft	15 mins	27 mins	32 mins	4min 30s
4.a	120 ft	5 mins		32 mins	4min 30s

TOTAL:	74 mins	18 mins

Hazardous repetitive dives

Two triple repetitive dives (Tables 8 & 9) which were shown to be hazardous during in-water trials, were extended to 6 and 8 repetitive dives with the same depth/duration and surface intervals, without requiring decompression according to the computer. These experiments were suspended not because the computer prevented us from continuing, but because we ran out of time and patience. The computer's scrolling of no-decompression times suggested that we had not nearly exhausted the computer's potential for such repetitive dives.

HAZARDOUS REPETITIVE DIVES, TABLE 8

Dive No.	Depth	Bottom	surface
	feet		
1.a	140	10 mins	120 mins
2.a	140	10 mins	120 mins
3.a	140	10 mins	120 mins
In-water	trials	suspended	
4.a	140	10 mins	120 mins
5.a	140	10 mins	120 mins
6.a	140	10 mins	120 mins

HAZARDOUS REPETITIVE DIVES, TABLE 9

Dive No.	Depth	Bottom	surface
	feet	mins	mins
1.a	147	5	60
2.a	147	5	60
3.a	147	5	60
In-water	trials	suspended	
4.a	147	5	60
5.a	147	5	60
6.a	147	5	60
7.a	147	5	60
8.a	147	5	60

DISCUSSION

No attempt has been made to validate the computer on the basis of solicited or unsolicited testimonials, or decompression theories. I do not question the need to develop computers based on such theories, but I do not believe that they should be evaluated for public use, other than by comparison to established tables or by controlled human trials, to determine the safety of the dive profiles they permit.

Single fixed level dives

The "bottom time" recorded in the EDGE manual and used to claim favorable comparison with other dive tables no-decompression times, is misleading. It does not include the time taken to reach depth. Descent rate is conventionally accepted as 60 feet or 18 meters/minute. To obtain the bottom times used in the manual, it appears that the manufacturers have presumed that the diver is instantaneously transported to that particular depth. The result is that the more gradual nitrogen load experienced with descent, when added to the actual time at the bottom, give greater "bottom times" for the EDGE than the manual or scrolling depicts.

Even without such corrections, the comparison of Spencer's no-decompression limits with those of the EDGE, does not really lend support to the claim that this computer is based on Spencer's figures. In the 30-80 feet range, the EDGE allows the same or more time without imposing decompression requirements. Spencer's exposures do not exceed 130 feet, but at that depth the EDGE allows almost twice as much time as Spencer.

At least the EDGE does give no-decompression figures to check, and in this way (as in many others), it may be considered superior to some of its competitors.

Repetitive dives

In comparisons of the dive computer with repetitive dive systems allowed by the U.S. and RNPL Tables, the computer is much less conservative that these tables. Some of the dive parameters chosen initially appeared to be prejudiced against the computer, such as the 141 feet dives which were rounded up to 150 feet. However, if one does the decompression table calculations for 140 feet, thus putting the depth bias in the computer's favor, the omitted decompression of the computer is still very considerable - over 2.5 hours for repetitive dive series B and 4 hours for C (Table 3).

In a recalculation of the 102 or 141 feet dive series (Tables 2,3) the U.S. Navy Tables still required decompression stops, even when the next shallower depth, the next shorter bottom time AND the next longer surface interval were used.

Other repetitive dives (depths, durations and surface intervals) were selected to avoid these "rounding up" safety factors in the U.S. Navy Tables (series 6 and 7) but even in these, the computer showed considerable omitted decompression compared to the tables.

On those triple repetitive dives which have been found to have been hazardous during in-water trials, the computer not only permitted such diving, but allowed more than twice the number of such dives. In these dives there were biases that should have made the computers appear more conservative.

The bottom line is that many divers get bent following the U.S. Navy Tables. They use them because they've been trained to use them. When the computers and the tables are compared, the computer requires much less decompression for most deep dives and repetitive dive profiles. How then can the computers be safer? I cannot understand therefore the advertiser's claim that the computer is safer than the U.S. Navy tables, except for single shallow dives.

Other comments

Although a number of multi-level dives were made with the computers, the absence of sufficiently safe and proven multi-level dive profiles makes it impossible to assess them on this basis. Some of these profiles caused us concern but this, like the computer, is based on theories which need validation.

The following recommendations were made after our trials in 1986 and have been recorded in various publications:

The dive computers should be restricted to single dives and to a maximum depth of 120 feet.

If a multi-level dive is carried out, then the deepest part of the dive should be performed first, and the diver should ascend throughout the dive, until he reaches a depth of 30 feet.

We would be pleased to modify these restrictions, once we have information on which to base such a modification.

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DIVE COMPUTER EXPERIENCE IN CANADA

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Dive computer research and development in Canada first started in 1962 at the Canadian Forces Medical Services Institute of Aviation Medicine. The Kidd-Stubbs pneumatic analogue dive computer was extensively tested with approximately 5000 man-dives involving single dives, repetitive dives and random depth dives. A commercial version of this computer was developed by SPAR Aerospace Products Ltd. When microprocessors became available, a series of digital, microprocessor-controlled dive computers was developed for the Defence and Civil Institute of Environmental Medicine, including a dive calculator, surface/hyperbaric chamber monitor and a diver-carried computer. This research and development resulted in the commercially available Cyberdiver diver-carried dive computer. In addition to the extensive monitoring of experimental, training and operational dives at DCIEM, dive computers have been used for developing dive tables and dive procedures.

INTRODUCTION

Dive computer research and development in Canada started in 1962 at the Canadian Forces Medical Services' Institute of Aviation Medicine (now a part of the Defence and Civil Institute of Environmental Medicine (DCIEM)). Although the concept of a dive computer for divers was not new and had been proposed as early as 1953 (Groves and Munk, 1953) and although other dive computers had been designed and built by that time (Alinari, 1964; Frederickson, 1956), the Canadian development represented the first concentrated effort into producing a viable, well-tested, and marketable multi-compartment dive computer. The pneumatic analogue decompression computer (PADC) was successful in that many thousands of experimental, training and operational dives were carried out by the Canadian Navy and DCIEM. With the introduction of the microprocessor in the 1970's, a new series of dive computers, based on the mathematical model underlying the PADC, was developed. Previous histories and surveys of dive computers have described some of the Canadian developments (Kuehn and Nishi, 1975; Huggins, 1987; Hills, 1977). This paper will review the history of the development and applications of dive computers in Canada from its origins in pneumatic technology to the present.

THE PNEUMATIC ANALOGUE DECOMPRESSION COMPUTER (PADC)

In 1962, a Canadian Navy surgeon, D.J. Kidd, and a Canadian Air Force scientist, R.A. Stubbs, recognized that the future of deep diving and deep submarine techniques was limited by the difficulty in using the then current tabular methods of decompression (Kidd and Stubbs, 1968). To provide optimum flexibility to the future diver, consistent with safety, they reasoned that some form of analogue computer sensing the diver's actual depth-time history, and continuously providing the decompression status based on the exposure history was required. The computer was originally conceived for oxygen-helium diving with complicated dive profiles and wide variations in gas mixtures which could not be handled with tabular methods. Because excellent data were available for air diving, the principle of computer-controlled decompression was first applied to diving using air as the breathing mixture.

Initial work was directed to simultaneously investigate various forms of analogue computers using pneumatic, hydraulic and electrical signals. The pneumatic approach was determined to be the most desirable because it was small, simple, rugged and required no external energy source other than that provided by the inspired gas. The first computer was a laboratory model based on the Haldane concept of four parallel compartments having half-times of 10, 20, 40 and 80 minutes. It was demonstrated that the computer could generate the theoretical formula for the safe ascent path from the mathematical model and the appropriate ascent constants.

The principle behind the PADC (Kidd and Stubbs, 1969; Nishi, 1978) is that the tissue compartment is simulated by a chamber, which is pressurized through an orifice or pneumatic resistor. The volume of the chamber and the flow rate through the pneumatic resistor determines the half-time of the compartment. Thus, for a given flow rate through the pneumatic resistor, a large volume would represent a slow tissue compartment. Conversely, for a given volume, a slow flow rate through the pneumatic resistor would represent a slow tissue. The pressure in each volume can be monitored by a pressure sensor such as a Bourdon tube and the output scaled by a supersaturation ratio. The resulting values from all compartments in the computer could then be compared and the deepest value chosen to give the safe ascent depth.

The prototype diver version of the computer was a pneumatic analogue constructed to display ambient depth and the safe ascent depth on the same scale. The diver, when ready to ascend, followed the correct ascent profile by keeping the ambient depth equal at all times to the safe ascent depth, which was being generated continuously by the computer. Although some ocean dives were carried out to test the computer, most exposures were made in a hyperbaric chamber because of the precise control of time and depth necessary for an accurate evaluation.

During the development of the computer, some 21 different models and configurations were built and examined and over 16,000 man hours of manned diving were conducted. Of primary interest, however, are three key models. The first series of exposures reported by Kidd and Stubbs (1969) was done with the Mark II P, designed deliberately to produce decompression profiles as close to the limiting threshold for man as existing data allowed. This computer had four parallel compartments of 10, 20, 40 and 80 minute half-times with supersaturation ratios of 2.65, 2.15, 1.85 and 1.65 respectively. Dives conducted consisted of 523 man-dives at depths from 70 feet of seawater (fsw) to 300 fsw for durations ranging from 10 minutes to 12 hours, resulting in a 5% incidence of decompression sickness (DCS). Half of these dives were single exposures and the other half were random depth and repetitive dives. This model showed the validity of using a dive computer for controlling safe decompression and for using its memory of the previous dive for controlling repetitive dives.

Multiple dives were also carried out to test the validity of the "threshold" concept by ascending from each dive deliberately shallower than the computed safe ascent with the object of provoking DCS. Seven subjects participated in 91 such dives, resulting in a 19% incidence of DCS.

The second series of dives was conducted with the Mark III P, with four compartments in parallel but with half-times of 20, 40, 80 and 160 minutes. After a mathematical analysis, a common supersaturation ratio of 1.6 was assigned to all compartments since it was felt that ascribing differing ratios to specific but arbitrarily chosen compartment half-times was an anomaly. This ratio also provided a greater margin of safety. With 478 man-dives conducted on dives ranging from 150 fsw to 250 fsw for durations from 15 minutes to 4 hours, the incidence of DCS was 1.5%.

Kidd and Stubbs felt that although the parallel configuration of diffusion compartments had empirical justification in man, physiologically, the transfer of gas between the lungs and the remote tissues was more likely a series or a series-parallel system of diffusion gradients. A detailed mathematical analysis and testing of a series model eventually led to the Mark V S and Mark VI S computers. (A much larger version of the Mark V S, the Mark VI S, with a chart recorder connected to the Bourdon tubes to provide a visual and permanent record of the dive, was designed and constructed for the automatic control of hyperbaric chambers or for surface-supported diving). These computers had four compartments in series, each with a half-time of 21 minutes and a common ratio of 1.44. Taken together, the effective terminal half-time of the computer was 172 minutes. By August 1967, a total of 3775 single and repetitive dives at depths from 30 fsw to 250 fsw for a duration of 15 minutes to 4 hours resulted in a bends incidence of only 0.6%.

The computer, calibrated for air, was also used for 20% oxygen/80% helium breathing mixture since theoretical studies showed that the decompression profile should be different from that for air. The computer was used successfully for oxygen-helium dives, confirming the laboratory predictions and a series of random depth dives, repetitive dives, repetitive dives followed by one or more air dives, and air dives followed by helium dives were conducted. Two-hundred and fifteen oxygen-helium dives and 178 air dives were carried out in this series over a range of depths from 50 fsw to 250 fsw and for durations from 10 to 90 minutes with a DCS incidence of 1%.

This computer was used extensively at DCIEM for experimental diving, primarily for physiological and psychological tests, in the hyperbaric chamber to depths as great as 300 fsw. In almost all cases, the decompression was a continuous ascent following as closely as possible the safe ascent depth predicted instead of the traditional staged decompression at fixed depths. However, in 1970, Stubbs discovered that the DCIEM hyperbaric chamber operators did not trust the computer for deep dives and had been adding their own "safety factor" for these dives. The operators were staying deeper than the computed safe ascent depth by as much as 10 fsw and then surfacing when the safe ascent depth reached zero. Although this was a safe procedure, it did not verify the validity of the ascent criteria. A detailed review of dive records for the previous three years in the 200 to 300 fsw depth range showed the incidence of DCS to be only 3%. Although this figure may seem high, it was far better than could be achieved with any existing table at that time. The chamber operators were then directed to follow the safe ascent depth to within 2 feet of the ascent indicator. This resulted in the DCS incidence rising to 20% in 76 man-dives. By reviewing all the depth-time records of the dives done with and without the "safety factor", Stubbs was able to work out a mathematical formulation of the chamber operators' procedures and to implement this modification into the hardware. The change in the model resulted in a depth-dependent supersaturation ratio. This version of the Kidd-Stubbs model is now known as the Kidd-Stubbs 1971 model.

The Mark VI S computer, modified with the new constants, was used operationally twice in 1971, first to locate and recover an aircraft and second to locate and identify a sunken trawler. On 43 dives at depths from 180 to 230 fsw, only two instances of DCS were encountered. Both of these could possibly have been ascribed to procedural problems. An additional 34 dives were done in the open ocean at depths from 60 to 230 fsw with one case of DCS.

A feature of the PADC was the nonlinearity of the gas flow through the pneumatic resistors and the resulting asymmetry between the uptake and elimination of gas, with uptake proceeding faster than elimination. Thus, the solution offered by the PADC differed significantly from those decompression models which treated inert gas exchange as a symmetrical process (Kidd, Stubbs and Weaver, 1971). Evidence from animal studies that the uptake and elimination of inert gases were not symmetrical had been presented earlier by Hempleman (1960). Hence, there was some justification for the use of a nonlinear model.

The primary advantage of a PADC is that it is self-powered. No external source of energy is required except that of the inspired gas. Although conceptually simple, the implementation of a multi-tissue mathematical decompression model makes the computer mechanically complex and requires extensive effort in maintenance and calibration. Pneumatic computers were successfully used at DCIEM because a technician could be assigned to maintain and calibrate the computers on a regular basis.

A major problem with the PADC, and probably with most dive computers presently on the market, is the inability to correct for a violation of the computed safe ascent, i.e., if the diver were to accidentally or deliberately ascend shallower than the safe depth. In this situation, the computer will compound the danger by accelerating the decompression instead of slowing it down. With a digital computer, it is theoretically possible to compensate for such a violation with an appropriate algorithm. With a pneumatic computer, it is almost impossible to correct for this violation. The only computers which actually implemented such a correction were laboratory devices (Hills, 1967; Hills, 1977).

COMMERCIAL DEVELOPMENT OF THE KIDD-STUBBS PADC

Commercial development of the PADC was started as early as 1963 when Huntec, Ltd. was licensed by Canadian Patents and Development, Ltd. to manufacture dive computers. Huntec, at that time, was also involved in a contract to develop a cavitation (bubble) detector (Evans, 1975). One by-product of the Huntec contract was an analysis of of the decompression procedure and the formulation of a new mathematical model of decompression (Dieter, 1967). In 1966, the license was transferred over to SPAR Aerospace Products Ltd. (then a part of DeHavilland Aircraft of Canada, Ltd.) with SPAR agreeing to supply 10 Mark V S PADC's to the Canadian Armed Forces. In 1968, the need for an improved version of the PADC had become apparent, since difficulties were encountered during the manufacturing and calibration stages and some changes to the basic design were required before production could occur. Government funding was obtained to improve the PADC and produce the MK II prototype.

SPAR undertook a market survey to identify the overall sales potential. Discussions were held with a number of potential customers and the market survey was extremely encouraging. Their forecasted sales from 1970 to 1977 were expected to be approximately 5500 units with a value of over $6,000,000. Initially, unit costs were high, at $4700 per unit, dropping to $1000 for 500 or more units. By 1971, however, the market forecast had been reduced to only about 450 units for a number of reasons.

Discussions were held with the US Navy who had a requirement for a dive computer for its Swimmer Life Support System (SLSS) project. Two units were supplied to the USN Experimental Diving Unit for testing. SPAR was awarded a contract by Scott Aviation of Buffalo, N.Y., to study whether the PADC could meet the requirements of the SLSS project and the feasibility of using the PADC in a closed circuit breathing apparatus. This study showed that the PADC could be adapted to the US Navy requirement. However, it was felt that the US Navy had too much invested in the TRACOR electronic analogue computer (Workman, 1963; Wittenborn, 1963) and this market was doubtful.

The MK II design was found to be suitable only for "dry" dives for hyperbaric chambers, lockout submersibles, and surface-supported diving where a simple interface containing a gas drying and purifying device could be attached. For swimming situations, or a free diver, with the computer immersed in the water, some method of preventing water ingression into the pneumatic resistors was required. A pressure deformable bag at the computer inlet was one approach, and although feasible, was thought to be disadvantageous because of the increased size of the PADC required and the difficulty in changing the stored gas if a diver were to switch from air to an oxygen-helium mixture. In addition, there was some thought that the deformable bag would infringe on the patent for the SOS Decompression Meter (Alinari, 1964). A second approach using a venting type ambient pressure regulator between the computer inlet port and a high pressure location in the breathing apparatus was investigated but not followed up beyond the breadboard stage because of changing market requirements.

Two units were purchased by J & J Marine for NASA for use in astronaut training. The evaluation by Peter Edel of J & J Marine was favorable and a recommendation for its use for all NASA diving decompression requirements was made. However, it appears that further purchase of the computers was not carried out due to budget cutbacks at NASA.

In 1971, the anticipated U.S. commercial market for a surface unit became doubtful since it was expected that U.S. legislation governing diving companies would be issued requiring the use of specific tables, most likely the US Navy tables, and the use of computers would not be allowed.

The Canadian Armed Forces requirements, which had previously been expected to be about a hundred units, also changed during this time period with all diving requiring decompression to be surface-supported with tethered divers. The Mark VI S units being built at DCIEM were adequate and a much less costly alternative to the Canadian Forces. With the 10 Mark V S units received from SPAR, there were some quality control problems and they were not used operationally to any great extent.

In late 1971, support from the Canadian Government ended with SPAR in a position to supply dive computers on a production basis. However, possibly because of the high manufacturing costs and the decreasing market for such devices, no further sales appear to have been made.

ELECTRONIC AND DIGITAL DIVE COMPUTERS

Electronic analogues provide an alternative to pneumatic analogues for simulating the tissue compartments of a decompression model. Such computers had been designed or proposed by others (Wittenborn, 1963; Bradner and Mackay, 1963; Buckles and Greenberg, 1968; Todd, 1969). One of the problems with such computers for real-time diver monitoring was that extremely stable and precise components had to be used because of the long time constants required, thus making the computers very costly. In the work of

Kidd and Stubbs, no diver-carried electronic analogue computers were designed or planned. However, considerable research was done by Stubbs using a general purpose electronic analogue computer for decompression modelling during the development of the PADC. A dedicated electronic analogue computer was designed and constructed, intended primarily for use in "fast" time with output on a digital display and on an X-Y plotter. It could also be used for real-time, off-line dive simulation. Several of these units were made for dive planning and analysis. Such units could be used, for example, to determine gas requirements and mission times for complicated dive profiles and repetitive dives, or to analyze previously conducted dive profiles.

Mechanical components and linkages in a PADC for measuring pressure and calculating safe ascent depths are vibration and acceleration sensitive and could result in calibration shifts or depth reading difficulties. In addition, mechanical readout devices such as gauges or paper chart recorders did not provide high accuracy for deep diving to depths such as 300 fsw. In 1972, a series of pneumatic computers were designed and constructed with all the mechanical components being replaced with electronics, using pressure transducers instead of Bourdon tubes and electronic digital displays for reading out the depth and computed safe ascent depths. An electronic comparator and operational amplifiers were used to compare the pressures in the four compartments, to select and compute the safe ascent depth instead of complicated mechanical linkages. These computers were hybrids of pneumatic and electronic technology and were referred to as pneumatic-electronic analogue dive computers.

In the early 1970's, the development of the microprocessor made it possible for the design of miniature diver-portable dive computers, using whatever decompression model was desired. DCIEM embarked on a program of developing a series of microprocessor-controlled dive computers (Nishi, 1978) with CTF Systems, Inc., Port Coquitlam, B.C. The first computer, the XDC-1, completed in 1975, was a dive calculator/real-time dive monitor (Lomnes, 1975) where information could be entered from a keyboard to generate dive profiles or analyze dive profiles. In the real-time mode, the computer could be programmed to monitor a pressure transducer and calculate and display the safe ascent depth for on-line dive control.

A second model, the XDC-2 series, completed in 1976, was designed for real-time dive monitoring (for surface-supported umbilical diving or for hyperbaric chamber use) and was designed to be "diver-proof" with a large digital display of the elapsed time, actual depth, and safe depth. A fourth display could be switched to show rate of dive or no-decompression/ascent time remaining. The only component requiring calibration was the pressure transducer. The XDC-2, as the XDC-1, was programmed with the Kidd-Stubbs 1971 decompression model and replaced both the Mark VI S PADC and the hybrid pneumatic-electronic analogue computers. Approximately 30 of these units were built with several being sold to other agencies for chamber monitoring. The XDC-2 is still in use at DCIEM for air diving. In 1983, the decompression model, in programmable read only memory, was changed to the DCIEM 1983 model.

A third model, completed in 1978, was the XDC-3 diver-portable computer designed for use to 200 fsw. One of the problems with the development of the XDC series of computers was that technology had not yet caught up to demands of the dive computer. Miniature pressure transducers were very costly and it was necessary for CTF to design their own transducer. Although the XDC-3 used a CMOS microprocessor, the Intersil IM6100, CMOS memory chips were not available and the device consumed considerable power. The LED display of elapsed time, depth, safe depth, and no-decompression/ascent time was controlled by an inertial switch that would turn on the display for six seconds on demand. With four 9-volt alkaline batteries, the operational life was only 4 hours, making the computer very costly to operate. Although the batteries could be changed one at a time without shutting off the power and losing the dive memory, it was not convenient to plan a series of repetitive dives. It was possible to utilize electronic tricks to conserve power as was done in the US Navy computer developed by Jennings (1977). Although he used an Intel 8080, he designed the algorithm so that the computer effectively shut itself off between calculations. With lithium oxide batteries, the operational life was estimated at 16 hours. With the cost of such batteries in 1977, this was a very expensive computer to use. Only five prototype XDC-3 computers were constructed.

A full micro-computer system designed specifically for decompression computations and decompression management (Retallack *et al.*, 1977) was the fourth phase of the DCIEM research program into microprocessor-controlled dive computer systems. It was intended to have a unique Dive Control Language to handle any mathematical approach to decompression in real or accelerated time. It had two microprocessor-based modules, operating simultaneously but separately, one for monitoring of an on-going dive and the other for preparation of dive tables, analysis of data, or experimental development of diving models. The XDC-4 was conceived and designed in the late 1970's before the personal computer became available. Because of hardware and software development delays, and the rapid proliferation of personal computers, the XDC-4 became obsolete before it could be completed. Most of the intended functions can now be performed on a personal computer for a fraction of the development costs of the XDC-4.

The direction taken at DCIEM for monitoring experimental and other dives in a hyperbaric chamber is to use personal computers as dive computers. A PC/XT compatible, with data acquisition hardware and software, has been programmed with the DCIEM 1983 decompression model and an experimental helium-oxygen decompression model for real-time dive monitoring. The advantage of a PC is the flexibility available for programming and making changes. A variety of higher level languages can be used for programming the model and the real-time data acquisition. With color monitors, the output dive information can be displayed effectively in a variety of ways with the judicious use of colors and graphics. The output information can also be stored on a hard disk for later analysis and for uploading to main-frame computers.

COMMERCIAL DEVELOPMENT OF A DIGITAL DIVER-CARRIED METER

The Cyberdiver computer was a commercial spin-off from the research done for DCIEM. Kybertec International Inc., was formed by two of the principals of CTF Systems, Inc., in 1978, to market a diver-carried computer based on the XDC-3. The first model, appearing in 1978-79, was based on the US Navy Tables and consisted primarily of look-up tables which were entered from the maximum depth and the bottom time. The second model, the "SKANA", was based on the Kidd-Stubbs 1971 model and was a real-time decompression calculator based on the actual depth of the dive. About 700 of both models of the Cyberdiver were sold. The USN version is probably no longer working as there was a battery which maintained all the calibration constants in CMOS RAM. After the battery died, the constants were gone. The Kidd-Stubbs version did not require any constants to be stored in RAM and there are reports that some SKANA's are still being used.

The Cyberdiver was an innovative computer and had many desirable features. However, it did not survive for several reasons. Kybertec was a small company and one of the major problems was the lack of funding to get the bugs out and market the computer properly. Technically, there were some problems. The designers, although they were experts in electronics and microprocessor applications, were not knowledgeable enough about underwater packaging, and leakage of water into the case was one of the main deficiencies. The depth sensor was based on a design resulting from a DCIEM research contract with CTF and was essentially a digital transducer. There was no real problem with the transducer except that it could fail because of water leakage. Because of lack of funding, the company never was able to start phase 2 of the packaging design. In 1981, the rights to the technology were sold to Newtec Industries Ltd., of Burnaby, B.C., who did not pursue further development because they thought the market was not large enough. As a result, the Cyberdiver died.

The other major problem with the Cyberdiver was that the designers were ahead of the times; technology had not quite caught up with what they wanted to do at an affordable price. The cost of the Cyberdiver was relatively high and the consumer market was not quite ready for it. Kybertec did not apply for a patent for the computer since it would have been too costly. Ideally, patents should be applied for in Canada, the US, UK and Japan at the minimum. DCIEM's experience with patenting the devices developed under the CTF contracts, in particular, the XDC-1, brought out the difficulties in applying for patents. The patent was granted in Canada (Burbank *et al.*, 1980) but was rejected in the US because, according to the US patent examiner, the US Navy patent (Jennings, 1977) had a prior claim on almost everything that was being claimed for the XDC-1. With that experience, it would have appeared to be very difficult to obtain a patent on a diver-carried computer which was more similar to the Jennings computer than the XDC-1 was. Kybertec also considered whether it was worthwhile to file a patent and to take to court any violators of the patent and decided it was not worth it.

APPLICATION OF COMPUTERS FOR DECOMPRESSION RESEARCH

In addition to the normal use of dive computers to monitor divers and to decompress them safely on an optimum decompression profile rather than on tables, dive computers have many other applications for diving and decompression research. Dive computers allow complicated dive profiles to be used, for example, during psychological or physiological testing of subjects at different depths or with different gases. When the subject is breathing one gas mixture and the researcher breathing another, both individuals can be monitored independently and be safely decompressed by following the deepest safe ascent. With the Mark VI S PADC, a large number of dives were done routinely to depths as great as 300 fsw on air or helium and in some cases, where subjects alternated between helium and air. Dives using argon-oxygen as a breathing gas were also conducted successfully with the Mark VI S.

One of the main uses for dive computers within the last ten years at DCIEM has been for the investigation of decompression models and the development of new "traditional" decompression tables. One of the advantages of the current microprocessor-controlled dive computers for chamber use is the large digital display of depth and safe ascent depth, so that the safe ascent depth, as calculated, can be followed exactly by the chamber operator. With the PADC, this was not possible since a separate "computer operator" was required to relay the depth information to the chamber operator. This always resulted in a delay in following the safe ascent depth so that the diver was always slightly deeper than the actual safe ascent depth. In 1979, it was decided to determine the operational limits of the Kidd-Stubbs 1971 model as implemented in the XDC-2 computers (Nishi *et al.*, 1980). It was found that as the bottom time increased for any given depth, the decompression stress, as determined by DCS and Doppler-detected bubbles, increased and that there was a limit where the risk of DCS became too high for operational use.

This led to the development of the DCIEM 1983 model and decompression tables (Nishi, 1987) for use as the Canadian Forces standard air tables. Because of the wealth of experience existing on the Kidd-Stubbs model (almost all dives done since 1964 at DCIEM are recorded with accurate time-depth information in a computer data bank), it was decided to improve on the safety of the Kidd-Stubbs model rather than to develop an entirely new model and tables. Thus it was possible to issue a well-tested set of tables in only two years. These tables have been well-received and are being used by many organizations.

In developing decompression tables, the testing procedure is to always follow the safe ascent depth rather than the printed table being tested. Ascending to the next stop depth is always dictated by when the safe depth reaches the next stop depth instead of waiting to the end of the stop time specified in the tables. This generally results in a slightly shorter decompression time for the dive. The advantage of using a dive computer to develop tables is that the computer takes into account any variation in the depth, such as holding for divers not able to clear their ears. Thus, with the dive computer, it is always the decompression model that is being tested and not the printed tables themselves. It is not necessary to discard dives or abort dives because it took too long to reach the bottom. If the dives as done by computer are safe, then the printed tables generated from the model will also be safe with a slightly longer decompression time since stop times are generally rounded up to the next whole minute. This will be particularly true with repetitive dives, since repetitive dive tables are designed for the worst case in each depth, bottom time and surface interval groupings.

At DCIEM, dive computers have also been used to develop oxygen decompression procedures and surface decompression procedures. Because the current generation of dive computers have the decompression model defined in software, it is easy to incorporate non-standard decompression procedures. With the Mark VI S PADC, oxygen decompression was carried out by disconnecting the pressure input to the computer when the subjects were breathing oxygen since, theoretically, the inert gas partial pressure should be zero. Surface decompression represents a violation of the decompression model during the surface interval and basically invalidates the decompression profile. The solution here is to assume that extra decompression is required to compensate for the violation, in effect, that a treatment is necessary. This has been done in the current DCIEM tables by changing the surfacing criterion from the 40 fsw oxygen stop. Instead of surfacing when the safe ascent depth reaches zero, subjects stay in the chamber on oxygen at 40 fsw until the safe ascent depth reaches -3 fsw (-1 msw). This procedure has been found to be safe even at the maximum limit of 240 fsw for 40 min in the DCIEM air tables. With this procedure, no changes to the decompression algorithm are necessary.

Current research at DCIEM using dive computers is directed at developing new helium-oxygen tables to replace the USN Partial Pressure Tables. The PC/XT-based dive computer described earlier is being used for this purpose.

SUMMARY

Dive computer research and development in Canada has embraced the entire technology from pneumatic and electronic analogues to microcomputers. Although the Kidd-Stubbs PADC did not succeed commercially, the Mark VI S version for hyperbaric chambers and surface-supported diving was used extensively for monitoring of experimental, training and operational dives. The XDC-2 microprocessor-based version was instrumental in the development of the new Canadian decompression tables for compressed air. The Cyberdiver diver-carried computer was a spin-off from the DCIEM dive computer research program and met with limited success as a commercial product.

Although little known, the Canadian experience is an important chapter in the history of dive computers.

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EXPERIENCES WITH DIVE COMPUTERS IN WEST GERMANY

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We subjected different dive computers in a small pressure chamber to a series of repetitive no-stop profiles of known DCS rate, and to proposed repetitive decompression profiles. Results showed that the instruments in general were: Rather different with respect to readings for identical profiles; More conservative than US NEDU no-stop profiles; Slightly to moderately less conservative than the new French tables prepared by COMEX; Mainly more conservative regarding 3 msw ceiling times. Insurance statistics of 223000 diver-years shows no significant change in DCS occurrence per insured diver since the DC's have been sold in quantities.

DEVELOPMENT OF THE DECOBRAIN

The first group to use dive computers in Germany were recreational diving instructors. In a promotional action, 150 DecoBrain 2 dive computers (Divetronic AG) were sold to instructors at a reduced price in 1985 and 1986. Coefficients of the DecoBrain 2 program were shifted to the safer side in two steps. The first DecoBrains used values proposed by Bühlmann (1983) as "P 2-1", but there were cases of DCS I reported by the users. These were mainly after repetitive dives with stops, and after chamber trials (Hahn *et al*, 1985). This led to the model "P 2-2".

During the summer of 1986 sensitive users still reported mild cases of DCS I (skin rashes), which also could be produced in wet chamber trials to 58 m depth. Further shifting of coefficients and application of a non-linear depth-PN_2 relation (Hahn, 1986) led to "P 2-3". Several thousand P 2-3 computers were sold, and obviously, no further reports of DCS were received. Due to major problems with leakage, production was stopped in 1987.

To my knowledge, dive computers are not yet used in commercial or scientific diving, in Germany at least, due mainly to lack of approval by insurance policies.

PERFORMANCE TESTING OF SOME DIVE COMPUTERS

To evaluate the performance of second generation dive computers, so-called "no-d-timers", several brands now on sale were subjected in our laboratory to no-d profiles, dives evaluated by NEDU (Thalmann, 1986), and decompression profiles taken from tables proposed by COMEX (Imbert and Bontoux, 1987). Details were reported on at the UHMS Annual Scientific Meeting in New Orleans, June, 1988 (Hahn, 1988). Numerical results of these measurements are given on the graphs. [Note: the Aladin is the same as the Beuchat]

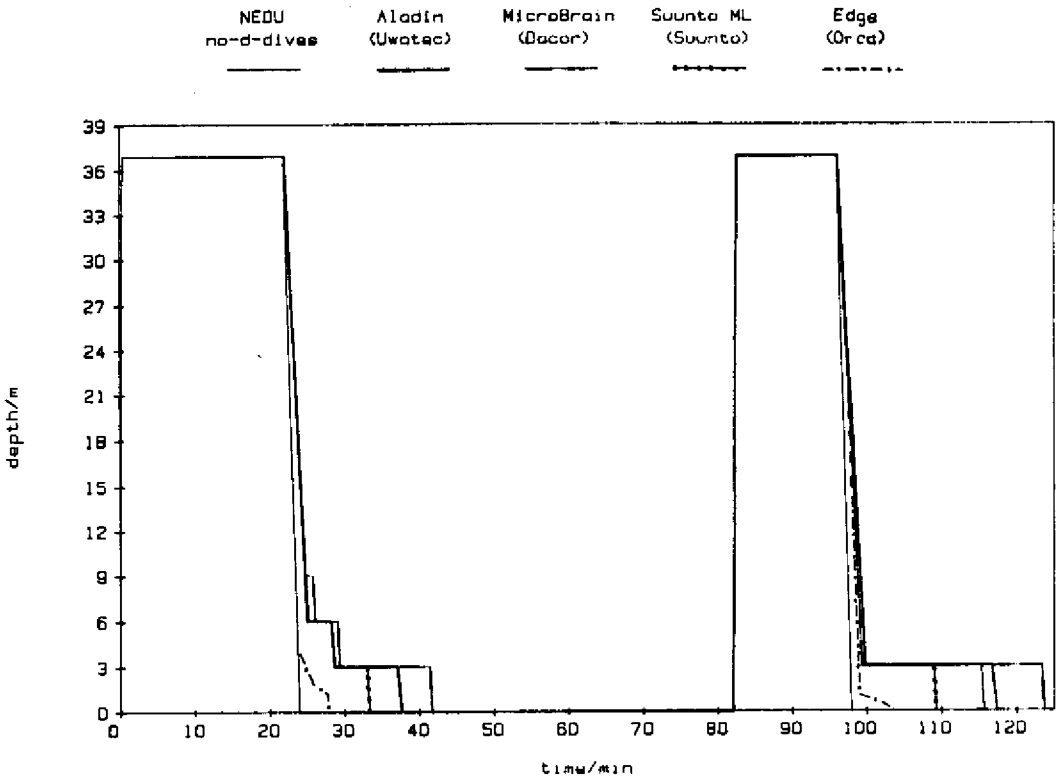

Figure 1. A pair of repetitive no-stop dives (NEDU Tb 32), 120 fsw (37 msw) for 22 min followed after 58 min by 120 fsw (37 msw) for 14 min, performed at NEDU and followed in our laboratory with 4 DC's. 20 dives caused no DCS. All of the DC's called for more decompression time than the NEDU table.

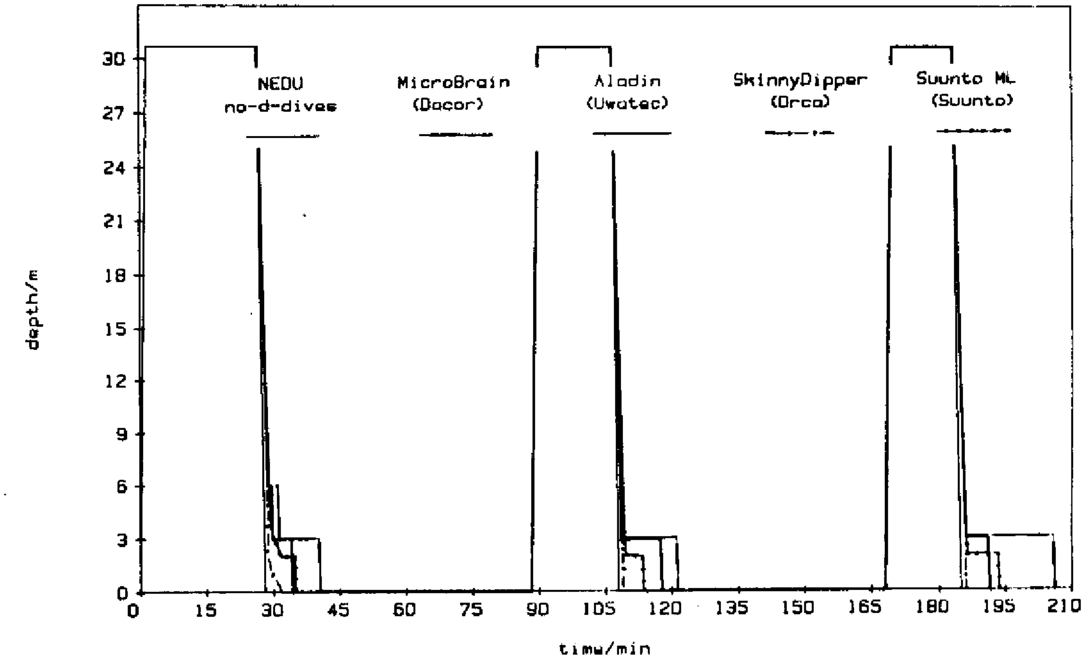

Figure 2. A 3-dive repetitive set of no-stop dives (NEDU Tb 31), 100 fsw (31 msw) for 26.5 min followed after 60 min by 100 fsw/18 min followed after 60 min by 31 msw/15 min, performed at NEDU and resulting in 2 cases of DCS in 19 dives. The DC's are all at least slightly more conservative than the NEDU table, but the additional decompression in most cases is not great.

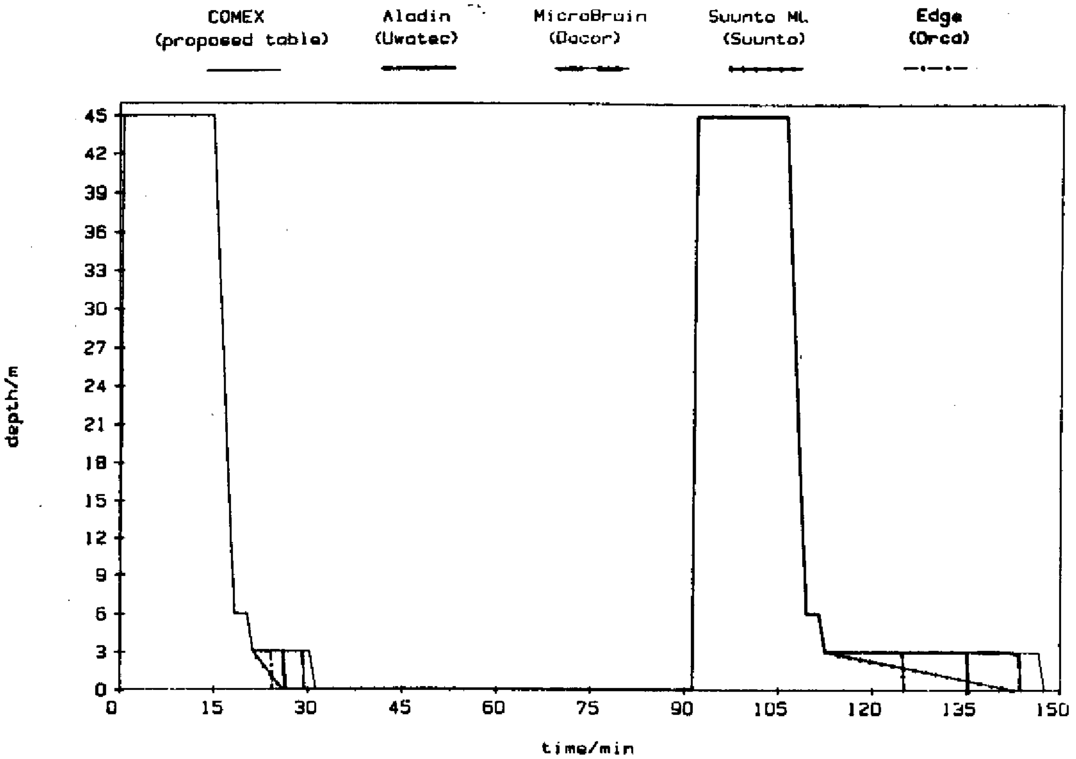

Figure 3. A pair of repetitive dives to 45 msw (147 fsw) / 15 min separated by an interval of 1:15, showing the decompression required by the proposed new French COMEX tables (Imbert and Bontoux, 1987) and the results of the same dive as it would be controlled by the 4 DC's. In this case the tables are more conservative than any of the DC's.

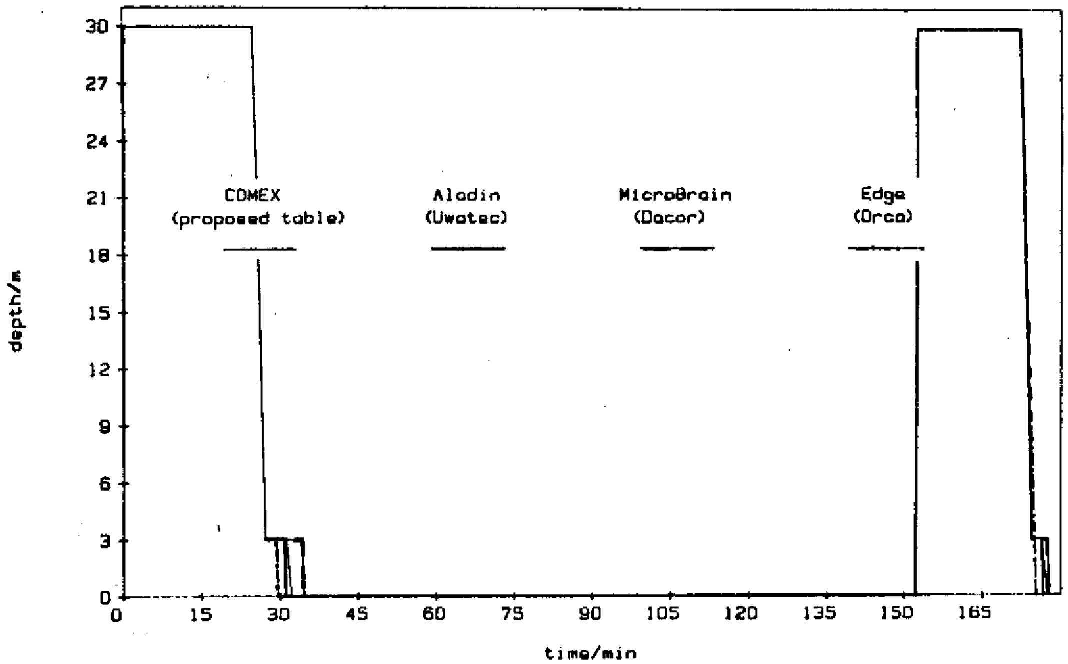

Figure 4. A pair of repetitive dives of 30 msw/25 min followed by 30 msw/20 min as they would be done on the new French COMEX tables and as calculated by 3 of the DC's. Here the differences are trivial.

No-d times and 3 meter ceiling times in minutes

	NEDU		COMEX		Aladin		MicroBrain		Suunto ML		SkinnyDipper		
Ceiling depth (m)	0	3	0	3	0	3	0	3	0	3	0	3	(m)
18	63	100	50	120	50	116	46	90	53	—	54	82	
21	48	80	35	70	37	79	29	62	38	57	40	59	
24	40	60	25	50	26	55	23	41	29	41	34	44	
27	32	40	20	40	20	37	19	30	23	33	25	35	
30	27	30	15	30	16	27	13	22	19	25	20	28	
33	23	30	10	20	13	22	10	16	14	19	15	22	
36	20	25	10	20	10	19	8	12	11	15	11	14	
39	18	20	5	15	8	13	7	10	9	12	9	11	
42	16	20	5	10	7	10	6	8	7	9	8	10	
45	15	15	5	10	6	9	5	7	6	8	8	9	
48	12	15	5	10	5	7	5	6	5	7	7	8	

DCS INCIDENCE FROM INSURANCE RECORDS

To estimate a possible change in DCS rate per dive, insurance files were checked for a total of 14 years, covering approximately 223,000 insurance-years.

Assuming Poisson distribution, two data sets can be compared using Fisher's F distribution:

t = insurance years;
x = number of DCS cases reported to insurance company;
$\mu = x / t$ = mean expected DCS rate. The index for larger $\mu = 1$, for smaller $\mu = 2$.

Hypothesis H_o: $\mu_1 = \mu_2$;
Hypothesis H_1: $\mu_1 > \mu_2$;

α= significance threshold
F = F distribution
f = degrees of freedom

H_1 holds, if:

$$\frac{x_1 \; t_2}{(x_2 + 1) \; t_1} \geq F_{1-\alpha} (f_1; f_2) \text{ with } f_1 = 2 (x_2 + 1); \; f_2 = 2 x_1 \text{ or } f_1 = 24; \; f_2 = 66$$

To the insurance of Verband Deutscher Sport Taucher (VDST) (i.e. German Sport Divers Association) were reported 33 cases of DCS (I + II) in the dive computer - free period 1974 through 1984, covering 150,000 insurance years. During 1985 - 1987, when DC's were on sale, covering 73,000 insurance years, 11 cases of DCS were reported.

We obtain:

$x_1 = 33$; $t_1 = 149{,}964$; $\mu_1 = 2.2 \times 10^{-4}$
$x_2 = 11$; $t_2 = 73,\ 020$; $\mu_2 = 1.5 \times 10^{-4}$

$$\frac{(33)\ (73{,}020)}{(11+1)\ (149{,}964)} \overset{?}{>} F_{1-.05}\ (24;\ 66)$$

Resulting in:

$1.339 < 1.68$

So, μ_1 is not significantly different from μ_2.

For $F(24;\ 66) = 1{,}339$ we find:

$1 - \alpha = 82\ \%$ and $\alpha = 18\ \%$, i.e. a 82 % probability for $\mu_2 < \mu_1$.

Thus, we conclude that, at least as far as insurance claims are concerned, the incidence of DCS is no greater since DC's have been in use than it was before they were introduced.

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INTERNATIONAL DIVE COMPUTER EXPERIENCE DISCUSSION

An additional point made by Carl Edmonds is that his arithmetic on the program for this Workshop shows 40 minutes for those against dive computers and 400 for those in favor of them.

Max Hahn mentioned also that one cannot use the same computational model in an on-line, real-time dive computer that is used for the generation of printed tables. The computer keeps you on the line the whole time, whereas tables are grouped. John Lewis made a most important point here, that if the model and the data do not agree, it is the data that is wrong.

Because Max Hahn was discussing the European scene, Bill Hamilton showed a couple of slides from the recent meeting of the European Undersea Medical Society. The slides were prepared by Dr. Jim Sykes and CAPT. Ramsey Pearson, who work at the Royal Navy's Institute of Naval Medicine facility at Portsmouth. Tasked with treating divers by the health ministry, these investigators have seen a stream of decompression cases, so are concerned about the factors that bring them on. Because these slides belong to others who are not here to defend them, we limit comment on them to the observation that the patterns in general seem to show little difference between divers that use DC's and those that do not.

RECREATIONAL DIVING ACCIDENTS REQUIRING RECOMPRESSION.
Cases treated by the Royal Navy or with advice from the Royal Navy

	1985	1986	1987	1988*
CAGE	9	18	7	2
TYPE I DCS	14	8	14	13
TYPE 2 DCS	28	38	37	66
	51	48	58	81

* up to 31 August 1988

DECOMPRESSION SICKNESS IN SPORTS DIVERS.
Factors involved in 79 cases from RN 1988 statistics

	No.
Diving > 38 msw	58
Repetitive diving	56
Dive computers	38
Age > 35	27
Novices poorly supervised	18
Unfit to dive	9

CASES OF DCS IN RECREATIONAL DIVERS TREATED BY, OR WITH ADVICE FROM ROYAL NAVY UP TO 31 AUGUST 1988.

	TYPE 1	TYPE 2
Use/abuse of diving tables	9	48
Alleged correct use of DC's	2	26
Abuse/incorrect use of DC's	1	1

DIVE COMPUTERS - ROLE IN DCS IN SPORTS DIVERS - 1988 ROYAL NAVY STATISTICS (n = 38)

	AL'N	SD	DB
Single dive	7(6)	2(1)	4(4)
Repet dives (single day)	8(6)	1(1)	---
Repet. dives (2-4 days)	7(6)	1(1)	---

Figures in parenthesis denote Type 2 DCS

DIVE COMPUTERS

For:

1. Alleged safer decompression from single/multiple dives.
2. Some claim to allow single multi-level dives.

Against:

1. Cannot take account of many important factors involved in inert gas uptake/release.
2. Adequacy of testing tables or mathematical model used in algorithm.
3. Inconsistent performance in examples of the same model.
4. Often ergonomically poor.

In a discussion of performance, particularly in reference to results of the sort mentioned by Carl Edmonds where successive, repetitive deep dives especially subject a diver to the likelihood of DCS, one participant asked, "What booger-eating moron would make four 140 fsw dives in a day?" This characterized a particularly high risk situation in a memorable manner, but also highlights what most feel is the real problem here. People are performing dives with the computers that they would not do otherwise. This could at first be attributed to lack of common sense, but there is no reason why the divers in question here could be expected to exercise good judgement if they do not have the background on which to base it. In other words, when it comes to the recreational diver, training is a big problem. There is no type of compliance or regulation that will constrain them, it has to be by a combination of training and limitations built into the computers. A good point on this topic was made in that divers regard decompression tables as providing information, while they see a dive computer as giving instructions.

USE OF DIVE COMPUTERS AT RESORTS AND LIVE ABOARD VESSELS

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Since the Spring of 1983 when ORCA Industries introduced the EDGE dive computer, the author has conducted more than 50 one to two week diving medical education programs for diving physicians at numerous Caribbean and Pacific destinations. The diving participants on these programs have numbered between 2,000 and 3,000 individuals. The diving practices and use of DC's by this select group of active sport divers will be presented. The incidence of decompression sickness occurring in the 20,000 to 50,000 individual dives represented by this population has been essentially nil.(1 atypical case will be described). The percentage of divers in this population who use DC's has grown over the period involved, yet no increase in incidence of DCS has been seen. Some possible explanations of these observations will be presented in terms of recommendations for the general sport diving community.

INTRODUCTION

Since April 1978, this author has conducted 77 one to two week diving medical educational programs for diving physicians and other sport divers at numerous Caribbean and Pacific destinations, as well as 8 trips utilizing live-aboard diving vessels. The total number of diving participants on these programs/trips have been 3,628. Conservative estimates of the average number of dives made by each participant includes 12 on each one week trip,24 on each two week trip,and 21 on each one week live-aboard vessel trip, representing an estimated total diving exposure of 47,457 dives. Since the spring of 1883 when ORCA Industries first introduced the Electronic Diver's Guide (EDGE), the number of diving participants on these programs/trips have numbered 2,388 and the estimated total diving exposure has been 30,875 dives. In the total experience with these programs/trips to date there has been only one case of decompression sickness (DCS) which occurred in 1984. This experience is summarized in Table l.

Because of the nature and financial status of the participants on these programs/trips, since 1983 a growing number of these divers have been utilizing the EDGE each year and, in the past 12 months, a number of other DC's. Conservative estimates of the number of participants on our programs/trips who utilize DC's has grown from 2.5 % in 1983 to nearly 38 % in 1988. From this increasing percentage of DC use the conservative estimate of dives made using DC's to date is 5,600 or 18 % of the total dives made by this population since 1983. These estimates are presented in Table 2.

POPULATION CHARACTERISTICS

Of the total population of divers described above, the distribution by sex is approximately 60 % men and 40 % women. The average age is estimated to be between 35 and 40 years. More than 60% of this population hold advanced academic degrees (M.D., Ph.D., etc.). A major consideration regarding this population of divers is that on nearly all programs/trips,4 to 6 hours of lectures on decompression sickness (theory,recognition, management and prevention) are presented as part of the total 20 to 40 hours of academic programming on diving, medical and physiological topics.

GENERAL DIVING EXPERIENCE AND PRACTICES

The diving experience of this population ranges from entry level/novice to over 20 years of recreational diving. More than 60 % of this population participate in underwater photographic activities. More than 60 % of the divers participate in two or more out-of-the-country dive trips each year and approximately 15 % participate in diving activities in their local communities. In terms of decompression, 100 % of these divers stay within the "no decompression" limits of the U.S. Navy tables or the DC used. Those who do not use DC's generally observe recommended limits that are more conservative than those of the U.S. Navy. However, approximately 25 % of those who do not use DC's extend their no decompression limits by following some sort of multi-level diving procedures. Nearly 100 % of the divers, both those using and those not using DC's, follow the practice of performing "safety stops" at 10 to 20 feet for 2 or more minutes at the end of every dive deeper than 30 to 40 feet. The maximum depth attained on approximately 80 % of dives made has been less than 100 feet and the remainder have been made to depths never greater than 150 feet.

Table 1

Diving experience from Human Underwater Biology Diving Medical Programs/Trips:
April 1978 through August 1988

	# Divers	# Dives	# DCS cases	Incidence of DCS
Total experience	3,628	47,457	1	0.002 %
Prior to April 1983	1,260	16,482	0	0
After April 1983	2,368	30,975	1	0.003 %

OBSERVATIONS REGARDING USE OF DIVE COMPUTERS

As a general observation, those divers using dive computers extend their bottom times beyond the dive times of divers who do not use DC's, whether or not the latter group utilized multi-level diving procedures. It has been observed that there has been a slightly greater tendency for divers using DC's to dive deeper than those without DC's, particularly on repetitive dives. Also, in buddy teams where only one diver has a DC, the majority of dives have been conducted in accordance with the dive computer readouts. Therefore, the previous estimate of 5,600 dives made using DC's since 1983 among this population could, in actuality, be conservatively increased by nearly 100 %. Regarding use of DC's by buddy teams, it has been observed that when both divers have carried DC's, the divers have used the most conservative readouts to base their ascent and repetitive dive decisions.

The majority of the described population of DC users have, until the past 12 months, utilized the EDGE. In using the EDGE, the majority of divers have utilized the graphics portion of the display in order to dive "conservatively". This involves never allowing any to the "tissue bars" to exceed 2 or more "pixels" above the limit curve of the graphics display at any phase of the dive. There have not been a sufficient number of divers in this population to date using DC's other than the EDGE upon which to base any general observations.

Finally, the use of DC's by the population described has rarely been observed to involve multi-level diving proceeding from shallow to deep. By far the majority of use has involved the standard recommended recreational diving procedure of starting the dive by descending to the maximum depth followed by ascents to and excursions at increasingly lesser depths. These general observations also apply to repetitive dives using DC's.

Table 2

Diving Experience with DC's from Human Underwater Biology Diving Medical Programs/Trips: 1983 through Aug 1888

Year	Avg. Divers	Avg. Dives	# DC Divers	% DC use	# DC dives
1983	394	5,162	10	2.5	131
1984	394	5,162	30	7.6	393
1985	394	5,162	60	15.0	786
1986	394	5,162	80	20.0	1,048
1987	394	5,162	100	25.4	1,310
1988*	394	5,162	150	38.0	1,965
Totals	2,364	30,975		18.2	5,633

*projected through Dec. 1988

DISCUSSION

As seen in the material presented, the use of dive computers, particularly the EDGE, in the population described has, to date, not resulted in any cases of DCS. There have been some observable changes in the manner in which users of DC's dive compared to non-users. While the population described is relatively small, some factors exist in this population which, according to some authorities, should increase the expected incidence of DCS (Fulton, 1951; Fryer, 1969; Bassett, 1978). These factors include the older average age, the proportion of women, and the relatively sedentary occupations and lack of rigorous physical conditioning of many within this population. The very low incidence of DCS (1 case/47,000 dives) indicates that this population dives very conservatively whether or not DC's are utilized.

Departing from the specific observations regarding this population of sport divers, it is appropriate to discuss some of the criticism that has been made regarding DC's, and the EDGE in particular. In tests comparing the EDGE with the U.S. Navy Tables (as well as with the RNPL/BSAC Tables), Edmonds (1987) has pointed out that the EDGE allows no-decompression dives which greatly exceed the table limits, particularly in the area of repetitive diving and repetitive multi-level diving.

Regarding repetitive diving, while the U.S. Navy Repetitive Dive Tables have existed for over 30 years and have been the standard used for repetitive diving by recreational scuba divers for that entire period, the documented utilization has been minimal. The initial testing by the U.S. Navy included only 61 repetitive dives (2 dive combinations) with no indication of how many different divers were utilized in this test series.(des Granges, 1957). Of the 61 test dives, 16 of the initial dives and 17 of the second dives involved depths beyond recreational diving limits (*i.e.*, greater than 150 feet). Counting all initial dives beyond 150 feet and all second dives beyond 150 ft, in which the initial dive was less than 150 feet, yields a total of 27 test dive combinations which were well beyond recreational diving limits. In addition, of the remaining 34 test dive combinations, 26 involved a second dive which was deeper than the initial dive. There were no cases of DCS on any dives which involved an initial and final depth of 150 feet or less.

The number and nature of human test dives performed on the ORCA EDGE compares favorably with the U.S. Navy experience.(Huggins, 1983) It should be stressed that the U.S. Navy tests described were the only specific repetitive dive tests performed before publishing the U.S. Navy Repetitive Dive Tables, which have remained unchanged for over 30 years. In searching for documentation from the U.S. Navy or other sources on the efficacy of these tables in preventing DCS in operational diving, none has been found to date. This lack of data can lead to several possible conclusions, among which are:

1. repetitive diving is rarely performed by U.S. Navy divers;
2. records of repetitive diving are not maintained; or
3. no problems have resulted from use of these tables/procedures.

It is suggested that if no problems (*i.e.*, DCS cases) have occurred, that the repetitive dive procedure may be overly conservative when compared to the U.S. Navy single dive tables. Possible conclusions 1 and 3 above are supported by the fact that in recent years it was discovered that there was a tabulation error made in presenting the repetitive groups for no-decompression dives from 10 to 30 feet. This error results in causing the selected repetitive group to be one group less conservative than the original calculations (and tests) indicated. For example, a dive to 30 feet for 120 minutes yields a repetitive group of G from the tables, but gives a group of H in the original data. It is believed that if there had been extensive use of the repetitive dive tables by U.S. Navy divers over the past 30+ years, that this error would have been discovered through an unexpected incidence of DCS. If use has been extensive (as it likely has been among recreational divers) without problems, the conclusion that the system is overly conservative is supported.

Also, a primary consideration involved in the decision to adopt a repetitive dive scheme based on only one theoretical half-time tissue (*i.e.*, $t_{0.5}$ = 120 min.) was the number of pages of tables that would be required to take all six theoretical half-time tissues into consideration for repetitive dives. An additional consideration was to keep the requirements and instructions for use of the tables as simple as possible for field use by operational divers.

The use of a single theoretical tissue for devising tables for repetitive dives was well thought out and produced a scheme which could be readily used, and which improved efficiency (*i.e.*, increased available bottom time) over the former method used by the U.S. Navy. The pre-1955 method involved simply adding bottom times of subsequent dives without credit given for time spent on the surface between dives. The older procedures resulted in excessively long and overly conservative decompression obligations. However, the decision to use the repetitive dive scheme described also resulted in sets of tables within the U.S. Navy Standard Air Decompression Tables which are based on two different sets of parameters. The tables describing single dive no-decompression limits and decompression schedules, exclusive of the Exceptional Exposure Schedules, are based on six theoretical half-time compartments, each with its own controlling P_{N2}/P_B ratio, while the Repetitive Group designations, Surface Interval Credit Table and Residual Nitrogen Time Table are based on a single theoretical half-time compartment with its single controlling ratio.

Regarding multi-level diving, this procedure was simply not considered during the development of the U.S. Navy Standard Air Decompression Tables, if for no other reason than the almost infinite number of combinations of depth-time profiles and the impossibility of calculating, tabulating and using the number of tables that would be required to meet the huge numbers of combinations. The U.S. Navy recently addressed this problem and developed a procedure for using the repetitive dive tables to meet the specific need of U.S. Navy underwater swimmers using advanced closed circuit, mixed gas equipment (Thalmann and Butler, 1983). This type of procedure has, however, been used successfully for many years by commercial divers as reported by the U.S. Navy (Workman, 1985, pers. comm.). This procedure, which uses the tables describing repetitive groups as "tables of equivalents", has also been adopted by an unknown number of sport divers over the past 10 to 12 years with no apparent increase in the incidence of DCS.(Graver, 1976). Considering the basically conservative construction of the repetitive dive system, this apparent lack of problems is not surprising.

The ORCA EDGE, and other more recent DC's, represent a departure from the standard because the microprocessor and reliable pressure transducers/timers provide something that the pre-calculated tabular approach could never provide, namely moment-by-moment calculation of theoretical gas loading and unloading. The claims made by the EDGE manufacturers that the computer is more conservative than the U.S. Navy Tables is only misleading if direct comparisons are made of dive profile results following the EDGE versus the U.S. Navy Tables. If, on the other hand, calculated nitrogen loading is the basis of comparison, there are no profiles allowed using the EDGE that will exceed the limiting surfacing nitrogen pressures allowed by the U.S. Navy table parameters for any given theoretical compartment. By design of the EDGE, these allowable pressures will always be less upon surfacing, *i.e.*, more conservative.

The "gray areas" in using the EDGE (and similarly designed DC's) are in two areas. In the form of questions these are:

1. Can the U.S. Navy's limiting parameters for constructing single, square-wave, dive profile no decompression limits and decompression schedules be used successfully to calculate limits for repetitive diving?

2. What are the implications of allowing more than one or two theoretical compartments to approach their maximum allowable surfacing nitrogen pressures (even though more conservative values may be used) as can be done in multi-level diving/multi-level repetitive diving using the EDGE compared to single no-decompression limit dives performed according to the U.S. Navy tables?

The answers to these types of questions can only be determined by either statistically adequate human testing, or by carefully documented practical use of the procedures/tables. In the history of the development of decompression procedures in the U.S., neither of these have ever been done satisfactorily, even by the U.S. Navy. This fact, however, has not prevented man from diving either as an occupational or a recreational endeavor. Certainly, obtaining documented practical use information has improved over the past 10+ years in the U.S. Navy (and probably in other controlled populations), but has never been feasible for the entire recreational diver population. The best we have been able to only roughly approximate have been the numbers of treated cases of DCS in recreational divers and, with even greater uncertainty, the approximate numbers of recreational divers.

CONCLUSIONS AND RECOMMENDATIONS

Because of the lack of apparent problems seen with the use of DC's in general, and the EDGE in particular, in the population described, the following recommendations are offered:

1. Training in the fundamentals of decompression theory and decompression sickness, beyond that provided in entry level scuba instruction, is strongly urged for everyone before using a dive computer.

2. Safety stops at 10 to 20 feet for 2 or more minutes are recommended at the end of all dives deeper than 30 to 40 feet.

3. Under normal circumstances, use of DC's is recommended for dives with a maximum depth of not greater than 150 feet, and preferably shallower.

4. Use of DC's for repetitive diving should be limited to no more than three dives in any 24 hour period.

5. Use of DC's for repetitive and/or multi-level dives should always follow the procedure of starting the dive, or series of dives, at the maximum planned depth with subsequent exposure always directed towards shallower depths.

6. Each diver in buddy teams should use the same brand of DC and always use the most conservative readouts on which to base their ascent and repetitive dive decisions. In addition, each diver should have a back-up depth gauge which records maximum depth attained and a separate timing device. Dive information from previous dives should be carried on subsequent dives so that the diver can revert to use of tables in the event of DC failure during any given dive.

7. Ascent rates specified for use by the given DC manufacturer should be carefully observed.

Because the general characteristics, diving experience and practices of the population described may be more closely aligned with the characteristics of the scientific diving community than the recreational diving population at large, the recommendations provided above may be most applicable and the experience most pertinent to the scientific diving community.

Due to the fact that the scientific diving community is a more "controlled" population than the recreational diving community, the documented use of DC's in the former group would be of great potential benefit to the entire diving community. It is urged that standardized utilization of DC's and, more importantly, standardized data collection be adopted within this community. It is further urged that funding be sought to provide a central data collecting agency to receive and analyze such data and report results in an efficient and timely manner. Manufacturers are urged to participate in this endeavor to establish a meaningful database for the safe use of such devices and for verification of the assumptions used in the design of the dive computers.

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FIELD USE OF DIVE COMPUTERS IN A UNIVERSITY PROGRAM

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Dive computers, specifically the ORCA EDGE, have, with the approval of the Diving Control Board, been in use at the Graduate School of Oceanography of the University of Rhode Island for about five years. Their greatest utility has proven to be on blue-water cruises aboard URI's ship the R/V ENDEAVOR. All dives were made without any incidents of any kind, including decompression problems. There have, however, been several examples of operational problems with the computers. These problems range from battery failure in arctic waters to the flooding of battery compartments. The usual effect was to lose the data in the computer. Several techniques have been developed to minimize these problems and to get divers back into the water after the computer data was lost. These techniques and procedures are discussed, as are the operational advantages and disadvantages of the dive computers.

BACKGROUND

Dive computers are built for the recreational diving market. Research divers are not recreational divers and do not represent a large enough market for a manufacturer to target. An examination of the differences in the practices of the two communities is important in any examination of the utility of recreational diver equipment for scientific divers. It is not my intent however, to discuss the reasons and rationales for these differences, since they are well documented. I wish to simply identify them and then to examine how they affect the field use of dive computers by scientific divers.

There are two primary differences between the diving done by the recreational and scientific communities:

1. Recreational divers have a maximum permissible depth of 130 feet, based on the switch-over by the U.S. Navy to surface supplied gear at that depth, while the science community uses a maximum permissible depth of 190 feet, based on the switch from the U.S. Navy Standard Air Tables to their Exceptional Exposure Tables; and
2. It is the policy of all the recreational diver agencies that recreational divers not engage in any decompression diving while the science community permits, with varying levels of control, decompression dives.

Potential usage differences include:

1. The potential for the use of dive computers from a storage pressure greater than atmospheric (habitats).

2. The potential for the use of dive computers with breathing mixtures other than air.

3. The potential use (or accidental exposure) of dive computers to gaseous environments in habitats and underwater phone booths.

EXPERIENCE WITH DIVE COMPUTERS

Divers from the North East Consortium Research Fleet (W.H.O.I., U.R.I. and L.D.G.O.) have, for the last five years, had a unique facility available to them. A National Science Foundation grant to U.R.I. resulted in the development, construction and fielding of the N.E.C.O.R. Oceanic Diving Facility. It is composed of a high volume, high pressure compressor, a filling system capable of filling 6 scuba tanks at a time, 12 scuba tanks, an air quality analysis system, 6 ORCA/EDGE and 6 ORCA/Skinny Dipper dive computers. All this equipment is housed in a 12 x 8 foot container that can be easily placed aboard a ship and hooks up to 480 volt three phase power.

When the system is not in the field, researcher divers are welcome to borrow components of it. The U.R.I. research diving program, as a result, has gained significant experience using these two dive computers. There have been no diving accidents or significant incidents of any kind within the U.R.I. research diving program, so none may be attributed to the computers.

URI RULES FOR USING DIVE COMPUTERS

1. The U.R.I. Diving Control Board permits normal use of the ORCA EDGE and SKINNY DIPPER computers as no decompression indicators and requires that divers always have at least 5 minutes of no decompression time available, regardless of depth. If, for any reason, the computer stops working the diver must terminate the dive immediately. A tank of oxygen was initially hung at ten feet and any diver who broke the 5 minute rule would have to take ten minutes on oxygen prior to ascending. This technique was discontinued after several dives since the divers never came close to crossing the five minute threshold.

2. Divers must adhere to the manufacturer's recommended ascent rate.

3. Dives must begin at the deepest point and work shallower and divers are encouraged to spend a significant amount of time in the twenty foot range at the end of the dive.

4. On blue-water dives, adherence to these rules was checked by requiring all divers using computers to check in with the pivot diver prior to ascent. They had to show the pivot diver that they had 5 or more minutes on their dive computer and that they had 500 PSI of air remaining in their tank.

5. Each diver must be equipped with his or her own dive computer.

FAILURE MODES

I know of no circumstances in which any of our computers have provided a diver with inaccurate information. There have been circumstances that resulted in the blanking of the computer with the resultant loss of previous diving history. There are two basic causes for such failures: those caused by users erroneously powering the computer down while they still had residual nitrogen in their body and those caused by crashing the computer by running out of battery power. Two common methods of running out of power are by not heeding the Low Battery Indicator and by flooding the battery compartment.

COLD WATER DIVING

An unexpected, and initially confusing, crash mode occurred during arctic dives. A diver would enter the water with an EDGE that had been used for several previous dives and was not indicating a low battery state. During the course of the dive the Low Battery Indicator would come on and by the end of the dive the display would be blank. This phenomenon caused an initial lack of confidence in the EDGE on the part of the divers.

To understand what happened we need to look at how the Low Battery Indicator of the EDGE (and many other computers) works. The 9-volt battery in the EDGE drops in voltage in a predictable fashion as a result of use. When it reaches a little more then 5 volts the computer can no longer function and crashes. The computer's designers took advantage of this fact to turn on the Low Battery Indicator when the battery voltage reached about 7 volts which should permit about four remaining hours of operation. This is not a problem under most circumstances. However, when a battery is cooled its voltage drops (this is also why a car is hard to start on a cold morning). If a 9-volt alkaline battery that is delivering slightly more than 7 volts is cooled to freezing, its voltage drops to below the critical threshold and the computer crashes. When the battery warms back up it is still capable of running the computer, sometimes without even showing a Low Battery Indicator. This problem resulted in our changing batteries on a daily basis rather than when the Low Battery Indicator came on. Fortunately, we had a sufficient number of batteries aboard to complete the cruise.

We solved that problem by switching to 9-volt nicad rechargeable batteries for cold water missions. Since nicads discharge at a different rate than do alkalines, we invalidated the Low Battery Indicator which was not working for us anyway. We put a freshly charged nicad in the computer every morning and before any night dives. This assures sufficient voltage to keep the computer up and obviates the need for the Low Battery Indicator. The problem of nicad battery "memory" is still there and may crop up. We have plans to build a nicad discharge/charge system that will run a battery into a dummy load until it is drained and then slowly charge it.

We are currently engaged in a project of testing, from 30 °C to -2 °C, all the dive computer batteries that we can obtain. We hope to have this project completed by January 1989. We will submit the results to the A.A.U.S. Slate for publication.

LOST RESIDUAL NITROGEN DATA PROCEDURES

When the data in the computer is lost, regardless of the cause, there are two considerations. The primary consideration (assuming the data is lost while in the water) is effecting a safe return to the surface and the secondary consideration is how to safely begin diving again. Getting back to the surface is easy if the diver is never in a decompression status, which is one of the reasons that U.R.I. requires that the diver always keep 5 minutes of no-decompression time available. The failure of a dive computer while a physiological ceiling is in effect could be a very serious problem (I suggest carrying a backup computer for all planned decompression dives).

Getting a diver back in the water after the failure of a computer is the second problem. The best way is to follow the manufacturer's recommendation on how long to wait to clear out the residual nitrogen and begin diving again with a restarted computer. This is not always possible. On occasion, a diver would prefer to get back into the water without waiting twenty-four to forty-eight hours. There are several techniques in use, all of which depend on keeping good dive records, especially records of the scrolling no-decompression limits that are displayed by most all computers in their surface mode. None of the currently available computers are set up to permit user access to set levels of tissue saturations. Thus it is impossible to "get back on the computer" without waiting for residual nitrogen to clear. So the first question is, "How long must I really wait?"

There is no complete answer to this question. Clearly, a diver who made a few, short (even deep) dives will clear out excess nitrogen before a diver who made many, long (even shallow) dives. If all the divers in the group have similar past profiles, it becomes a judgement call to permit a diver to reenter the water with a computer when other computers in the group are clear. This has been done successfully and usually involved waits of 12 to 18 hours, but the ultimate safety of this procedures is clearly problematical.

More to the point is the question, "How can I immediately get onto a set of written tables?" A technique that was independently developed by Mike Emmerman of LifeGuard Systems and myself has been used. It requires that the diver record the time of day and scrolling no-decompression limits after every dive. Refer to M. Emmerman - "Dive computer log for the EDGE or SkinnyDipper" in these AAUS Dive Computer Workshop Proceedings for the complete procedure and warnings.

If a computer fails the diver must then:

1. Look back at the scrolling no decompression limits and subtract the available time for each depth to come up with a series of time/depth pairs describing dives that would have resulted in equivalent nitrogen uptake.
2. Determine the repetitive dive designator for each of the time/depth pairs determined.
3. Use the designator that represents the greatest amount of nitrogen to enters the tables and continue on.

There are some potential problems with this approach, especially through the use of a set of tables that is inappropriate for the model used by the computer to determine the scrolling no decompression limits. This technique seems to yield reasonable results using the Huggins Tables with the EDGE or SKINNY DIPPER or the Swiss Tables with dive computer programmed with the Bühlmann Model. This technique has not been proven, so use it at your own risk.

WHAT DOES A SCIENTIFIC DIVER NEED IN A DIVE COMPUTER?

Essential features of a dive computer for scientific divers include:

1. the capacity to be safely used for decompression dives, not just as a no-decompression indicator.
2. an operational depth of at least 200 feet.

Useful features in a dive computer for scientific divers might include:

1. the ability to display something like a repetitive dive group that would permit switching to a set of hard copy tables.
2. the possibility to update, permitting the input of tissue pressure values, either to provide a "safety margin" or in combination with a surface computer to be able to have several divers "share" a dive computer.
3. a dive logging function that could either display previous dive profiles or write them out to a microcomputer.
4. an algorithm for the low battery indicator that includes the ambient temperature.
5. displaying not just the bottom time and maximum depth, but also displaying by a numerical representation the diver's maximum "worst case" nitrogen situation. That is to say, how close was any no-decompression limit approached or by how much was it exceeded.

CONCLUSION

Dive computers have been used by research divers associated with the University of Rhode Island for five years without any instances of diving maladies. The current generation of such computers have greatly aided scientists by increasing their bottom time for multi-level dives. Future instruments hold great potential for assisting scientific research programs as long as the dive computers are philosophically viewed as automated dive tables rather than as devices that are to be "followed to the letter". Proper training in dive computer use is the critical factor.

PROFESSIONAL DIVERS USE OF DIVE COMPUTERS

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The intelligent use of dive computers is required. Advantages of dive computer use are listed and the prime concerns of human error and technical problems are addressed. Applications of DC use in the teaching of SCUBA, commercial diving and tourist diving are clarified. Examples are given of dive profiles comparing decompression requirements of the Navy tables and the dive computers. Back-off procedures are recommended for working dives or for out-of-shape divers. The importance of a backup procedure, a back-off procedure and a failure plan is stressed.

INTRODUCTION

The reality is that we are here to find out how to safely and effectively use the dive computers (DC's) we have now. In addition, we are going to significantly influence the future on how these DC's might be manufactured and how we choose to use them. The outcome of this reality is that the information from this workshop is applicable to every diver.

Divers want dive computers. So whether some scientists or physicians say they are not good enough or do not work right, we still want them.

For historical perspective, I wrote a paper ten years ago (Hardy, 1978) on the use of the SOS meter. There was an intelligent way to use the SOS meter, and divers used them regardless of the people who said they were not good enough for us to use. We had needs and met those needs with the meter.

Now we have a multiplicity of advanced dive computers and we are going to use them as professional working divers. We are figuring out ways to use them safely.

We need to be realistic. There is a calculated risk. The theory, the tests and the practice in the field do not agree with each other. It appears that DC's safely add to the time we can spend underwater. Over the years it has also been said that civilian divers are more likely to get bent, when in fact they really are not. However, it is a real problem to measure that. There is an enormous mass of civilian divers performing recreational dives. The Navy's number of dives is minuscule compared to the number of divers we train in one year, all of whom have to have four open water dives as a minimum certification criterion. Our base is enormous, but it is not well recorded, so we have a hard time telling what is going on.

THE PROFESSIONAL DIVER'S USE OF DC'S

As a professional working diver, I do commercial diving, instructional diving and guided tours. I am going to talk about these professional divers that do physical work underwater. For my particular dive business here on Catalina Island, we spend 50% of our dives taking recreational divers underwater on training dives and guided tours and the other 50% doing light industrial, commercial work. Many of these dives are quite deep. I personally put in over 500 dives per year. In addition, in my consulting business I do accident investigations, insurance work, expert witness work and contract writing.

Regarding the intelligent use of computers, I describe two contrasting examples.

1. A new instructor, diving here at Ship Rock from my dive boat,.is bringing up a certified tourist diver who is low on air, about to go into an out-of-air situation. He controls the ascent with his DC and is not allowing the diver to come up any faster. He is not sharing air because he is monitoring his computer. So I move in, abort that procedure, take over, share air and make the ascent. The new instructor later said he was making sure he did not exceed his DC's safe ascent indicator. We cannot become a slave of these devices. We are intelligent human beings who can make rational decisions and know that being without air is more dangerous than what the ascent indicator says on the way up.

2. Not a stone's throw away at Blue Caverns, unfortunately, a fatal diving accident occurred. One diver comes up and says he has lost his buddy, he has gone off into deep water. The divemaster on the boat had a dive computer, with dives already on it, but was able to make a search because she did have it. She made the search without jeopardizing her own safety in deep water and came up after making the necessary decompression stops. If she had hit the right spot, and she was not off by much, it might have been a successful rescue. Unfortunately, she just missed the area. The sheriffs brought back the body later. She was able to dive out of order because she had a DC and then, because she knew the working procedure used here on the island, was able to back-off since she had done an out of order dive.

The documented material that I have, is based on some 30 divers diving in 30-190 fsw, primarily on the EDGE, but also using half a dozen other dive computers. I do not have hard facts on the tourist dives, but have observed them over the last several years using all the other dive computers. We have 7500 computer dives in our log basis and additionally, dives "controlled" by DC's number in the thousands beyond that.

Other types of work, besides instructional and tourist dives performed with these DC's are: search & recovery, boat bottom cleaning, mooring work, photography, marine surveys, salvage, boat repairs, equipment testing and accident investigations. This range of work includes significant decompression. We do a great deal of mooring work, many of which are rigged below 100 ft.

Of the 7500 dives we have recorded, the thousands of additional tourist computer dives and dives controlled by dive computers, we have only one case of decompression sickness. That incident would have violated the tables also because, in addition to other reasons, it repeatedly violated the ascent rate.

DC ADVANTAGES AND CONCERNS

I have compiled a list of 23 perceived advantages of dive computers. Dive Computers:

1. Use actual dive profiles, not approximations;
2. Are extremely flexible to let you change dive plan;
3. Provide a readout for dive planning;
4. Relieve diver from the need to concentrate on and figure decompression status, particularly while in the water;
5. Make safer repetitive dive calculations due to the use of several versus one compartment for repetitive group;
6. Are outstanding ascent monitors;
7. Have a very high accuracy as a depth gage;
8. Perform a diagnostic check and will not proceed if not OK;
9. Do not forget to turn on or off to log information;
10. Do not make mathematical errors;
11. Do not transfer information incorrectly;
12. Have electronics already incorporated into every other facet of our modern lives, so dive computers fit right in;
13. Provide more effective ways of incorporating margins of safety;
14. Provide for longer multi-level dives;
15. Have safer cut-off points built in;
16. Use more tissues than decompression tables;
17. Comprise a smaller package than the separate instruments;
18. Have built in warning devices;
19. Are safer for multi-day diving since nitrogen is carried over;
20. Can handle the unplanned event;
21. Offer less likelihood of mistakes under stress;
22. Can be programmed with newer information;
23. Do not make human errors.

We have agreed that the general diving public really does not know or understand the dive computers or the procedures. Some of my major concerns are in the many ways human beings fail to properly operate the DC's and therefore make mistakes with them. The dive computer on a string underwater during the diver's surface interval is a real story. There are also other ways of doing the same thing. Turning the DC off between dives so the diver could start over again after clearing it is another way. Human error and not paying attention are my prime concerns. Just because people wear a DC, does not mean they are paying attention to it or will act on the information.

There are a number of questions about the DC programs, but that goes beyond my scope and understanding. I am concerned however when I see us able to make so many deep dives so rapidly.

There are a number of technical deficiencies such as battery problems and flooding problems. The DC's will get better and better as there is a greater market for them.

I would like to point out a special concern for those individuals who are instructors. The rate of ascent and error modes can create problems when you are performing ascent training with SCUBA students. It is very difficult to do ascent training and not have your ascent indicator tell you to go slower.

We have had a lot of talks and layouts of various profiles that have gone wrong. We have safely made the following working dives, some of which did require decompression.

Example 1

Dive # 1	30 fsw/ 25 min	No decompression stop
SI	15 min	
Dive # 2	136 fsw/ 23 min	No decompression stop
SI	120 min	
Dive # 3	101 fsw/ 35 min	Stop at 10 fsw/ 3 min

Total decompression required by tables	80 min
Total required by DC	0 min
Actual time taken	3 min

Example 2

Dive # 1	151 fsw/ 8 min	No decompression stop
SI	5 min	
Dive # 2	145 fsw/ 9 min	No decompression stop
SI	4 min	
Dive # 3	145 fsw/ 8 min	No decompression stop

Total decompression required by tables	79 min
Total by tables single dive rule	27 min
Total required by DC	0 min
Actual time taken	0 min

Example 3

Dive # 1	137 fsw/ 30 min	Safety stop at 15 fsw/ 3 min
SI	182 min	
Dive # 2	98 fsw/ 34 min	No decompression stop

Total decompression required by tables	63 min
Total required by DC	0 min
Actual time taken	3 min

BACKUP, BACK-OFF AND FAILURE PLANS

We are often worried since not all divers are in the best of shape or there may be other problems, so we have a back-off procedure for use with the EDGE. Normal back-off for working dives consists of bringing all the tissue bars back to the 60 fsw mark. We are arbitrarily using these numbers. This is our practice in the field to get away from some of the concerns we have. If we are more concerned because of the difficulty of the operation, we back off to 50 fsw. If we are diving with some of the out-of-shape tourists, we back off to 40 fsw. If we are really concerned about the tourist, we keep a blank pixel line just above the curve, in addition to the three back-off steps. We regularly perform deep decompression working dives on the EDGE. We do our decompress on and then we bring the pixels back. Graphics are incredibly valuable in this respect. We have done this on other DC's, but it is more difficult without having graphics to use.

There is a definite need for really good DC training. We also need backup procedures, which we already have for working divers, such as other DC's, decompression tables, back-off procedures. We can not expect the recreational diver to be that comprehensive, but we can certainly expect scientific divers to go with what working divers have done for backup. What we should really push for is an increase in the diver's awareness level of depth-time, just as we do to increase their awareness level of gauge pressure.

We need a DC failure plan. We have several, such as going to 15 fsw and burning the rest of our air, or a slow stop ascent, which we substituted for the Navy's omitted decompression procedure years ago, because we could not remember it. We also have ways to keep diving and ways to get back into the tables, which are rather complicated. We do out of order diving. We did 147 dives on one job, constantly out of order, deep dive after shallow dive, with no problems whatsoever. We were, however, constantly using our back-off procedure.

Another problem area are the tour dives "controlled" by one DC. This is being done all the time by resort guides. The guide has as many as six divers diving on his DC. The guide goes to the deepest depth and stays the longest. One of the trickiest things we have is buoyancy control with the new ascent rates. This is really tough in training situations. You can come up a line, you can follow the up slope on the bottom or you can put your BC inflator right next to your dive computer and control buoyancy and the DC at the same time. We have used a procedure on working dives where we just run up to "ascend slower" then stop, run up to "ascend slower", then stop, and so on. It stops you about every five feet. That's just another possible way to do it.

Legal implications are a very important area we need to discuss.

SUMMARY

DC's are here with both their advantages and problems, there is a risk to what we are doing. They are intelligently being used by professionals in the field to get more time underwater and it is being done safely. Instruction is a key issue, we need it. None of the DC's are good enough. They have got to get better as we go along.

We need a back-off procedure, a backup procedure and a failure plan. We need to improve our ascent procedures and we need to consider the legal implications of what we are doing.

LITERATURE CITED

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CAVE DIVING AND DIVE COMPUTERS

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The cave diving community performs more in-water decompression than any other group of divers. Specialized equipment, techniques and training are essential, as is a thorough knowledge of decompression procedures. Cave divers started using dive computers as soon as they appeared on the market. An evaluation of the experience of cave diver's use of DC's reveals that almost 50 % of the cave diving community is diving longer and deeper with DC's in a relatively safe fashion. Oxygen is often used in decompression, and although DC's are used as a guide, additional safety factors are added to the U.S. Navy tables, and the most conservative schedule followed.

INTRODUCTION

Florida has 17 freshwater springs of the first magnitude (discharging 100 cubic feet of water per second or greater), 49 springs of the second magnitude (discharging a flow between 10 and 100 cubic feet per second), and hundreds of smaller springs. Most of these springs discharge crystal clear water, with an average temperature range of 68 to 78 degrees Fahrenheit. It is little wonder that these pristine pools of "gin clear" water annually attract thousands of divers.

Ever since 1951, when scuba divers from the National Speleological Society first ventured underwater into the cave at Blue Hole Springs (also known as JUGG Spring) along the Ichetucknee River, cave divers have explored many of the underwater caves in Florida. From the beginning, cave divers have been on the cutting edge of diving technology. Single hose regulators, submersible pressure gauges, octopus regulators, long hose octopus regulators, redundant life support systems and dry suits are just a few of the many innovations in diving that the cave diving community embraced soon after their introduction.

Cave divers typically are diving longer and deeper than they did as little as 5 years ago. As such, the need for decompression has become almost the de facto standard for a cave dive. However, since most cave dives are done in remote areas, with limited access to immediate evacuation to a medical treatment facility, most cave divers are concerned with minimizing the incidence of Decompression Sickness (DCS) while at the same time, not prolonging in water times to an extreme degree.

CAVE DIVING EQUIPMENT

Cave divers have also been in the vanguard of equipment development. The "Sling Shot Valve", the dual outlet manifold, buoyancy compensators, power inflators for BC's, and the many underwater lighting systems are just a few of the equipment innovations that can be directly traced to the cave diving community.

Cave divers have been involved in both air and mixed gas diving, with the latest technology being the use of customized decompression tables for use with mixed gas diving in the Wakulla Cave Diving Project in late 1987, and in the exploration and connection of the Sullivan Sink Cave system with the Emerald Sink Cave system in late 1987 and early 1988. The Wakulla project also saw the testing of a computerized rebreathing system, and the first use of an in-water habitat for decompression in a major cave diving venture.

Cave divers had used and discarded the SOS decompression meter in the late 1960's and the early 1970's. The current use of dive computers (DC's) by cave divers began almost as soon as the Orca EDGE was introduced to the diving public. With the current proliferation of DC's, the use by the cave diving community has exploded.

CAVE DIVING DECOMPRESSION SURVEY RESULTS

The authors have recently completed an evaluation of the use of DC's in the cave diving community. 250 questionnaires were mailed out to the voting membership of the National Association for Cave Diving (NACD). The respondents were/are divers who are fully certified in cave diving, and are active members of the NACD. 100 responses were evaluated for this report, for a response rate of 40%.

The background information on the divers is enumerated below:

How long have you been cave diving?

6% - < 1 year
45% - > 1 year, but < 5 years
28% - > 5 years, but < 10 years
23% - > 10 years

How many cave dives did you make in the last year?

14% - < 10
21% - > 10, but < 25
32% - > 25, but < 50
10% - > 50, but < 75
23% - > 75

What percentage of your cave dives were decompression dives?

21% - < 50%
23% - > 50%, but < 75%
20% - > 75%, but < 90%
36% - > 90%

How many dives in the last year were classified as exceptional exposure dives?

46% - No dives in the last year of exceptional exposure
19% - 1 - 5 dives
12% - 6 - 10 dives

9% - 11 - 15 dives
14% - > 16 dives

During the last year did you use any gas mixture other than air during cave dives?

10% - Yes
90% - No

Do you use a dive computer for cave diving?

43% - Yes
57% - No

If you use a dive computer for decompression, do you:

22% - Follow the dive computer schedule exactly.
78% - Use the dive computer as a guide for decompression

Most of the divers who use DC's utilize them in conjunction with dive tables (US Navy or British tables most commonly). The usual mode is to check both the DC and the tables, and go with the most conservative schedule.

Did you use oxygen during any of your decompression dives last year?

48% - Yes
52% - No

What is the deepest depth at which you use oxygen for decompression?

5/48 - 10 Ft.
35/48 - 20 Ft.
5/48 - 30 Ft.
1/48 - 40 Ft.

Do you use the US Navy tables?

82% - Yes
18% - No

If you use the US Navy tables, do you follow them exactly or do you use them as a guide for decompression?

28% - Follow exactly
72% - Use as a guide to decompression

The consensus among the respondents was that the US Navy tables were not conservative enough, and the following techniques were used:

A - Additional time was added to the 10 ft. stop.
B - Use the next greater depth and/or bottom time.
C - Use oxygen in decompression after deep/long dives

Questions concerning occurrence of Decompression Sickness were as follows:

Have you ever had "SKIN BENDS"?
22% - Yes
78% - No

Have you ever had Type 1 decompression sickness - Pain only?

9% - Yes
91% - No

Have you ever had Type 1 DCS and not received medical treatment for it?

8/9 - Yes
1/9 - No

The most common comment was that the victim self-treated with oxygen, fluids, and analgesics. One victim related his protocol of fluids, oxygen and a 80-100 foot dive the following day with extensions during decompression.

Have you ever had Type 2 Decompression sickness - Peripheral nervous system involvement / Central nervous system deficits / respiratory involvement?

4% - Yes
96% - No

Have you ever had Type 2 DCS and not received medical attention for it?

1/5 - Yes
4/5 - No

A final question was asked of the respondents:

What would be your ideal dive computer?

A - Compact
B - Long battery life
C - More conservative than current models
D - More information on the required stops
E - Able to use to pre-plan repetitive dives
F - Greater depth capacity
G - Able to handle in-water oxygen decompression
H - Able to customize for individual diver (input "fudge" factors for smoker, cold, heavy work, overweight, etc.)
I - Redundant circuitry
J - Mixed gas capability

SUMMARY

In summary, the typical cave diver today is diving deeper and longer than ever before. Thus, the risks of DCS are becoming much more evident to these divers. The use of DC's to increase the safety factor is the major reason for the acceptance of DC's by almost 50% of the cave diving community.

SURVEY OF DIVE COMPUTER USERS AND POTENTIAL USERS

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Questionnaires were collected from 116 divers. Of that total, I had interviewed 91 of the respondents in person. The verbal interviews revealed very different knowledge levels than the respondents indicated on the written questionnaires. On the questionnaires, 68 divers said that they were familiar with multi-level calculations. Only 17 of these divers could actually show this ability. When asked to explain tissue half-times, 34 out of 116 indicated they could; but only 12 of the 34 came close. Of the 116 respondents, 49 were owners of dive computers (DC's). The most commonly expressed concerns by all 116 respondents were:#1, malfunction; #2, lack of knowledge; #3, reliability; and #4, dependency. The results of this survey (and interviewing process) indicate a vast lack of knowledge about the basis upon which DC's function.

In carrying on with a long standing interest in the safe use of dive computers in the recreational diving community (Emmerman, 1988a; 1988b), I sent out questionnaires to a number of divers of various experience levels A total of 116 questionnaires were completed and returned. I followed 91 of these up with verbal interviews.

THE QUESTIONNAIRE

The questionnaire that was distributed requested the following information:

1. Name, address and telephone number of the diver.
2. Date questionnaire was completed.
3. Years of diving experience.
4. Level of current certification.
5. Does the diver own a dive computer?
6. If so, which brand and model?
7. Number of dives made with this unit?
8. Ever experienced a mechanical malfunction?
9. Familiar with Multi-level dive calculations?
10. Can calculate a Multi-level dive profile?
11. Can explain Tissue 1/2-times to a friend?
12. Log dive profiles?
13. Log dives when using a dive computer?
14. If dive computer malfunctioned, could re-enter a dive table correctly?
15. Any concerns or worries about using dive computers?

THE DIVERS

Of the 116 questionnaires that were returned, 91 were completed by divers who were either in rescue programs taught by me or otherwise known to me. The remainder of the questionnaires were returned through the mail after being distributed by dive stores and other instructors. A bias exists in that 97 of the divers were from the New York metropolitan area (NY, NJ, CT, and PA).

Table 1 shows the summary of all of the "yes or no" questions from the questionnaire. Respondents covered all levels of divers: Open Water (47), Advanced Open Water (36), Master Diver (2), Dive Master (9), Assistant Instructor (4), and Instructor (18). The breakdown between owners and non-owners of DC's within the above categories is also shown in Table 1.

THE RAW DATA

Of the 116 divers, 67 did not (49 did) own DC's. The 49 divers who owned DC's made a total of 4,959 dives using these computers. Out of 49, 18 divers experienced a mechanical malfunction. When all 116 divers were asked if they were familiar with multi-level calculations, 68 said yes and 48 said no. When asked if they could actually work out a multi-level profile, 39 said yes and 77 said no. Asked if they could explain tissue half-times to a friend, 34 said yes and 82 said no. Those who regularly log their dives amount to 91 (vs. 25 who said they do not). Of the 49 dive computer owners, 34 said they log dives when using the DC; 15 said they did not. Asked if these dive computer owners could re-enter a dive table in the event of a malfunction, 43 said yes and 6 said no.

When asked the question, "what bothers or worries you the most about using a dive computer": 23 made no comment; 34 mentioned malfunction during or after a dive; 12 felt that they personally, or divers they knew, lacked the knowledge necessary to properly use a dive computer; 11 questioned the reliability of the information generated by the computer; 9 were worried about becoming dependent on a mechanical device.

Some of the other more frightening comments include:
"My buddy getting bent"
"I want to be able to see my compass"
"Limited depth"

Many of the advanced divers mentioned:
"Multi-level controversy"
"Difference between models (algorithms)"
"Repetitive diving"
"No adjustment for individual physiology"
"Tendency to push limits"

The responses to the question about computer malfunction are summarized as follows:

		TOT	OW	AOW	DM	AI	INS
Edge:	Owners	23	6	7	2	1	7
	Malfunction	6	2	2	1	0	1

SkinnyDipper: Owners	11	4	5	1	0	1
Malfunction	6	2	2	1	0	1
Beuchat: Owners	5	3	0	0	0	2
Malfunction	2	2	0	0	0	0
Suunto ML: Owners	5	2	2	1	0	0
Malfunction	2	1	1	0	0	0
SOS: Owner	1	1	0	0	0	0
Malfunction	1	1	0	0	0	0
Aladin: Owner	1	0	1	0	0	1
Malfunction	0	0	0	0	0	0
DecoBrain: Owner	2	0	1	0	0	1
Malfunction	1	0	1	0	0	0
Aquatech: Owner	1	0	0	0	0	1
Malfunction	0	0	0	0	0	0

In the above summary, OW stands for Open Water diver, AOW for Advanced Open Water, DM for Divemaster, AI for Assistant Instructor and INS for Instructor. I do not believe that the response universe is large enough to allow for any meaningful analysis of the data relative to **malfunction** of DC's. It is interesting, however, to note that 14 out of 18 malfunctions were experienced by Open Water and Advanced Open Water divers. Only 2 Divemasters and 2 Instructors had this problem.

Table 2 lists all responses to the questionnaire. The names of the actual respondents have been replaced by a Diver Number (column 1). The divers are listed in certification ranking (i.e. Open Water to Instructor). In each category the non-DC users are grouped first. The column showing the responses to the question "What worries you most." is only an edited review of the diver's full comments. All questionnaires were completed between January and August of 1988.

OBSERVATIONS

The most interesting (to me) question asked of these divers was "can you re-enter a table if your computer malfunctions." My research has indicated that you **can not** simply re-enter a table after a DC malfunction. In fact, if you do not have a table based on the mathematical model which was used to program your DC, you would have to wait the appropriate length of time for your particular DC to totally off-gas. Even if you **did** have such a table (i.e. the Huggins NO-Bubble Table relative to the Edge & Skinny Dipper), you would have to be well versed in the manipulation of the data to properly perform the calculations. Of the 49 owners of DC's, 43 said that they knew how to re-enter a table after a malfunction. I believe that only a few, if any, of these divers could actually perform this difficult calculation.

From the work done in connection with this survey, it is my opinion that having divers fill out a form asking them if they "can" or "can not" do certain things is totally useless unless these divers are tested. My survey would have shown misleading information if I had not had the opportunity to interview the vast majority of the respondents in person. A better survey would have included a series of test questions in order to prove proficiency.

Having had the opportunity to make such interviews, I can offer the following observations. The accuracy and dependability of DC's is not our primary problem. Our primary problem is a lack of knowledge on the part of the diving community about diving physiology. The majority of divers I interviewed did not understand tissue half-times. Most of these divers had never even heard of multi-level dive profiles. Yet, only **one** diver said that he will **not** use a DC due to this lack of knowledge. We must do a better job of educating divers before they purchase and use dive computers. Divers can not make a rational personal judgement about the risk of using any particular dive table or dive computer without first understanding the basis upon which such tables and computers function.

Table 1. Summary of questionnaire data

CERTIFICATION LEVEL OF DIVER	DIVER OWNS DIVE COMP (DCC)	# OF DIVERS	# OF DIVES WITH COMP	EVER EXP MAL-FUNC	FAMILIAR WITH MULTI LEVEL CALC		CAN DO MULTI LEVEL CALC		CAN EXPLAIN TISSUE HALF TIMES		DOES LOG DIVES		DOES LOG DIVES WITH COMP		CAN ENTER TABLE IF COMP MALFUNC		# OF DIVERS INTER-VIEWED IN PERSON
				YES	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	
OPEN WATER	NO	31	--	--	12	19	7	24	4	27	28	3	4	27	8	23	30
OPEN WATER	YES	16	1496	8	10	6	5	11	5	11	11	5	11	5	14	2	12
ADVANCED OPEN WATER	NO	20	--	--	7	13	4	16	3	17	14	6	4	16	4	16	20
ADVANCED OPEN WATER	YES	16	1604	6	14	2	8	8	6	10	11	5	12	4	15	1	13
MASTER SCUBA DIVER	NO	2	--	--	1	1	0	2	0	2	2	0	0	2	0	2	2
DIVE MASTER	NO	5	--	--	4	1	1	4	3	2	4	1	1	4	2	3	4
DIVE MASTER	YES	4	525	2	3	1	3	1	2	2	3	1	3	1	4	0	2
ASSISTANT INSTRUCTOR	NO	3	--	--	0	3	0	3	0	3	3	0	1	2	2	1	1
ASSISTANT INSTRUCTOR	YES	1	70	0	1	0	1	0	1	0	1	0	1	0	1	0	1
INSTRUCTOR	NO	6	--	--	5	1	4	2	4	2	6	0	1	5	4	2	2
INSTRUCTOR	YES	12	1264	2	11	1	6	6	6	6	8	4	7	5	9	3	4
NON DCC OWNER SUB-TOTAL		67	0	0	29	38	16	51	14	53	57	10	11	56	20	47	59
DCC OWNER SUB-TOTAL		49	4959	18	39	10	23	26	20	29	34	15	34	15	43	6	32
TOTAL		116	4959	18	68	48	39	77	34	82	91	25	45	71	63	53	91

Table 2. Questionnaire Review

DIVER	STATE	YEARS	LEVEL OF CERT	OWN DIVE COMP (DCC)	IF YES BRAND	# OF DVS WITH COMP	EVER EXP MAL FUNC	FAMIL WITH MULTI LEVEL CALC	CAN DO MULTI LEVEL CALC	CAN EXPL TISS 1/2 TIME	DOES LOG DIVE	DOES LOG DIVE WITH COMP	CAN ENTER TABLE IF COMP MALFUNC	WHAT WORRIES YOU MOST ABOUT USING DIVE COMPUTERS (DCCs)	DIVERS INTERVIEWED IN PERSON
OPEN WATER DIVERS - NON-OWNERS OF DCCs															
1	NJ	1	1 OW	NO	NA	NA	NA	YES	NO	NO	YES	NA	YES	WHAT IS A DIVE COMPUTER?	YES
2	NJ	1	1 OW	NO	NA	NA	NA	NO	NO	NO	YES	NA	YES	MALFUNCTION	YES
3	NJ	1	1 OW	NO	NA	NA	NA	NO	NO	NO	YES	NA	NA	WOULD LIKE TO SEE ONE IN USE	YES
4	NJ	1	1 OW	NO	NA	NA	NA	YES	YES	NO	YES	NA	NO	NOTHING	YES
5	PA	1	1 OW	NO	NA	NA	NA	NO	NO	NO	YES	NO	NO	DOES NOT EXPECT TO USE ONE	YES
6	NJ	1	1 OW	NO	NA	NA	NA	NO	NO	NO	YES	NA	NO	RELIANCE ON MECHANICAL EQUIPMENT	YES
7	NJ	1	1 OW	NO	NA	NA	NA	NO	NO	NO	YES	NA	NO	MALFUNCTION RE: BATTERY	YES
8	NJ	1	1 OW	NO	NA	NA	NA	YES	NO	YES	YES	YES	YES	RELIABILITY, WHAT INFO IS BASED ON	NO
9	NJ	1	1 OW	NO	NA	NA	NA	NO	NO	NO	YES	NO	NO	DON'T KNOW ENOUGH ABOUT THEM	YES
10	NJ	2	1 OW	NO	NA	NA	NA	NO	NO	NO	YES	NA	NO	MALFUNCTION, WANTS TO LEARN MORE	YES
11	PA	2	1 OW	NO	NA	NA	NA	NO	NO	NO	YES	YES	NO	MALFUNCTION	YES
12	NJ	2	1 OW	NO	NA	NA	NA	NO	NO	NO	YES	NA	NA	MALFUNCTION	YES
13	NJ	2	1 OW	NO	NA	NA	NA	NO	NO	NO	YES	NA	NO	COST	YES
14	NJ	3	1 OW	NO	NA	NA	NA	YES	NO	NO	YES	NA	NO	RELIABILITY & ACCURACY	YES
15	NJ	4	1 OW	NO	NA	NA	NA	NO	NO	NO	YES	NA	NA	LACK OF KNOWLEDGE OF USE	YES
16	NY	4	1 OW	NO	NA	NA	NA	YES	NO	NO	YES	NA	NO	DIFF COMP USING DIFF TISSUE GROUPS	YES
17	NJ	4	1 OW	NO	NA	NA	NA	YES	YES	NO	YES	NA	NA	MALFUNCTION	YES
18	NY	4	1 OW	NO	NA	NA	NA	NO	NO	NO	YES	NA	NO	MALFUNCTION	YES
19	NY	5	1 OW	NO	NA	NA	NA	NO	NO	NO	NO	NA	NO	NO COMMENT	YES
20	NY	6	1 OW	NO	NA	NA	NA	NO	NO	NO	YES	NA	YES	NOT AS RELIABLE AS I AM	YES
21	NJ	7	1 OW	NO	NA	NA	NA	NO	NO	NO	YES	NA	NO	NO COMMENT	YES
22	NJ	8	1 OW	NO	NA	NA	NA	NO	NO	NO	YES	NA	NO	NO COMMENT	YES
23	BRAZ	10	1 OW	NO	NA	NA	NA	NO	NO	NO	YES	NA	NA	DON'T HAVE THEM IN BRAZIL (COSTLY)	YES
24	NJ	10	1 OW	NO	NA	NA	NA	YES	YES	NO	YES	YES	NO	TISSUE DIFFERENCES	YES
25	NJ	12	1 OW	NO	NA	NA	NA	YES	NO	NO	YES	NA	NA	PLAN TO BUY ONE	YES
26	NJ	12	1 OW	NO	NA	NA	NA	YES	NO	NO	YES	NA	YES	DEPENDIENCE (sic)	YES
27	CA	16	1 OW	NO	NA	NA	NA	YES	YES	YES	YES	YES	YES	SIMULATING ONLY CERTAIN TISSUES	YES
28	NJ	20	1 OW	NO	NA	NA	NA	YES	YES	YES	YES	NA	YES	NO COMMENT	YES
29	NY	25	1 OW	NO	NA	NA	NA	YES	YES	YES	NO	NA	YES	NO COMMENT	YES
30	NJ	30	1 OW	NO	NA	NA	NA	NA	NA	NA	NA	NA	NA	NO COMMENT	YES
31	NJ	30	1 OW	NO	NA	NA	NA	NO	YES	NO	YES	NO	NO	NOTHING	YES
OPEN WATER DIVERS - OWNERS OF DCCs															
32	PA	1	1 OW	YES	EDGE	6	NO	YES	NO	NO	YES	YES	NO	ONLY AS REFERENCE, STILL USES TABLES	YES
33	NJ	1	1 OW	YES	SKDP	45	YES	YES	YES	YES	YES	YES	YES	MALFUNCTION ON REP DIVE	NO
34	NJ	1	1 OW	YES	EDGE	10	NO	YES	YES	YES	YES	YES	YES	BUDDY GETTING BENT	NO
35	NJ	1	1 OW	YES	BEUCHAT	35	YES	YES	YES	NO	YES	YES	YES	NO WORRIES, HAS BACKUP	YES
36	NJ	1	1 OW	YES	SKDP	35	YES	YES	YES	NO	YES	YES	YES	NO WORRIES, HAS BACKUP	YES
37	NJ	1	1 OW	YES	SKDP	70	NO	NO	NO	YES	YES	YES	YES	NO COMMENT	YES
38	NJ	4	1 OW	YES	EDGE	60	NO	NO	NO	NO	YES	YES	YES	DEPENDENCY	YES
39	NJ	4	1 OW	YES	SNTO ML	1	NO	NO	NO	NO	YES	YES	YES	TWO DIVERS USING ONE COMPUTER	YES
40	NJ	5	1 OW	YES	EDGE	200	YES	NO	NO	NO	YES	YES	YES	MALFUNCTION AT ANY TIME	YES
41	NY	11	1 OW	YES	EDGE	100	YES	YES	NO	NO	NO	NO	NO	MISCALCULATION OF DEPTH	YES
42	MA	12	1 OW	YES	EDGE	50	NO	YES	YES	YES	YES	YES	YES	MALFUNCTION, NOT PHYSIOLOGICAL PROFILE	NO
43	DE	14	1 OW	YES	BEUCHAT	15	YES	NO	NO	NO	NO	NO	YES	NO BETTER ALTERNATIVES, ONLY WORSE	YES
44	NJ	19	1 OW	YES	SKDP	14	NO	NO	NO	YES	NO	NO	YES	MALFUNCTION, UNEDUCATED USERS	NO
45	PA	20	1 OW	YES	BEUCHAT	25	NO	YES	NO	NO	NO	NO	YES	DEPENDENCY, NEED TOTAL ASCENT TIME	YES
46	PA	20	1 OW	YES	SOS	800	YES	YES	NO	NO	NO	NO	YES	DEPENDENCY, NEED TOTAL ASCENT TIME	YES
47	NY	22	1 OW	YES	SNTO ML	30	YES	YES	NO	NO	YES	YES	YES	MALFUNCTION; DEPENDENCY	YES

Table 2.(cont'd). Questionnaire Review

DIVER	STATE	YEARS	LEVEL OF CERT	OWN DIVE COMP (DCC)	IF YES BRAND	# OF DVS WITH COMP	EVER EXP MAL FUNC	FAMIL WITH MULTI LEVEL CALC	CAN DO MULTI LEVEL CALC	CAN EXPL TISS 1/2 TIME	DOES LOG DIVE	DOES LOG DIVE WITH COMP	CAN ENTER TABLE IF COMP MALFUNC	WHAT WORRIES YOU MOST ABOUT USING DIVE COMPUTERS (DCCs)	DIVERS INTER-VIEWED IN PERSON
ADVANCED OPEN WATER DIVERS - NON-OWNERS OF DCCs															
48	NJ	NA	2 AOW	NO	NA	NA	NA	NA	NA	NA	YES	NA	NA	NO COMMENT	YES
49	NY	1	2 AOW	NO	NA	NA	NA	NO	NO	NO	YES	NA	NO	NO COMMENT	YES
50	NJ	1	2 AOW	NO	NA	NA	NA	YES	YES	NO	YES	YES	NO	MALFUNCTION	YES
51	NJ	1	2 AOW	NO	NA	NA	NA	YES	YES	NO	YES	NA	NO	MALFUNCTION	YES
52	NY	1	2 AOW	NO	NA	NA	NA	NO	NO	NO	NO	NA	NO	NO COMMENT	YES
53	NY	1	2 AOW	NO	NA	NA	NA	NO	NO	NO	YES	NA	NO	NO COMMENT	YES
54	CT	1	2 AOW	NO	NA	NA	NA	NO	NO	YES	YES	YES	YES	DIVERS NOT CONCERNED WITH PROFILES	YES
55	NY	1	2 AOW	NO	NA	NA	NA	NO	NO	NO	NO	NO	NO	NO COMMENT	YES
56	NJ	2	2 AOW	NO	NA	NA	NA	YES	YES	YES	YES	NA	NO	NO COMMENT	YES
57	NJ	3	2 AOW	NO	NA	NA	NA	YES	NO	NO	YES	YES	NO	WANTS TO SEE COMPASS + OTHER GAUGES	YES
58	NJ	4	2 AOW	NO	NA	NA	NA	YES	YES	YES	YES	NA	NA	MULTI-LEVEL CONTROVERSY	YES
59	NJ	4	2 AOW	NO	NA	NA	NA	NA	NA	NA	NA	NA	NA	NO COMMENT	YES
60	PA	4	2 AOW	NO	NA	NA	NA	NO	NO	NO	NO	NO	YES	NO COMMENT	YES
61	NJ	7	2 AOW	NO	NA	NA	NA	YES	NO	NO	YES	NA	NO	QUESTIONS RELIABILITY	YES
62	NJ	9	2 AOW	NO	NA	NA	NA	NO	NO	NO	YES	NA	NA	MALFUNCTION, DEPENDABILITY, DEPENDENCE	YES
63	NY	9	2 AOW	NO	NA	NA	NA	NO	NO	NO	YES	YES	YES	VARIABLES OF INDIVIDUAL BODY MAKE-UP	YES
64	NJ	9	2 AOW	NO	NA	NA	NA	NO	NO	NO	YES	NA	NA	MALFUNCTION, DIFF. BETWEEN MODELS	YES
65	NJ	10	2 AOW	NO	NA	NA	NA	NA	NA	NA	NA	NA	NA	NO COMMENT	YES
66	NY	12	2 AOW	NO	NA	NA	NA	NO	NO	NO	YES	NA	NO	NEVER USED ONE	YES
67	NJ	27	2 AOW	NO	NA	NA	NA	YES	NO	NO	NO	NO	YES	MECHANICAL; LIMITED DEPTH; FIELD EXP	YES
ADVANCED OPEN WATER DIVERS - OWNERS OF DCCs															
68	NJ	1	2 AOW	YES	SKDP	10	NO	YES	NO	NO	YES	YES	YES	NO COMMENT	YES
69	NJ	1	2 AOW	YES	SKDP	0	NA	NO	NO	NO	YES	YES	NO	SURFACE INTERVAL / USE IT WITH BUDDY	YES
70	NJ	1	2 AOW	YES	SKDP	7	NO	NO	NO	NO	YES	YES	YES	RISK OF OVER RELIANCE	YES
71	NJ	2	2 AOW	YES	SKDP	30	YES	YES	NO	NO	YES	YES	YES	MULTI-LEVEL CONTROVERSY	YES
72	NJ	2	2 AOW	YES	SKDP	30	YES	YES	YES	NO	YES	YES	YES	TENDENCY TO PUSH LIMITS	YES
73	GA	2	2 AOW	YES	EDGE	7	NO	YES	YES	YES	YES	YES	YES	WHAT MODEL IT IS BASED ON.	NO
74	NJ	3	2 AOW	YES	EDGE	300	NO	YES	YES	YES	NO	NO	YES	UNIT FLOODING OR BATTERY FAILURE	YES
75	NY	3	2 AOW	YES	SNTO ML	30	YES	YES	NO	NO	YES	YES	YES	INSUFFICIENT KNOWLEDGE	YES
76	NJ	4	2 AOW	YES	SNTO ML	6	NO	YES	YES	NO	YES	YES	YES	NO COMMENT	NO
77	NJ	6	2 AOW	YES	ALADIN	50	NO	YES	NO	NO	YES	YES	YES	DCS HIT WHEN USING COMPUTER	YES
78	NJ	6	2 AOW	YES	DECOBRAIN	50	YES	YES	NO	NO	YES	YES	YES	DCS HIT WHEN USING COMPUTER	YES
79	NJ	6	2 AOW	YES	EDGE	200	NO	YES	YES	YES	NO	YES	YES	MALFUNCTION, EST. DECOMPRESSION	YES
80	PA	7	2 AOW	YES	EDGE	4	NO	YES	YES	NO	YES	YES	YES	FEAR THAT DIVERS WILL NOT USE TABLES	YES
81	NY	10	2 AOW	YES	EDGE	60	YES	YES	YES	YES	NO	NO	YES	LOSS OF DATA WHEN CHANGING BATTERIES	YES
82	NY	11	2 AOW	YES	EDGE	200	YES	YES	NO	YES	NO	NO	YES	LONG HANG ON LONG SECOND DEEP DIVE	YES
83	NJ	13	2 AOW	YES	EDGE	600	NO	YES	YES	YES	NO	NO	YES	NO COMMENT	NO
MASTER SCUBA DIVERS - NON-OWNERS OF DCCs															
84	NY	1	3 MSD	NO	NA	NA	NA	NO	NO	NO	YES	NA	NO	MALFUNCTION	YES
85	NY	1	3 MSD	NO	NA	NA	NA	YES	NO	NO	YES	NA	NO	BECOME LAZY & TRUST ONLY COMPUTER	YES
DIVE MASTERS - NON-OWNERS OF DCCs															
86	NY	5	4 DK	NO	NA	NA	NA	YES	NO	YES	YES	YES	YES	COMPUTER ERROR	NO
87	NY	12	4 DM	NO	NA	NA	NA	YES	NO	YES	YES	NA	NO	WANTS PERSONAL SAFETY FACTOR IN COMP	YES
88	NY	13	4 DM	NO	NA	NA	NA	YES	NO	NO	YES	NA	YES	MALFUNCTION, SHE USES TABLES	YES
89	NJ	19	4 DM	NO	NA	NA	NA	YES	YES	YES	YES	NA	NA	MALFUNCTION, ACCURACY, TRUST	YES
90	NY	19	4 DM	NO	NA	NA	NA	NO	NO	NO	NO	NA	NO	NOT ON THEIR PAYROLL AS TEST PILOT	YES
DIVE MASTERS - OWNERS OF DCCs															
91	NY	4	4 DM	YES	SKDP	20	YES	YES	YES	YES	YES	YES	YES	DEPENDENCY, MALFUNCTION	NO
92	NJ	5	4 DM	YES	SNTO ML	75	NO	YES	YES	YES	YES	YES	YES	DIRT BUILDUP ON SENSOR PORTS	NO
93	NY	6	4 DM	YES	EDGE	130	NO	NO	NO	NO	YES	YES	YES	REPETITIVE DIVING	YES
94	NJ	12	4 DM	YES	EDGE	300	YES	YES	YES	NO	NO	NO	YES	NOTHING	YES

Table 2. (cont'd). Questionnaire Review

DIVER	STATE	YEARS	LEVEL OF CERT	OWN DIVE COMP (DCC)	IF YES BRAND	# OF DVS WITH COMP	EVER EXP MAL FUNC	FAMIL WITH MULTI LEVEL CALC	CAN DO MULTI LEVEL CALC	CAN EXPL TISS 1/2 TIME	DOES LOG DIVE	DOES LOG DIVE WITH COMP	CAN ENTER TABLE IF COMP MALFUNC	WHAT WORRIES YOU MOST ABOUT USING DIVE COMPUTERS (DCCs)	DIVERS INTER-VIEWED IN PERSON
ASSISTANT INSTRUCTORS - NON-OWNERS OF DCCs															
95	CT	3	5 AI	NO	NA	NA	NA	NO	NO	YES	YES	NA	NA	MALFUNCTION, INDIVIDUAL ACCOUNTABILITY	NO
96	RI	8	5 AI	NO	NA	NA	NA	NO	NO	NP	YES	YES	YES	LACK OF KNOWLEDGE BY USERS	NO
97	NY	10	5 AI	NO	NA	NA	NA	NO	NO	NO	YES	NA	YES	USE ONLY TABLES	YES
ASSISTANT INSTRUCTORS - OWNERS OF DCCs															
98	MD	7	5 AI	YES	EDGE	70	NO	YES	YES	NO	YES	YES	YES	MALFUNCTION, FLOODING	YES
INSTRUCTORS - NON-OWNERS OF DCCs															
99	MA	5	6 INS	NO	NA	NA	NA	YES	YES	YES	YES	NA	YES	BECOME AN INDUSTRY STANDARD	NO
100	MD	7	6 INS	NO	NA	NA	NA	YES	YES	YES	YES	YES	YES	MOST DON'T GO DEEP ENOUGH, BATTERIES	YES
101	USVI	8	6 INS	NO	NA	NA	NA	NO	NO	YES	YES	NA	YES	ONE COMPUTER - 2 PEOPLE, USER IGNORANCE	NO
102	MA	10	6 INS	NO	NA	NA	NA	YES	YES	YES	YES	NA	NA	TO COSTLY TO BUY, WANTS TO OWN EDGE	NO
103	NY	11	6 INS	NO	NA	NA	NA	YES	NO	YES	YES	NA	YES	MALFUNCTION & READING #'S DURING DIVE	YES
104	MD	16	6 INS	NO	NA	NA	NA	YES	YES	YES	YES	NA	NA	NO COMMENT	NO
INSTRUCTORS - OWNERS OF DCCs															
105	RI	4	6 INS	YES	EDGE	10	NO	YES	NO	YES	YES	NO	YES	NO COMMENT	NO
106	RI	5	6 INS	YES	EDGE	75	NO	YES	NO	YES	YES	YES	NO	MALFUNCTION, MUST USE CONSERVATIVELY	NO
107	NH	8	6 INS	YES	EDGE	40	NO	YES	NO	YES	NO	NO	YES	DIVERS WHO TURN UNIT OFF AFTER DIVES	YES
108	NI	10	6 INS	YES	AQUATECH	80	NO	YES	YES	YES	NO	NO	YES	MALFUNCTION OF BATTERY DURING DIVE	NO
109	NJ	12	6 INS	YES	BEUCHAT	4	NO	NO	NO	NO	YES	YES	YES	DOESN'T TRUST COMPUTER YET	YES
110	NJ	13	6 INS	YES	EDGE	450	NO	YES	YES	YES	YES	YES	NO	MALFUNCTION	YES
111	NJ	13	6 INS	YES	DECOBRAIN	450	NO	YES	YES	YES	YES	YES	NO	MALFUNCTION	YES
112	MA	14	6 INS	YES	EDGE	30	YES	YES	NO	YES	NO	NO	YES	TURNING OFF COMPUTERS BETWEEN DIVES	NO
113	MA	16	6 INS	YES	EDGE	30	NO	YES	YES	YES	YES	YES	YES	NO ADJ. FOR PERSONAL PHYSIOLOGY	NO
114	NM	19	6 INS	YES	BEUCHAT	10	NO	YES	YES	YES	YES	YES	YES	MALFUNCTION ON REP DIVE	NO
115	MA	22	6 INS	YES	SKDP	40	YES	YES	YES	YES	NO	NO	YES	UNPROVEN ALGORITHMS, PUSHING LIMITS	NO
116	NY	23	6 INS	YES	EDGE	45	NO	YES	NO	YES	YES	YES	YES	NO COMMENT	NO

= Years of diving experience.

LISTING OF THE RESPONSES TO THE QUESTION:

"What bothers or worries you the most about using a dive computer?"

All responses are reproduced from the original questionnaire.

How to read the codes on the left side of the page:

NO	NO = Respondent <u>does not own</u> a dive computer. YES = Respondent <u>does own</u> a dive computer
OW	OW = Open Water Diver AOW = Advanced Open Water Diver MSD = Master Scuba Diver DM = Dive Master AI = Assistant Instructor INS = Instructor

1	1 = One year of diving experience. Number of years of diving experience is indicated in this position.

Order of listings:

Non-Owners who made comments.
Non-Owners who did not make comments.
Owners who made comments.
Owners who did not make comments.

In each category the responses are in order of least diving experience through longest diving experience.

THE COMMENTS

NO OW 1

I'd like to know exactly what dive tables they are using, what multi-level calculations & what the tested reliability of the particular unit is.

NO AOW 1

Too much flexibility for a diver - I don't feel that they're as concerned with their dive profiles as they should be.

NO MSD 1

That it would fail

NO OW 1

Nothing

NO OW 1

Having to rely on a mechanical device which runs off a battery.

NO OW 1

What bothers me most about dive computers is what seems to be a problem in diving in general. People are relying more and more on equipment, which is getting more technological every year, instead of relying on themselves and their abilities to think and plan.

NO OW 1

Would like to learn how to use - have not seen one in use.

NO OW 1

Batteries going dead or just malfunction - computers are too critical of environment to trust in the ocean.

NO OW 1

What is a dive computer? How do they work?

NO AOW 1

Malfunction.

NO AOW 1

Mechanical malfunction

NO MSD 1

That I become very lazy and put all my trust in the computer.

NO OW 1

N/A Do not know enough about them.

NO OW 1

Nothing (Do not expect to own a computer).

NO OW 2

Black out of readouts

NO OW 2

If I were to use one, the possibility of malfunction - at least with tables you're diving using a maximum depth-time limit. I would be interested in learning about these computers and how they function.

NO AOW 2

Just a piece of mechanical equipment that could malfunction at any time and you would lose all records of time down etc. - Rather just use tables, watch, depth gauge etc.

NO OW2 2

Cost

NO AOW 3

I would like to be able to see my compass while reading the rest of my gauges.

NO OW 3

Reliability & Accuracy

NO AI 3

1) Mechanical reliability,.including battery life

2) Individual accountability (allowing for personal, anatomical, physiological differences & habits - e.g. smoking) - health compromise.

NO AOW 4

I was going to buy one until I read an article in Undercurrent Newsletter about the controversy about multi-level profiles. I am going to wait and watch.

NO OW 4

Not knowing how to use one - Never seen one or used one

NO OW 4

The fact that each make seems to use different tissue compartments to calculate saturation - plus the natural tendency to rely solely on the computer.

NO OW 4

I don't use one but I have heard enough horror stories about them breaking down - and why not know how to compute your logging without a computer.

NO OW 4

Malfunction.

NO DM 5

I am more comfortable using depth gauge and watch. Computer error.

NO INS 5

That it will become an industry standard and that OWI students, who are not even sure if they like to dive, will be required to purchase a computer for the class.

NO OW 6

Not as reliable as I am - I would use it more as a check against my calculations.

NO AOW 7

I have found NO independent study relating to accuracy, etc., of dive computers. They are relatively new on the market so I have decided to wait.

NO INS 7

Except for Beuchat, they don't go deep enough.

Changing batteries. - Still like to add extra time to the 10' hangs - Still use the Navy Tables, I guess.

NO INS 8

2 or more people using one computer - people using them to their limit when physiological variations in body types are not considered - people diving with them without reading their instruction manual.

NO AI 8

User doesn't read instructions - violates "rules" ex. 60'/min ascent.

User shares buddy's decomputer / 1 computer / 2+divers

Diver can't properly plan repetitive dive w/o future dive profile limit information

Diver may use decomputer for a dive and dive Navy tables later in day.

NO AOW 9

What worries me is people who depend on computers, sometimes don't know what to do in a computer malfunction. I think computers are great but not fully dependable.

NO INS 9

The variables with individual body make-up. How does the computer account for an obese diver, out of shape diver, etc. As we have learned, there are no absolutes, so how reliable are the computers?

NO AOW 9

1) Inconsistencies with the different models
2) Breakdowns or malfunctions

NO AI 10

I don't use a dive computer - except for dive tables

NO AOW 10

Don't have in Brazil

NO OW 10
Tissue differences

NO INS 10
Just don't have funds for an EDGE or Skinny Dipper. Also waiting for dust to settle on Doppler testing, but think I will go with the EDGE from ORCA Industries.

NO INS 11
1) Malfunction during dive
2) Inability to understand info during dive

NO AOW 12
Never used one

NO OW 12
Dependence

NO OW 12
Plan to buy one

NO DM 12
It should have the capability to add your own safety factor (personal safety factor) in the programming

NO DM 13
I try to rely on my own table calculations. I don't care much for gadget that could malfunction.

NO OW 16
Dependability on a mechanical device simulating only certain tissue properties

NO DM 19
I'm not on their payroll as a test pilot. I'm waiting a few years to see if they're really safe.

NO DM 19
1) accuracy
2) malfunctions
3) feeling that the computer is "failsafe"

NO AOW 27
They are mechanical. Generally limited in depth. Not enough experience with them in the industry

NO OW 30
Nothing

The next grouping is a list of respondents who do not own dive computers and made no comments at all on the questionnaires. This list shows the certification level and years of diving experience for each respondent.

NO	AOW	?	NO	AOW	1	NO	AOW	1	NO	AOW	1

NO	AOW	1	NO	AOW	2	NO	AOW	4	NO	OW2	4
NO	INS	4	NO	OW	5	NO	OW	5	NO	OW	7
NO	OW	8	NO	AOW	10	NO	INS	16	NO	?	20
NO	AOW	25	NO	OW	30						

YES AOW 1

I use it primarily as a back-up unit. I think there is a great risk of over-reliance.

YES AOW 1

I use it with my buddy - We dive together, but we still check with log tables. Bothers me most - surface interval

YES OW2 1

Nothing, have back-up

YES AOW 1

A malfunction during a repetitive decompression dive. Example: 2nd dive of the day and one that requires decompression.

YES AOW 1

Failure during a long deep decompression dive. Buddy getting bent using my computer profile.

YES OW 2

*Note! I only use it as a reference tool. I still dive by the tables

YES OW 2

Different opinions concerning validity of multi-level computations. Is the data safe?

YES OW2 2

The tendency to push the limits and forget to record prior to second, third dive. You can not buddy dive with someone who uses one because your profiles are not the same.

YES AOW 2

What model it is based on!

YES AOW 3

The people who see fit to use them without sufficient knowledge of decompression theory or people who don't know the tables at all. People who use them without taking tables for backup.

YES AOW 3

Unit flooding or battery failure.

YES OW2 4

The person that tells someone else to follow him with his computer and not to worry about the tables. Also when divers become dependent on them instead of knowing the tables.

YES AI 4

1) Dependency on computer / pushing the limits.

2) Computer should be a tool, not a "cure-all"

3) If computer fails, must wait at least 24 hours since Navy table could have required a decompression stop which wasn't made.

YES INS 5

Failure of unit at a critical time, flooding etc. In general, I believe that the EDGE is safe when used within its' limits and is not "redlined"

YES OW 5

The fact that it can malfunction at any time

YES DM 5

I have found that dirt buildup on the sensor port could block the sensor from reading depth. I have to clean console and computer very well after each dive.

YES DM 6

Second Dive - I always use shorter time and shallower depth - do very long hangs when I have air.

YES AOW 6

A malfunction could happen at any time during a dive and must be able to convert to an estimated decompression for my maximum depth.

YES AOW 6

I have been hit when using a computer

YES AOW 7

That most people will only use the computer & not also use the normal dive tables for the dive profile & residual nitrogen times

YES AI 7

A malfunction while underwater, flooding

YES INS 8

In theory I would match my ANDL times with an RNT group conservatively.

In practice I wait 24 hours and depending on previous history

Also, others who do not use them correctly - e.g. turning it off each day etc.- for my use none really

YES INS 10

Batteries - should have a battery malfunction lock. When battery fails, unit should lock last dive and not recalibrate until new battery is place in. I just purchased the Edge II. No dives yet.

YES AOW 10

I constantly lose my previous dive info when changing batteries - which makes all future info incorrect. I don't like the fact that people making the same dives - i.e. next morning - one has no dots another has top row of dots left.

YES OW 11

Subtle miscalculations - i.e. if it misreads your depth all calculations are invalid - and dangerous. Must check computer against other device (depth gauge or other computer.

YES AOW 11

Long hang on long second deep dive. Not knowing how long hang will be before going in the water

YES OW 12

The potential for electro-mechanical failure notwithstanding, I appreciate that the unit has a mathematic & not physiologic model as its basis, and that may ultimately be less than accurate

YES INS 12

My biggest problem at the present time is convincing myself it is safe to switch to a new system of diving after 12 years of using the Navy tables. I feel that this will pass with time.

YES DM 12

Nothing

YES INS 13

If the computer malfunctions during the first dive of the day, you're done for the day. Whether using computer or dive tables you are trusting your welfare to the research of others, but the Navy tables aren't battery operated!

YES INS 14

That divers will no longer be able to use dive tables & will rely on the computer. Also, that some divers are dumb & don't use the computer properly (i.e. turn it off between dives, etc)

YES OW 14

There seems to be no better alternative, only worse ones.

YES INS 16

The large variety and make-up of divers tied to one (1) single dive profile. Same problems w/dive tables.

YES INS 19

Failure of computer in the middle of a repetitive dive due to a dying battery or introduction of seawater into the unit, shorting out the circuitry. As an instructor, I remain facile with the tables (US Navy). Most students of diving have difficulty learning and easily forget these calculations. My concern is their dependence on this "aid" to diving.

YES OW 19

I have been diving long enough (400+ dives) to have a good feel for where I am in the tables. I always check tables before and after each dive.

If my computer wiped out completely, I would feel comfortable re-entering the tables. (I also carry a credit card-size table inside my BC pocket for underwater calcs.in a pinch.) My only real concern would be if my computer was giving me info.that was just out of whack enough to get me bent.

My wife-buddy also has a skinny-dipper and we frequently compare readings.

As an experienced diver I feel very comfortable using a computer. (Ask me again in a year after another 50-75 dives.)

What does bother me about dive computers is the large number of morons who probably would have no idea how to re-enter the tables after a computer malfunction. If feel that when inexperienced people play Sea Hunt with their new toy, there is a potential for problems. From what I have read (an article by you guys, two articles In Undercurrent, and Skindiver, I feel that the Skinny dipper is probably quite reliable.

YES OW 20

That you tend to depend on it completely without total pre-dive planning

Computer should give you total ascent time before leaving the bottom (Incl. decomp. time)

YES OW2 22

Malfunction / Creates a false dependency

YES INS 22

Algorithms unproven. Not sure how close to the edge you can push them safely. As a result, I ascend as slowly or slower than the unit recommends and use safety stops at 10', 20', 30' even though the unit says I don't need them.

The next grouping is a list of respondents who do own dive computers and made no comments at all on the questionnaires. This list shows the certification level and years of diving experience for each respondent.

YES OW 1 YES AOW 1 YES AOW 1 YES AOW 13
YES INS 23

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DIVE COMPUTER UTILIZATION DISCUSSION

Discussion after Bruce Bassett

Al Carpenter asked what kind of working knowledge of the DC's Bruce's divers have when they arrive to dive. He said it was pretty good, that they read the manuals and ask questions, and that they understand tables as well. These are not naive divers. Where they lack information, they get it from instructors on the tours.

[The message here is that this experience shows that DC's can yield reliable decompressions if used properly. It does not show that this degree of reliability can be expected from the general recreational diver population. - RWH]

Additional comment by Phil Sharkey

An additional constraint not mentioned in the paper is that when dives deeper than 130 fsw are to be made, they have to be "repet up" dives. This requires that the diver spend some time in shallow water, which has the effect of a short decompression and greatly reduces the risk of DCS. We do not require a "safety stop" but most of our dives have some shallow time at the end.

Additional comments by Mike Emmerman

Mike learned other things from his interviews. As an example of lack of knowledge of decompression he said some thought that a multi-level dive was one with divers of different experience levels (actually, as someone pointed out, that term is used by some instructors who would understand a multi-level profile). Further, a high percentage of divers cannot spell.

The number of questionnaires returned by the time of the Workshop was 150, and 119 of these were interviewed.

Discussion

Tom Neuman endorsed the comment that a great deal more understanding of diving physiology and decompression technology is needed, and that divers need to know how the computers work and what they do. He wondered, though, how much trouble the "booger-eating morons" will get into if they lack the knowledge, and noted that Bruce Bassett has shown that informed divers using DC's can dive without DCS problems. Mike Emmerman responded that they don't know the tables either. In fact, the general knowledge there is worse than it is about DC's. Phil Sharkey told how the diver regards the computer differently from the tables, looking to the table for information, but taking directions from the computers. With the rapid increase in the numbers of computers being used, Mike Emmerman felt this could lead to an increasingly risky situation. Another opinion reminded us that divers have never known the tables well enough, and the resort instructors still have the responsibility to update their customers before diving.

Glen Egstrom noted that it is a poor carpenter who blames his tools. We should be concerned about the decrease in training programs that teach "the why" of things. We cannot expect the divers to understand the details of DC's until they understand the physics and physiology; we should teach this without apology. They do not read instructions because they don't think it is important, and they don't read the warnings because they do not want to hear them. We have to do a better job of teaching, not only the details, but also the fact that there is risk involved, and that there are limitations. Currently, our teaching fails to do this.

Mike Emmerman says we are forgetting other things also, that divers come up watching the computer instead of holding their hand up and smash their heads on the bottom of the boat.

Dennis Graver spoke from the training agencies' perspective, noting that they can teach half times, etc., but it may not be feasible to teach all the different dive computers. He reviewed some unacceptable options, then offered some recommendations. First, educate the instructors. Next, hold seminars, such as at DEMA. Third, manufacturers should provide study guides which potential buyers have to complete, successfully, before being allowed to purchase a DC. Mike Lang suggested that someone, perhaps AAUS, should collate all the instruction manuals (and training guides) into a single volume for use by instructors. This would have to be updated periodically.

Max Hahn noted that "half times" refer to a particular model, and that the teaching of coupled non-linear inhomogenious differential equations might not be well received. But, Ralph Osterhout pointed out, the divers could learn about the algorithms. Max asked how much thermodynamics one needed to know to drive a car. The message here is that we have to be careful to teach the right things. Bill Hamilton warned again about "believing the numbers," not to take the models' results too seriously. Even though the Edge's pixels may not represent a real analogy of gas in the body, they are useful.

Karl Huggins made an excellent analogy about the driver of a recreational vehicle who bought a "cruise control" (which only regulates speed), having been told by the salesman it was "sorta like an automatic pilot." He turned it on and went back for a nap and the vehicle crashed. It is the same with computers, the tendency being to expect too much. Some people think the devices measure the nitrogen in their bodies. They need to know more than this.

Mark Walsh read the outline of Dacor's training program for the MicroBrain. They recommend following the training with a test. Ralph Osterhout said manufacturers have the responsibility to provide the training materials, but also to make the displays intuitive. Paul Heinmiller said special training could indeed be required of the scientific divers, and that they would grasp it more easily.

Ralph Osterhout recommended lithium batteries, not only for longer life, but also for better performance in cold temperatures. In addition, their voltage runs down more gradually and therefore can do a better job of warning of their demise than nicads can. DC users should be warned about the effect of cold on batteries. Paul Heinmiller said that Orca currently includes the lithium batteries.

DAN'S RESULTS AND PERSPECTIVE OF DIVE COMPUTER USE

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Repetitive, multi-day dives were common risk factors for computers and the U.S. Navy decompression tables. Decompression sickness was relatively more frequent at greater depths for computers than for tables. There appears to be a small but unavoidable risk of decompression sickness from which no table or computer is immune. Deep, repetitive, multi-day diving should be avoided, but risk estimation is impossible without knowing how many safe dives were conducted. New decompression algorithms must be tested during repetitive, multi-day diving. Depth-time recorders will someday provide information needed to assess decompression risk.

Advances in technology have made dive computers a practical reality and may someday make them as commonplace as regulators. How safe are dive computers, and can they be safer?

Diving risk is commonly judged by the number of diving accidents divided by the total number of dives. While our information on recreational diving accidents is improving, we know little about diving habits or frequency, and risk estimates based on this knowledge are not very enlightening. In 1985, for example, the Divers Alert Network (DAN) estimated that there were between 3 and 8 incidents of air embolism or decompression sickness in every 100,000 dives (Wachholz, 1985). Our 1988 risk estimate, 3 to 33 incidents per 100,000 dives, shows that our knowledge has not improved (Wachholz, 1988). These estimates allow us to conclude that diving accidents are relatively rare but provide no insight concerning the circumstances in which accidents are likely to occur.

The Divers Alert Network was created in 1980 with the primary goal of providing medical assistance and consultation to victims of recreational diving accidents and a secondary goal of collecting and analyzing epidemiological data. While most of our resources have been directed at the immediate management of diving accidents, epidemiology has become recognized as a key factor for improving diving safety. We are increasing our efforts towards the collection and analysis of data and, in the future, hope to follow the complete habits of several thousand divers for 5 years (Wachholz, 1988).

The following analysis was presented at the June 1988 UHMS meeting in New Orleans (Vann *et al.*, 1988). At that time, DAN had received reports of 557 diving accidents during 1987 from 53 participating treatment centers. We are indebted to the cooperation and support of personnel at these centers for completing and forwarding the accident questionnaires. (A list of treatment centers is appended). Of the 557 accidents, which included both decompression sickness and air embolism, sufficient information was gathered on 220 cases of decompression sickness to allow them to be entered into a diving accident database. One hundred and eighty cases occurred after dives that reportedly used the U.S. Navy Standard Air Decompression Tables, and 40 followed dives with computers. The computers were used improperly, or there were symptoms of air embolism in 9 cases suggesting that even a perfect dive computer will not completely eliminate accident. These cases were omitted from further analysis. Of the 31 remaining computer cases, 68% had symptoms of Type II decompression sickness while 79% of the 180 table cases had Type II symptoms. This difference is not statistically significant.

Reported dive profiles were analyzed according to a series of simple attributes. Were the dives "square" with bottom times taken at single depths or were they "multi-level" with time spent at several depths? Were they "no-stop" with direct ascent to the surface or did they use stage or continuous decompression as some computers allow? Was there a single dive or were the dives repetitive? Did all dives take place on a single day or were there multiple days of diving? Profiles also were examined to determine if they fell within the limits of the Navy Tables and to determine the depths of the deepest and the last dives. It must be remembered that the figures which follow refer to the frequency and not the risk of decompression sickness and apply only to this particular population of accidents.

For decompression sickness with tables, 79% occurred after square dives, 75% after no-stop dives, 65% after multi-day dives, and 60% after repetitive dives. Decompression sickness was least often associated with decompression dives, multi-level dives, single dives, and single day dives.

A similar analysis for computer diving indicated that 77% of all decompression sickness occurred after repetitive dives, 74% occurred after multi-day dives, 68% after multi-level dives, and 52% after decompression dives. Decompression sickness was least frequent during no-stop, square, single day, and single dives.

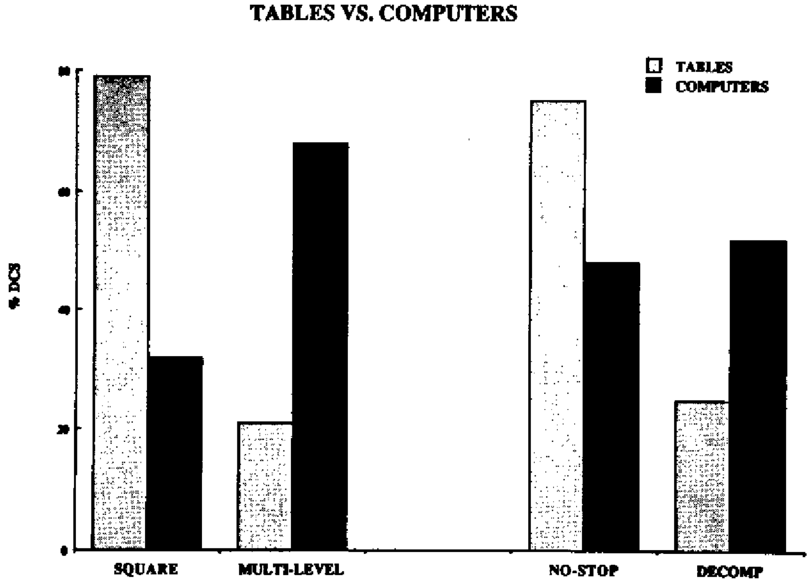
Figure 1 shows that the greatest difference between decompression sickness with tables and with computers was for square and multi-level diving. There was 47% more decompression sickness reported for multi-level diving with computers than with tables. This difference is statistically significant by Chi-square test ($p < 0.000001$) and might indicate greater decompression risk for multi-level diving with computers but, more likely, less multi-level diving with tables.

The next greatest difference between computers and tables was for no-stop diving and decompression diving (Fig. 1). There was 27% more decompression sickness for decompression diving with computers than with tables. This difference is significant ($p = 0.005$) and could be the result of the tables' longer no-stop exposure limits but probably was because decompression diving is more common with computers.

Figure 2 shows that decompression sickness was common for repetitive and multi-day diving with both computers and tables, but there was 17% more decompression sickness in repetitive diving with computers. This difference is not statistically significant. Repetitive dives were clearly more hazardous than single dives as the first dive in every series of repetitive dives is a single dive.

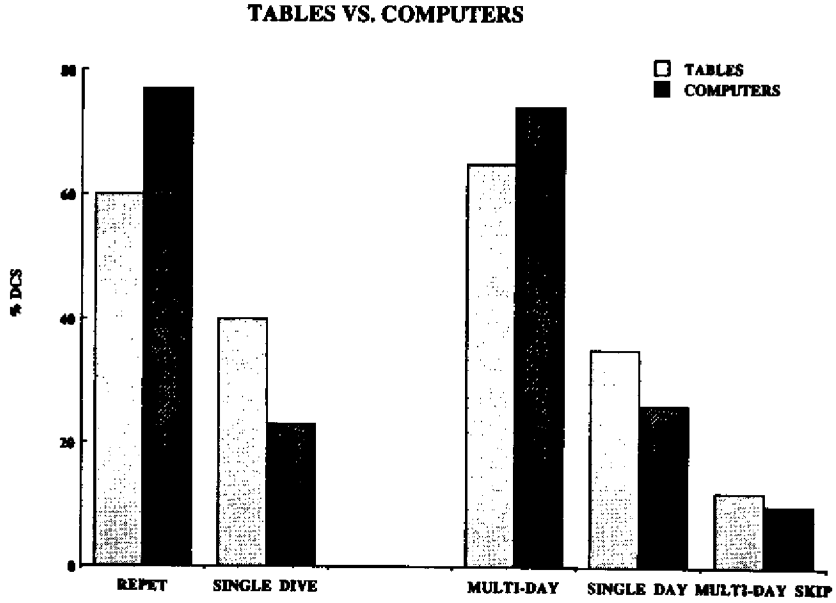
There was a similar relationship between single day and multi-day diving (Fig. 2). Decompression sickness was 2-3 times as common in multi-day diving for both DC's and tables. Since the first day in a series of multi-day dives is a single day of diving, multi-day diving must be a significant risk factor. This probably reflects a gradual accumulation of bubbles or dissolved nitrogen.

Figure 1. Decompression sickness for table and computer diving during square/multi-level and no-stop/decompression dive profiles.



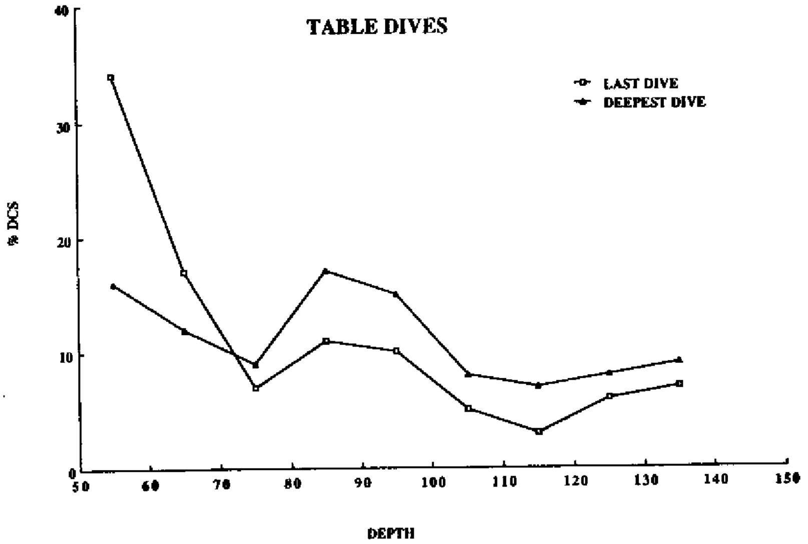
The widespread popularity of multi-day diving is indicated by the small and insignificant difference in bends between computers and tables, only 9%, for single and multi-day dives. The category "multi-day skip" refers to multi-day dives with no diving the day before the decompression incident. One might infer from this category that a day off provides some protection from decompression sickness.

Figure 2. Decompression sickness for table and computer diving during repetitive/single dive and multi-day/single day dive profiles.



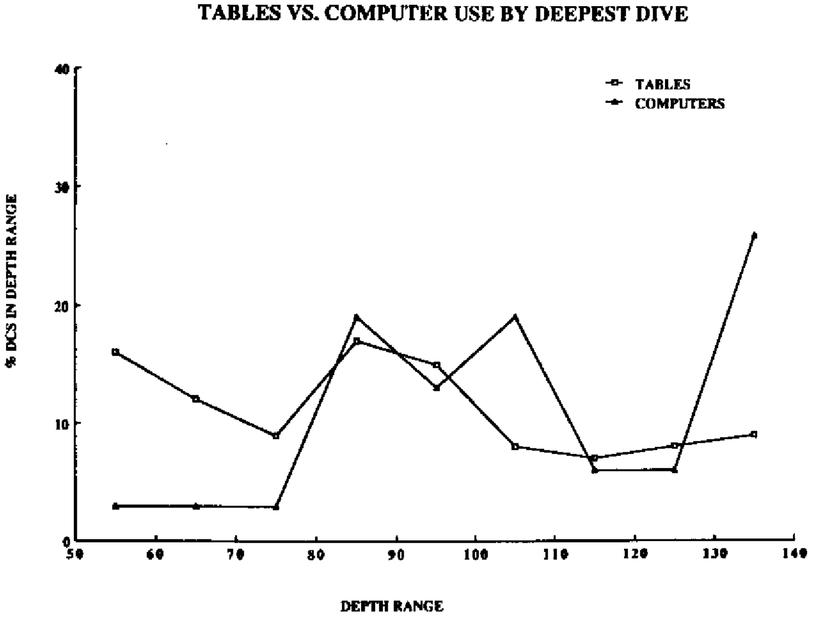
The distribution of decompression sickness over depth is shown in Fig. 3 for table diving. Because repetitive diving was so frequent, both the deepest and the last dive depths were studied. For single dives, of course, the deepest and last depths are the same. The left-most point represents all dives shallower than 60 fsw, and the right-most point is all dives to 130 fsw or deeper. Intermediate points are at the centers of 10 foot depth ranges. The line representing the deepest dive indicates that decompression sickness was more frequent deeper than 80 fsw. This suggests that the deepest dive in a repetitive dive series was a more important risk factor than the last dive. The alternate hypothesis leads to a conclusion of greater risk at shallow depth. A similar effect occurred for computer diving.

Figure 3. Distribution of decompression sickness for table diving over the deepest dive depth and last dive depth.



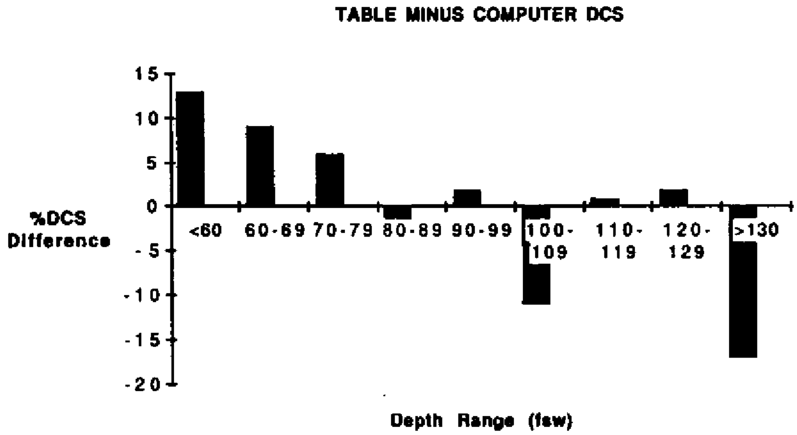
When the deepest dive lines for table and computer decompression sickness are shown together in Fig. 4, it is evident that decompression sickness occurred more often at greater depths for computer diving than for table diving.

Figure 4. Distribution of decompression sickness over the deepest dive depth for table and computer diving.



This distinction is more evident in Fig. 5 when the relative differences in bends between tables and computers are examined in each depth range. Decompression sickness was 13% more common with tables than with computers at depths of less than 60 fsw. The difference fell to 9% between 60 and 69 fsw and to 6% between 70 and 79 fsw. From 100 to 109 fsw, 11% more decompression sickness occurred with computers than with tables, and at 130 fsw and deeper, computers had 17% more decompression sickness than tables. This may reflect more decompression diving with computers because most sport diving editions of the Navy tables do not publish decompression schedules.

Figure 5. Relative differences in decompression sickness for table and computer diving over the deepest dive depth.



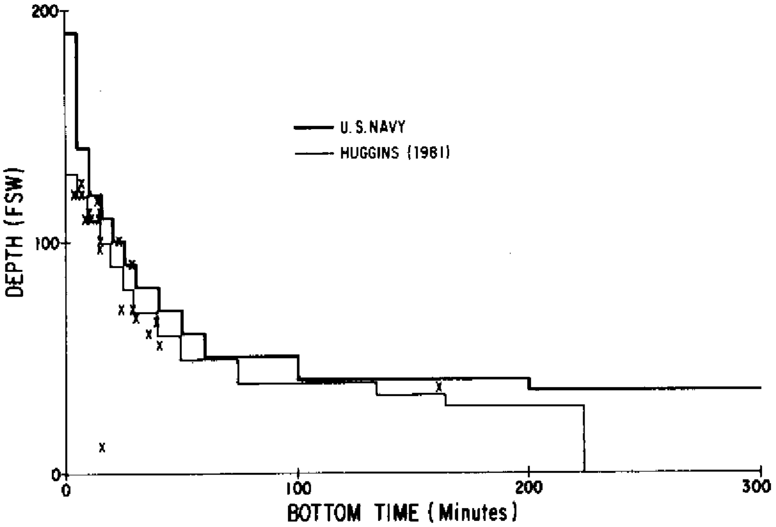
Of the 180 decompression incidents using the Navy tables in this sample population, 63% were reported to be within the table limits. For the 31 incidents with computers, only 26% were within the table limits. Had the restrictions of both computer and table diving been observed, it is likely that less decompression sickness would have occurred, but obeying the Navy tables alone apparently does not guarantee freedom from bends.

While the U.S. Navy tables are a familiar benchmark, the question of whether a dive which resulted in bends fell within the table limits often presumes decompression safety to be well-defined and decompression sickness to be inevitable if table limits are violated. The error of this presumption is illustrated in Figure 6 by 22 incidents of single dive decompression sickness which occurred in Navy diving between 1977 and 1981 (Naval Safety Center 1977, 1978, 1979, 1981). Thirteen were Type I and nine were Type II. Most of the incidents fell within both the Navy no-stop exposure limits and the shorter limits proposed by Huggins (1981). Is this cause for concern? Certainly, as is all decompression sickness, but this concern must be tempered by the realization that over 240,000 no-stop dives were conducted giving an average decompression risk of less than 0.01%.

These and similar data suggest there is a small and unavoidable risk of decompression sickness from which no table or computer is immune. While we may never know all the causes of this risk, several mechanisms relating to intravascular bubbles are under consideration.

Venous gas bubbles can be detected by CW Doppler and are relatively common in all types of diving. Spencer (1976), for example, reported that 4 of 13 divers had venous bubbles after 60 min chamber dives to 60 fsw, and open water dives were even more likely to result in bubbles. A more recent investigation by DAN found that 18% of 173 sport divers had VGE after diving to between 30 and 129 fsw (Dunford *et al*, 1988).

Figure 6. Depth and bottom times of 22 decompression incidents after single, no-stop dives (Naval Safety Center 1977, 1978, 1979, 1981). The U.S. Navy no-stop limits and the limits of Huggins (1981) are shown for comparison.



The pulmonary circulation is an effective filter for bubbles, and venous bubbles are usually eliminated except at very high levels where they can pass through the lungs and enter the arterial blood (Powell *et al*, 1982). Besides causing arterial gas embolism, arterial bubbles can lead to decompression sickness by seeding nitrogen-saturated tissues that otherwise would be bubble-free.

Venous bubbles also can enter the arterial circulation in divers with communication between the right and left sides of the heart. Autopsy findings indicate that right-to-left shunting may be present in about a quarter of the population (Fryer, 1971). This cardiac defect now can be detected non-invasively with two-dimensional echocardiography. We used this technique to study patients with decompression sickness and found evidence of right-to-left shunting in 8 of 13 who had severe neurological symptoms (Moon and Camporesi, 1988).

The "micro-air embolism" is another potential source of arterial bubbles and of severe symptoms after dives that should have been innocuous. Proposed by Walder (1973), a micro-air embolism releases a small number of bubbles into the arterial circulation as a result of minor lung damage. This damage can be caused by the rupture of pulmonary blebs or by the local overexpansion of alveoli from mucus which blocks a terminal bronchiole.

The data presented earlier were accumulated up to June of 1988. As accident reports continued to come in, we can now extend our analysis of computer bends to 79 cases. Table 1 summarizes the totals for each year since 1984. The overall incidence of Type II symptoms was 63%. Using the attributes described earlier, we can define 16 categories of dive profile. In Table 2, these categories are arranged from least to greatest frequency of decompression sickness. "NS" and "D" refer to no-stop and decompression dives, "Sq" and "ML" to square and multi-level dives, "SD" and "R" to a single and repetitive dives, and "1D" and "MD" refer to single and multi-day dives.

The profile with the highest bends frequency was no-stop, multi-level, repetitive, multi-day diving. There were no bends, however, during single no-stop dives on a single day. Since a single dive on a single day is the first in a series of repetitive multi-day dives, we infer that no-stop square or multi-level diving is a safe activity if limited to a single dive on a single day. Indeed, 62% of all decompression sickness was associated with repetitive, multi-day diving. Once again, attention is focused on repetitive and multi-day diving as primary risk factors.

Table 1. Decompression sickness by year using dive computers. Cases of apparent misuse are not included.

Year	1984	1985	1986	1987	1988	Total
Cases	2	2	8	32	35	79

This inference may explain the contradiction between earlier reports (Elliott and Kindwall, 1982) that the symptoms of decompression sickness are predominantly Type I (70-79%) and DAN's observations here and in a previous report (Dick and Massey, 1985) that Type II symptoms predominate (63-77%). Compared with the week-long diving vacations of today, repetitive and multi-day diving were probably rare activities in the '40's, '50's, and '60's at the time of the earlier observations. Thus, incessant diving may pre-dispose to Type II symptoms.

Table 2. Computer dive profile categories

Profile Category	Cases
NS-Sq-SD-1D	0
NS-ML-SD-1D	0
D-Sq-SD-1D	1
D-Sq-SD-MD	1
NS-Sq-R-1D	2
NS-Sq-SD-MD	2
D-ML-SD-MD	2
D-ML-SD-1D	3
D-ML-R-1D	3
NS-ML-SD-MD	3
NS-ML-R-1D	4
NS-Sq-R-MD	8
D-Sq-R-1D	9
D-ML-R-MD	12
D-Sq-R-MD	13
NS-ML-R-MD	16

Table 3 shows the effect of maximum dive depth on the profile categories of Table 2. The depth increases in 10 fsw increments from left to right. Only 6% of all decompression sickness occurred at depths of less than 70 fsw. When multi-day repetitive dives were excluded, only 1% of the bends occurred at less than 70 fsw. The letters next the numbers indicate the presence of possible pre-disposing risk factors. In order of frequency, risk factors include 18 cases in which the diver had 2 or more bends, 11 cases in which the diver flew or travelled to altitude after diving, and 8 cases with back or spine disorders. Single or multiple risk factors were present in 39% of the 79 cases.

What does this tell us about the safety of today's dive computers? We can say with confidence that it is safest to avoid deep, repetitive, multi-day diving, but we have no idea what the risks are without knowing how many safe dives were made. If current diving habits persist and future risks are to be reduced, decompression algorithms in dive computers must be made more conservative for deep, repetitive, multi-day diving. Adding slower tissues to a Haldane decompression model may not accomplish this goal as these tissues do not seem to absorb enough nitrogen to control decompression during multi-day diving. It could be helpful to simulate the slow release of nitrogen after bubbles form by increasing tissue halftimes. Thus, a 60 min halftime tissue at depth might become a 100 min tissue during surface intervals.

Table 3. The effect of maximum dive depth on computer decompression sickness for dive profile categories arranged in order of frequency

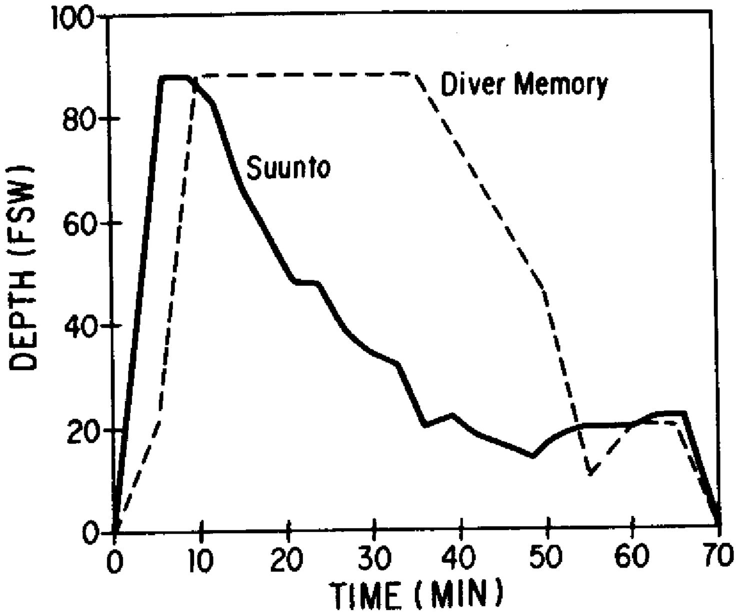
Profile Category	Maximum Depth 30 -39	40 -49	50 -59	60 -69	70 -79	80 -89	90 -99	100 -109	110 -119	120 -130	130 -149	150 -230	% of Tot
NS-Sq-SD-1D													0
NS-ML-SD-1D													0
D-Sq-SD-1D												1	1
D-Sq-SD-MD											1a		3
NS-Sq-R-1D					1			1					5
NS-Sq-SD-MD					1	1							8
D-ML-SD-MD									1	1c			10
D-ML-SD-1D									1a	1a	1c		14
D-ML-R-1D									1	1	1a		18
NS-ML-SD-MD	1					1						1b	22
NS-ML-R-1D						1	1	1				1	27
NS-Sq-R-MD	1c					3	aa3bc		1				37
D-Sq-R-1D						1b	1	2		2	2a	1a	48
D-ML-R-MD						3b	2a	1	1		a4c	1a	63
D-Sq-R-MD				a1b		a1b		b4c	3			4a	80
NS-ML-R-MD		1b	1a		a3b	3	aa2bc	2		1	1	2c	100
% of Total	3	4	5	6	13	30	42	56	66	73	86	100	

a - 18 multiple DCS
b - 11 back/spine disorder
c - 8 post-dive altitude exposure

Whatever decompression algorithm is used must be tested during repetitive, multi-day diving. Chamber tests should be conducted first to determine if the algorithm has any "hot-spots" which make further evaluation hazardous. These tests should cover the full range of intended use. Chamber dives would be followed by repetitive, multi-day sea trials with tightly controlled depths, bottom times, and surface intervals. If the sea trials were successful, the computer could be issued for general use, but just as with a new drug which receives FDA approval, unexpected symptoms may occur despite prior testing.

This is the same dilemma we face with existing decompression procedures. Which dive profiles lead to symptoms, and which are safe? Diving accident reports are immensely helpful, but the profile a diver remembers can be very different from what he actually did. This is illustrated in Fig. 7 by profiles recalled from the diver's memory and from the memory of a Suunto depth-time recorder he wore. Dive computers which incorporate both depth-time recorders and decompression algorithms will someday provide the information needed to assess decompression risk and allow modification of decompression algorithms when problem areas are identified.

Figure 7. Dive profiles recalled by a sport diver and stored in a Suunto dive computer (Dunford *et al.* 1988).



In summary, the average risk of decompression sickness for recreational diving with computers or tables appears to be small and is predominantly associated with deep, repetitive, multi-day diving. Future dive computers must treat this form of diving more conservatively and also should incorporate depth-time recorders to permit accurate assessment of diving safety.

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APPENDIX

Treatment Centers Providing Accident Reports to DAN Central

George C Marshall Flight Center	Huntsville, AL
Carraway Methodist Hospital	Birmingham, AL
USS Holland	Charleston, SC
Richland Memorial Hospital	Columbia, SC
McLeod Regional Medical Center	Florence, SC
Baptist Memorial Hospital	Atlanta, GA
Shand's Teaching Hospital	Gainesville, FL
NOAA - NMGD Center	Miami, FL
US Army Special Forces School	Fleming Key, FL
NEDU	Panama City, FL
Bay Memorial Medical Center	Panama City, FL

Martin Memorial Hospital	Stewart, FL
Orlando Regional Medical Center	Orlando, FL
Center for Neurological Services	Ft Lauderdale, FL
Vanderbilt University Hospital	Nashville, TN
Duke University Medical Center	Durham, NC
Discovery Bay Marine Laboratory	Jamaica
Cayman Clinic, Georgetown	Caymans
Barbados Defence Force Chamber	Barbados
Bonaire Hospital	Curacao
Shady Grove	Rockville, MD
Maryland Institute for Emergency	Baltimore, MD
Norwalk Hospital	Norwalk, CT
International Underwater Contractors	City Island, NY
Institute for Environmental Medicine	Philadelphia,PA
University of New Hampshire	Durham, NH
Geisinger Medical Center	Danville, PA
Mount Vernon Medical Center	Alexandria, VA
Hyperbaric Medical Center	Sanford, ME
Emergency and Hyperbaric Medicine	New Orleans, LA
St Patrick's Hospital	Lake Charles, LA
Our Lady of the Lake Medical Center	Baton Rouge, LA
Marine Biomed Institute	Galveston, TX
Plano General Hospital	Plano, TX
St David's Community Hospital	Austin, TX
St Luke's Hospital	Denver, CO
St Vincent's Infirmary	Little Rock, AR
St Luke's West	Chesterfield, MO
St Luke's Hospital	Milwaukee, WI
Edgewater Hospital	Chicago, IL
Springfield Memorial Hospital	Springfield, IL
Hennepin City Medical Center	Minneapolis, MN
Alpena General Hospital	Alpena, MI
Bronson Methodist Hospital	Kalamazoo, MI
Butterworth Hospital	Grand Rapids, MI
Santa Barbara Medical Center	Santa Barbara, CA
Northridge Hospital	North LA, CA
Monterey-Pacific Grove	Monterey,CA
Brookside Hospital	San Pablo, CA
LDS Hospital	Salt Lake City, UT
Virginia Mason Medical Center	Seattle, WA

USE OF DIVE COMPUTERS BY SCIENTIFIC DIVERS

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Beaufort, NORTH CAROLINA 28516-9721 U.S.A.

Although no formal policy on dive computers has been established by the Academy, many members are carrying them on both their scientific dives and recreational dives. My summary of the use of DC's by AAUS members relates the diver's personal characteristics, e.g. age and number of years diving, to their reason(s) for using the computers and the types of dives, e.g. shallow, deep or multi-level, on which the computers are used. In addition, I examined the type of training the diver acquired prior to the use of the DC and the individual's implementation of conservative diving practices above those inherent to the computers.

INTRODUCTION

In order to assess the use of dive computers (DC's) on scientific research dives, a survey (Appendix A) was distributed to American Academy of Underwater Sciences (AAUS) members. A list of 287 names was compiled from the AAUS membership rosters for 1987 and 1988. Postcards requesting indication of DC use were mailed to these divers. The postcards also contained requests for names of other scientific divers which had used DC's. Of these 287, 13 were returned by the postal service as undeliverable. Positive responses were received by 58 divers. A survey form was mailed to each of these individuals, with additional copies included for diving officers. This paper is based on the data communicated by the 45 completed surveys that were returned by the time of its writing.

PERSONAL STATISTICS

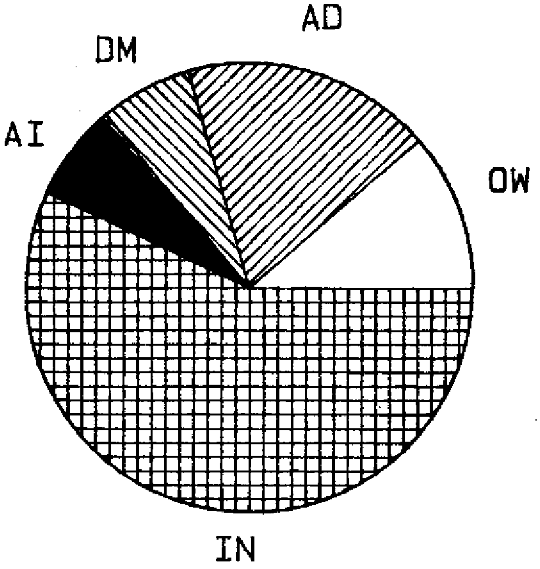
Assuming that postcard recipients had ample opportunity to respond and lack of a response represented no experience with DC's, 21.2% of AAUS divers have, or are, using dive computers. However, 5 divers indicated that use of DC's is not permitted on scientific dives and thus responded with data from solely recreational dives.

Of the 45 completed surveys, 3 were from female divers and 42 from male. The age of divers using DC's ranged from 27 to 60, with a median of 37.5 years. The typical respondent had been diving for 18 years; the newest diver had 5 years of experience and the oldest had 33 years. Only two divers indicated a depth certification of less than 100 feet sea water, one at 60 and one at 90. The median depth was 130 fsw, the acceptable maximum of many AAUS organizational members.

The majority of divers responding to the survey (Fig. 1) were certified instructors (56.8%). Three (6.8%) were certified as Assistant Instructor and three as Divemaster.

Those who classified themselves as research or scientific diver were combined with the advanced open water divers (18.2%). Divers with open water certification comprised 11.4% of the respondents.

Figure 1. Certification of AAUS divers using DC's (IN = instructor, AI = Asst. Instructor, DM = Divemaster, AD = Advanced open water, OW = Open water)



When asked reasons for using dive computers (Fig. 2), the one given most frequently was their application for multi-level diving (84.4%). Many of the scientific divers used DC's to increase their bottom time (68.9%), because of their logging features (60%), and to aid in monitoring their ascent rate (55.6%). Slightly less than half thought DC's were safer than using tables (44.4%) and 35.6% used DC's because they were easier than tables. Only 8.9% of the divers used DC's because their buddies also used one. Other reasons for their use was time saved not having to plot/plan dive profiles and the continuous visual graphical display of nitrogen uptake and release provided on some models.

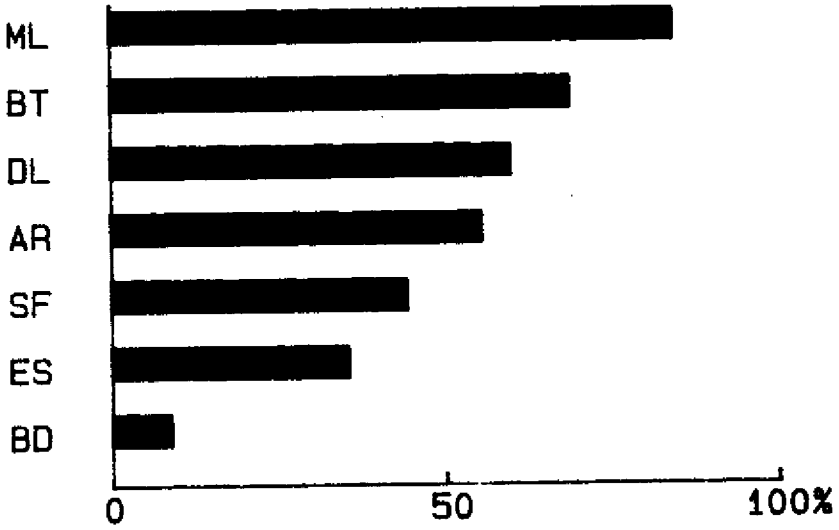
Twenty-eight divers reported that they use the DC as their primary decompression device. Ten said that they use it only as backup to dive tables.

Thirty-nine divers (86.7%) answered that they fully understood the use of their dive computer, not necessarily the technical functioning, but how to operate the device and read and interpret the output. Only two responded negatively. Concerning their training in the use of the DC, thirty divers reported none other than the owner's manual. Ten divers were aided by colleagues who were familiar with DC's, one gained information from the retailer (dive shop), and four consulted the manufacturer.

Nine of the divers responding relied solely on the DC for decompression guidance and practiced no additional safety measures beyond those inherent in the computers (Fig. 3). The others used the DC's conservatively by employing tables to backup the device (4 divers), spending less time than allotted at depth (15 divers), or spending extra time at stops during ascent (16 divers).

The most popular DC among scientific divers is the EDGE by Orca (Fig. 4); 27 (60%) of the 45 indicated its use. Eighteen divers (40%) were/are using the SkinnyDipper, also manufactured by Orca. The SME-ML by Suunto/SeaQuest was/is used by 6 divers (13.3%), Divetronic's DecoBrain by 5 divers (11.1%), and Uwatec's Aladin by 2 divers (4.4%). One diver (2.2%) reported use of U.S. Diver's DataScan.

Figure 2. Reasons given for using DC's (ML = Multi-level diving, BT = Increase bottom time, DL = Dive logging, AR = Monitor ascent rate, SF = Safer than tables, ES = Easier than tables, BD = Buddy uses DC)



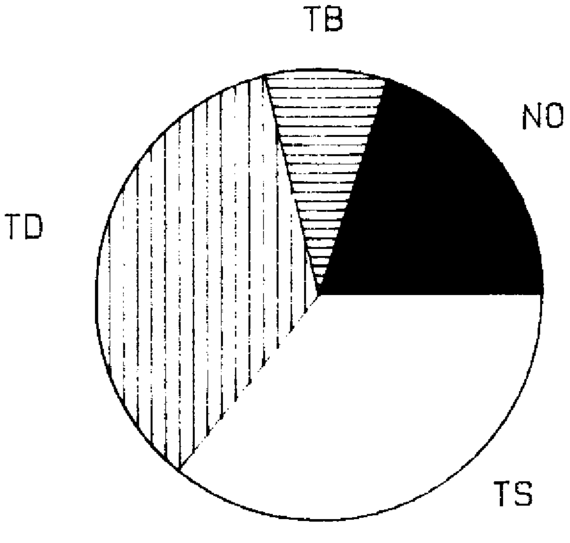
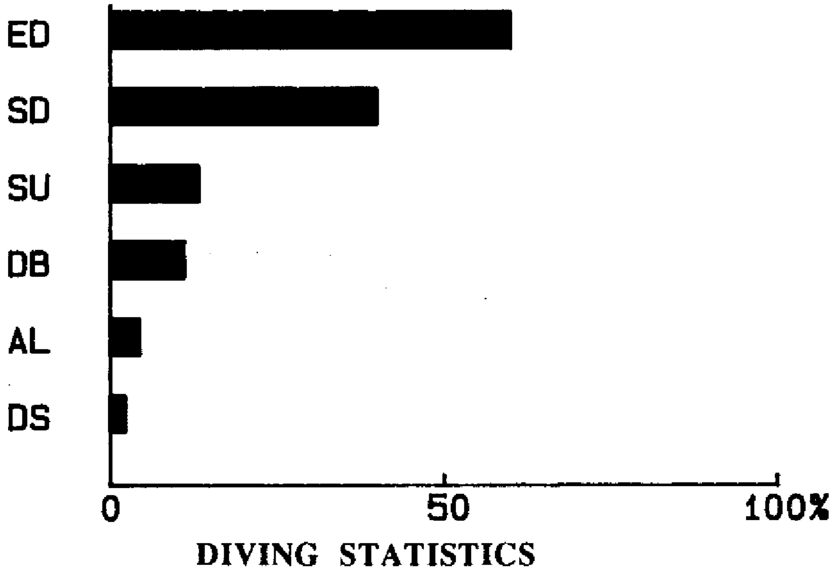


Figure 3. Conservative use of DC's by AAUS divers (NO = none, TB = Tables as backup, TD = Less time at depth, TS = More time at depth)

Nearly half (48.89%) of the scientific divers reported malfunctions of the dive computers. One malfunction was left undefined. A US Diver's DataScan would not properly access the tables. A DecoBrain had an error in the software and another's case cracked. The battery compartments of six SkinnyDippers leaked and were flooded; another had an undefined battery failure. There was a response of the rapid ascent light on a SkinnyDipper flashing while on the bottom. A diver reported that his SkinnyDipper often fails to record the first dive of the day. The battery compartment of the EDGE had flooded for five divers. Two divers reported inadvertently turning off the EDGE during a dive. An EDGE was reported having a faulty pressure transducer and another had a battery failure without the low battery warning.

Figure 4. Percentage of survey respondents who use specific DC's (ED = EDGE, SD = SkinnyDipper, SU = Suunto SME, DB = DecoBrain, AL = Aladin, DS = Datascan)



The recipients of this survey were asked to submit the number of dives and total bottom time for each of five depth categories:

a) 0 to 30 fsw,
b) 31 to 60 fsw,
c) 61 to 100 fsw,
d) 101 to 130 fsw, and
e) deeper than 130 fsw.

The divers were to separate recreational from scientific dives and label them accordingly. It was assumed a single unlabeled listing of dives was scientific. Nonparametric statistical procedures were used to analyze the data since it is unreasonable to assume diving data to be from normally distributed populations.

The forty-five scientific divers responding to this survey performed 4580 dives while using a dive computer. Of these, 487 were reported as recreational dives. The remaining 4093 were scientific or training dives. None of the divers reported any personal accidents while using DC's, however three reported first-hand knowledge of such accidents. No details were given.

The first hypothesis tested was whether there existed a difference in the dives reported as recreational and those reported as scientific. Table 1 shows the two distributions of number of dives per depth category. There is a significant difference (Chi-squared test of proportions, $p < .01$) between recreational and scientific dives. Relatively more deep dives were made for recreational than for scientific purposes (Fig. 5). Significant differences (Wilcoxon rank sum test) were also found between sport and scientific dives in the average bottom time per dive in the 0 to 30 fsw ($p = .013$), 61 to 100 ($p < .01$), and 101 to 130 fsw ($p = .05$) depth categories (Fig. 6). Data from recreational dives were omitted in further analyses due to these differences.

Table 1. Total number of reported dives using DC's (depth in fsw)

			Depths		
	0-30	31-60	61-100	100-130	> 130
Recreational	45	195	137	76	34
Scientific	412	2703	725	168	85

Figure 5. Percentage of dives made per depth category

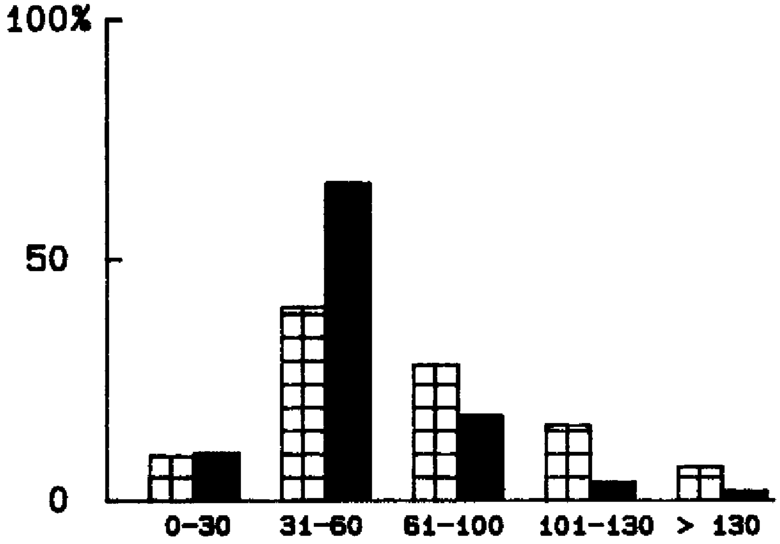


Table 2. AAUS organizational members submitting 1987 annual reports

Organization	Diving Officer
University of Miami	Jack Nichols
FL Dept. of Natural Resources	Walter Jaap
Woods Hole Oceanographic Institution	Terrence Rioux
The Living Seas	Stan Johnson
VA Institute of Marine Science	Daniel Gouge
Stanford University	Christopher Harrold
Florida State University	Gregg Stanton
University of Washington	John Eriksen
Harbor Branch Oceanographic Institution	Dudley Crosson

Data of scientific dives made using DC's were compared with that reported by AAUS organizational members (Table 2) for scientific dives made during 1987. Dive computers were used on only 1.26% of the 7239 dives reported by the organizational members (Fig. 7). The method of reporting made it impossible to eliminate these data from the organizational records. It was therefore assumed that their small percentage would have little effect on the overall data. Dives of the organizational members were thus taken as being made while using tables.

Figure 6. Median bottom time per dive using DC (hatched = recreational, solid = scientific, * = significant difference)

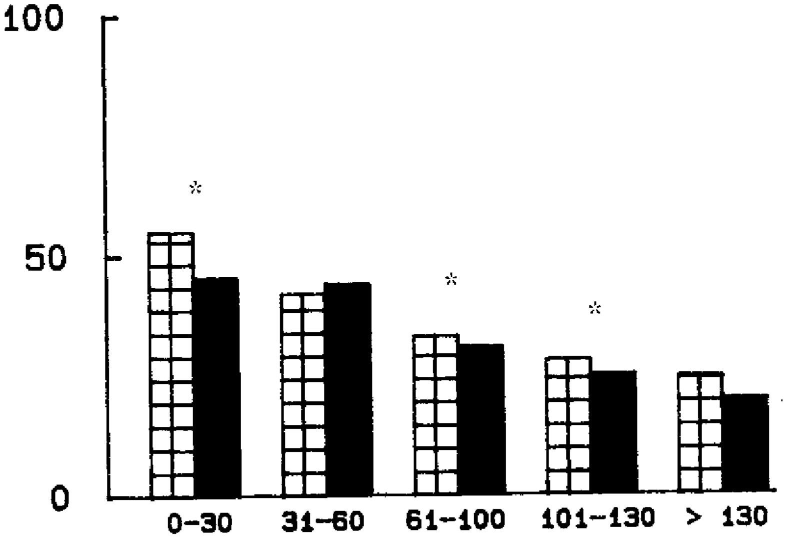


Table 3. Total number of dives reported using tables (Org. members) and DC's. (Depths in fsw)

	Depths				
	0-30	31-60	61-100	100-130	> 130
Tables	8664	1839	659	93	15
DC's	394	2677	713	165	85

Again a significant difference (Chi-squared test of proportions, p <.005) was discovered in the number of dives per depth category between dives from the organizational member reports and from the DC survey (Table 3). The organizational data were biased in the shallow depths by the 6214 dives reported by The Living Seas in the 0 to 30 fsw category. These data were omitted from a second analysis (Figure 8), however the results were unchanged (p <.005). It may be argued that there is no advantage in using a DC on dives shallower than 30 fsw since the US Navy Dive Tables give no decompression limit for these depths. A third analysis was performed on data only from dives deeper than 30 fsw. The significant difference (p <.005) between dives made using tables (organizational members) and dives made using DC's persisted.

The average bottom time per dive in four of the five depth categories was significantly different (Wilcoxon rank sum test; 0 to 30 fsw: p = .02, 31 to 60 fsw: p = .002, 61 - 100 fsw: p = .012, > 130 fsw: p = .044) in dives reported by organizational members versus those reported in the DC survey (Fig. 9).

Figure 7. Decompression devices used on dives reported by AAUS members (BRN = British Royal Navy Tables, BAS = Bassett tables, USN = US Navy tables, DC = Dive Computer)

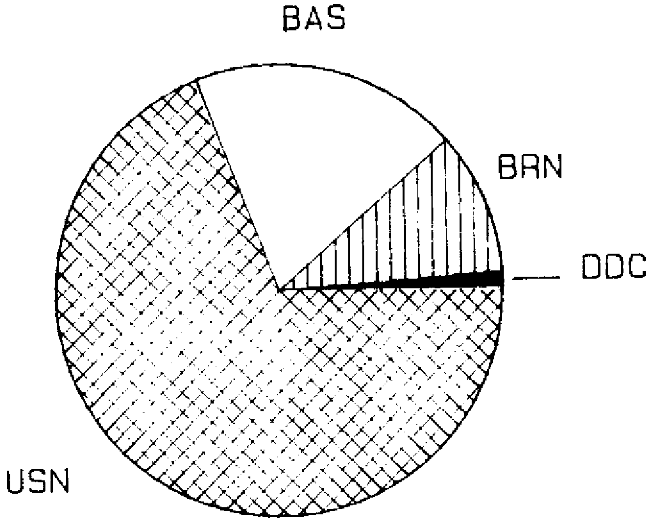
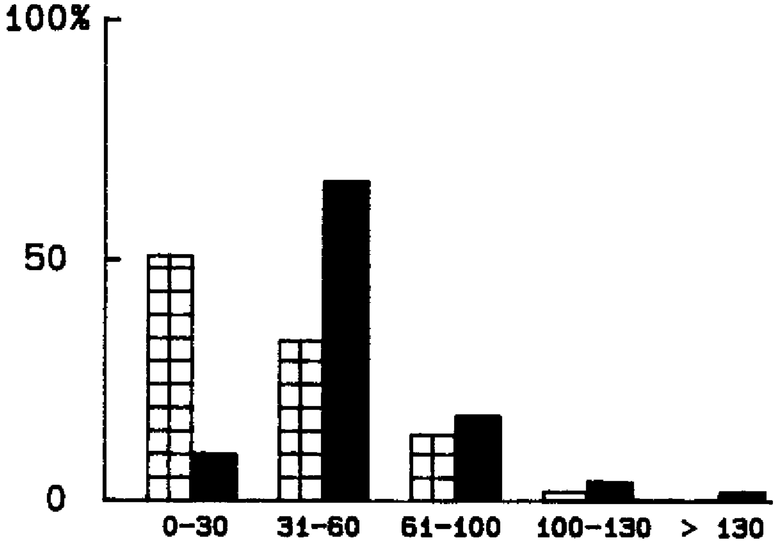


Figure 8. Dive distributions omitting shallow dives reported by The Living Seas (hatched = org. members, solid = DC survey)



CONCLUSIONS

The adage of "you can't teach an old dog new tricks" does not appear to be applicable to the use of dive computers by AAUS divers. The typical respondent of this survey of DC use by scientific divers had 18 years of diving experience and was certified as a SCUBA instructor.

An unnerving statistic is that a median of 36.5% of the DC's used reportedly malfunctioned (Fig. 10). This may not represent a current realistic value since a large proportion of AAUS divers are on the leading edge of diving technology and may have acquired first production models before all of the manufacturing problems were solved. However, these data suggest that a maintenance and calibration schedule for DC's may need to be established. A defect which tends to stand out is the inadequate sealing of the battery compartment of the Orca products.

Figure 9. Median bottom time per dive (hatched = org. member, solid = DC survey; * = significant difference)

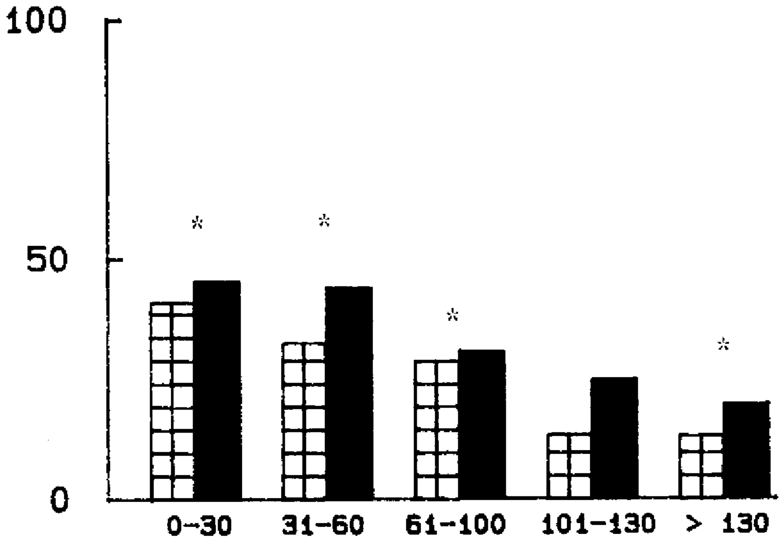
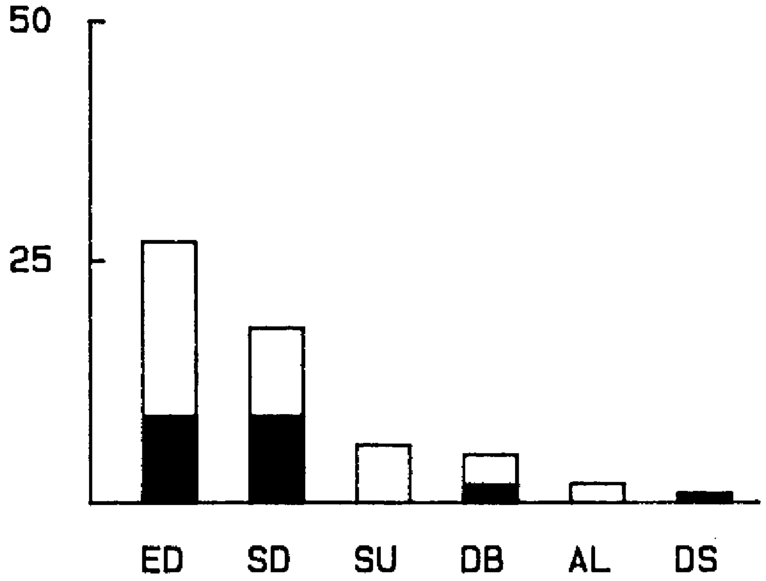


Figure 10. DC malfunctions (outline = # DC's used, solid = # malfunctions reported)



Although DC's may claim to be safer than dive tables, 80% of AAUS divers who use them employ additional conservative measures during their dives. This is probably not such a noteworthy statement taking into account the consequences and the fact that dive tables are most often used conservatively as well. The safe use of DC's by scientific divers is reflected in the absence of a single reported accident in over 4500 dives.

The findings of this survey are that scientific divers using dive computers on research dives safely remain underwater longer (in 4 of the 5 depth categories) than divers using tables. These longer bottom times still remain less than the US Navy no decompression limits for dives shallower than 60 fsw, so no significant gain is made over using the tables. The greatest advantage of the DC's was on dives deeper than 60 fsw. The magnitude of this advantage increased with depth as scientific divers were exceeding the US Navy no decompression limits by 6 minutes on dives up to 100 fsw and 15 minutes on dives between 100 and 130 fsw. This suggests that DC's may extend the safe working time of the scientific diver on dives greater than 60 fsw.

APPENDIX A

AAUS DIVE COMPUTER SURVEY

(Please fill in as many items as are applicable)

Your Age: ___ Sex: ____ Level of Certification: ____________________

Depth Certified: ______ # Years Diving: ______

Make & Model of Dive Computer(s) used:

Reason(s) for using Dive Computer (circle ALL that apply):

- Feel they're safer than tables
- Increase bottom time
- Buddy uses one
- Perform multi-level dives
- Easier to use than tables
- Dive logging features
- Control ascent rate
- Other: ____________________________

Dives Made With Computer:	Total # Dives	Total Bottom Time
0 - 30 fsw	____________	______________________
31 - 60 fsw	____________	______________________
61 - 100 fsw	____________	______________________
101 - 130 fsw	____________	______________________
over 130 fsw	____________	______________________

(Please distinguish scientific from sport dives and list separately)

Is computer used as PRIMARY decompression device or BACKUP to tables ?

Do you use any conservative measures with the computer ? If yes, explain.

Would you say you FULLY UNDERSTAND the use of your computer ?

What training did you receive in the use of the computer ?

Has your computer malfunctioned in any way? If yes, explain.

Have you been involved in or personally know of any diving accidents where a computer was used ? If so, please elaborate.

COMPUTER SIMULATION, NO-STOP DIVES, AND VALIDATION

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Several topics are covered. In order to compare the various dive computers it was our intention to define the details of the various models and to simulate their calculations on a desktop computer. This did not get finished in time for the workshop, but the models and their performance are covered in other papers. Additional evidence is reviewed here supporting the concept that the USN no-stop tables have performed well. Current practice in validation of decompression tables involves several small steps with feedback loops leading from concept to open water operations, occasionally requiring judgement. This can be provided by an in-house group of knowledgeable people charged with this task.

It was my intention, working with a colleague, to simulate the various dive computers and to present in this paper a comparison of the profiles they generate. We were not able to do this, and this Workshop has taught me that there was a bit of a flaw in our approach. How this went and the lessons learned are worth discussing here.

The "models" used by several of the dive computers are covered in the paper by Karl Huggins (Huggins, 1989) and in the presentations by the manufacturers, so much of what I had intended to say would be redundant here anyway. Further, the output of the models in a few relevant examples is shown in the graphs in Max Hahn's paper (Hahn, 1989), and this shows well enough what the profiles look like side by side.

INTENDED SIMULATION AND ANALYSIS

We began by requesting from the manufacturers the details of the computational models they used. We expected some initial resistance to this request, expecting the manufacturers to consider the computational algorithms as proprietary. We reasoned, however, that for liability reasons they could not afford to maintain secrecy. If the computer calculates against a certain algorithm or model which is disclosed to the user or to the public, then the manufacturer's responsibility is that the dive computer will calculate the results of the algorithm correctly. On the other hand, if the manufacturer chooses to keep the algorithm proprietary, then, it seems to me, their responsibility is that the "black box" has to perform a correct decompression. This seems to me to be a much greater burden, and we did not expect any to be adamant about maintaining their secret formula.

As it turned out, we got excellent cooperation which we felt was all we needed from the manufacturers. Prof. Bühlmann gave us the details of the computers that used his models, and we got simulator disks from two manufacturers. Other information was available, such as the detailed description of the development of the Edge by Karl Huggins

(Huggins, 1987), and this needed only to be updated. Several of the developers filled out a chart of profiles for a set of selected dives. A couple of manufacturers held out some details about their algorithms following our initial request, but we did not have time to follow up anyway and considered that this was not a problem.

The analytical and programming work was performed with the collaboration of Mr. Yuanchen Lee, a biophysicist and decompression specialist from the Chinese Underwater Technology Institute in Shanghai. Mr. Lee spent a half year on a work-study program at Hamilton Research, and is presently continuing this work at Duke University. We were able to emulate one of the models and were close with another, but we eventually realized that we could not devote the time required to finish the set by the time of the Workshop.

Elsewhere in this volume Don Short shows clever use of a spread sheet program to perform calculations such as those used for the U.S. Navy air tables. This might be another means of emulating the various DC's.

Part of the effort was in collaboration with CAPT. Edward D. Thalmann, a researcher at the Naval Medical Research Institute in Bethesda, and the developer of the algorithms in the U.S. Navy's underwater decompression computer. Ed had intended to attend this Workshop, and we regret that he could not. The program which he headed for several years at the Navy Experimental Diving Unit in Panama City (FL) was a massive effort to develop algorithms for a real-time dive computer. I am not sure of the operational status of the computer at this time, but Ed's exponential-linear model is a major contribution to decompression technology (Thalmann, 1983; 1984; 1985; 1986). He prepared the list of dives to be used for our comparison profiles.

Here is where our approach was not as appropriate as it could have been. Even the most sophisticated of the dive computers being considered in this Workshop is regarded as a "no-decompression" or more properly "no-stop" computer, whereas the Navy's computer and my thinking in terms of the analysis I had set out to do are both directed toward decompression from more demanding dives that may involve considerable time in stops. The Workshop had enough to do with the no-stop approach, and would not have had the time to deal fairly with this other approach as well.

Let me sincerely thank those who contributed to this effort. This includes Ed Thalmann for providing the sample dives and for preparing a paper which he later had to cancel. We thank Dr. Paul Weathersby, another Navy researcher based at the Submarine Medical Research Laboratory, New London, who had agreed to perform a "maximum likelihood" analysis (Weathersby *et al*, 1984) but did not have the chance because we did not get the profiles to him. We appreciate the help of Professor A.A. Bühlmann who provided details of some of the models used, and to the developers of some of the other DC's, who provided us with sample profiles. We hope to pursue this effort in the future.

COMMENT ON THE USN NO-STOP TABLES

One of the topics that is always brought up in a meeting like this is the traditional condemnation of "the U.S. Navy tables." This is the topic of Tom Neuman's paper which follows, but I want to mention some additional data and my impressions.

First, a comment on terminology. Traditionally, both scientific and recreational diving rules discourage "decompression diving," or dives that "require decompression." I submit that virtually all dives are decompression dives, although some of them do not require stops on the way to the surface. I would like to suggest that we call dives that do not require stops "no-stop" dives rather than "no-decompression." This is to avoid the impression that there is no decompression involved in no-stop dives, and so as not to imply that there is a definite, big difference in risk between dives that do and do not require stops. In fact, Weathersby's analysis (1986) lists several no-stop dives that have higher predicted risk than many depth/time combinations that require stops. The increase in DCS (decompression sickness) risk as dive time and depth increase is a continuum, and there is no discontinuity or sharp break at the point where stops are required. However, that is an excellent practical point at which to limit recreational diving, and I do not disagree with teaching it that way. I only want to try to make divers realize they have a "gas loading" and a decompression obligation even in those dives where decompression is done at the surface after the dive. There is still decompression going on.

A report by Dr. Tom Shields and Dr. W.B. Lee of Robert Gordon's Institute of Technology in Aberdeen (1986) looks at the experience by commercial diving companies in the North Sea with no-stop diving. Their first analysis showed that some 8700 no-stop dives had been logged, with only 1 case of DCS reported. A later unpublished analysis with more data included some 25,000 no-stop dives with 6 or so cases of DCS, about the same incidence level. This by no means suggests that these dives were all done to the limit, in fact probably none or at most very few of them were. But it does make a case that the no-stop times are not in great need of repair.

A disturbing fact, however, is that the incidence of neurological or Type II DCS in the cases that have occurred from no-stop diving is much higher than normal. It appears that many of these cases of DCS are not the same mechanism as conventional limb bends, but may be due to bubbles somehow bypassing the lung "filter" where they would normally be trapped. This suggests that it is not likely that a small reduction in the allowed no-stop dive time would make much difference in the result.

Neuman (1989) mentions that many divers brought in for treatment have grossly violated the USN tables. On the other hand, many of them being treated for serious symptoms have been well below the table limits.

What might make a real difference is a short stop at 10 or 20 fsw, possibly along with a reduction of the ascent rate. Andy Pilmanis shows evidence for this in discussion after Tom Neuman's paper.

VALIDATION OF DECOMPRESSION TABLES

Whenever new decompression procedures are produced there is always a call for some kind of "testing." The difficulties this concept poses are not generally appreciated, in view of the rather large number of tests required to establish a low incidence of DCS (Neuman, 1989). More important than "testing" per se is the whole process of validation of decompression procedures, from theoretical concept through laboratory testing, provisional open water use, and eventual operational readiness. This includes several feedback loops, and a number of points along the way where judgement is required.

Although the process of validation is quite relevant to dive computer development and use, it is not a main topic of this Workshop. Fortunately, however, the process has been addressed recently in another workshop (Schreiner and Hamilton, in preparation). In addition to describing and justifying the validation process, that workshop made realistic recommendations about the sticky issue of providing the necessary judgement. Briefly, the organization doing the development has a group or committee of qualified people which is charged with the responsibility of making the judgmental decisions. It is important to note that the "monitoring group" or whatever it may be called, is part of the organization and is not a government nor publicly constituted body.

Another important point is that because it takes thousands of trials to establish with confidence a level of reliability, it is necessary to have feedback from field use of a procedure in order to understand its behavior and if necessary, refine it. This is one reason why it is important to keep logs of dive profiles, and why we recommend that dive computers record profiles.

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DISCUSSION OF DCS RISK, STATISTICS AND SIMULATIONS

Woody Sutherland said that the few replies that came in since the paper was prepared did not change any conclusions.

Ray Rogers commented that a significant fraction of AAUS divers had no understanding of the algorithm in the computers they use. Woody responded that they understood how to use the computers, but may not have known about the algorithms. The scientific divers' understanding of decompression theory is much higher than that of recreational divers, however.

Tom Neuman, acknowledging the statistical or somewhat random nature of DCS, wondered if the multi-day diving imposes a higher risk than the same dives conducted independently. Dick Vann said his data did not answer this. Another question asked if the reported dive and the dive actually done are the same. Dick said the DAN people call the treatment center and/or the diver; even so, the profile data is not very specific. Phil Sharkey wondered why we were seeing problems now with procedures that have been in use for some 30 years with no great indication of problems. Dick Vann mentioned several factors, among them that some of the DCS was after rather deep dives, and that there were differences in individual susceptibility (the same divers keep coming back). To this was added the chance that the reports are inaccurate. This made a case for data logging.

Glen Egstrom gave an example from another field where people who had injured themselves almost invariably felt that they had done nothing wrong. Not only would they not say publicly that they have made a mistake, most of them would not even admit it to themselves. The issue of risk and risk assessment was brought up. If the risk of using DC's was offset by the benefits, AAUS should be able to deal with it. If it was not, then we have a problem.

We used the Navy tables for 25 or so years with all the modifications and restrictions and penalties, but we did not know that we had problems. Karl Huggins brought up the question of how entrenched the models were in the different dive computers. In discussion with a manufacturer he made the suggestion to reduce some of the M values, thus adding a bit of conservatism. The manufacturer felt that could not be done because it would be an admission that the previous version was inadequate.

Bruce Bassett did not help keep things clear by quoting an NMRI survey of seven years of USN operational diving through the Naval Safety Center that in some 100 dives to 100 fsw for 25 min taken to the limit there was a 9% incidence of bends (Berghage, 1980). Where is the discrepancy?

John Burr said the manufacturers looked to the scientists for the best model information. An offer was made by Ralph Osterhout to share the model data and assumptions with other manufacturers. The role of the algorithm is relatively minor in the marketing of a DC. Paul Heinmiller noted that Orca has published its assumptions all along. The problem here, stated well by Glen Egstrom, was that we do not really know what the correct algorithm is. And standardizing may be difficult.We were told that it took 8 years to set up a standard for the glass in face masks. Ralph Osterhout offered the resources of both his company and DEMA in an effort to get a uniform algorithm.

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DIVE COMPUTERS, DIVE TABLES AND DECOMPRESSION

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Current recreational diving guidelines regarding tables and dive computers reflect the need to clarify the confusion regarding decompression. Training and behavior of the diver are integral components for the proper functioning of dive computers. The risk and difficulty in decompression practices are contrasted to the conservative use of the US Navy tables. Several specific questions are posed regarding decompression issues. Dive computers were tested under a series of profiles to reveal that they had "personalities", but the timing and depth capabilities proved nonetheless to be surprisingly accurate. Standardization of the procedures and education of the divers is accentuated.

The use of dive computers has become both widespread and confusing within the diving community. It is unfortunate that the technology for the development of dive computers impacted at a time when a number of issues regarding decompression theory have been raised. These have led to a reduced level of confidence in tables in general. One of the national training organizations, NAUI, has effected an official set of guidelines for its membership which has the following consequences as reported in Underwater USA.

1. All recreational diving is to be conducted well within the U.S. Navy no-decompression limits at depths not to exceed 130 feet.
2. Multi-level dives shall not be planned using the U.S. Navy Dive Tables, because they were not developed for multi-level purposes.
3. NAUI does not endorse the use of any dive tables other than the U.S. Navy-based dive tables because "we cannot attest to their validity and safety".
4. A safety decompression stop at a depth between 10 and 20 feet for a period of at least 3 minutes at the end of any dive in excess of 50 feet is recommended. The stop time is added to the bottom time for the dive.
5. The use of mechanical dive monitors (computers) is not recommended.
6. If electronic dive monitors (computers) are used, they are to be used in accordance with the manufacturer's instructions.
7. NAUI does not endorse the use of gas mixtures other than compressed air for recreational scuba diving.

It is a depressing commentary on the state of the art that a major training association would feel the need to issue such a statement, which upon examination, would appear to raise a number of additional questions.

Dive computers were tested under a series of dive profiles and an example is provided. The bench tests reveal that the computers have "personalities" which require the user to pay particular attention to the traits of the unit. The individuals who were asked to read the instructions and run the computers through the tests made errors in activating the devices, in reading the devices, and in the interpretation of the data. Although the computers tested were internally consistent in the tests that were run, there were differences that would require decisions if two "buddies" were wearing devices of different manufacture.

The depth gauges operated in an envelope of three feet. The timing devices were comparable within seconds. The dive time remaining varied up to 10 minutes on a single dive and up to 15 minutes on three dive repetitive dives. An illustrative example is appended.

A series of articles are to be found in the current literature and they appear to support the following points.

1. There is a need for basic education on decompression theory in order to inform the diving public on the nature of the calculated risk involved in diving as a sport. It is a fact that every dive is a dive requiring decompression and that there are the familiar "dose-response" requirements which place greater restrictions on increased amounts of gas uptake in the tissues. A fundamental concept in safety awareness focuses on the requirement that the individual has sufficient knowledge to be able to understand "why" they should use care in interpreting the data from the dive computer. Knowing the limitations of the computer as well as the limitations of the diver becomes a common sense requirement for safe diving.

2. The dive computer is a tool, not a crutch, and should be used as such. The techniques in the use of the computer should be overlearned so that the individual can use it comfortably and intelligently. The computers cannot duplicate human response and as a result they cannot identify all of the variables which may be operational in a given individual's relative susceptibility to a decompression crisis at any given time. They do provide guidance based upon a set of assumptions and a model of conditions anticipated to be present during a "normal" dive. Understand the assumptions!

3. There is a need for a procedure to be followed in the event of a failure. Even though the current dive computers appear to be well designed and well constructed, they can and will fail under certain circumstances, just as any other machine. The diver must understand the problem in order to reach a decision on the appropriate procedure for surfacing with minimal risk. The decision must be rational and based upon an appreciation of techniques which can minimize the risk of ascent to the surface when decompression status may be in question. For example, a stop of 5 min. at between 10 and 30 feet for any dives over 50' (which is recommended by many as a routine precaution) would be reasonable for a situation where the diver experienced a failure on a dive which had been planned appropriately as a conservative

dive before a failure occurred. The diver who suspects a less conservative dive profile would through necessity use a more conservative ascent profile.

4. There are clearly learning curves associated with any tool. The diver should develop a level of comfort in the use of the computer that essentially eliminates stress during the use of the DC. For example, improper initiating technique will cause some of the computers to remain "off" following entry into the water even though wetting the device before the entry is the proper way to turn it on.

5. The current generation of the computers offer different bottom times for each of the "different " models. In some cases, the same model is used in more than one computer. For example the Orca Edge, Skinny Dipper and the Sherwood Sigmatech computers all operate on the same model. The USD and Oceanic devices are basically the same devices with different displays. The envelope of performance for the computers as a group appears to place the Orca devices at the liberal end of the spectrum with the Suunto, Beuchat, Dacor Microbrain and the USD and Oceanic computers becoming progressively more conservative, i.e. shorter permissible exposure for identical depth profiles.

6. The important area of care and maintenance must include understanding of the expected life of the battery which can range from hours to years depending upon the computer and the environmental conditions. Many batteries will not last as long in cold working conditions and in some cases the batteries can lose power during the course of a dive in cold water.

It appears that we are in troublesome times relative to decompression practices. The number of theoretical solutions to the problem in the form of decompression tables and dive computers has created confusion. Currently there appear to be too many choices available without any clear distinction as to the nature of the risk involved in any given choice. Most divers would want to use the "best" tables available and certainly would not want to use any "dangerous" tables. The current facts would seem to support the view that there are no completely safe tables or dive computers. The current tables and dive computers involve a calculated risk that is reasonably but not perfectly understood, even by the experts. This less than perfect circumstance would seem to require that we must refocus on training objectives. Education and training must be aligned in order to provide the modern diver with knowledge that will enable the individual to make an informed personal choice about the nature and limitations of their chosen technique for avoiding a decompression crisis.

The decompression issue in SCUBA Diving has been a continuing source of difficulty since the inception of civilian use of the apparatus. The US Navy tables which were designed by and for Navy divers were accepted as the standard in the civilian sector for a number of years with the understanding that their use probably carried an additional risk for the civilian population of divers who did not fit the Navy profiles. This additional risk was often mitigated by using conservative dive profiles designed to provide a margin of safety by using greater depth and time designations than the tables might actually call for. At the same time, there were individuals who made independent decisions that they could dive beyond the limits of the tables and did so. A significant number, but not all, of those divers did not develop clinical signs of decompression sickness, or if they did, they ignored them and life went on. Over the years, education and information transfer led more divers to the recognition and appreciation of the "fine print" in the growing decompression literature. Terms such as "silent bubbles", "cold and/or arduous dives", "bone necrosis", "multi level diving", "decomputers", "tissue half times", and "safety stops" are familiar to most well trained divers. This has resulted in an awareness that, at this time, we don't have all of the answers for, regarding our depth and time limitations and relative risk.

The effects of increasing numbers of variables upon the decompression profiles and the disturbing findings of the presence of bubbles in circulation following no decompression dives has clouded the confidence in the historical acceptance of the US Navy Standard Decompression Tables. It is interesting to note that there is little or no direct evidence that supports the position that the conservative use of the US Navy tables represents a hazard to the scientific or recreational diving populations that is not found in other models of decompression. The use of the next greater bottom time and depth with extra caution given to cold or difficult dives and slower ascents and "safety stops" as routine diving procedures is considered conservative use. The overwhelming majority of decompression accident investigations have implicated marginal or inappropriate dive profiles for the conditions present at the time of the incident. There would appear to be little confidence that "improved tables" would be free of the same problems associated with the current tables unless the education of the diving public is improved with regard to the nature of the calculated risk they must take each time they expose themselves to decompression sickness. The development of improved decompression protocols is a valuable and necessary advancement in the state of the art.

The development of additional decompression tables seems to have had its origins in the military and commercial programs where the concern for improving the divers effectiveness, i.e. getting the most work done for the least decompression penalty, led to a diversity of solutions. Some of these solutions have nationalistic identifications (British, French, Swiss, Canadian, Australian, Finnish, etc.) others have labels such as U.S. Navy, Spencer, Michigan, Bassett, Multi-level, Bühlmann, Pandora, PADI, etc. In addition, there are the extrapolations or rearrangements of the previously identified efforts into "simplified" formats or devices which are designed to do the calculations for the diver. Unfortunately, this proliferation of tables has resulted in confusion for the general diving population who have limited insight with regard to the assumptions which are incorporated into the various models under development. Karl Huggins (1987) presented an excellent review of the problem and added significant perspective to the development of both the tables and the dive computers. The study appeared to carry the analysis through the year 1986. Since this time, PADI has entered a new set of recreational diving tables and the 1988 DEMA Trade Show revealed a significant number of new devices for calculating decompression for SCUBA divers. Nearly a dozen devices using at least six somewhat different approaches are now available and none of these devices use the PADI tables, which are an attempt to provide a specialized set of tables for the recreational diver.

This rather sudden turn of events has focused attention on the obvious following questions:

1. Which tables or dive computers are the best for our purposes and what are their risk factors ?
2. If diving buddies have different decompression procedures or dive computers, how do they decide on the dive plan?
3. How do the instructional organizations teach basic students how to deal with decompression issues?
4. What is the effect on reciprocity of credentials between scientific diving agencies?

5. What are the criteria for accepting or rejecting tables or dive computers for use in our programs?
6. Are the differences between the various tables and between the dive computers likely to increase our liability exposure?
7. Can divers safely make deep dives following shallower dives?
8. Can we standardize this very important procedure?

It is unlikely that the dilemma caused by the proliferation of decompression tables and dive computers will be resolved in the near future. It is clear that the selection of "a" table or "a" computer will require significant review of strengths and weaknesses underlying the assumptions that were made with regard to the model used by the designer. It is also clear that the diver must be educated and informed with regard to the risks that are inherent in the selection of any table or computer. Tables and dive computers are and will continue to be identified as "causes" for injuries and deaths during SCUBA dives, whether they are or not. It may be possible to reduce the number of incidents through standardization of the procedures and the education of the users to the point where they can reasonably make informed choices regarding the conduct of the dive and their behavior. All divers must operate within their personal limitations as well as the limitations of their equipment and the diving conditions. Should they fail to do so, it could become necessary to demonstrate objectively where the cause(s) could be assigned with respect to liability.

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APPENDIX

The following table reflects a single day, multi-level dive conducted in a chamber with a water temperature of 75 degrees Fahrenheit. The chamber has a calibrated Heise gauge that indicates depth to 0.25 % accuracy. The five dive computers used in this test were:

1. ORCA SkinnyDipper
2. Suunto SME-ML
3. Dacor Microbrain
4. Beuchat Aladin
5. ORCA EDGE

The profile began with a dive to a Heise gauge depth of 68' for 15 min. (touched 70' / < 1 min.), followed by an ascent to 45' by 19 min.elapsed time, then remaining at 45' until 25 min. elapsed time into the dive. At 27:15 min., there was a descent to 66' with minor excursions around 60' until 44 min. into the dive, when ascent to 40', then 30' was done. The dive was terminated at 50 min.

	Heise	SD	SME-ML	MicroBrain	Aladin	EDGE
Initial depth for 15 min. (fsw)	68	67	68	67	67	66
Dive time remaining 'DTR' (min.)	35	29	25	30	25	30:51
Ascent to 45 fsw in 4 min.: depth	45	46	46	45	44	45
BT: 19 min, DTR	31	63	58	++	55	71:11
BT: 25 min, DTR	25	62	56	++	51	68:31
Descent to 66 fsw: depth	66	66	67	65	65	64
BT: 27:15 min, DTR @ 66 fsw	22	23	20	30	19	24:20
BT: 30 min: depth		62	63	62	62	61
DTR	20	22	20	15	17	23:45
BT: 35 min.: depth		65	66	64	64	64
DTR	15	16	13	15	11	17:19
BT: 38 min.: depth		62	63	62	62	62
DTR	12	13	12	8	9	14:45
BT: 40 min.: depth		62	63	61	61	61
DTR	10	12	11	8	8	13:26
BT: 42 min.: depth		61	61	60	60	60
DTR	8	10	9	4	7	11:57
BT: 44 min.: depth		60	60	59	59	59
DTR	6	9	8	0	5	10:10
Ascent to 40 fsw : depth	40	41	41	41	40	41
DTR	4	40	25	4	19	47:04
Ascent to 30 fsw: depth	30	32	31	31	30	31
DTR	3	99	91	++	99	+hrs
Surface at 50 min. DTR display		--	--	++	99	--
Post dive 10 min. DT for 100 fsw		8	8	6	--	8

Depth logs read:
SkinnyDipper: 72' // 51 min
SME-ML: 70' // 50 min.
Microbrain: 70' // 50 min.
Aladin: 70' // 50 min.
EDGE: 70' // 50:57 min.

UNITED STATES NAVY DIVE TABLES AND NO-STOP DIVING

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Integral to the discussion of the use of computers in diving is the reality that the only practical available alternatives to computers are the United States Navy (USN) diving tables. USN tables have been used by the recreational scuba diving community basically since their release over thirty years ago (des Granges, 1956). Nonetheless, for the last few years considerable controversy has arisen concerning their safety and reliability. Interestingly, there are several "myths" concerning Navy tables that have gained a level of acceptance that almost makes them sacred cows. So perhaps the most reasonable way to begin a discussion of Navy tables is by starting with these "facts."

The first concept that has gained almost universal acceptance is that the USN tables are not appropriate for use by recreational divers because they were only tested on young, fit Navy divers.

Aside from the fact that it is by no means clear that the unfit, female, older, or heavier diver is more susceptible to decompression sickness (DCS), the tables were actually tested on a group whose "ability and physical condition ... varied throughout the range of Navy divers (des Granges, 1956).

The other great myth that has been almost elevated to the status of truth is that there is a built-in incidence of DCS, usually quoted to be 5%, in the USN tables. Where this "fact" comes from is difficult to establish. Perhaps it is because during the original testing of the standard air tables there were 26 cases of DCS in 609 "dives." Yet this does not reflect the incidence of DCS on the standard air tables because whenever DCS occurred on a profile being tested, that schedule was recomputed and retested until there was no DCS. Thus, the incidence of DCS on the final tables as they were released was not 5% but rather 0% (des Granges, 1956).

Unfortunately, that is not the answer to the incidence question since, to quote the original report, "schedules that produced at least 4 normal dives and 0 bends were considered safe" (des Granges, 1956). From a statistical point of view, 4 dives per schedule is simply not sufficient to be sure of a "safe" decompression profile. Indeed, if you want to be reasonably confident that a schedule has an incidence of DCS of 5% or less, it would require approximately 50 dives without a single case of DCS. To be confident that a table had an incidence of DCS of 1% or less would require almost 100 incident-free dives. Needless to say, such extensive testing was not done and for that matter probably will never be done on any of the tables. Thus, based upon the original research report, we do not know what is the incidence of DCS on the standard air tables.

On the other hand, these tables have been in use for almost 30 years and, as a result, a tremendous amount of experience has occurred with their use. As we are most interested in the no-stop tables, I will restrict the rest of my comments to those tables alone before we discuss the Navy repetitive dive tables.

Looking at statistics from the Naval Safety Center, there are approximately 70-80 thousand no-stop dives made each year. If one looks at each case of DCS that occurred while diving those schedules correctly, the incidence of DCS is in the order of 1 in 10,000.

Unfortunately, these statistics include all no-stop dives (*i.e.*, a 10 fsw dive for 20 minutes or a 60 fsw dive for 10 minutes). Thus, the extremely low incidence of DCS, while commendable does not shed light on the incidence of DCS were the tables used to the "limit".

We are, therefore, forced to look at other data. There were two series of experiments performed that are widely quoted. The first by Spencer (1976) was one of the original studies examining the use of Doppler ultrasonic bubble detectors. In his series, testing the tables to the limit (again, the size of the sample was not statistically valid), he obtained an incidence of approximately 5% DCS. Unfortunately, the criteria used to make the diagnosis of DCS were questionable and, as a result, the implications of these data have their limitations as well.

The other important study was done by Bassett (1982). In that study, rather than testing Navy tables to their limits per se, patients were brought to altitude following exposures shorter than the Navy limits. With these exposures, calculations of gas tension within various compartments were similar to the gas tensions calculated to exist at the limit of the no-stop tables. This resulted in an approximate 8% incidence of DCS. Unfortunately, this is a model of a model and although the results are extremely important and useful for flying after diving, they shouldn't be used to provide an estimate of DCS on no-stop tables.

In spite of the limitations of these studies, the USN no-stop tables continued to get criticized as unsafe and dangerous. Partly as a result of this I suspect, included in NEDU Report No. 8-85 (Thalmann, 1986) is a series of 197 man dives testing the no-stop tables. In that series, the no-stop limits were exceeded from 10-100 % yet there was a 0 % incidence of DCS. Notably absent from these tests, however, were trials of the 40 and 50 fsw no-stop limits.

Finally, it is relevant to examine the numbers of patients seen at recompression chambers for DCS. Without question, the vast majority of patients treated for DCS have grossly violated USN tables.

Thus, in summary, thirty years of experience tell us that USN tables used as intended have an extraordinarily safe record, even though these tables were not adequately tested prior to their release. Furthermore, the most comprehensive series of tests done to re-evaluate the safety of those tables tends to confirm that safety.

In contradistinction to the moderate data available on the no-stop tables, almost no statistical base exists for the repetitive tables. The entire repetitive dive concept was tested doing only 62 dives (des Granges, 1957) and only a handful were done in the no-stop range with surface intervals akin to what SCUBA divers use. Furthermore, dive series consisted of only two dives.

Thus, there are almost no data by which to evaluate these tables. Once again, my experience (*i.e.*, at recompression chambers) reveals that most divers are either incapable or unwilling to use the repetitive tables properly and that the majority of cases of DCS arise from violations of the tables rather than their failure.

Reviewing data collected by DAN reveals similar results. Their data suggests that most diving accidents occur in single dives (75 %) and that 15 % of divers carry no depth gauge or watch. 50 % of accidents involved the use of alcohol and approximately 5 % other recreational drugs (Bond *et al*, 1988).

Thus, analysis of the tables, their history and accident data do not support the notion that USN tables are the primary cause of most diving accidents. Furthermore, it appears that used the way they are intended, the USN no-stop and repetitive dive tables have an impressive safety record.

No discussion of this topic would be complete without mentioning Weathersby's (1984) maximum likelihood statistical model. In this method, a number of models were fit to both animal and human data. The models that best fit the data can then be used to predict the incidence of DCS on a given profile. Using this method, no-stop decompression limits were established at a predicted 1 % and 5 % incidence of DCS (Table 1 - Weathersby, 1985).

TABLE 1

Depth (fsw)	U.S.N.	N.M.R.I. 1%	N.M.R.I. 5%	Huggins	
				time	risk
30	none	170	240	n/a	
40	200	100	170	135	4.4 %
50	100	70	120	75	3.4 %
60	60	40	80	50	3.1 %
70	50	25	80	40	3.5 %
80	40	15	60	30	3.4 %
90	30	10	50	25	3.7 %
100	25	8	50	20	3.6 %
110	20	7	40	15	3.0 %
120	15	5	40	10	1.9 %
130	10	5	30	5	0.7 %

As can be seen, at depths in excess of 40 fsw, the method predicts an incidence of DCS on no-stop tables somewhere between 1 % and 5 %.

In 1985, Vann also analyzed USN no-stop tables according to these methods. His analysis (Vann, 1985) also included a prediction of the incidence of DCS based upon the Huggins limits (used in some multi-level dive computers).

As can also be seen in Table 1, reduction of the no-stop limits by a few minutes does not appreciably alter the predicted DCS risk, and to reduce the risk to the NMRI prediction of 1 % requires a reduction in no-stop limits that I believe most divers would find unacceptable. This method also predicts that the common practice of reducing no-stop limits by a few minutes will not have a large effect upon DCS incidence. Whether other safety precautions such as a "safety stop" will have a greater effect remains to be tested.

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ESTIMATING DECOMPRESSION RISK

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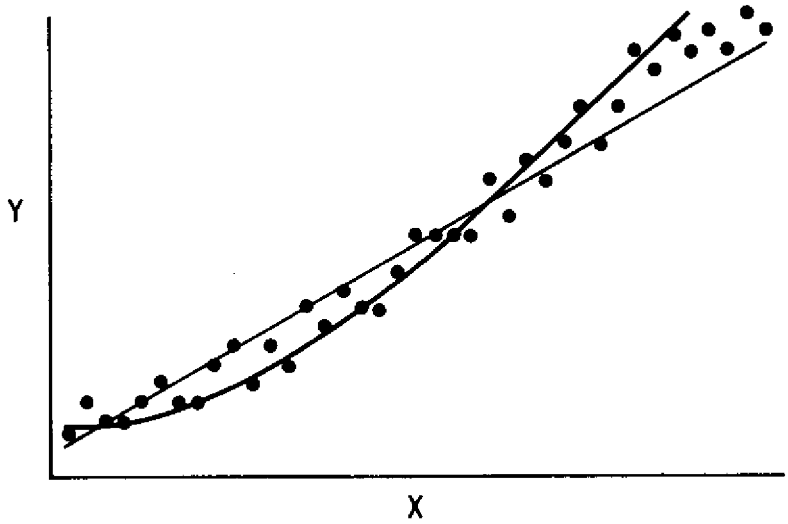
The unpredictability of diseases such as AIDS, heart attack, and decompression sickness (DCS) reflects our ignorance of their causes. Although individual incidents of these diseases cannot be anticipated with certainty, their risks can be estimated by analysis of occurrence data (Lui *et al*, 1988; Walker and Duncan, 1967; Weathersby *et al*, 1984). The principles of this analysis are illustrated in Figs. 1 and 2.

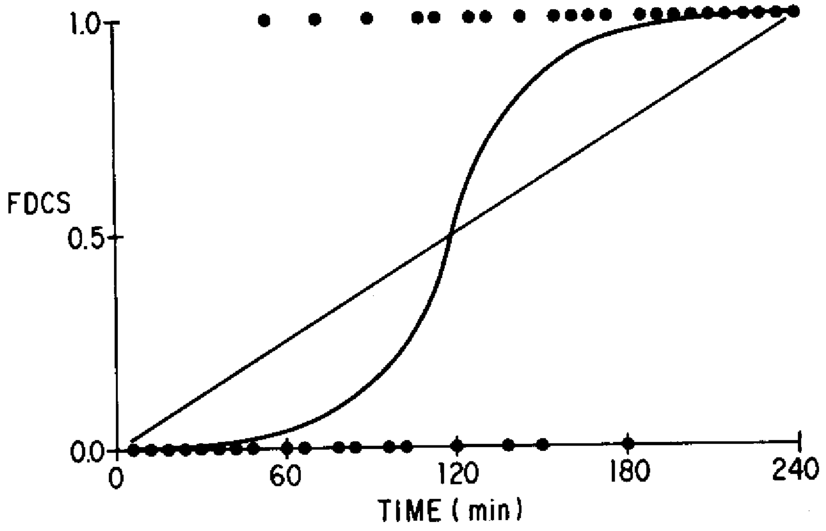
In Fig. 1, experimental observations of the hypothetical variables X and Y appear partly related by the linear function Y = MX + B where the parameters M and B determine the position of the line in the X-Y plane. The best fit of the line to the data occurs when the error between them is reduced to a minimum by appropriate choice of M and B. The curvilinear function has a smaller error and fits the data better than the straight line.

Figure 1. Hypothetical experimental observations relating the variables X and Y. A straight line and a curve are fit to the data.



While the data of Fig. 1 can have a multiplicity of values, the fractional incidence of decompression sickness (FDCS) can have only two values, zero after a safe dive and one after a bend. Figure 2 shows how FDCS might vary during a hypothetical series of no-stop air dives to 60 fsw where the first dive is six minutes long and successive dives are each six minutes longer. All dives are safe (FDCS = 0) for short bottom times, but an occasional bend occurs (FDCS = 1) at times approaching 60 min. For times of 2-4 hours, decompression sickness is the rule.

Figure 2. A hypothetical series of no-stop dives to 60 fsw. The fractional DCS incidence (FDCS) is shown against the bottom time. The first dive is 6 minutes long and subsequent dives are six minutes longer. A straight line and a sigmoidal function are fit to the data.



A straight line can be fit to these data, but a sigmoidal function is a better fit. The sigmoidal function transforms the binary decompression data into a continuous DCS probability so that each bottom time is associated with a specific decompression risk. If the bottom time is replaced by some measure of decompression stress such as a ratio from a Haldane algorithm (Vann, 1987), this becomes a powerful technique which can be applied to an unlimited number of dive profiles. This is the basis for decompression data analysis and risk estimation.

Table 1. DCS risk estimates for single 60 fsw no-stop air dives.

	Bottom time (minutes)	
% Risk	Vann (1985)	Weathersby *et al* (1985b)
1	47	40
2	62	---
3	72	---
4	81	---
5	88	80

Table 1 lists risk estimates for single no-stop air dives to 60 fsw (Weathersby *et al*, 1985b; Vann, 1985). These estimates suggest that the 60 min U.S. Navy no-stop limit at 60 fsw has a decompression risk of 2-3 %.

This risk seems high given that the incidence of recreational diving accidents is estimated at 0.003 -0.033 % (Wachholz, 1988). Most dives, however, are well within the Navy no-stop limits, and bends occur principally in susceptible divers. These divers probably are responsible for the 2-3 % risk, and most people can dive safely to 60 fsw for 60 min. Thirty-one percent of the 79 DAN dive computer cases, for example, occurred in

19 % of the affected divers (Vann *et al*, 1988). A larger study of the 376 tunnel workers during 40,000 compressed air exposures found that 10 % of the population had five times the mean DCS incidence (Paton and Walder, 1954).

Table 1 suggests that the DCS risk at 60 fsw could be reduced from about 2 to 1 % by decreasing the no-stop exposure limits from 60 to 45 minutes. Susceptible divers, however, will make some risk unavoidable even at shorter limits (Vann *et al*, 1988). Individual susceptibility, moreover, changes with time. Until it is possible to distinguish susceptible from resistant divers, the resistant may have to endure the more restrictive limits established for the susceptible.

Estimation of decompression risk is a recent development which offers great potential for improving decompression safety (Weathersby *et al*, 1985b; Vann, 1987; Tikuisis *et al*, 1988). Software and documentation necessary to analyze decompression data and to estimate risk are available on request.

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DC's, TABLES AND NO-STOP DIVING DISCUSSION

Additional comments by Tom Neuman

In reference to the risk involved in using the USN tables, Tom mentioned that PADI was being sued because they reproduced the Navy tables and failed to tell the customers that there was a risk of getting decompression sickness. A Florida product liability law requires a manufacturer to warn customers when there is a danger associated with the use of a product.

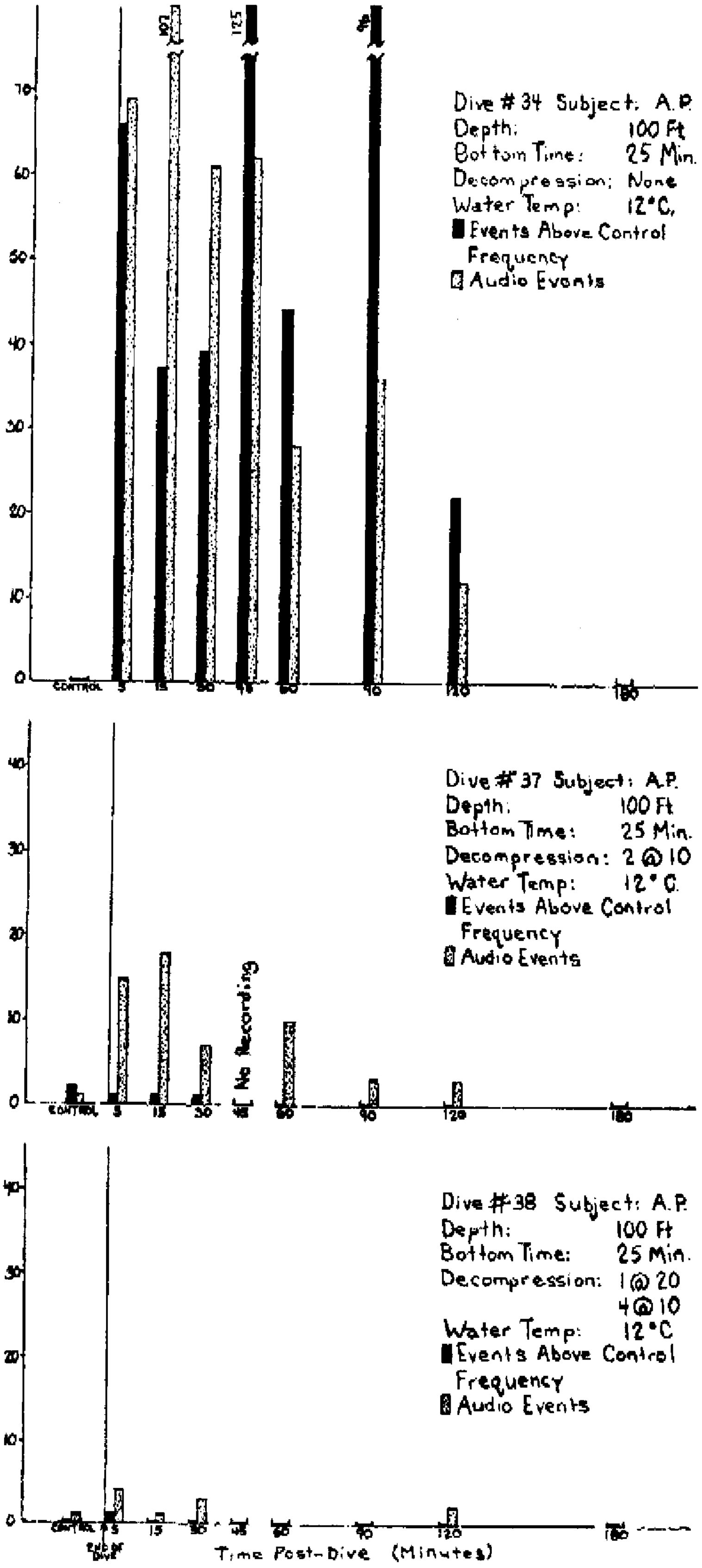
Tom also mentioned that there were very few cases in his experience where the diver being treated was clearly within the limits of the USN tables. He added that some of these were well within the tables (*e.g.*, 30 min at 60 fsw) and that most of these cases were serious DCS. The other cases involved violations. Asked if DCS cases from divers using DC's were worse than from those using tables, he said no. Regarding doppler bubble detection, he sees bubble grades generally paralleling the decompression stress of the dive, but that doppler bubbles cannot be used to predict bends. But if bubbles cause DCS, which they surely do, then if you can use doppler to get rid of bubbles it should improve the DCS scores.

Bubble-reducing effect of a shallow stop

Andy Pilmanis presented data from work he had done for ONR in 1976. In that study, 110 subject-dives in the open ocean for the purpose of vge monitoring were made, diving the Navy tables, exactly to the time, depth, and ascent rate limits. No symptoms of DCS were seen as a result of any of the diving. Intravascular "silent bubbles" were present, to some degree, after all of the dives reported. These silent bubbles were present within a few minutes after surfacing from the dives. The number of events usually peaked within an hour post-dive, declined and was close to control levels by three hours post-dive. A great range of individual variability was seen. Furthermore, each individual showed a relatively consistent degree of bubble formation on various dive profiles and repeated dives. In particular, the subject in figure 1 consistently produced large numbers of events. A bottom time of 25 minutes is the no decompression limit for a depth of 100 fsw according to the U.S. Navy Standard Air Decompression Tables. Yet, this subject always exhibited large numbers of events after such an exposure. However, when relatively short decompression periods were added to the dive profile, the number of post-dive events was drastically reduced. The U.S. Navy Tables were tested without the benefit of the Doppler. If one accepts that vge are related to DCS, then it would appear from these data that relatively small modifications in the U.S. Navy Tables in the conservative direction may significantly reduce the occurrence of vge and, therefore, the occurrence of DCS.

Tom Neuman reported a series of dives to 210 fsw for 50 min with the USN tables, which of course caused extensive bubbling. In some modifications (a short stop 10 fsw deeper than the first stop) did more good than increasing all the stops with a much longer increase in total decompression time. He endorses putting in a stop at 10 or 20 fsw following no-stop dives. Someone commented that every dive should be a multi-level dive. Another comment said using a very slow ascent rate, just creeping, between stops after 40 fsw was a characteristic separating groups with DCS from those without DCS. Andy noted that the size of his chamber makes rapid ascent the last few fsw impossible, and this may explain why they have had no DCS in some 10,000 man-dives.

Figure 1.Vge data from subject A.P. after 3 dive profiles; depth and bottom times were identical, only the decompression was changed



Glen Egstrom asked what constitutes DCS in the doppler interpretation, is it Grade III? How many bubbles does it take? Ron Nishi said they consider 0 and I acceptable, Grade II is marginal, and Grades III and IV are unacceptable, but there is more to their assessment. Glen elaborates that a diver may pick up bubbles on a dive. What does this do to him later?. Andy told about a patient who was paralyzed from a 60 fsw/30 min dive, but that this diver had been bent twice in the last few weeks, and did not report this at the time. Mike Powell thinks that the Haldanian algorithms are not suitable for many dives in a day, or diving day after day. When this is worked out, it can be put into the DC's.

Mike Powell further said that his impression of the bubbles is that those heard with the doppler are probably from muscle and fat and do not really comply with the "half-time" concept. Pain-only DCS is probably extravascular gas phase forming in tendons and ligaments. The bubbles being monitored follow about the same time constants as the gas formed in tendons and ligaments, which is why the doppler works fairly well with some dives, for example no-stop dives. But using the doppler to control a decompression from a deeper or longer dive has not been made to work. Bubbles in the venous return are probably not the same as those in the tendons and ligaments.

An important aspect of Dick's presentation was support for the capability of having dive computers record dive profiles. Karl Huggins asked how one would compare "multi-level" profiles when each was a totally unique dive. Dick answered that the beauty of the maximum likelihood approach is that it is independent of profiles, that it can compare totally different profiles. Ron Nishi said however that it does not yet do repetitive dives, but Paul Weathersby is working on this now. The data set used by Dick Vann is from a somewhat different form of diving, involving more "decompression" diving than is common for scientific divers. Others suggested other sources of data.

Bill Hamilton pointed out that an example shown by Tom Neuman had minor corrections to a profile converting an incidence of say, 2 out of 6 with DCS, to no cases, suggesting that the table was now all right. This is a hazard of doing decompression research with small numbers of dives. It might be better not to do any rather than be misled. Ron Nishi added that this is even more true with maximum likelihood, that his current dive series has some 600 dives and this is not enough to get good results using maximum likelihood. So far this kind of data is not available. We have to be diligent in recording data. Dick Vann emphasized that we need the DCS cases as well as the clean dives. John Lewis said that the distribution of the data set can have a big effect on the results of the analysis, and Dick Vann agreed with him, adding that one cannot have confidence in predictions if they are outside the data set.

Woody Sutherland made the point that experienced divers are doing well with the tools they have, and that our recommendations ought to tell divers how to use the DC's safely.

Max Hahn gave a short discussion of the legal aspects affecting the German scientific divers. They are not yet ready to use DC's. Andy Pilmanis compared this with the situation in the U.S., noting that the Dive Control Board catches most of the responsibility, not the Risk Management department, and not the Government. Based on a show of hands, among U.S. programs 5 use DC's, 10 do not. Of these, about half require table diving to be done on USN air tables. Mark Flahan said some of the boards have decided not to decide. By collectively defining the state of the art we might well create a zone where we can operate comfortably, according to Glen Egstrom. He illustrated this with a hypothetical case where two divers are diving together, doing the same dive, and one gets DCS. The manufacturer of this diver's DC will get sued. The other DC obviously worked correctly because that diver did not get DCS. Dennis Graver pointed out that benefits may outweigh the risks, using the example of free ascent training. Glen added that whatever the approach, we have to inform the users of the risks. We also might recommend that divers limit repetitive deep dives, do the shallow dive after the deep, do shallow stops, and other such procedural techniques that may make it work.

Jon Hardy discussed legal implications, suggesting that we are here at the cutting edge, setting the state of the art. We should determine what the user should know, and what the instructor should know and teach. We have to behave with the standard of care for the time and place. If there is a better way known, one might be held to that. Jon felt the "safety stop" was a reasonable and prudent thing to do. Thus, it is best to do it. Glen said there is no big problem with changes, that new information introduced after a case is not admissible. Retrofits, properly executed, do not expose the manufacturer excessively. The fact that we have had this workshop puts all of us in a better position than we were before. Max Hahn suggested that we might not be able to define profiles, but we might recommend the minimum contents of instructions for users.

RECONSTRUCTING THE NAVY TABLES

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The Navy Tables were created during the 1950's as a solution to the problem of decompression during repetitive dives. Over the past thirty years, the safety of millions of scuba dives has been governed by these tables with an accident rate of a few per one hundred thousand exposures. A folklore of fact and fancy has evolved during this period. By looking in depth at the construction of these tables, the underlying principles can be understood. Hopefully, with this understanding will come safer applications of these tables.

THE MODEL

Following the work of Haldane and an earlier set of Navy Tables, the currently used set was developed. The Haldanian Model assumes that the change in the internal pressure of inert gas is proportional to the difference between the external and internal pressures. Thus, the equation governing the Haldanian decompression model is the rate equation:

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

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

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

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

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

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

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

In the model for the Navy Tables, six different half times were used namely; 5, 10, 20, 40, 80, and 120 minutes, giving rise to a six compartment model. From the solution of the rate equation, given any dive profile d as a function of time, the internal pressure, for each of the six compartments, can be calculated for any time t. The final component of the Haldanian model assumes that at all times during the dive the internal pressure of the inert gas will not exceed a preset maximum amount, denoted by M(d), which can depend on the depth and which differs for each half time compartment. While descending, the internal pressure is always less than M(d) so the problem of exceeding an M-value is never encountered. However, on ascent the reverse is usually true. This condition in practice leads to limited bottom times, controlled ascent rates, and decompression stops. For the implementation in the Navy model, the formula for the M-values which depends on depth is determined by two constants for each compartment, denoted by M_0, the maximum allowed at the surface, and DM, the increment allowed for each foot of depth in sea water. M_0 is measured in feet of sea water absolute.

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

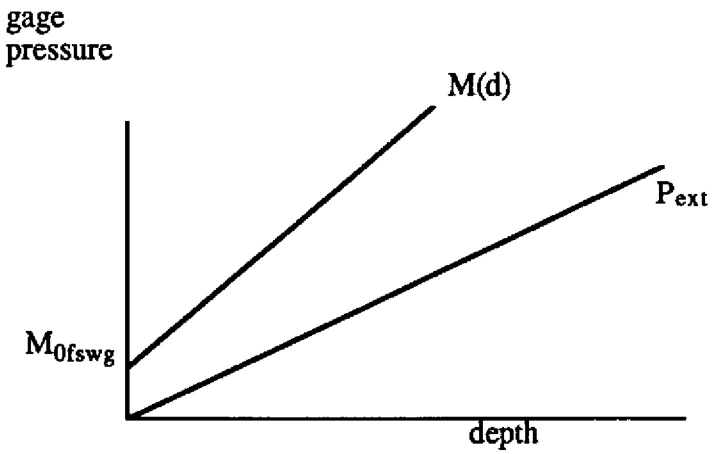
For simulating the Navy Model, these values are given in Table 1.

Half time(min)	5	10	20	40	80	120
M_0 (fsw)	104	88	72	58	52	51
ΔM	2.27	2.0	1.71	1.4	1.29	1.27

Table 1.

If we graph the maximum allowable internal inert gas pressure M(d) and compare with the ambient pressure of the inert component P_{ext}, we see that the allowable overpressure increases with depth (Figure 1).

Figure 1.



Based on this model, if at each point in time

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

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

COMPUTER IMPLEMENTATION

CAUTION

The following computer implementation of the Navy Model *should not* be used to govern the safety of any scuba dive. The Navy Tables derived from this model are what have been tested over the past thirty years and not the model directly. In fact, the Edge, an underwater decompression computer manufactured by ORCA Industries, uses the Haldanian model with *more conservative* M values and twice the number of compartments.

Anyone having access to a personal computer running most spread sheet programs will be able to implement the Navy Model on their machine. Table 2 provides an example of the output of this spread sheet program. The first two columns represent the dive profile, the first column is time measured in minutes and the second is the corresponding depth measured in feet. The columns are entered for each application of the model.

In the case of our example given by Table 2, the dive profile is illustrated by Figure 2.

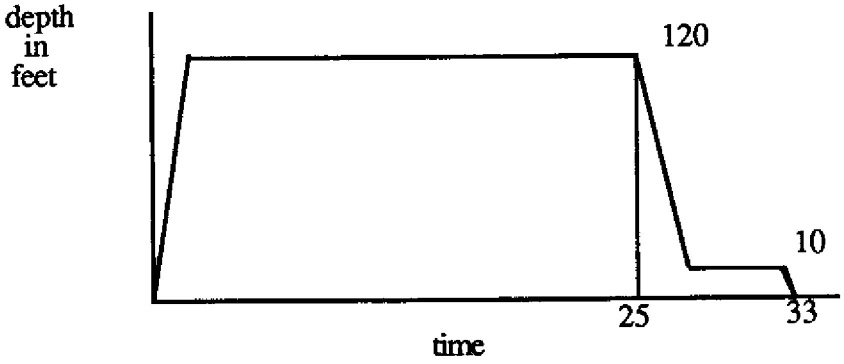


Figure 2.

Referring to Table 2, columns D through I represent the six compartments in the model. The first six rows are constants associated with each compartment and the remaining rows list the fraction of the maximum gage pressure of inert gas allowed in that compartment at the surface. The formulas for column D are presented in the Microsoft Excel notation. For example, if the current cell is D9 then D8 represents the cell just above D9 in the relative sense and D$2 represents the cell column D and row 2 with row 2 fixed. The other compartment columns E through I can be programmed by a fill to the right command.

Row 1	5	(Half Time in minutes)
Row 2	LN(2) / D1	(LN is the function natural logarithm)

Row 3	104	(M_0 value)
Row 4	0.7902 / (D2*(D3 - 26.1))	
Row 5	2.27	(ΔM value)
Row 6	(D3 - 26.1) / D5	
Row 7		(blank)
Row 8	0	(initial fraction of inert gas)
Row 9	`D8*EXP(-D$2*($A9 - $A8)) + D$4*($B9*D$2*($A9 - $A8) - ($B9 - $B8) + EXP(-D$2*($A9 - $A8))*($B9 - $B8 - $B8*D$2*($A9 - $A8))) / ($A9 - $A8)`	

Row 10 and beyond fill down using D9

Column J is the minimum ceiling allowed at that moment of time in the dive profile. From Table 2 one can see that as the no-decompression limit of 15 minutes is exceeded, the ceiling, measured in feet of sea water, becomes non-zero. At the 25 minute mark the ceiling is 7.6 feet, thus to remain within the safe region of the model, the diver should remain below 7.6 feet to decompress. The formulas for column J are:

Row 8 `MAX(0, (D8 - 1)*D$6, (E8 - 1)*E$6, (F8 - 1)*F$6, (G8 - 1)*G$6, (H8 - 1)*H$6, (I8 - 1)*I$6)`

Row 9 and beyond fill down using J8

Column K is the gage inert gas pressure in the 120 minute compartment measured in feet of seawater. For column K the formulas are:

Row 8 `I8*(I$3 - 26.1)`

Row 9 and beyond fill down using K8

Column L scales column K in order to calculate the repetitive dive group.

Row 8 K8 / 1.58 + 0.1

Row 9 and beyond fill down using L8

Column M gives the letter value of the repetitive dive group.

Row 8 LOOKUP(L8, TAB)

Row 9 and beyond fill down using M8

Finally the lookup table referred to above as TAB is given in columns O and P.

Using these formulas in Microsoft Excel or their translation to other spreadsheet programs will produce Table 2 for any dive profile entered into columns A and B.

NAVY TABLES

With the computerization of the six compartment Navy Model accomplished, we can now reconstruct the Navy Tables. To do this we must apply the same simplifying assumptions used by the Navy. Only recently have computers attained a size where it is feasible for an underwater application which could follow any dive profile.

TABLE 2.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1			HALF L	5	10	20	40	80	120	TOP					0.34	A
2			K	0.14	0.07	0.03	0.02	0.01	0.01						1	B
3			M0	104	88	72	58	52	51						2	C
4				0.07	0.18	0.5	1.43	3.52	5.49						3	D
5			DM	2.27	2	1.71	1.4	1.29	1.27						4	E
6			M0G/DM	34.3	31	26.8	22.8	20.1	19.6						5	F
7	TIME	DEPTH													6	G
8	0	0		0	0	0	0	0	0	0	0	0.1	####		7	H
9	1.6	120		0.13	0.08	0.06	0.04	0.03	0.02	0	0.44	0.38	A		8	I
10	2	120		0.18	0.12	0.08	0.06	0.04	0.03	0	0.65	0.51	A		9	J
11	3	120		0.32	0.22	0.15	0.11	0.07	0.05	0	1.2	0.86	A		10	K
12	4	120		0.43	0.3	0.22	0.16	0.1	0.07	0	1.74	1.2	B		11	L
13	5	120		0.54	0.39	0.28	0.21	0.13	0.09	0	2.27	1.54	B		12	M
14	6	120		0.62	0.46	0.34	0.26	0.16	0.11	0	2.81	1.88	B		13	N
15	7	120		0.7	0.53	0.4	0.3	0.19	0.13	0	3.34	2.21	C		14	O
16	8	120		0.77	0.6	0.46	0.35	0.22	0.16	0	3.86	2.54	C		15	Z
17	9	120		0.83	0.66	0.51	0.39	0.25	0.18	0	4.39	2.88	C		15.5	*
18	10	120		0.88	0.72	0.56	0.44	0.28	0.2	0	4.91	3.21	D			
19	11	120		0.92	0.78	0.61	0.48	0.31	0.22	0	5.43	3.53	D			
20	12	120		0.96	0.83	0.66	0.52	0.34	0.24	0	5.94	3.86	D			
21	13	120		0.99	0.87	0.71	0.57	0.37	0.26	0	6.45	4.18	E			
22	14	120		1.02	0.92	0.76	0.61	0.4	0.28	0.74	6.96	4.51	E			
23	15	120		1.05	0.96	0.8	0.65	0.42	0.3	1.61	7.47	4.83	E			
24	16	120		1.07	1	0.85	0.69	0.45	0.32	2.37	7.97	5.14	F			
25	17	120		1.09	1.03	0.89	0.73	0.48	0.34	3.03	8.47	5.46	F			
26	18	120		1.1	1.07	0.93	0.77	0.51	0.36	3.6	8.97	5.78	F			
27	19	120		1.12	1.1	0.97	0.8	0.53	0.38	4.1	9.46	6.09	G			
28	20	120		1.13	1.13	1	0.84	0.56	0.4	4.53	9.95	6.4	G			
29	21	120		1.14	1.15	1.04	0.88	0.59	0.42	4.91	10.4	6.71	G			
30	22	120		1.15	1.18	1.07	0.91	0.61	0.44	5.55	10.9	7.02	H			
31	23	120		1.16	1.2	1.11	0.95	0.64	0.46	6.28	11.4	7.32	H			
32	24	120		1.17	1.22	1.14	0.98	0.67	0.48	6.96	11.9	7.63	H			
33	25	120		1.17	1.25	1.17	1.02	0.69	0.5	7.6	12.4	7.93	H			
34	26.8	10		1.06	1.2	1.17	1.04	0.71	0.51	6.04	12.8	8.18	I			
35	32.8	10		0.52	0.83	0.98	0.96	0.69	0.51	0	12.6	8.08	I			
36	33	0		0.5	0.82	0.98	0.96	0.69	0.51	0	12.6	8.07	I			
37	43	0		0.13	0.41	0.69	0.8	0.63	0.48	0	11.9	7.63	H			
38	60	0		0.01	0.13	0.38	0.6	0.55	0.43	0	10.8	6.92	G			
39	120	0		0	0	0.05	0.21	0.33	0.31	0	7.62	4.92	E			
40	180	0		0	0	0.01	0.07	0.19	0.22	0	5.39	3.51	D			
41	240	0		0	0	0	0.03	0.11	0.15	0	3.81	2.51	C			
42	300	0		0	0	0	0.01	0.07	0.11	0	2.69	1.81	B			
43	360	0		0	0	0	0	0.04	0.08	0	1.91	1.31	B			
44	420	0		0	0	0	0	0.02	0.05	0	1.35	0.95	A			
45	480	0		0	0	0	0	0.01	0.04	0	0.95	0.7	A			
46	540	0		0	0	0	0	0.01	0.03	0	0.67	0.53	A			
47	600	0		0	0	0	0	0.01	0.02	0	0.48	0.4	A			
48	660	0		0	0	0	0	0	0.01	0	0.34	0.31	####			

The first simplification was to limit the dive profiles considered to "square profiles" at even 10 foot depth intervals. Thus, we obtain the first rule:

Rule 1: Any dive profile is replaced by the "square profile" that contains it.

The only important parameters for any dive profile are now maximum depth and bottom time, since these determine the appropriate square profile. The definition of bottom time for the Navy Tables is the time from leaving the surface to beginning the ascent. By studying Table 2, we notice that the during the ascent the ceiling changed from 7.6 feet to 6.04 feet. Thus, the ascent was a form of decompression. If we were to change the ascent rate we would decompress either more or less. To produce a set of tables, the Navy chose to standardize this form of decompression to an ascent rate of 60 feet per minute.

Rule 2: The ascent rate will be 60 feet per minute.

Again, referring to Table 2, we note that the square dive profile is 120 feet for 25 minutes. On leaving the bottom at the standard ascent rate, we have a ceiling of 7.6 feet and on reaching the 10 foot level we still have a ceiling of 6.04 feet. Taking a 6 minute decompression stop at 10 feet reduces the inert gas to below the maximum allowable at the surface, so we may now return to the surface. By generalizing this example, we can now reproduce the no-decompression limits and the decompression schedules recorded in the Navy Tables. One additional simplification will reduce the size of these tables, we will only consider a representative selection of times.

Rule 3: Do not interpolate, use the next higher time.

Up to now we have only considered a single dive. The real value of the Navy Tables is that they provide a decompression schedule for repetitive dives. The basic principle is to compute the amount of inert gas remaining in the six compartments and then use this information to enter the desired square dive profile, not at the beginning, but at a time when the content of each of the compartments is less than the compartmentwide content of the square dive profile. For example, if the current inert gas content, expressed as a fraction of the maximum allowable at the surface, is given by Table 3,

Half Time	5	10	20	40	80	120
	0.60	0.54	0.45	0.36	0.24	0.17

Table 3.

We can enter the dive profile given in Table 2 at the 9 minute mark. This time of 9 minutes is called the Residual Nitrogen Time (RNT), which we would add to the actual bottom time (ABT) of this 120 foot dive to find the inert gas content of each of the six compartments from the square dive profile given in Table 2.

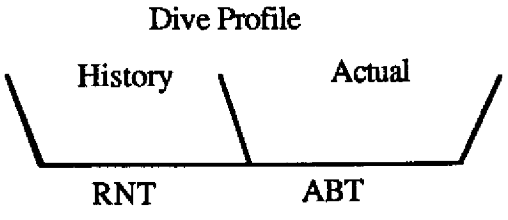


Figure 3.

Without any further simplification, a separate set of tables would be necessary for each of the six compartments. However, if we again return to Table 2 and consider the outgassing of each compartment after the completion of the dive, we note that the shorter half time compartments, after a brief surface interval, return to zero. As a consequence, these compartments will not have a controlling role in the calculation of the Residual Nitrogen Time. If we compare the content at 33 minutes with 43 minutes, 10 minutes later, we note that the 10 minute compartment's content, 0.82, is reduced by half to 0.41, and the 5 minute compartment's content, 0.50 is reduced by half of a half, or by a quarter to 0.13. This clearly demonstrates the meaning of half time. The question becomes, how short a surface interval will allow the 120 minute compartment to control the Residual Nitrogen Time?

Rule 4: For repetitive dives a minimum surface interval of 10 minutes is required.

With this rule, we now only need to have detailed information on the inert gas content of the 120 minute compartment. This content will be designated by a letter group which will have increments of approximately 1.58 measured in feet of seawater. Table 2 includes this calculation and displays the letter group in column M. The outgassing of the 120 minute compartment is displayed in the Navy Tables by the Surface Interval Table. This represents the time required to outgas from the top of one letter group to the middle of another. For example from Table 2, the content of the 120 minute compartment at the 60 minute mark is 10.8 measured in feet of seawater or 6.92 measured on the letter group scale giving a letter group of G. Since 6.92 is at the top of the G letter group and two hours latter we have a content of 3.51 or a letter group of D, we see that a surface interval of two hours will change a G into a D as noted in the Surface Interval Table. Table 2 also shows that an additional hour, or a three hour surface interval, will reduce a G to a C. Again, this is realized in the Surface Interval Table. Using our computer model the other values within the Surface Interval Table can be calculated. The Residual Nitrogen Time Table can also be determined from Table 2. For this dive profile of 120 feet, record the last time that each letter group appears. These numbers are displayed in table 4.

Letter Group	A	B	C	D	E	F	G	H
Time	3	6	9	12	15	18	21	25

Table 4.

Comparing with the Residual Nitrogen Table at the 120 foot level, we see that we have complete agreement. In a similar manner all the other entries in this table can be computed by our model.

DIVE COMPUTER LOG for the EDGE or SKINNY DIPPER

Michael N. Emmerman
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Weehawken, NEW JERSEY 07087-6905.U.S.A.

This Dive Computer Log system is designed to help the dive computer user keep track of his/her dive profiles. The instructions under <u>How to Use This Log</u>, tells you what information should be entered in each of the three log sections.

The second page of this paper contains information on an <u>EXPERIMENTAL</u> method for re-entering the Huggins "No-Bubble" Tables in the unlikely possibility that your EDGE or SKINNY DIPPER malfunctions. READ ALL INSTRUCTIONS ON THE NEXT PAGE CAREFULLY !

HOW TO USE THIS LOG

TRIPLOG (top section)

This is your master sheet. Note the date, day, time, location, etc. Most important is to note the number of the dive (i.e., dive #1, 2, 3, etc.). The blank area on the right is for general comments.

TRIPLOG DIVE PROFILES (middle section)

Using the dive # from the TRIPLOG section; make note of the data requested in this section. Most important are the depth and time figures.

COMPUTER LOG (bottom section)

You can make entries in this section at any time during a dive trip. Your objective is to log the readings of the computer at a <u>fixed point in time</u>. The best times to do this are just before a dive and just after the dive. You will be able to match the readings to the actual dive # by comparing the date and time entries with the top two sections. By using this section, you will have a better chance of evaluating your dive profile status in case of computer malfunction. For further details about using this section of the log, review the instructions for re-entering the Huggins No-Bubble Tables on the next page.

IMPORTANT WARNING !!

This method for re-entering the Huggins No-Bubble Tables has been developed mathematically and has NOT been subjected to

human testing for validation. The procedure described here is offered as an EMERGENCY protocol only and requires detailed record keeping. The user of this method may suffer a diving related illness or injury that may or may not be related to the use of this procedure.

The Huggins No-Bubble Table (reproduced on the next page) and the Edge and Skinny Dipper (both manufactured by Orca Industries) calculate dive profile data based on the same mathematical algorithm. The EMERGENCY re-entry procedure is based on this commonality. DO NOT ATTEMPT TO USE THIS METHOD WITH ANY DIVE COMPUTER OTHER THAN AN EDGE OR SKINNY DIPPER !!

COMPUTER LOG: PLACE EXOTIC SEA

	MINUTES ALLOWED AT:										
DATE TIME	30 FT	40 FT	50 FT	60 FT	70 FT	80 FT	90 FT	100 FT	110 FT	120 FT	130 FT
12/24/87 9:01A	187	129	75	53	39	31	24	19	13	10	9
10:01A	131	90	50	33	25	20	16	13	11	10	8

ALLOWABLE BOTTOM TIME FOR EACH DEPTH AS SHOWN
ON THE SCREEN OF THE DIVE COMPUTER

EXAMPLE - Using the data provided above, and assuming that I was using an Edge or SkinnyDipper: If my computer malfunctioned at 11:00 AM (that day), I would first deduct my Allowable Bottom Times (ALLOWBT) shown above from the No-Decompression Limits (NDL) of the "NO-BUBBLE TABLES" (Huggins).

	@30 ft	@40 ft	@50 ft	@60 ft	@70 ft	@80 ft	@90 ft	@100 ft	@110 ft	@120 ft
NDL	225	135	75	50	40	30	25	20	15	10
Less ALLOWBT	131	90	50	33	25	20	16	13	11	10
= RNT	94	45	25	17	15	10	9	7	4	0

The Residual Nitrogen Times (RNT) would be those indicated by the computer readings at 10:01 AM !! If you now compare these RNT numbers with the "Bottom Time and Repetitive Group Code" section the "NO-BUBBLE TABLES", you will find a group letter for each depth.

REPETITIVE GROUP	H	G	E	E	E	E	F	E	E	F

Remembering that the surface interval started at 10:01 AM, use the MOST CONSERVATIVE repetitive group letter and enter the Surface Interval Table as you normally would for a repetitive dive.

SURFACE INTERVAL TABLE

NEW GROUP	A	B	C	D	E	F	G	H	I	J	K	L	M	N
A	12:00 0:10	12:00 2:31	12:00 3:42	12:00 4:43	12:00 5:23	12:00 5:57	12:00 6:21	12:00 6:49	12:00 7:09	12:00 7:30	12:00 7:46	12:00 8:01	12:00 8:18	12:00 8:27
B		2:30 0:10	3:41 1:20	4:42 2:21	5:22 3:01	5:56 3:35	6:20 3:59	6:48 4:27	7:08 4:47	7:29 5:08	7:45 5:24	8:00 5:39	8:17 5:56	8:26 6:05
C			1:19 0:10	2:20 1:04	3:00 1:44	3:34 2:18	3:58 2:42	4:26 3:10	4:46 3:30	5:07 3:51	5:23 4:07	5:38 4:22	5:55 4:39	6:04 4:48
D				1:03 0:10	1:43 0:50	2:17 1:24	2:41 1:48	3:09 2:16	3:29 2:36	3:50 2:57	4:06 3:13	4:21 3:28	4:38 3:45	4:47 3:54
E					0:49 0:10	1:23 0:43	1:47 1:07	2:15 1:35	2:35 1:55	2:56 2:16	3:12 2:32	3:27 2:47	3:44 3:04	3:53 3:13
F						0:42 0:10	1:06 0:34	1:34 1:02	1:54 1:22	2:15 1:43	2:31 1:59	2:46 2:14	3:03 2:31	3:12 2:40
G							0:33 0:10	1:01 0:34	1:21 0:54	1:42 1:15	1:58 1:31	2:13 1:46	2:30 2:03	2:39 2:12
H								0:33 0:10	0:53 0:30	1:14 0:51	1:30 1:07	1:45 1:22	2:02 1:39	2:11 1:48
I									0:29 0:10	0:50 0:29	1:06 0:45	1:21 1:01	1:38 1:17	1:47 1:26
J										0:28 0:10	0:44 0:26	1:00 0:42	1:16 0:58	1:25 1:07
K											0:25 0:10	0:41 0:24	0:57 0:40	1:06 0:49
L												0:23 0:10	0:39 0:24	0:48 0:33
M													0:23 0:10	0:32 0:18
N														0:17 0:10

RESIDUAL NITROGEN TIME TABLE

NEW GROUP	20	30	35	40	50	60	70	80	90	100	110	120	130
A	12	8	7	6	5	4	4	3	3	3	3	2	2
B	28	18	16	14	11	9	8	7	6	6	5	5	4
C	45	29	25	21	17	14	12	9	8	6	6	5	5
D	65	41	34	30	23	19	15	10	8	7	6	5	5
E	86	53	44	37	28	22	17	12	9	8	7	6	5
F	111	66	53	43	32	24	19	14	11	9	7	6	6
G	140	80	62	49	36	27	22	17	12	10	8	7	6
H	175	96	73	57	40	30	24	19	14	11	9	8	7
I	219	113	86	65	45	34	26	21	16	12	10	8	7
J	279	132	103	75	51	38	29	23	18	13	11	9	8
K	369	154	122	88	57	43	32	26	20	15	12	10	8
L	-	178	139	103	64	47	35	28	22	18	13	11	9
M	-	207	158	124	71	52	40	30	25	20	15	12	10
N	-	225	165	135	75	53	41	31	26	21	16	13	11

DEPTH

DEPTH (FT.)	NO DECOM. LIMITS	BOTTOM TIME AND REPETITIVE GROUP CODE													
		A	B	C	D	E	F	G	H	I	J	K	L	M	N
20	-	10	25	40	60	85	110	135	170	215	275	325			
30	225	5	15	25	40	50	65	75	95	110	130	150	175	205	225
35	165	5	15	20	30	40	50	60	70	85	100	120	135	155	165
40	135	5	10	20	25	35	40	45	55	60	70	85	100	120	135
50	75	-	10	15	20	25	30	35	37	40	50	55	60	70	75
60	50	-	5	10	15	20	23	25	27	30	35	40	45	47	50
70	40	-	5	10	13	15	17	20	23	25	27	30	33	35	40
80	30	-	5	7	→	10	13	15	17	20	→	25	27	→	30
90	25	-	-	5	7	→	10	→	13	15	17	→	20	23	25
100	20	-	-	-	5	7	→	→	10	→	→	13	15	17	20
110	15	-	-	-	-	5	→	7	→	→	10	→	→	13	15
170	10	-	-	-	-	-	5	→	→	7	→	→	10		
130	5	-	-	-	-	-	5								

"NO-BUBBLE"

NO-DECOMPRESSION TABLES

by KARL E. HUGGINS

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MICHIGAN SEA GRANT COLLEGE PROGRAM
Ann Arbor, MI 48109

EXAMPLE OF ACTUAL DIVE TRIP RECORD

TRIPLOG: PLACE GALAPAGOS

DATE DAY	TIME	LOCATION	TYPE OF DIVE BEACH BOAT	DIVE #	MAP #	COMMENTS
4.25 MON	A 8:16	ROCCA REDONDO	BOAT/BEACH	10	6	SHARKS, TURTLES, MASSIVE SCHOOLS OF BARRACUDA, HOT SAND WITH BUBBLES BEING RELEASED, LUSH FISH LIFE, VERY COLD WATER
MON	A 9:30	ROCCA REDONDO	DINGHY	—	6	CHASE SCHOOL OF 30+ DOLPHINES, DOLPHINES WOULD DIVE AS SOON AS DIVERS ENTERED THE WATER.
MON	P 4:15	SANTIAGO, JAMES BAY	LAND TOUR + SNORKLE	—	12	LAYERED LAVA, GALAPAGOS FUR SEALS, FLAT TERRAIN, SALLY LIGHTFOOTS, SNORKLED WITH FUR SEALS, BIRDS, HERON'S, NATURAL BRIDGES
4.26 TUE	A 8:00	SANTA CRUZ, DARWIN STATION	LAND TOUR	—	13	VISIT DARWIN STATION + HIGHLANDS. CRATERS, LUSH VEGITATION.
4.27 WED	A 8:22	SANTA MARIA, ENDERBY ISL	DINGHY	11	14	13 TO 15 GALAPAGOS SHARKS AT ONE TIME, WHITE TIPS, BLACK TIPS. LARGE TURTLES, LUSH LIFE.
WED	A 11:30	SANTA MARIA, ENDERBY ISL.	DINGHY	12	14	WHITE + BLACK SEA URCHIN, MANY SHARKS
WED	P 3:37	SANTA MARIA, CHAMPION ISL.	DINGHY	13	15	GALAPAGOS SHARKS, MANY LARGE SEA TURTLES (HELD ON TO ONE), SPOTTED STING RAY, LUSH MARINE LIFE, NAPOLEAN WRASSES.

TRIPLOG DIVE PROFILES: DATE APRIL 88 LOCATION GALAPAGOS

			DEPTH	PSI		TIME		MINUTES			DIVE TABLE CALC.				
DIVE #	DATE DAY	WATER TEMP	MAX AVG	IN OUT	USED	IN TO 1 STOP	AT 1 STOP OUT	ABT	RNT	TBT	FEET MIN	REP GRP	SURFACE INTERVAL	REP GRP	COMMENTS
10	4.25 MON	60?	126 50	2600 700	1900	8:16 :33	5 A 8:55	38	—	38	130 40	10:25 N	47:35	—	FL 80, 1/4 WET, BL— 16 lbs 1 LEG FLOAT Z OK
11	4.27 WED	64?	77 40	2700 600	2100	8:22 :46	8 A 9:16	54	—	54	80 55	17 L	2:14	G	SAME AS # 10
12	WED	64?	55 35	2900 800	2100	11:30 :52	10 12:32	62	44	106	60 106	26 N	3:05	F	SAME AS # 10
13	WED	64?	50 30	2700 900	1800	3:37 :46	10 P 4:33	56	47	103	50 103	10 M	15:47	—	SAME AS # 10
14	4.28 THUR	64?	66 35	2900 500	2400	8:20 A :45	15 A 9:20	60	—	60	70 60	8 K	2:02	G	SAME AS # 10
15	THUR	69	38 25	2800 1400	1400	11:22 :43	0 P 12:05	43	73	116	40 120	K	8:25		SAME AS # 10

COMPUTER LOG: PLACE GALAPAGOS 1988

APR 16
NEW BATT SAT 9A.

	MINUTES ALLOWED AT													EQUIVALENT REP-GROUPS		
DATE TIME	30 FT	40 FT	50 FT	60 FT	70 FT	80 FT	90 FT	100 FT	110 FT	120 FT	130 FT	MULTI-LEVEL PROFILE	STANDARD PROFILE	USN	MULTI	COMP
TUE 4.19 6:38 P	229	127	74	52	39	31	24	19	13	11	9	44/5 25/24				
WED 4.20 12:48 P	205	116	69	47	36	29	24	19	13	11	9	73/10 30/20	1 FT	100 HOURS ΔBATT 2PM		
7:33 P	210	129	76	53	40	31	24	19	13	11	9	59/10 35/42				
TH 4.21 10:22 A	204	121	73	51	39	31	24	19	13	11	9	74/10 40/15 25/3				
12:51 P	173	103	66	45	34	28	23	19	13	11	9	70/5 50/5 85/25 25/5				
FRI 4.22 10:26 A	190	113	72	50	39	31	24	19	13	11	9	145/2 70/7 40/21				
1:[illegible] P	161	97	63	43	33	26	22	18	13	11	9	70/3 50/20 55/9				
7:00 P	220	134	76	54	40	31	24	19	13	11	9	———				
SAT 4.23 10:54 P	200	113	67	46	35	28	23	19	13	11	9	53/5 40/20 [illegible]/20				
SUN 4.24 11:56 A	209	121	70	49	38	30	24	19	13	11	9	42/7 30/23 25/10	(BATTERY DIED MID-AFTERNOON)			
MON 4.25 10:49 A	191	118	72	50	39	31	24	19	13	10	9	126/3 50/10 40/10 30/10 15/5	8 AM Δ BATTERY SHUT DOWN @ 11AM			
WED 4.27 9:49 A	145	84	56	37	28	22	19	16	13	11	9	77/10 70/10 50/10 40/10 30/10				
WED 12:58 P	110	68	49	38	29	23	20	17	13	10	9	55/5 50/15 40/10 30/20 20/12				
WED 5:40 P	139	88	65	48	37	29	24	19	13	11	9	50/5 40/20 30/20 20/11				
THUR 4.28 6:37 A	219	134	76	53	40	31	24	19	13	11	9	3 PIX ON RIGHT				
THUR 9:54 A	158	97	62	42	32	26	21	19	13	11	9	66/5 50/10 40/10 30/25 20/10				
THUR 12:44 P	157	101	68	47	36	28	23	19	13	11	9	38/5 25/30 20/8				

Emmerman: *Dive computer log for EDGE or SkinnyDipper*

MNE 9.88

TRIPLOG: PLACE ____________________ DATES ____________

DATE DAY	TIME	LOCATION	TYPE OF DIVE BEACH BOAT	DIVE #	MAP #	COMMENTS

TRIPLOG DIVE PROFILES: DATE ____________ LOCATION ______________________________

			DEPTH	PSI		TIME		MINUTES			DIVE TABLE CALC.				
DIVE #	DATE DAY	WATER TEMP	MAX AVG	IN OUT	USED	IN TO 1 STOP	AT 1 STOP OUT	ABT	RNT	TBT	FEET MIN	REP GRP	SURFACE INTERVAL	REP GRP	COMMENTS

COMPUTER LOG: PLACE ______________________________

	MINUTES ALLOWED AT													EQUIVALENT REP-GROUPS		
DATE TIME	30 FT	40 FT	50 FT	60 FT	70 FT	80 FT	90 FT	100 FT	110 FT	120 FT	130 FT	MULTI-LEVEL PROFILE	STANDARD PROFILE	USN	MULTI	COMP

DIVE COMPUTER PERSPECTIVES

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My first experience with dive computers was in 1983, when I was one of 12 subjects monitored for "silent" bubbles during 10 chamber dives testing the decompression algorithm for the Orca EDGE. My confidence in the algorithm increased as a result of not forming any bubbles despite multi-level dive profiles more rigorous than typical research dives. From 1984 to the present, I made over 500 dives using the EDGE while carrying out projects for the Channel Islands Research Program. Typically, 3-4 multi-level dives per day were made to depths of 30-60 ft during five-day scientific survey cruises. The EDGE was used conservatively and mostly as a back-up to the Huggins "No Bubble" dive tables. Dives were planned using the tables; however, I did go beyond table limits by a few minutes and/or a few feet in dives where relatively little time was spent at the deeper levels. Recently, I made 25 dives using the SkinnyDipper. Also, I have observed others using these Orca products for scientific diving in the Channel Islands Research Program and in the Channel Islands National Park Kelp Forest Monitoring Program.

At no time did I or any of my associates diving with EDGE's or SkinnyDippers suffer symptoms of decompression sickness. Various units gave consistent and accurate values when compared side-by-side in simple chamber and underwater tests. I was amazed by the extended bottom times and shorter surface intervals permitted by the EDGE for typical multi-level survey dives when compared with the US Navy or Huggins No Bubble tables. Advantages of the EDGE over tables for scientific diving include simplicity (the diver can concentrate more on the research), accuracy (the units function well and eliminate table calculation mistakes), flexibility (the dive plan can be modified easily at any time), productivity (the computers extend bottom time and lessen surface interval for most dives), and safety (the EDGE presumably prevents silent bubbles and reduces risk of bends when used properly).

The EDGE performed well, but some problems occurred over four years of use. The most serious problem was occasional loss of power due to loose battery terminal connections and crimping of wires in the cramped battery compartment. Other drawbacks to the EDGE include high cost, short battery life (2-3 days), poor O-ring and battery compartment design, and a display that is hard to read in low light conditions. Most of these problems have been improved or eliminated in the SkinnyDipper; however, my SkinnyDipper (and several others) had chronic problems with water leaking into the battery compartment. Orca currently is addressing this problem. They have a good service record.

I believe that dive computers can increase the efficiency and safety of scientific diving as long as their underlying algorithms are reasonable, the units are well-constructed and reliable, and proper guidelines for safe use are implemented. Algorithms should be tested thoroughly with human subjects to demonstrate absence of silent bubbles (*e.g.*, using multi-level, multi-dive, deeper depth, deep diving after shallow, and true decompression profiles). Each brand of computer should be subjected to an independent

"Consumer Reports" type evaluation. Desirable characteristics include long-life battery, memory back-up in case of power loss, reliable O-ring seals, and incorporation of tank pressure/air consumption data. Recommended guidelines for safe use include emphasizing (through training programs) proper methods for diving with dive computers (*e.g.*, stressing the importance of following prescribed ascent rates), requiring each diver in a pair to have their own unit, and devising contingency plans for situations when a unit fails. With guidelines for responsible use incorporated into dive manuals, dive computers should be permitted in scientific dive programs.

DCS CASE REPORTS INVOLVING DIVE COMPUTERS

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There have been six cases of decompression sickness treated at the Hyperbaric Treatment Center in Honolulu in which dive computers were involved. One additional case is reported that was treated in Suva, Fiji, in a monoplace chamber. All of the reported cases used the EDGE dive computer, except the one from Fiji which used the SkinnyDipper. All but one of the EDGE cases was reported within the graph limits of the computer. These cases do not condemn the use of computers at all, but rather point out that decompression sickness (DCS) can occur with their use, and furthermore that use of these devices beyond the designed and recommended envelope is more likely to result in an accident.

These cases range from single dives with accelerated ascent rates through multiple dives and multiple days to very deep exposures. All of the cases reflect poor judgment. Case one illustrates pre-dive activities that would predispose to DCS. Case two presents the reverse profile. Case three performed repetitive deep exposures. Case four is an accident situation that resulted in a rapid ascent. Case five has multiple dives at multiple levels. Case six is deep as well as multiple dives on two successive days. Case seven points out the need for caution in regards to flying despite a reasonable time lag.

In one case, the diver used the EDGE to assist in determining when to terminate his immediate in-water recompression. Although he was successful, this was never intended by the designer/manufacturer, nor would it be recommended.

Patient's name: Doctor Tourist. Date: 6/22/88

Age:	40
Smoker:	yes
Sex:	Male
Chief Complaint:	Tingling in hands and left foot
Past Medical History:	Unremarkable
Past Diving History:	Nothing significant; Diving Instructor
Pre-dive History:	Party Saturday night Several days of diving: Sunday 90/30 (70) 50/40 - Edge of EDGE - Party Monday 45/40 - PM dive 50/40 - Party Tuesday

Dive 1	SI	Dive 2	SI	Dive 3	
80/30	30	20/15	90	35/50	
		Oxygen		Air	
		10/5		30/15	
		Air		Air	Air
				20/20	10/5

Post Dive Events: Tingling left 3rd finger, malaise; Tingling, right arm; Twenty five minutes later tingling left leg; No relief from oxygen; No change with dive 2; Felt fine after dive 3, with some soreness in finger. Also noted urchin spine in finger.
First Aid: Surface oxygen and dives 2 and 3 above
Physical Examination: Normal except hypertension.
Preliminary Diagnosis: DCS; IIWR
Treatment(s): 60 fsw similar to USN Table 6.
Recurrence: None
Residual: None
Disposition: Discharged
Final Diagnosis: DCS, most likely successful IIWR.

Patient's name: Dive T'Maui. Date: 12/16/87

Age: 29
Sex: Male
Smoker: no
Chief Complaint: Pain in right knee radiating to right hip
Past Medical History: DCS 8 years ago, untreated
Past Diving History: Instructor, 700 dives/12 months
Pre-dive History: Unremarkable
Dive History:

Dive 1	SI	Dive 2
80/28	30	170/10

Post Dive Events: 90 minutes post-dive developed mild ache in right knee which progressed to sharp pain in knee radiating to right hip.
First Aid: Oxygen - complete relief in transit to HTC
Physical Examination: Completely normal; Subjectively a vague sensation in right knee
Preliminary Diagnosis: DCS, pain
Treatment: 220FSW Treatment
Residual: None
Disposition: Discharged
Final Diagnosis: DCS, pain only

Patient's name: Randall Myson. Date: 6/25/88

Age: 25
Sex: Male
Smoker: no
Chief Complaint: CNS symptoms resolved in IIWR
Past Medical History: No prior DCS known
Past Diving History: Scientific diver, NAUI, experienced
Pre-dive History: Unremarkable
Dive History:

Dive 1	SI	Dive 2	SI	Dive 3
190/10	2:30	190/10	<0:05	80/8 50 min travel 15 fsw until EDGE cleared

Post Dive Events: On ascent from Dive 2 patient had ^ indication on Edge; Proceeded to 10 fsw and had ^ indication with 4 fsw ceiling.

	At that time noted weakness in both arms and right leg. After 3 minutes of symptoms patient started Dive 3.		
First Aid:	IIWR		
Physical Examination:	Normal at examination after IIWR		
Preliminary Diagnosis:	DCS, CNS successfully treated		
Treatment:	60 FSW Treatment Table 2/2/2		
Residual:	None		
Disposition:	Discharged		
Final Diagnosis:	DCS, CNS successfully treated in water.		

Patient's name: West Teacher. Date: 6/30/88

Age:	34		
Sex:	Male		
Smoker:	No		
Chief Complaint:	Tingling, numbness left arm, frontal headache.		
Past Medical History:	Unremarkable		
Past Diving History:	Instructor, experienced 4 years		
Pre-dive History:	Several dives day prior		
Dive History:	Dive 1	SI	Dive 2
	150/20	Unknown	IIWR profile unknown
Post Dive Events:	Rapid ascent secondary to running out of air while attempting rescue of deceased diver. On surface he was noted to have slurred speech by a physician in the dive party. He noted only the tingling.		
First Aid:	IIWR		
Physical Examination:	Completely normal at time of examination approximately 4 hours after first symptoms.		
Preliminary Diagnosis:	AGE +/- DCS treated with IIWR		
Treatment:	60 FSW Treatment Table similar to USN TT6		
Residual:	None		
Disposition:	Discharged		
Final Diagnosis:	AGE +/- DCS treated successfully with IIWR		

Patient's name: Lady Fiji. Date: 3/10/88

Age:	43		
Sex:	Female		
Smoker:	No		
Dive Computer:	ORCA SkinnyDipper		
Chief Complaint:	Pain, numbness, weakness in arms; Numbness in feet; Weakness in legs, especially the right leg.		
Past Medical History:	Unremarkable		
Personal physician:	T. Mua, Suva, Fiji		
Past Diving History:	18 years experience, over 500 dives, many to 200 fsw.		
Dive History:	21 February		
	Dive 1	Dive 2	Dive 3
	0700	1000	1500
	85/3	85/3	75/5
	Stops 60/45	Stops 50/15	Stops 50/30
	22 February		
	Dive 1	Dive 2	Dive 3

	0700	0810	0918
	120/5	60/3	10/20
	75/15	30/10	
	45/20	20/20	
	30/10	10/20	
	Surfaced 07:50	Surfaced 09:03	
Post Dive Events:	After Dive 1 (22 Feb) patient had progressive arm and back weakness and pain 5 minutes after surfacing. Dive 2 was for in-water treatment (IWR). Tingling and pain resolved during first 10 minutes of IWR. After 3 hours rest and some juice, numbness developed in the right leg and foot with shocks running down both legs. Air evacuation to Suva.		
First Aid:	IWR and Oxygen on surface		
Physical Examination:	Alert and cooperative. Shoulder, arm, and hand weakness. Decreased sensation in hands and right foot. Numbness in quads and lateral legs.		
Preliminary Diagnosis:	DCS, Spinal cord.		
Treatment(s):	60FSW, USN TT6 three times.		
Residual:	Weakness and some decreased sensation. Transferred to another facility for further treatment.		

Patient's name: Brian Deepdiver. Date: 9/6/88

Age:	38		
Sex:	Male		
Smoker:	No		
Height:	6'2"		
Weight:	205		
Smoker:	No		
Chief Complaint:	Pain in left shoulder post dive.		
Past Medical History:	Unremarkable		
Past Diving History:	NAUI, Divemaster, experienced		
Pre-dive History:	Unremarkable		
Dive History:	Sunday		
	Dive 1	SI	Dive 2
	160/16	3:00	90/15
	Monday		
	Dive 1	SI	Dive 2
	156/16	2:45	90/15
Post Dive Events:	On return to boat noted pain in shoulder		
First Aid:	Oxygen -> relief for 45 - 60 minutes		
Physical Examination:	Normal		
Preliminary Diagnosis:	DCS, pain		
Treatment:	TT220 twice		
Complications:	Positive bone scan		
Disposition:	Discharged		
Patient Instructions:	No diving		
Final Diagnosis:	DCS		

Patient's name: Barian Deep. 1/3/88

Age:	39

Sex: Male
Smoker: No
Chief Complaint: Pain right elbow
Past Medical History: Unremarkable
Past Diving History: 365 lifetime dives.
Pre-dive History: Unremarkable
Dive History:

Dive 1	Dive 2	Dive 3	Dive 4	Dive 5
126/30	110/30	30/20	110/40	60/40
Stops	Stops		Stops	Stops
20/10	10/10		20/10	20/5
10/10			10/10	10/9

Last dive: 17 min left on Deco Stop with 1' ceiling; No pixels over line.

Post Dive Events: No symptoms until 26 hours post dive. At 23 hours post dive, 90 minute flight to Guam. After landing at Guam, noted slight dull pain. On 6 hour flight to Honolulu pain progressed, and oxygen was given for 1 hour which provided some relief.
First Aid: Oxygen during flight
Physical Examination: Normal
Preliminary Diagnosis: DCS
Treatment: TT220 -> complete relief
Disposition: Discharged
Final Diagnosis: DCS

DIVE COMPUTERS IN SCIENTIFIC DIVING PROGRAMS

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INTRODUCTION

The age of electronic diving has arrived. It has been suggested that the development of the modern electronic dive computer is the most significant advancement in self-contained diving since the invention of the Aqualung by Cousteau. Although many physiologists, scientific divers, diving officers, and instructors view the current generation of dive computers with some degree of skepticism, the dive computers of the near future will be representative of the state-of-the-art diving.

The multi-level and multi-dive computation capabilities afforded by dive computers significantly enhance operational efficiency on certain types of dives. For example, a coral reef biologist can markedly increase underwater research time on any given dive by performing deep to shallow transects.

DEVELOPING SAFE DIVING PRACTICES

Continuous computation of the diver's theoretical inert gas saturation status and adjustment of the available no-decompression time does eliminate one of the potential safety margins inherent to the "maximum depth-maximum time" procedure for using conventional dive tables. Consequently, the computer-equipped diver must look to other procedures in order to maintain reasonable safety margins while utilizing the advantage continuous dive profile tracking affords by some computers. Moreover, similar procedures must be used to compensate for the concerns associated with age, thermal stress, physical fitness, body fat, extensive repetitive diving, multi-day diving, and so on. The diver can no longer "jump schedules" as in using the tables.

Conservative diving practices and compensation guidelines may be developed for computer divers. For example, when diving a deep to shallow multi-level profile, I generally adjust my time at depth in order to allow for 30 to 60 minutes of no-decompression time to remain at 20 feet before I proceed to the surface. Other procedures include maintaining a safety margin in terms of no-decompression time remaining at any given depth (i.e., always having at least 5 minutes of no-decompression time remaining).

There are subjective determinations. However, until there is more available computer diving data and a better understanding of the "models" used for computations, diving the current computers to the limits of their theoretical models does, in my opinion, constitute a potential element of risk.

DEVELOPING A DATABASE

Computer diving procedures and safety remain as the major concern for divers and diving officers. In order to determine the validity of decompression models used to program these computers, decompression modelers have and computer designers must first conduct controlled tests in both the laboratory and open water. Although such tests can do much to assess the validity of the theoretical model, a more complete database must be established based on "real world" diving operations.

The scientific diving community is probably the best source of information for developing a database on computer diving. First, the divers and diving coordinators have a basic understanding of scientific method and data collection. Second, scientific divers work under the control of a diving officer and Diving Control Board. This provides an excellent mechanism for locally monitoring data collection and forwarding it to a central data collection institution. Third, several institutions currently have Doppler equipment and the expertise to use such equipment. Fourth, a limited number of profile recording dive computers could be provided to the American Academy of Underwater Sciences for selective loan to member institutions and responsible investigators.

The next generation of dive computer must include an accessible memory for retaining a record of a large number of individual dive profiles. The dive computer should be designed with the capability of interfacing with a standard personal computer or special memory reader.

TRAINING PROGRAMS

Proper training is vital to safe computer diving. Divers must understand the basic concepts of dive computer design and operation. They must be capable of reading and interpreting the computer display, planning and conducting safe, conservative computer controlled dives. In the event of a computer malfunction or "crash" they must understand safe procedures for ascent and subsequent diving using either tables or another computer. Finally, they must be capable of properly maintaining the dive computer.

A dive computer training program must include, but not be limited to, lectures/video presentation on computer diving concepts and operations, advantages and limitations, display interpretation, proper operation/function evaluation, and maintenance. Through the use of specially modified dive simulator units, the basics of computer diving can be practiced in the classroom. Both practical and written/oral examinations should be included as well as a supervised initial open water dive. Instruction manuals, work books, and other educational materials should be acquired from manufacturers or developed by individual institutions. Self-teaching workbooks should also be considered.

GUIDELINES FOR INSTITUTIONAL ADOPTION OF DIVE COMPUTERS

The Diving Control Board or a committee/individual designated by the Board should review the diving requirements of the institution to determine if the introduction of dive computers into the institutional program is truly beneficial. Will the use of dive computers safely increase research productivity? Are there specific multi-level diving requirements within the current research programs? Will the advantages of computer diving outweigh the high cost and operational safety "unknowns" associated with current dive computers?

Once it is determined that the use of dive computers would be significantly beneficial to the institutional program, the various operational parameters of available computers must be reviewed and an appropriate dive computer recommended for institutional approval. In some cases, the Board may wish to test several computers before final selection. Although any of the currently available computers might be acceptable, certain limitations such as use at altitude or battery performance limitations under polar conditions might be a factor. Since most computers are currently designed for recreational diver applications as no-decompression dive monitors, institutions with decompression diving requirements will need to investigate performance history (decompression sickness incidence) and decompression data display.

I recommend that an institution seriously consider officially designating only one or two models for their diving program. This simplifies and standardizes training procedures, the purchase of simulators and the issue of operational guidelines. Furthermore, conflicts resulting from performance and display variables would be eliminated or at least minimized.

The Diving Control Board must issue specific guidelines for dive documentation, periodic computer inspection/maintenance, safety margin procedures for individual and environmental variables, dealing with malfunctions, flying following computer controlled dives, and so on. For example, each individual that will be diving on any given day must have a computer. I discourage the use of a single unit for more than one diver. Additional operational guidelines for computer diving are addressed elsewhere in this publication.

SUMMARY

Dive computers may be used to safely improve operational efficiency in selected diving activities. Dive schedules may be adjusted to include safety factor adjustments for age, thermal stress, physical fitness, multi-day diving, etc. The scientific diving community should establish procedures for collecting computer diving information and establish a database in order to assist Diving Control Boards, decompression modelers, and dive computer designers in the development of safer models, computers, and diving practices. A complete computer diving training program is also recommended. Finally, Diving Control Boards must establish guidelines for computer selection and use at the institutional level.

...THOUGHTS ON TABLES AND COMPUTERS...

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Obviously, the dive computer I use is printed on the set of U.S. Navy tables. I grew up with the Navy tables and have been on a promulgation dive. At this workshop we have heard that there was a great lack of testing on the repetitive tables. I asked Tom Neuman last night as to what happened to all the data the Navy has collected since those dives. One of the dive series we performed in 1958 on Hardtack, was just after the tables had been promulgated. Ed Lanphier was our diving officer and Bob Workman came to San Diego. On that whole dive series, just on SCUBA diving alone, we made 1200 dives, mostly repetitive. The cumulative dive data has got to be somewhere with the Navy.

Over the years, we used the Navy tables consistently. We were pretty straight on the tables, we didn't fudge them, we used them as they were printed. We have logged 200,000 dives on the tables, with a single case of bends. Suddenly we get real worried about the them. What is not right here?

The reason the scientific diving community is organized today is due to a simple wording in 1976 by Federal OSHA, which said that in any diving situation in which there is an employee - employer relationship, you are automatically a commercial diver. The Australian, Canadians and Brits have now gone through a similar process. We were able, through the simple means of having a history of self-regulation and data collection, to establish a safety record totalling over 800,000 dives. Our hit rate was something like 0.0037. Upon submitting these data to OSHA, we were asked:"Why are you here?"

Diving as far as we are concerned is really kind of a non-problem. People assume it's a risk, which they understand. I've chaired a Coroner's committee for 25 years, and the reason people die is because they run out of air.

From what we've heard at this workshop, dive computers are here and are safe. I have no problem with that aside from the fact that it's going to be difficult for me, with 130 divers, to buy 130 DC's. The tables have been very good to us over the years, and I will go back to my diving control board and make the recommendation that we authorize computers as needed. I know however that, until I can get enough money in my budget to provide one for every diver, I'll still have to use the tables.

I think DC's are here to stay, that there is a high degree of safety, equal to or more than the tables maybe. We are just in the infancy of the capability and reliability of the dive computers. I think that one of the most important items from Tom and Andy's perspective is the dive recall capability of the DC to find out what the diver's profile was and not have to rely on the diver's testimony. That will aid everyone, especially from an insurance standpoint.

What we have seen here at this workshop, and you're all the big kids on the block, is that there is probably more expertise in this room from the diving community (sport, physiology, medical and scientific), than you're going to have together in the same room for a long, long time. The major thing this meeting has accomplished is given us the chance to know each other and know that, as was pointed out, the manufacturers aren't all bad guys. I just want to thank you all for participating. I have a vast group of dive logs in San Diego I'd be more than willing to share with any of you, and I think this has been a wonderful meeting.

INDIVIDUAL EXPERIENCES AND PERSONAL PERSPECTIVES DISCUSSION

This session was to let individuals have a chance to make short presentations of specific experiences or ideas about the use of dive computers, for either speakers who had more to say or others not already on the program.

Comments by Mike Emmerman

Mike is not concerned about the performance of the individual computers, but he is concerned about the training needed. He has designed a log that makes it possible to backtrack based on the no-d scrolling into a conservative table (the Huggins No-Bubbles tables, not the US Navy Tables). Please refer to Emmerman's paper in this session.

Comments by John Lewis

John's theme was that all algorithms are not created equal. He referred again to Figure 1 of his paper. The Haldane-like models "have only two knobs" for adjustment, the half-times and the M values. He said one could have all compartments take up gas at the usual rates but then have them all "relax" with a 120 min half-time, and could then reproduce the USN [repetitive] tables. This was regarded as the worst case, but was better than the British approach, which just adds the bottom times for the second of a repetitive dive pair.

Thalmann set out to program his real-time computer with the straight Haldane "E-E" (exponential-exponential) model which had symmetrical uptake and elimination. It did not work well in practice, because he could not make long dives conservative enough and still preserve the short dives which were not in need of fixing. He then developed the "E-L" (exponential-linear) model, which works well with the extremely long decompressions he was trying to do.

The Datamaster II seeks to be conservative in a different manner of asymmetric gas transport. This has been put in perspective by the experiments of Rogers and Powell (Powell et al, 1988). Ray Rogers noted that most dives done by recreational divers were controlled by the 40 minute compartment, and he did his tables using the 60 minute compartment to control repetitive dives. This seems to be working in practice, and the experiments Rogers and Powell are doing may validate this model. They are also providing data to support the concept of the Datamaster II.

Bill Hamilton confirmed that longer dives have to be even longer, and said that he had been able to code long dives successfully by making the M values more conservative as the dives got longer; this is an asymmetrical method also.

Reference: Powell M.R., M.P. Spencer and R.E. Rogers. 1988. Doppler ultrasound monitoring of gas phase formation following decompression in repetitive dives. Seattle: Diving Science and Technology

Comments by Jon Hardy

There are risks in diving, and there are risks in making love. If the human race had waited until all the risks of making love could be defined before doing it, there would be no human race right now. We may not be able to wait on full understanding of diving either. To apply this, he gave some recommendations. First, review what information is available. Set a policy. Decide on which tables and procedures, and which DC's and procedures are to be used. He feels the USN tables with their "safety factors" would do, but there are some more conservative tables available. Select the DC that meets the operational need and performance criteria for your operation. Divers are to be trained and evaluated regularly on the procedures. Use a slower ascent rate, and a safety stop. Consider deeper stops and reduced no-stop times. Dive deep followed by shallow. For DC's, have a back-off procedure and a failure plan, and have one computer per diver. Have a written emergency plan, and when needed, follow it.

Glen is concerned about the USN tables, which seem to have been endorsed here. But why do they back away from the longer and deeper USN tables? Bill Hamilton added to what John Lewis had said, that one cannot get a long, deep dive to work (*i.e.*, make the decompression long enough for it to be reliable) with the Haldane model without messing up the shorter and no-stop profiles. Others, in addition to Thalmann, have noted this problem and dealt with it. The no-stop times work well, but the longer, deeper USN tables are not reliable. It was pointed out that if we use slower ascent rates, safety stops, reduce the no-stop limits, etc., we are not using the Navy tables anymore.

Comments by Don Harper

He mentioned a project in which they had to do a series of 70 fsw/ 5 min dives with 10 minutes between them. This would make the divers "D" divers using USN repetitive status, or "C" using DCIEM. They did 4 of these, then 2-3 hours later did 3 more, or 3 at 50 fsw. They did this for seven years, a total of over 5500 dives, and had one case of DCS. This was a neurological case in 1982. DCS happens.

Another comment on teaching. Those of you who teach undergraduates know that the minute they walk out of your classroom, there is an immediate data dump. One needs to continuously use a technique to stay proficient in it.

The safety aspect and risk of DC use is far better than travelling to the dive site. People need to learn to accept a certain level of risk. There will always be some risk involved.

Comments by Bob Overlock

The cases I've presented illustrate many of the topics we've talked about. Pre-dive activities that could predispose, reverse profiles, multi-day, multi-dive exposures, repetitive deep exposures. None of these condemn the instruments used in a direct sense. They all do however point to a direct need for common sense and exercise of good judgment.

Comments by Carl Edmonds

Based on our work, this is what we're recommending for Australian divers, irrespective of what is decided here. The Suunto USN meter we recommend, the Datamaster, Data Scan and MicroBrain we have not tested, so we cannot recommend them. The DC's we've tested are advised to be used for single, no-decompression dives up to 120 feet for fixed depths. If they have to use multi-level profiles, that's OK, they use them for single no-decompression dives with the maximum depth at the first part of the dive.

Next, an ascent to a depth of 30 fsw, after that they can do whatever they want. These recommendations are for abalone divers, pearl divers, reef divers.and commercial divers. We do not accept repetitive dives, re-descending beyond 30 fsw on these meters. If the ascent rate is exceeded at any time, we produce a stop at 10 to 20 fsw. There are three points I want to make before I finish.

First, I have never attended such a fascinating, interesting, instructive workshop, run very well at such a superb place. Second, I've done a lot of work testing these meters, so I knew what lousy folks these manufacturers were. I came here and found out they were really a nice group of people who are genuinely concerned about diving safety. The third point comes from the first two. I guess that in about five years time, we'll all be using these meters safely. Safer diving will result from this group, so I congratulate you.

Comments by Bruce Bassett

I want to address some items about the U.S. Navy tables I've included in my paper, but could not cover in the allotted time yesterday. Some of the direct comparisons with the U.S. Navy tables such as Carl Edmonds presents is like throwing the baby out with the bathwater. Looking at John Lewis' chart may be somewhat misleading as well. I think there are some other areas that need work. Putting exceptions in these computers where you don't make deep repetitive dives I think is legitimate, based on experience that our unbenders come up with. But saying that all repetitive or multi-level diving is not recommended is unrealistic. I think the dive computers do have a place in repetitive diving, because the model of the Navy table is so poor for repetitive diving. That's really what I'd like to address here. Bruce continued presenting his paper (included in Session 4).

Comments by Ralph Osterhout

I want to integrate suggestions I have heard and concerns that have been voiced into suggestions as to what we might do for future generations of dive computers. I also want to orient some of you as to what is going to transpire and the rate at which it will transpire in the world of digital instrumentation. Currently, 25% of all instruments being sold in the U.S. are digital, within three years, 50-75% of all instruments sold will be digital. Within 5 years, virtually 100% will be digital with the exception of rental or very low end of market units.

It is relatively rare for people to die from decompression sickness. It is not that rare for people to die from running out of air. John Hardy made a very important and dramatic point. People become transfixed looking at their DC, to the exclusion of examining their pressure gage.

The realities are that an 8 byte microprocessor, which just 4 or 5 years ago was the heart and guts of an Apple II, we were fascinated with its power. Many of you don't realize that the computational power prevalent in most of the DC's on the market now is tantamount in strength to an Apple II. What that means is that you have excess amounts of computational power that's going to waste. You might as well use the power available to you to integrate things such as remaining tank pressure, and with stunning accuracy can then determine how much remaining time you have left before you run out of air. That's a relatively easy thing to do.

You can also easily integrate a multiplicity of other functions and give the diver the information. I don't think we have to look at this as being a gimmick or approach digital instrumentation as people who are skeptical, saying "we don't need to be junkies towards information". It's part of our mandate and responsibilities as manufacturers, with input from experts like you, to say "give us displays that can prioritize the importance of information. You can't isolate and just focus on decompression only.

I am asking the people in this room because for the most part, you represent the greatest technical knowledge in the world with respect to diving physiology and decompression requirements. If we recognize that, then it's up to you to take the responsibility as concerned and dedicated people to suggest to us as manufacturers where we fall short, where we might incorporate important things in the future. I want to fold that into suggestions for future DC's and I'm not talking about ten years from now. It costs only $3500 to remask our processors and put in new software, aside from the software development costs. If you recognize that, let me mention the following suggestions which we discussed and tabulated last night.

Recommendations for future DC's

1. Uniform bottom time calculations
   7 fsw +/- 1 fsw DC turns on; 4 fsw +/- 1 fsw DC turns off
2. Reconfiguration of software to prevent multiple deep exposures in a day
3. Penalize diver for out of sequence dives by adding additional bottom time to actual bottom time
4. Establish a uniform ascent rate (< 40 fsw)
5. Standard required stop or ceiling procedure
6. Uniform emergency surfacing procedures
7. Uniform scrolling format
8. Establishing maximum allowable residual tissue pressures for safe flying indication
9. Common algorithm for all.DC's
10. Recording and downloading to PC capabilities
11. Non-volatile (static) retrievable LCD displays

Max Hahn pointed out the need for standardization of units. Assuming the water density always to be 1.02 kg/l, we can get rid of the non-SI units such as atmospheres or fsw and step to the SI unit bar and a compromise between fresh water and sea water densities.

Tom Neuman summarized a statement he felt the manufacturers really needed to know. If one combined all the people who died in the water because of medical problems that could have been screened out by physical exams (diabetes, asthma, epilepsy), with the exclusion of coronary artery disease, it does not come close to the number of people who die as a result of running out of air.

Bill Hamilton pointed out that why we're really here is the search for more bottom time. You also can see how much struggle we had dancing around inside a box that's pretty well fixed. There's a way to make the box bigger by the only other way left, and that is oxygen. If you're doing decompression, then you can use oxygen for decompression.You can use it safely in the water if it's done right, you can go to the surface and you can use it in the chamber. There is also something you can use called enriched air mixture or nitrox. It is being done, it is in the NOAA manual, and it is an established technique. Nitrox is in its infancy as far as this group is concerned. It not only gives you more bottom time, but also makes the dive and decompression more safe and reliable. The nature of the breathing medium may be something else than air, so the manufacturers might keep that in mind for future DC implementation.

GENERAL DISCUSSION AND CONCLUDING REMARKS

Mike Lang lead the workshop to a consensus to use the term "Dive Computer" (DC) for the purpose of uniformity in these proceedings and the elimination of approximately 22 acronyms. It was pointed out that several manufacturers already used this term and that it was the term being supported by the recreational diving groups.

Bill Hamilton asked Parker Turner to elaborate on a cave diver "feeling better". Parker responded that the people he worked with do a couple hundred decompression dives per year per person. Based on personal experience, they have physically been feeling a lot better using the Royal Navy or the DCIEM tables, which they are relating to the fact that they are stopping deeper or sooner. The Royal Navy tables will have times that are similar to the US Navy tables, but they'll have you take stops at 20 fsw and 10 fsw. The Brits will have you take part of it sooner or at a deeper point. With two divers, each using a different table, the diver performing the shallower stop seems to have more problems typical of a subclinical hit, feeling tired or not feeling well after the dive. The divers on the Royal Navy tables feel a lot better. It seems to me that the DC's bring divers up for decompression at much shallower depths.

Bill Hamilton suggested that part of that is solved by the slow ascent rates that are chosen. Parker's comment was that the recreational divers probably won't make these very slow ascent rates. The flashing ascent warning on the Edge is a good method of slowing the ascent rate.

Paul Heinmiller said that was a complex topic and responded that we really hadn't talked about decompression at all during the workshop. We had talked about the no-decompression limits and agreed that they are in the ball park, reflected by M_0 and the uptake equations. We had looked at the repetitive question with John Lewis and Thalmann's "E-L" model, and that's dictated by the outgassing equations. But the decompression stops are dictated by DM in a Haldanian system. Edge uses deeper stops but expresses it as a ceiling. What that means is for example in a 10 minute tissue, the Navy's DM is 2. That means that the tissue is 1 foot over its limits, you're allowed to go to 1/2 foot. With the Edge you're only allowed to go to a 1 foot ceiling. That doesn't make any difference there because the Navy is expressing it as a 10 foot stop. But if we extend it, when the Navy would ask for a 10 foot stop based on a 10 minute tissue, the Edge would ask for a 20 foot ceiling. So the Edge has deeper stops in it when you get beyond the 10 foot stop step approximation of the tables and most other computers. Most comments echoed that it is preferable to stop deeper.

We accept the existence of dive computers, we acknowledge that there are risks involved with them but that they stand to give us a great deal of benefit. Therefore we think they can be used in scientific diving programs, that there is a place for them.

Mike Lang next lead the group discussion to reach consensus on the guidelines for use of dive computers. These 13 points had been thoroughly discussed and compiled the night before, so that most of the additional comments were for clarification and precision. The following items are the guidelines for use of dive computers for the scientific diving community. It was again reinforced that almost all of these guidelines were also applicable to the diving community at large.

Guidelines for use of dive computers

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.

Bill Hamilton chaired a lengthy discussion on the dive computer "wish list". Items we would like to see the the ideal dive computer have. The discussion and opinions varied so widely, that, as editors, we decided not to include this topic in the proceedings, since it was a difficult topic to reach any consensus on.

With the departure time of the SEA WATCH just minutes away, Mike Lang made the appropriate acknowledgements and closed the workshop with the remarks that we now needed to let this information disseminate and that this workshop was just the first in a series. Finally, all participants lined up in the sun for a consensus-photo opportunity.

AMERICAN ACADEMY OF UNDERWATER SCIENCES

Decompression Computer Workshop
Catalina Marine Science Center
September 26-28, 1988

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THE AMERICAN ACADEMY OF UNDERWATER SCIENCES

DECOMPRESSION COMPUTER WORKSHOP

University of Southern California
CATALINA MARINE SCIENCE CENTER

September 26 - 28, 1988

PROGRAM

Project Leader: Mike Lang, AAUS
Program Chair: R.W.(Bill) Hamilton, Hamilton Research, Ltd.
Workshop Coordinator: Glen Egstrom, AAUS
Local Hosts: Andy Pilmanis and Jack Engle, USC/CMSC

Sponsored by the American Academy of Underwater Sciences
and the California Sea Grant College Program

MONDAY, SEPTEMBER 26, 1988

08:00: Workshop participants meet at the U.S.C.- ICMS Harbor Research Laboratory, Terminal Island

09:00: R/V SEA WATCH departs for Catalina Marine Science Center

11:15: Arrival at CMSC, orientation and check-in.

12:30-13:00: Lunch

13:30: *Welcoming address*
Mike Lang, President, A.A.U.S.

14:00: *Presentation of the issues.*
Andy Pilmanis, Director, C.M.S.C. Hyperbaric Chamber

14:30: *The history of underwater decompression devices and computers*
Karl Huggins, University of Michigan

15:15: Break

Decompression computer manufacturers' "technical sales pitch" to acquaint the workshop with the various decompression computers.

15:30: Al Carpenter *BEUCHAT-USA*, Inc. [GUIDE].

15:40: Mark Walsh, *DACOR Corporation.* [MICROBRAIN].

15:50: Paul Heinmiller, *ORCA Industries.* [EDGE and SKINNY DIPPER].

16:00: John Lewis, *OCEANIC USA.* [DATAMASTER II].

16:10: Chuck Locke, *U.S. DIVERS Company.* [DATASCAN II]

16:20: Bill Oliver, *SUUNTO OY.* [SME-ML]

16:30-17:30: Discussion Leader - R.W. Hamilton

17:30-18:00: DINNER

18:30: A.A.U.S. RECEPTION

TUESDAY, SEPTEMBER 27, 1988

07:30-08:00: Breakfast - Cafeteria

08:30: *Decompression meters - the Australian experience*
Carl Edmonds, Diving Medical Centre, St. Leonards, Australia

08:50: *Decompression computer experience in Canada*
Ron Nishi, DCIEM, Ontario, Canada

09:10: *Evaluation of diver-carried computers: European perspective*
Max Hahn, University of Düsseldorf, West Germany

09:30-10:00: Discussion leader - R.W. Hamilton

10:00-10:15: Break

10:15: *Use of decompression computers at dive resorts and on live-aboard vessels*
Bruce Bassett, Human Underwater Biology, San Antonio, Texas

10:30: *Field use of digital decompression computers*
Phil Sharkey, University of Rhode Island

10:45: *A professional diver's use of decompression computers*
Jon Hardy, Argo Diving Services, Avalon, California

11:00: *Use of DCC's for cave diving*
John Crea and Parker Turner, National Association of Cave Divers

11:15: *Survey of diver-carried computer users and potential users*
Michael Emmerman, Lifeguard Systems

11:30: Discussion leader: Mike Lang

12:30-13:00: Lunch

13:30: *DAN's results and perspective on decompression computer use*
Dick Vann, Diver's Alert Network

13:50: *Use of DDC's by AAUS scientific divers*
Woody Sutherland, AAUS Statistics Committee Chair, Duke University

14:10: *"Models" and generation of decompression computer profiles*
Bill Hamilton, Hamilton Research, Ltd.

14:30-15:00: Discussion leader: Glen Egstrom

15:00-15:30: Break

15:30: *Bench tests of different decompression computers*
Glen Egstrom, UCLA

15:50: *The U.S. Navy dive tables and no stop diving*
Tom Neuman, UCSD Medical Center

16:10: T.B.A.

16:30-17:30: Discussion leader: Andy Pilmanis

17:30-18:00: Dinner

19:00: Tours of Catalina Hyperbaric Chamber and CMSC
Andy Pilmanis and Jack Engle, CMSC

20:00: *Computer display of some decompression computer profiles*
Don Short, San Diego State University

Following the presentation, this practical session will be a "lab" where participants may take a close look at each of the units (demonstrated by the manufacturers) and experiment with some of the algorithms as modelled on personal computers (provided by manufacturers and workshop participants). Both Macintosh and IBM PC type computers will be available for demonstrations, as will a high pressure chamber for simulations.

WEDNESDAY, SEPTEMBER 28, 1988

07:30-08:00: Breakfast

08:15 - 09:30: Presentations of individual experiences and personal perspectives

09:30: Break

09:45: Personal recommendations: Lee Somers, University of Michigan

10:00: Personal recommendations: Jim Stewart, Scripps Institution of Oceanography

10:15 - 10:45: Discussion leader: R.W. Hamilton

10:45: Summary of findings
R.W. Hamilton

11:00: General discussion and development of consensus recommendations
Discussion leaders: Mike Lang and R.W. Hamilton

11:45: Closing of workshop
Mike Lang

12:00: SEA WATCH departs for mainland, lunch on board

14:30: Arrival at USC Harbor Research Laboratory, depart for San Diego or LAX

THURSDAY, SEPTEMBER 29, 1988
through
SUNDAY, OCTOBER 2, 1988

The 8th Annual Scientific Diving Symposium sponsored by
the American Academy of Underwater Sciences:

Advances in Underwater Science...88

Scripps Institution of Oceanography, La Jolla, California

DIVE-COMPUTER DESCRIPTION

	1	2	3	4	5	6	
COMPUTER	TYPE	DECOMPRESSION-TABLE BASIS	ALGORITHM AUTHOR	NO. OF TISSUE GROUPS	TISSUE HALF-TIMES (minutes)	APPROXIMATE PRICE	
						DEALER	RETAIL
U.S. Divers Data Scan 2	No Decompression	Modified U.S. Navy	John E. Lewis	6	5 to 120	$267	$495-$550
U.S. Divers Monitor 1	No Decompression	Swiss (Buhlmann)		6	6 to 320	$184-$210	
U.S. Divers Monitor 2	Decompression	Swiss (Buhlmann)		6	6 to 320	$249-$335	
Orca E.D.G.E.	Decompression	Spencer	Craig Barshinger Karl Huggins	12	5 to 480	$360-$440	$550-$600
Orca Skinnydipper	No Decompression	Spencer	Craig Barshinger Karl Huggins	12	5 to 480	$180-$229	$325-375 +$60w/ga
Sherwood Sigmatech						$242-281 w/gauge	$495-550 console
Beuchat G.U.I.D.E.	No Decompression	Swiss (Buhlmann)		6	4 to 480		
Parkway Black Fox							
Uwatec Aladin							
Dacor Micro Brain	Decompression	Swiss (Buhlmann/Hahn		6	4 to 397		$499
Oceanic Datamaster II	No Decompression	Modified U.S. Navy	John E. Lewis	6	5 to 120		
SeaQuest/ Suunto SME-ML	Decompression	Spencer		9	2.5 to 480		$560 Wrist; $680 Console.
Tekna Digitek	Neither	not applicable	not applicable	n/a	n/a		$425

PRE-DIVE INFORMATION

COMPUTER	7 DIVE NO.	8 TANK PRESSURE (psi)	9 SELF-DIAGNOSTIC CHECK	10 SCROLL NO-DECO LIMITS	11 ADJUSTS FOR ALTITUDE
U.S. Divers Data Scan 2	yes	yes, to 4000 psi	yes	yes	to 2000 ft.
U.S. Divers Monitor 1	yes	yes, in console	yes	yes	to 13200 ft
U.S. Divers Monitor 2	yes	yes, in console	yes	yes	to 13200 ft
Orca E.D.G.E.	no	no	yes	yes	to 2000 ft.
Orca Skinnydipper	no	no	yes	yes	to 2000 ft.
Sherwood Sigmatech		yes, in console			
Beuchat G.U.I.D.E.	yes	no	yes	no	to 13200 ft
Parkway Black Fox					
Uwatec Aladin					
Dacor Micro Brain	no	no	yes	yes	to 6560 ft.
Oceanic Datamaster II	yes	yes	yes	yes	to 2000 ft.
SeaQuest/ Suunto SME-ML	yes	yes, in console model	yes	yes, moisten contacts	to 1600 ft.
Tekna Digitek	yes	yes, to 3250 psi	yes	no	

DIVE INFORMATION

COMPUTER	12	13	14	15	16	17	18	19
	CURRENT DEPTH (fsw)	MAXIMUM DEPTH DISPLAY	DIVE TIME (min)	DIVE NUMBER	DIVE-TIME REMAINING FOR		TANK PRESSURE	TEMPERATURE
					NO DECOMPRESSION	AIR		
U.S. Divers Data Scan 2	0-249	yes	yes	yes	yes	yes	yes	no
U.S. Divers Monitor 1	0-330	yes	yes	yes	yes	no	yes, in console model	no
U.S. Divers Monitor 2	0-330	yes	yes	yes	yes	no	yes, in console model	no
Orca E.D.G.E.	0-160	yes	yes	no	yes	no	no	yes
Orca Skinnydipper	0-199	yes	yes		yes	no	no	no
Sherwood Sigmatech								
Beuchat G.U.I.D.E.	0-330	yes	yes	yes	yes	no	no	no
Parkway Black Fox								
Uwatec Aladin								
Dacor Micro Brain	0-330	yes	yes	no	flashing display @ 1 minute to NDL	no	no	no
Oceanic Datamaster II	0-249	yes	yes	yes	yes	yes	yes	yes
SeaQuest/ Suunto SME-ML	0-200all calcs; 201-230 depth & time	yes, bar graph	yes	yes	yes	no	yes, in console model	no
Tekna Digitek	0-220	yes,10f increm.	yes	yes	no	yes	yes	yes

ASCENT INFORMATION

	20	21	22	23	24	25	26	27
COMPUTER	ASCENT RATE DISPL.	RAPID-ASCENT		REQUIRED DECO STOP			ASCENT CEILING	MISSED DECO STOP WARNING
		LIMIT	WARNING	WARNING	DEPTH	TIME		
U.S. Divers Data Scan 2	no	60fpm	none	caution zone	10 ft	+CZ	caution zone	gauge shuts off
U.S. Divers Monitor 1	no	33fpm	@40fpm, arrow flashes	display "DECO"	to 80 ft stop	no	yes	"DECO" flashes
U.S. Divers Monitor 2	no	33fpm	@40fpm, arrow + audio	display "DECO"	to 80 ft stop	yes	yes	"DECO" flashes + audio
Orca E.D.G.E.	no	20-60 fpm	display flashes	up arrow	yes	yes	numeric & graph	bars over line
Orca Skinnydipper	no	20-60 fpm	LED flashes	LED flashes + display flashes "go up"	no	no	yes	top two displays flash altern-ately
Sherwood Sigmatech								
Beuchat G.U.I.D.E.	no	30fpm	no	yes	yes, at 10 ft or 20 ft	no	10 ft or 20 ft.	display flashes "DIVE" + down arrow
Parkway Black Fox								
Uwatec Aladin								
Dacor Micro Brain	yes	50fpm	display flashes descend	flashing deco stop display	yes	yes	flashing ascend display	flashing descend display
Oceanic Datamaster II	no	60fpm	none	caution zone	10 ft	+CZ	caution zone	gauge shuts off
SeaQuest/ Suunto SME-ML	yes	33fpm	display "SLOW"	display "DEC TIME"	yes	yes	yes	"STOP" + down arrow
Tekna Digitek	yes	60fpm	depth flashes	no	n/a	n/a	n/a	n/a

SURFACE-INTERVAL INFORMATION (2 Sheets)

	28	29	30	31	32	33
COMPUTER	SURFACE TIME	NO. OF DIVES IN MEMORY	GO TO NEXT DIVE AFTER	RETAIN DIVE PROFILE	DO NOT FLY WARNING	RESET COMPUTER AFTER
U.S. Divers Data Scan 2	yes	9	10 min.	no	no	12 hr
U.S. Divers Monitor 1	yes	9		no	yes	24 hr
U.S. Divers Monitor 2	yes	9		no	yes	24 hr
Orca E.D.G.E.	yes	1	-	no	yes	48 hr
Orca Skinnydipper Sherwood Sigmatech	yes	1	-	no	yes	48 hr
Beuchat G.U.I.D.E. Parkway Black Fox Uwatec Aladin	yes	5	10 min.	no	no	nitrogen tissue pressure adapts to atmospheric pressure
Dacor Micro Brain		6 (48 hrs)		no	yes	reset w/ magnet
Oceanic Datamaster II	yes	9	10 min.	no	no	12 hr.
SeaQuest/ Suunto SME-ML	yes	unlimited; retains 10 hrs dive info.	10 min.	yes, 3-min. intervals.	yes	9 compartments return to surface level pressures.
Tekna Digitek	yes	4	10 min.	no	yes, at 12 hr.	press. off+12hr

SURFACE-INTERVAL INFORMATION (continued)

COMPUTER	34	35	36	37	38	39	40	41
	SCROLL PREVIOUS DIVE					SCROLL NEXT DIVE		
	DIVE NUMBER	MAX DEPTH	BOTTOM TIME	DIVE PROFILE	MISSED DECO STOP	NDC DEPTH	NDC TIME	REPET GROUP DESIGNATION
U.S. Divers Data Scan 2	yes	yes	yes	no	gauge shutoff	yes	yes	yes
U.S. Divers Monitor 1	yes	yes	yes	no	flashing "DECO" display	yes	yes	no
U.S. Divers Monitor 2	yes	yes	yes	no	flashing "DECO" + beep	yes yes	yes yes yes	no
Orca E.D.G.E.	no	yes	yes	no	descend warning	yes	yes	no
Orca Skinnydipper	no	yes	yes	no	flashing LED.	yes	yes	no
Sherwood Sigmatech								
Beuchat G.U.I.D.E.	yes	yes	yes	no	flashing "DIVE" + down arrow	no	no	no
Parkway Black Fox								
Uwatec Aladin								
Dacor Micro Brain	no	yes	yes	no	warning	yes	yes	no
Oceanic Datamaster II	yes	yes	yes	no	gauge shutoff	yes	yes	no
SeaQuest/ Suunto SME-ML	yes	yes	yes	yes	ERR alternating w/down arrow	yes	yes	no
Tekna Digitek	yes	yes	yes	no	n/a	n/a	n/a	n/a

ELECTRICAL SPECIFICATIONS

COMPUTER	42	43	44	45	46	47	48
	ON-OFF SWITCH		BATTERIES				
	TEST	DIVE	TYPE	NUMBER	LIFE	LOW-BATTERY WARNING	REPLACEMENT
U.S. Divers Data Scan 2	turn on pressure	on 7 fsw off 3 fsw	lithium	2	6000hr	at 15% remaining life	factory
U.S. Divers Monitor 1	moisten contacts	automatic on water entry	lithium	1	5000hr	yes	authorized agent
U.S. Divers Monitor 2	moisten contacts	automatic on water entry	lithium	1	5000hr	yes	authorized agent
Orca E.D.G.E.	manual magnetic switch		lithium 9-Volt	1	200 hr	4-hour warning	user
Orca Skinnydipper	manual switch	manual switch	lithium 1/2 AA 3-Volt	3	750 hr	yes	user
Sherwood Sigmatech							
Beuchat G.U.I.D.E.	moisten contacts	moisten contacts	lithium 3.6 V.	1	800 hr	yes	authorized agent
Parkway Black Fox							
Uwatec Aladin							
Dacor Micro Brain	moisten contacts	moisten contacts	lithium	2	1000hr		factory
Oceanic Datamaster II	turn on pressure	on 7 fsw off 3 fsw	lithium	2	6000hr	at 15% remaining life	factory
SeaQuest/ Suunto SME-ML	moisten contacts	on 5 fsw off 5 fsw	silver oxide	2	1500hr	"BAT" display	authorized agent
Tekna Digitek	turn on pressure	turn on pressure	lithium 3 V.	1		"BAT" display	user