

The Future of Diving:

100 Years of Haldane and Beyond

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Editors

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The Future of Dive Computers

Michael A. Lang and Sergio Angelini

ABSTRACT. The age of electronic diving has arrived with the development of the modern electronic dive computer as the most significant advancement in self-contained diving since the invention of the Aqualung by Jacques Cousteau. Twenty-five years after modern day dive computer introduction several key questions remain surrounding the decompression models used, validation and human testing, acceptable risk, limitations, failures, and operational reliability. A brief history of analog dive computers and electronic digital computers and their function is discussed. Existing decompression models incorporated into dive computers are discussed with comments on the variety of approaches since Haldane. Educated predictions are offered on the functionality, features and configurations of future dive computer evolution based on benefits from advances in consumer electronics technology, and monitoring technology integrated into the dive computer algorithm that allows for a closer approximation of physiological parameters. Final remarks conclude with how advances in diving physiology research based mainly on Haldane's original work in 1908 will shape the dive computer landscape of the future.

INTRODUCTION

Historically, the diving community has depended predominantly on the United States Navy Air Decompression tables, a direct descendant of Haldane's work, which has served divers well for over five decades. Dive computers, utilizing mathematical models of human tissue compartments and gas exchange, allow the constant computation of the diver's decompression status during the dive. They vary in the assumptions incorporated in their models and in their capabilities. As predicted by Lang and Hamilton (1989) these real-time tools now enjoy widespread use in the recreational, scientific and military diving sectors. Logically, dive computer evolution was a natural progression from decompression tables and as they experienced several generations of development. Computers replaced the diver's watch and depth gauge, provided greater accuracy and computerized, real-time, at-depth, continuous dive profile data, eliminating the need for the diver to remember tables and make decompression decisions while under water and while multi-level diving, allowed for longer bottom times than permitted by tables. Many divers are highly motivated in their activities and interested in maximizing underwater time and efficiency. They view decompression requirements as a hindrance and distraction from their dive objectives, yet are generally concerned about safety.

Evaluations of the available databases on pressure-related injuries to examine the effectiveness of dive computers showed that these devices had demonstrable advantages over dive tables. It remains clear that neither tables nor dive computers can eliminate all decompression problems, which have a probabilistic component to their occurrence. However, the current generation of dive computer technology represents an important tool for further improving diver safety. Divers Alert Network has managed to collect 172,000 dive profiles from 1999 to 2009 through its Project Dive Exploration (PDE), a

worldwide study of recreational diving to record more than one million dives to produce statistically accurate analyses of depth profiles, diver characteristics, and diver behavior. This collection of real-time depth/time profiles for statistical analysis and modeling will assist in characterizing the relationship between diving and health effects, developing flexible, low-risk decompression procedures for multilevel, multiday repetitive diving; and studying the effects of flying after diving.

Since the appearance of the first commercially mass-produced electronic dive computer, the 1983 ORCA Industries' EDGE model, the operational experience with dive computers is enormous, yet some key considerations remain:

1. **Decompression models:** What models are dive computers programmed with? Does it matter? Should the manufacturers specify the model in their brochures? What are the primary criteria for model effectiveness and "acceptability"?
2. **Validation and human testing:** What comprises an acceptable validation protocol? Should all computers be tested on human subjects with Doppler monitoring? If so, what type of dive profiles should be used, and what does this really prove? And the rejection criteria would be what exactly? Comparisons with existing decompression tables demonstrate the range of no-decompression limits (NDLs) for tables and computers. For square-wave dive profiles, NDLs of dive computers are generally more conservative. Multi-level profile comparisons are more tenuous because of mechanical constraints of the organization of dive table limits versus real-time interval updates of dive computers. Should the manufacturer publish validation data or divulge their modifications or adjustments of published algorithms? Should they be evaluated by an independent agency?
3. **Acceptable risk:** It is generally recognized that zero bends is unachievable and that for operational reasons sectors of the diving community accept different DCS rates. What levels of "bends" risk are acceptable?
4. **Limitations:** Should depth and time limitations be imposed on dive computers? If so, how is this determined? Specifically, what is the applicability of dive computers with regard to long shallow dives, short deep "bounce" dives, stage-decompression dives, repetitive multi-day, multi-level dives, reverse dive profiles, variable ascent rates, diving at altitude and desaturation levels for flying after diving.
5. **Dive computer failure:** What is a diver to do regarding decompression during or after a dive should the computer fail? Are there standardized contingency plans to continue diving after a computer failure, or a requirement for a back-up dive computer?
6. **Operational reliability:** The operational experience has been generally good. Are there specific dive computer component or battery failures? Should the manufacturer provide reliability data?

The incidence of decompression sickness would appear to be

an appropriate metric to evaluate the efficiency of dive computers. Assuming that the diver wore the computer, actually looked at it during the dive, and the computer can be interrogated by the hyperbaric chamber operator, useful dive profile information can be retrieved and used in treatment decision making protocols.

HISTORY

The introduction of scuba in the mid-1940s changed diving operations that were carried out by hardhat divers using surface-supplied air for dives at single depths for as long as they needed to complete the mission while decompression status was monitored by surface tenders. Scuba divers without surface contact now had to be responsible for their own decompression status under water. Without an unlimited air supply from the surface the repetitive dive concept became an actuality with the exchange of full scuba cylinders. Three-dimensional freedom of movement during a dive led to multi-level dive profiles.

Various mechanical and electrical analog and microprocessor-based digital dive computers to determine a diver's decompression status in real time have been produced since the advent of scuba in the 1950s. Current computers only use depth and time as variables to compute decompression status. Future computers should incorporate individual and environmental variations and additional variables that play a role in decompression sickness susceptibility, and perhaps ultimately monitor actual inert gas levels in the diver.

The U.S. Navy Committee for Undersea Warfare and Underwater Swimmers met in 1951 at Scripps Institution of Oceanography to identify improvements required in scuba diving equipment and how to control the decompression of a non-tethered, free swimming scuba diver. Groves and Monk's (1953) report established the foundation for most of the early designs for decompression devices and presented a preliminary design for a diver-carried pneumatic analog computer which simulated nitrogen uptake and elimination in two theoretical tissue groups and summarized its benefits:

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 recompression procedure.

This report also included a basic design for the "Ultimate Gauge," an electrical analog computer that 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.

Searle (1956) indicated in a Navy Experimental Diving Unit report the need for some type of decompression device because of the ever-widening fields of both civilian and military free-swimming diving using self contained breathing apparatus. Particularly when scuba diving was untended from the surface, there arose a very pressing need for a small portable apparatus to be used by the diver to indicate proper decompression and ascent. Huggins (1989) thoroughly reviewed the history of dive computer evolution through 1988.

ANALOG COMPUTERS

1955: Foxboro Decomputer Mark I

Designed by Hugh Bradner and Mead Bradner, manufactured by the Foxboro Company with 40- and 75-minute halftime compartments (both with 1.75:1 surfacing ratios), a pneumatic design, and 5 bellows (Fredrickson, 1956). 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. Searle's (1956) evaluation reported the actual compartment half-times simulated by the Foxboro Decomputer Mark I as 27.7 and 52 minutes, causing deviations from U.S. Navy Table decompression ranges for some dives. No further development occurred because the U.S. Navy published new air no-decompression/decompression tables and repetitive dive tables in 1957. The Navy apparently rejected the idea of a decompression computer and accepted option "a" of the Groves and Munk report, i.e., depth gauge, watch, tables, and diver wits (Huggins, 1989).

1959: SOS Decompression Meter

Designed by Carlo Alinari, manufactured by SOS Diving Equipment Limited as a one-compartment pneumatic computer with half-time variations with the pressure differential across the ceramic resistor. The ambient pressure increased on the flexible bag, forcing gas through the ceramic resistor (simulating nitrogen uptake and elimination in the body) into the constant volume chamber. The pressure increase was measured by the bourdon tube gauge, indicating the safe ascent depth to the diver. On ascent, the gas pressure in the constant volume chamber became greater than the external pressure and the gas flow reversed (Huggins, 1989). Howard and Schmitt (1975) evaluated ten SOS meters and determined their no-decompression limits to be more conservative than the U.S. Navy limits at depths shallower than 20 msw, but less conservative at deeper depths.

1963: TRACOR Electrical Analog Computer

Developed by Texas Research Associates Inc. as the first electrical analog decompression computer, employing 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 that varied the voltage supplied to the network. Two 1/2D alkaline cells powered an oven that 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 calibrated in fsw displaying how many feet the diver could safely ascend. Workman (1963) found that minimal decompression requirements were adequately predicted for schedules throughout the depth range tested (40–190 fsw) 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 U.S. Navy air decompression tables. Continuous ascent decompression predicted by the TRACOR computer 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 (1963) further suggested that a mechanical analog computer could be used to avoid the instability and breakdowns that occurred in the electrical circuitry.

1962: DCIEM Analog Computer Series (Nishi, 1989)

Developed by D.J. Kidd and R.A. Stubbs at the Defence and Civil Institute for Environmental Medicine (DCIEM) with four compartments to simulate the nitrogen absorption and elimination in the diver. Initial versions' compartments were arranged in parallel, the final design's arranged in series, resulting in the Kidd-Stubbs decompression model (Kidd and Stubbs, 1966). The MARK V S was the first thoroughly tested, successful decompression computer. The four serial compartments gave effective half-times of 5 to over 300 mins (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 (Huggins, 1989). 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 VI S, was designed utilizing the same algorithm for hyperbaric chamber use. The MARK V S was produced by Spar Aerospace in the late 1960s for sale to industrial and military agencies with operational depth limits to 60 msw. In 1970, Spar developed a smaller and lighter version operational to 90 msw. 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 recreational divers.

1973: GE Decompression Meter

Designed by Borom and Johnson (1973) utilizing semipermeable silicon membranes to simulate nitrogen diffusion. These

membranes operated better than porous resistors because the simulated half-time of a compartment did 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 mins. 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 was available (Huggins, 1989).

1975: Farallon Decomputer

Manufactured by Farallon Industries, the device was a pneumatic analog computer utilizing four semipermeable membranes (two for gas uptake, 2 for elimination) that simulated two theoretical tissue groups. Air from the collapsible gas chamber flowed through the “fast tissue” (large) and “slow tissue” (small) membranes when exposed to elevated pressures. The increased pressure within the mechanism caused the pistons to move along the display color-coded green, yellow, and red, indicating the diver’s decompression status. When the ambient pressure was reduced to a lower pressure than inside the tissue simulator, the air flowed out through the “repetitive dive membrane.” Both compartments had offgassing membranes that simulated a slow offgassing rate. Testing at Scripps Institution of Oceanography determined that the Farallon Decomputer failed to “approximate” the U.S. Navy Air Decompression limits and repetitive dives proved even less acceptable, was too permissive, and developed too much mechanical deterioration with use (Flynn, 1978).

DIGITAL COMPUTERS

The dive computer consists of a watertight housing with a through-hull pressure transducer that transforms pressure sensed through an analog-digital converter to the microprocessor, powered by a battery. Read-only memory, random-access memory and a clock feed into the microprocessor, which outputs information to the diver via the computer’s display (Fig. 1). Huggins (1989) outlined the evolution of a series of digital dive computers once the microprocessor revolution was underway in the mid 1970s. DCIEM unveiled the XDC Digital Decompression Computer Series using the Kidd-Stubbs model. The XDC3 Cyberdiver was actually the first diver-carried microprocessor-based underwater decompression computer. Like the Cyberdiver, the DACOR Dive Computer suffered from very high power consumption and was a US Navy dive table reader. Thalmann (et al., 1980; 1983; 1984) and Presswood et al. (1986) worked on developing an E-L (exponential linear) decompression model and algorithm to program into an Underwater Decompression Computer to be used with the USN constant partial pressure of oxygen closed-circuit mixed gas system. This model assumed that nitrogen absorbed by tissues at an exponential rate

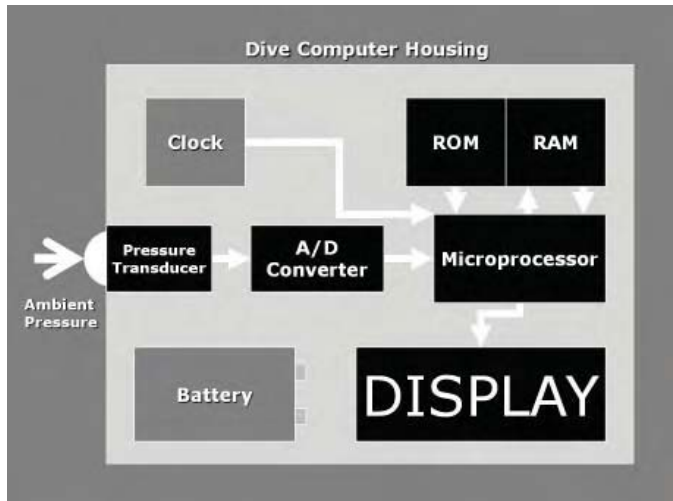


FIGURE 1. Dive computer schematic.

(as in Haldanean models), discharged at a slower linear rate. In 1996, Thalmann’s VVAL 18 model was tested in the USN’s Cochran Navy dive computer.

ORCA Industries, Inc. released the EDGE (Electronic Dive Guide) in 1983, the world’s first commercially successful, mass produced electronic dive computer that paved the way into this new approach to decompression status monitoring. The ORCA 12-compartment model (half times from 5 to 480 mins) was based on no-decompression limits (to 130fsw) determined, in part, by Doppler ultrasonic bubble detection (Spencer, 1976). The EDGE display was perhaps one of the most innovative to date, divided into graphical and digital information split into two sections by a curve (limit-line) representing the maximum pressure (M-values) allowed in the twelve compartments. One glance by the diver established whether all compartment bars were above the limit-line, indicating a no-decompression dive. The SkinnyDipper (also distributed as a private labeling, Sigmatech, by Sherwood Scuba) from ORCA Industries utilized the same decompression model as the EDGE, but its simpler display scheme consisted of three numerical segments and no graphics. The SME-ML, a nine-compartment Haldanean model with half-times ranging from 2.5 to 480 mins, is also based on Doppler research and was manufactured by SUUNTO of Finland. It stored ten hours of dive information that could be recalled at any time after the dive. The Datamaster II (also distributed as the DataScan II by U.S. Divers Co.) was manufactured by Oceanic using a pseudo-Haldanean decompression model of six compartments with half-times of 5 to 120 mins. This model allowed no off-gassing from the compartments until reaching the surface. The Datamaster II lead the way in calculating air consumption, tank pressure and air time remaining.

In 1979, the Hans Hass Decobrain I was a Swiss table-based computer for high-altitude diving that could perform multi-level computations using the table’s repetitive group designators but only by using the 80-minute half-time compartment, which easily put it “out of range” as a decompression

device. In 1985, the Decobrain II by Divetronic was based on Bühlmann's 16-compartment Swiss model (ZHL-16) developed with compartment half-times ranging from 4 to 635 mins and designed for altitude diving up to 4500 meters above sea level. Time to fly information was first introduced. The DACOR Microbrain (also manufactured by Divetronics) used six compartments (4.5 to 395 minute half-times) that corresponded to the 16-compartment Swiss model. The Aladin (Uwatec), G.U.I.D.E. (Beuchat) and the Black Fox (Parkway) is the same unit manufactured by Uwatec with a 6-compartment version of the Swiss decompression model utilizing four sets of M-values based on the altitude ranges of the dive. The Uwatec computer could be interrogated and the log entries for the last five dives recalled by activating two wet switches. The Aladin Pro Plus in 1987 was likely the second commercially successful mass-produced dive computer.

Huggins (1989) aptly concludes

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.

DECOMPRESSION MODELS

In 1908 John Scott Haldane published a paper (Boycott et al., 1908) that to date represents the most significant milestone in decompression physiology. A multitude of researchers (Hills, 1966; Workman, 1963, 1965; Bühlmann, 1990) and many others over the years have published numerous versions of decompression models which, by and large, are all intrinsically linked to this century-old publication.

As a diver descends in the water column and is exposed to increased ambient pressure, the partial pressure of the inhaled inert gas is higher than that of the dissolved inert gas in the various bodily tissues. This imbalance leads to inert gas traveling from the lungs via the blood stream throughout the body, where it is absorbed in the various tissues at a rate which is a function of the tissue itself (e.g., muscle tissue will "load" up with inert gas faster than fat tissue). The characteristic by which a tissue loads with inert gas is defined by the term "half time", an artificial parameter that defines the time required for a tissue to equilibrate to within 50% of the imposed external pressure.

Similarly, as the diver ascends at the end of the dive and is exposed to a diminishing ambient pressure, the partial pressure of inert gas in a tissue will become higher than the partial pressure of the inhaled inert gas (supersaturation), and hence the inert gas transfer process is inverted. Excess inert gas is returned from the tissues via the blood stream to the lungs, from where it is eliminated by exhalation. The key concept in every form

of Haldanean implementation is that decompression sickness is preceded by inert gas bubbles forming due to excessive supersaturation. Therefore, a successful decompression strategy involves controlling the supersaturation in each tissue within defined values. The various versions of Haldanean models differ primarily in the number of tissues considered, their half times and their tolerance to supersaturation (up to the tipping point of bubble formation) and mathematical tricks are applied to cover a variety of influencing factors (e.g., cold, workload, repetitive diving). The primary reason for the success of Haldanean models is that, in spite of their simplistic approach, a vast amount of data exists to which the models have been fitted. Similar to the flower-like trajectory of Mars around the Earth in a Ptolemaic view, enough empirical observation and data fitting can make any model yield excellent results within its tested range.

During the 1980s the prevailing opinion was that bubbles formed during almost all dives, even those not producing any sign or symptom of decompression sickness. This prompted a new wave in decompression modeling that implicitly included bubble formation and growth, and its consequences to the diver. As a main departure from the Haldanean model, inert gas was not only present in dissolved form, but also in free form as a bubble. David Yount proposed a free-phase decompression model, the Variable Permeability Model (Yount and Hoffman, 1986), Michael Gernhardt the Tissue Bubble Dynamics Model (Gernhardt, 1991), and Wayne Gerth and Richard Vann (Gerth and Vann, 1997) the Probabilistic Gas and Bubble Dynamics Model. The most widely implemented model in a simplified version in a variety of dive computers is the Reduced Gradient Bubble Model (Wienke, 1990). Gutvik and Brubakk (2009) are the proponents of Copernicus, and Lewis and Crow (2008) presented an introduction to their Gas Formation Model (GFM). Whereas Yount and Hoffman, and Wienke consider supersaturation as a mechanism to begin bubble formation, Gernhardt, Gerth and Vann, and Gutvik and Brubakk track bubbles from their initial form as microscopic nuclei and follow their evolution and growth as the dive progresses. These latter models are of considerable higher mathematical complexity and cannot be solved within the realm of a modern microprocessor.

The overarching goal of future dive computer models should be to more closely reflect the individual physiology of the diver, evolving as a true electronic instrument designed to solve a physiological problem. Moon et al. (1995) reinforced that the probabilistic models on which tables and computers are based should reflect the individual reality of the divers, to enable them to conduct their dives in accordance with their individual characteristics.

ASCENT RATES, REPETITIVE DIVING, TIME TO FLY, AND MIXED GAS FUNCTIONS

Divers must adhere to the manufacturer's recommended ascent rate, whether variable or uniform, which is an integral

component of the algorithm's tissue tension calculations. Training in, and understanding of, proper ascent techniques is fundamental to safe diving practice, including mastering proper buoyancy control, weighting and a controlled ascent with a "hovering" safety stop in the 10–30 fsw zone for 3–5 min (Lang and Egstrom, 1990). It is in the ascent phase of the dive that computers reveal one of their strengths. Existing computers have maximum ascent rates that do not exceed 60 fsw/min from depth and many are limited to 30 fsw/min in shallower water. Future dive computer models may favor slower rates but we make the observation that operationally, the 30 fsw/min is achievable and effective, while slower rates most likely are not.

Multi-level, multiday repetitive computer diving within the tested envelope is the mainstream practice today, and it appears to be less stressful than square wave profile diving. Deep repetitive dives with short surface intervals should nevertheless be given special consideration. Because of limited analysis of the existing profile databases, no firm conclusions have been reached regarding repetitive diving limits to date (Lang and Vann, 1992). The maximum depth sequence of repetitive dive profiles is not restricted by dive computers. Lang and Lehner (2000) found that there was no physiological reason for prohibiting reverse dive profiles for no-decompression dives less than 40 msw (130 fsw) and depth differentials less than 12 msw (40 fsw) because this was never a rule in either U.S. Navy or commercial diving, but more of an operational constraint of the organization of depth/time profiles in a square-wave table format.

There exists no dependable distinction between "safe to fly" and "not safe to fly" in dive computers. There is a gradual reduction of risk for which the diver needs to choose an acceptable degree (e.g., wait at least 24 hours, the longer the wait, the further the reduction in probability of decompression sickness). Lang and Hamilton (1989) provide examples of dive computer computations for "time to fly" that include offgassing to 1–2 fsw (2–4 psi) over ambient pressure, waiting until 12 hrs have elapsed after the last dive, or not exceeding 0.58 bar as maximum ceiling setting (against a minimum aircraft cabin pressure of 0.75 bar).

Adjusting oxygen fractions in dive computer software from 0.21 to standard oxygen-enriched air (nitrox) of 0.32 or 0.36 is simple and an available function of most computers. Huggins (2006) evaluated several dive computers capable of calculating heliox and trimix dive profiles (the EMC-20H by Cochran Undersea Technology, the HS Explorer by HydroSpace Engineering, the NiTek He by Dive Rite, and the VR3 by Delta P Technology). The decompression software that purportedly emulated these four dive computers was used to calculate the response to specific 300 fsw/20 min total bottom time (TBT) dive scenarios, including decompression gas switches. Huggins opined that in surface-supplied mixed-gas operations diver-carried dive computers are best used as a backup and that the major control of decompression should be assigned to the surface-support personnel using a preplanned set of heliox or trimix tables that the dive computer emulates.

THE FUTURE: FUNCTIONALITY, FEATURES AND CONFIGURATIONS

The dive computer of the future will benefit from advances in science and technology. These can be grouped into three distinct categories: benefits from advances in consumer electronics technology, monitoring technology integrated in the algorithm, and advances in decompression physiology research.

BENEFITS FROM ADVANCES IN CONSUMER ELECTRONICS TECHNOLOGY

The combined worldwide sales of dive computers from all manufacturers does not exceed 500,000 units per year, while Apple alone sold over 30 million iPhones in the first 12 months. It becomes obvious then that dive computers do not drive new technologies, but rather benefit from a trickledown effect. In a world dominated by PDAs, Smartphones and iPods, not only is the technological development unbridled, but the cost of these new technologies keeps declining and becoming more affordable. Hence, in spite of the relatively small volumes of dive computer produced, we can expect to start seeing more and more advanced embedded technologies. Other outdoor activities, such as hiking, climbing and camping, are also promoters of new technologies that can find an application within a dive computer.

High Resolution Color Display

Barring a few exceptions dive computers today utilize a segment display. In these types of displays, information is presented by "turning on" certain segments within a large array. Due to the constraints of fitting a wide variety of information on a small display, segment displays typically present only numbers and symbols. Advantages of this technology are low energy consumption and very sharp representation. The main disadvantage, however, is the inability to show anything other than what is "preprogrammed" into the display. This means that any interaction between the diver and the computer takes place through a display of numbers and symbols. In an emergency situation, the diver sees blinking symbols and/or numbers and from this has to infer the nature of the emergency and take appropriate action. The possibility exists that, if the diver does not recognize or otherwise understand the meaning of the blinking symbol, this can lead to an increase in stress in the diver and could potentially precipitate a risky situation.

The switch to a high resolution color display is the most obvious consequence of the proliferation of PDAs and Smartphones. Color dot-matrix displays can play an important role in enhancing the safety of the dive in many ways:

- a. Before the dive: menu navigation via text in a language of choice means simplicity and clarity in setting up the computer for the dive;
- b. During the dive: one obvious advantage is the clear

representation of all relevant information, possibly with a choice of font size and in a pattern customized by the user. In addition, the combination of text and color can be tremendously helpful in alerting the diver of a potentially risky situation by describing the exact nature of the problem and recommending a course of action. For instance, a diver on nitrox exceeding the maximum operating depth of the breathing gas would see a clear text message such as MAX OPERATING DEPTH EXCEEDED (the nature of the problem) followed by a clear text message such as ASCEND TO 40 MSW (the recommended course of action).

- A dive computer with a standard segment display cannot do more than beep madly and show blinking symbols; and,
- c. After the dive: logbook viewing function with several pages of information, including a graphic representation of the dive.

Rechargeable Battery

Today's computers function well with replaceable batteries, allowing between 100 and 800 dives before the battery runs out. In most cases replacing the battery is a very simple process which, combined with a battery price of a few dollars/euros, makes this an attractive solution. Reliability, an important factor in a life support system, is also very high in this configuration. Color displays, however, require higher energy consumption and thus the switch to a rechargeable battery becomes necessary. With a typical lifetime of 500 charge/discharge cycles and assuming 5 to 10 dives on each full charge, this would allow 2500 to 5000 dives before the battery needs to be replaced. Charging of the battery can take place via a USB cable connected to a PC or directly to a power outlet, or, as in the case of the UEMIS Scuba Diver Assistant, via solar cells.

GPS Receiver

GPS receiver use has become wide spread in outdoor instruments and the automotive industry, where its role is of much higher importance and obvious benefit than in a dive computer. GPS works only through air, hence on the surface, and therefore an application in a dive computer might seem inappropriate. However, it would allow divers to locate dive sites simply by recording their GPS coordinates. Additionally, at the end of the dive, the emerging diver would be able to estimate the distance and direction from the point of entry (boat or shore), which could be useful in a situation of low visibility.

Underwater Communication and Navigation

Communicating underwater with the dive buddy or even all the way to the dive vessel would represent an enormous step forward in diver safety (but perhaps not necessarily in dive enjoyment, because many divers love diving for the peace and quiet provided by the silent world). Furthermore, with the proliferation of navigation systems in automotive technology,

it seems only logical to have similar gadgets guiding us through a dive. Data transmission underwater over a certain distance requires the use of ultrasound technology. Radio frequency, as utilized for instance for the transmission of tank information from a sensor on the first stage regulator to the dive computer, is strongly attenuated by water and thus would require too much power to be useful over a longer distance. Ultrasound, on the other hand, can travel very far underwater with relatively little power. Unfortunately, ultrasound is not necessarily a universal technology in consumer electronics, hence its integration in a dive computer may not be in the near future. Attempts have been made though, and for professional use there are voice communication systems which, though bulky, function rather well. GPS-like underwater navigation would require the reproduction of a satellite system for triangulation (set of buoys that translate the GPS signal from the surface to an ultrasound signal underwater) and, as such, would be costly and cumbersome. Simpler devices, which only show the direction and distance to the boat, have been introduced several years ago (Uwatec NEVERLOST, Desert Star Systems DIVETRACKER) but have not enjoyed extensive market penetration.

EPIRB

Emergency Position Indicating Radio Beacon (EPIRB) is a distress signal technology utilized in the maritime industry. EPIRBs are tracking transmitters that aid in the detection and location of boats, aircraft, and people in distress. Strictly speaking, they are radio beacons that interface with Cospas-Sarsat, the international satellite system for search and rescue (SAR). When activated, such beacons send out a distress signal that, when detected by non-geostationary satellites, can be located through triangulation. Often using the initial position provided via the satellite system, the distress signals from the beacons can be homed in on by SAR aircraft and ground search parties who can in turn come to the aid of the concerned boat, aircraft, or people. For instance, should a diver get carried away by a current during a drift dive, an EPIRB built into the dive computer would allow for a relatively quick location and rescue. The related technology is unfortunately rather costly and most divers may never need to be rescued at sea.

BENEFITS FROM MONITORING TECHNOLOGY INTEGRATED INTO THE ALGORITHM

The principal objective of a dive computer is to recommend an ascent schedule as a result of the diver's exposure to a specific depth/time profile. The depth defines the inert gas partial pressure in the inhaled breathing gas which, combined with the length of the exposure (time at depth), drives the inert gas uptake into the diver's tissues. Clearly, perfusion (blood circulation through the body) plays a significant role in that it transports the inert gas through the body from and to the lungs. Consequently, a change in perfusion during the dive, as may be

induced by exercise (increased perfusion) or exposure to cold (vasoconstriction in the arms or legs, hence a reduced perfusion), is expected to play a role in the on-gassing and off-gassing of inert gas. In particular, if the perfusion was increased during the deeper parts of the dive when much inert gas uptake is occurring, and/or the perfusion were reduced during the shallower parts towards the end of the dive, when inert gas elimination is occurring, the simplistic approach of considering only inert gas partial pressures may not be sufficient. In today's dive computers evidently enough conservatism is built in to cover these effects, as evidenced by the relatively low incidence rates of decompression sickness.

There are attempts to account for changes in perfusion. One approach is to lump any deviation from a "normal" exposure into additional conservatism in the model ("personal factors"). The clear disadvantage of this method is that the diver needs to define and predict before the dive whether strenuous exercise or chilling is expected to occur. The other approach, followed at the moment only by UWATEC and UEMIS, is to evaluate changes in perfusion based on actual measurements during the dive. An increase in workload is measured either by heart rate monitoring (UWATEC) or by a change in breathing pattern (UWATEC and UEMIS). Cold water effects, which theoretically could lead to a reduction in perfusion during the decompression phase of the dive, are based on the concept that the colder the water, the more vasoconstriction plays a role (Angelini, 2007). A thermally insulated diver, however, may be warmer in 4 °C water than a poorly protected diver in the Caribbean, and here a pre-dive set cold factor could be more practical.

Regardless, in spite of the theoretical validity of the effect of changes in perfusion during the dive, the actual implementation within a decompression model has not been experimentally validated or clinically proven. A thorough review of cold as decompression sickness stress factor was performed by Mueller (2007). One can argue that diving is a reasonably safe activity and that therefore these model complications are uncalled for. Another point of view is that this is an indication of excessive conservatism in today's models so that, with proper implementation of these phenomena, a diver could enjoy more freedom.

However, as advances in science and decompression physiology are made, we propose the continued development of the following technologies:

1. **Heart rate monitoring.** There is a proliferation of heart-rate monitoring devices in most outdoor and fitness activities. As people become more aware of the importance of exercise to their well being, they also discover heart rate monitoring as an excellent tool for fitness evaluation. Recording the heart rate during a dive can be useful, besides from an implementation of workload-related nitrogen calculations, to become aware of how the body responds to the environment, leading to either increased comfort and enjoyment (recorded heart rate is low and consistent) or the avoidance of certain types of stressful dives (high and/or erratic heart rate).
2. **Skin temperature measurements.** Vasoconstriction is the result of the brain's recognition that the core body temperature is diminishing. In order to maintain the function of critical body parts the brain reduces blood circulation to the limbs (arms and legs) with their large surface to volume ratio to reduce heat loss and protect the heart, lungs, and brain. Skin temperature measurements transmitted to the dive computer would allow for a quantification of the cooling. In addition to an implementation of vasoconstriction in the decompression model, this could be very important as an alarm trigger for approaching hypothermia. Hypothermia is an acute danger when pain and feeling of cold disappears once the body gives up on shivering as a mechanism of generate warmth.
3. **Oxygen saturation measurement.** This is of primary interest to free divers because the risk of oxygen depletion and consequent shallow-water blackout is high. Nevertheless, this and other blood monitoring technologies could find applications in scuba or rebreather diving.
4. **Inert gas bubble detection.** Inert gas uptake and consequent off-gassing is in and of itself not the cause of decompression sickness. Problems can occur when the combination of excessive amounts of inert gas dissolved in the body and a diminishing ambient pressure lead to the gas coming out of solution and forming free gas bubbles in the body. Some decompression models attempt to describe this free gas formation, with all the complexity that follows from the physics associated with such an event. It would be very useful if it were possible to detect bubble formation during the dive, integrated into a feedback loop into the decompression algorithm (regardless of the nature of the algorithm itself). There exist, however, two rather large obstacles to this. First, the bubble detection technology existing today is based on ultrasound or Doppler monitoring, both requiring rather cumbersome equipment that could hardly be placed on a diver during the dive. The second problem is that bubbles really do not grow to a discernible level until 20 to 40 minutes after the dive, so that in-water detection might only be useful in extreme dives in which something went seriously wrong. On the other hand, this line of thinking could lead to the development of a similar or new kind of technology aimed at detecting a physiologically viable parameter that gives an indication of decompression stress in the body. Any parameter that gives online feedback into a decompression model as to the state of the diver with respect to potential DCS would be a tremendous benefit.

BENEFITS FROM ADVANCES IN DECOMPRESSION PHYSIOLOGY RESEARCH

As described above, decompression models in existence today are, aside from a few mathematical manipulations, almost

entirely based on the ideas of John Scott Haldane presented in the historic 1908 paper (Doolette, 2009). Actual bubble models that carry out the pertinent bubble-dynamics calculations (and the related non-linear differential equations) are too complex to be managed by the limited processing power of a dive computer microprocessor. Even if this were to be solved, what remains is the need to validate such a radically different approach to decompression. There is an attempt by the Norwegian University for Science and Technology to build a complete bubble model under the project name Copernicus. As much as the earth-centered planetary model was intrinsically flawed yet allowed reasonable ocean navigation via immense empirical observations of the movements of the stars (made to fit this wrong model), a sun-centered planetary system yielded much better and accurate results allowing for significant broadening of the range of validity of the model itself. Haldanean theory, which does not consider inert gas in free form, and consequently its effects on the human body, has been refined over a century with the input of Workman (1963), Bühlmann (1990), Thalmann et al. (1980) and Thalmann (1983; 1984) to name a few, and provides us today with an extremely valuable and powerful tool in spite of its underlying wrong assumption. Copernicus, the decompression model, is the attempt to find the sun-centered model for decompression physiology, yet at the moment the wealth of data with which the existing models have been refined gives the Haldanean-based models a clear advantage. Science and its related research should nevertheless persist in the pursuit of the “truth”. A full bubble model availability within a few years would be very welcome. Such a model should incorporate those aspects of relevance in approximating the human body such as body fat, age, gender, and fitness level.

CONCLUSION

Electronic dive computers have for all practical purposes replaced dive tables in recreational and scientific diving and are increasingly implemented in particular segments of the military diving community. For the commercial diving industry and its standard operating methods of surface-supplied/controlled diving or saturation diving, a dive computer’s advantages in monitoring decompression status appear to be minimal. It would not be unreasonable to state that regardless of the number of algorithm variations incorporated in modern dive computers, they all appear to fall within an acceptable window of effectiveness based on available databases of pressure-related injuries. It is also clear that neither tables nor dive computers can eliminate all decompression problems, but if utilized conservatively, computers have emerged as an important tool for the improvement of diver safety.

All things considered, the dive computer’s functions of ascent rate monitoring, real-time computation of nitrogen balances, air consumption monitoring and profile downloading capability form a solid, reliable basis for advancements that will emerge in the future. Benefits from advances in consumer

electronics technology will undoubtedly incorporate features such as high resolution color display, rechargeable battery, GPS receiver, underwater communication and navigation, and EPIRB. Further, benefits from monitoring technology integrated in the dive computer algorithm will surely include heart rate monitoring, skin temperature measurements, oxygen saturation monitoring, and perhaps even inert gas bubble detection. We can only imagine the progress that John Scott Haldane’s brilliant decompression insight would have made had the dive computer tools available to us now and in the future been available to him 100 years ago.

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