

Understanding Dive Computers

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Abstract

Dive computers are important and useful underwater instruments across sport, commercial, military, scientific, exploration, and technical diving sectors. We discuss dive computers, 2 basic underlying models, uses and misuses, data collection and correlations, and some observed features of modern diving with computers. Selected references cover topics in great detail.

Keywords: Sport diving; Dive computers; Uses and misuses; Diving algorithms; Correlations

Introduction

Modern digital dive computers [1-5] date to the early 80s, though analog devices simulating tissue gas uptake and elimination through porous membranes date back to the 70s. Analog devices were limited to nonstop diving and had a short shelf life. Digital dive computers proved highly successful and very useful right from the start, progressing from just table emulators to full up algorithmic staging devices across mixed gas, open circuit (OC), rebreather (RB), nonstop, decompression, deep, and shallow diving. Dive computers are moderately expensive items these days, and high end units range beyond \$1500. Basically, a decompression computer is a microprocessor consisting of a power source, pressure transducer, analog to digital signal converter, internal clock, chip with RAM (random access memory) and ROM (read only memory), and pixel display screen [5]. Pressure readings from the transducer are converted to digital format by the converter, and sent to memory with the elapsed clock time for model calculations, somewhere in 3-10 second intervals. Results are displayed on the screen, including diver time remaining, time at a stop, tissue gas and bubble buildup, time to fly, oxygen toxicity levels (CNS and pulmonary), and other warnings (model violations). Some 3-9 volts is sufficient power to drive the computer for a couple of years, assuming about 100 dives per year. The ROM contains the model program (time step application of model equations), all constants, and queries the transducer and clock. The RAM maintains storage registers for all dive calculations ultimately sent to the display screen. Dive computers can be worn on the wrist, incorporated into consoles, or even integrated into heads up displays in masks.

Depending on model implementations and ad hoc practices, dive computers can signal divers with audible and displayed warnings for violations. Underwater, modern dive computers can accommodate manual and programmed breathing gas switches in their computational synthesis as OC tank and RB set point changes are made. Some units are equipped with tank-to-computer wireless connections to read tank pressures. USB computer-to-computer connections permit downloading of dive profiles for later analysis and data storage. Dive computer updates from manufacturers are also easily accommodated in the same computer-to-computer mode. With software supplied by the manufacturer, dive planning is seamlessly executed using the same algorithm hard wired into the dive computer. Conservancy levels are user knobs based on age, gender, water temperature, workload, diving experience, and related factors. Dive computers today are sophisticated devices supplying a wealth of information and controls for safe diving.

Definitions

1. Mixed gases: any combination of oxygen, nitrogen, and helium breathing mixtures inspired and exhaled by divers underwater.
2. OC: underwater breathing system using mixed gases from a tank that are exhausted after exhalation.
3. RB: underwater breathing system using mixed gases from a tank that are recirculated after carbon dioxide is scrubbed from the exhalant and oxygen from another tank is injected into the breathing loop.
4. RAM: data storage array in modern computers.
5. ROM: computational array in modern computers that processes information, does calculations, and sends output to registers and displays.
6. Diving algorithm: combination of a gas transport and/or bubble formation model and coupled diver ascent strategy.
7. Decompression stop: necessary pause in a diver ascent strategy to eliminate dissolved gas and/or bubbles safely and is model based. Stops are usually made in 10 feet increments.
8. Deep stop: decompression stop made in the deep zone to control bubble growth.
9. Shallow stop: decompression stop made in the shallow zone to eliminate dissolved gas.
10. OT: pulmonary and/or central nervous system oxygen toxicity resulting from overexposure to oxygen at depth or high pressure.
11. DCS: crippling malady resulting from bubble formation and tissue damage in divers breathing compressed gases at depth and ascending too rapidly.
12. DGM: dissolved gas model dividing the body into tissue

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compartments with hypothetical half times for uptake and elimination of inert gases. Throughout the dive, tissue tensions are constrained by limit points called M-values, or critical tensions.

13. BPM: bubble phase model dividing the body into tissue compartments with hypothetical half times that are coupled to inert gas diffusion across bubble film surfaces. An exponential size distribution of bubble seeds is usually assumed. Throughout the dive, the cumulative volume of growing bubble seeds is constrained by a single limit point called the critical volume, or phase volume, in all tissue compartments.
14. Recreational diving: air and nitrox nonstop diving.
15. Technical diving: mixed gas (nitrogen, helium, oxygen), OC and RB, deep and decompression diving.

Literature Review

There are literally 100s of articles in medical, mathematical, physics, chemistry, and computing science peer re-viewed journals on dive computers. Additional and very useful information about specific operations of any particular dive computer can be found in user manuals, which are extensive, complete, and lengthy.

Key Concepts

Dive computers are useful tools across recreational and technical diving. Able to process depth-time readings in fractions of a second, modern dive computers routinely estimate hypothetical dissolved gas loadings, bubble buildup, ascent and descent rates, diver ceilings, time remaining, decompression profiles, oxygen toxicity, and many related variables. Estimates of these parameters made on the fly rely on two basic approaches [3], namely, the classical dissolved gas model (DGM) and the modern bubble phase model (BPM). Both have seen meaningful correlations with real diving data over limited ranges but differ in staging regimens. Dissolved gas models focus on controlling and eliminating hypothetical dissolved gas by bringing the diver as close to the surface as possible. Bubble models focus on controlling hypothetical bubble growth and coupled dissolved gas by staging the diver deeper before surfacing. The former gives rise to *shallow* decompression stops while the latter requires *deep* decompression stops, in the popular lingo these days. As models go, both are fairly primitive, only addressing the coarser dynamics of dissolved gas buildup and bubble growth in tissues and blood. Obviously, their use and implementation is limited, but purposeful when correlated with available data. To coin a phrase from a community at large, *all models are wrong, but some are use ful*. As research plods forward, computer manufacturers are both quick and flexible in responding to change and update, adding to computer viability as a diving tool. It's reasonable to expect usage in diving to grow with commensurate sophistication.

Presently, some 15 -25 companies manufacture dive computers employing both the DGM and BPM in another 200-250 models by last count. Recreational dive computers mainly rely on the DGM while technical dive computers use the BPM. In the limit of nominal exposures and short time (nonstop diving), the DGM and BPM converge in diver staging. Dive planning and decompression software is also readily available from some 15 -25 vendors.

Important Model Estimators

Instantaneous estimates of parameters needed to stage divers by dive computers rely an mathematical relationships coupled to pressure

sensors and clocks in the unit. Important ones follow [3]:

Dissolved Gas Model (DGM)

Diver staging in the classical Haldane approach limits inert gas tissue tensions, p , across all tissue compartments, λ , with halftimes, τ , by a limit point, called the critical tension, M , according to,

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

With P_a ambient gas partial pressure, p_i initial partial tension, t exposure time at p_a , and,

$$\lambda = \frac{0.693}{T}$$

Halftimes range, $3 \leq \tau \leq 540 \text{ min}$, in applications, and critical tensions, M , are linear functions of depth, d , with roughly,

$$M = \tau^{-0.25} (153.3 + 4.11d) f \text{ sw}$$

If M is exceeded at any point on ascent, a decompression stop is required. Helium tissue halftimes are 1/3 nitrogen tissue halftimes. Algorithm is used in recreational and technical diving across OC and RB systems. Algorithm typically brings diver into the shallow zone for decompression (shallow stops). Ascent rates are nominally a slow 30 f sw/min.

Bubble Phase Model (BPM)

Modern bubble phase models (BPM) couple tissue tensions to bubbles directly by assuming an exponential dis-tribution, n , of bubble seeds in radii, r , excited into growth by changing ambient, P , and dissolved gas, p , total pressure,

$$n = N \exp(-\beta r)$$

for N and β constants obtained and/or fitted to laboratory or diving data. To date, distributions of bubble seeds have not been measured *in vivo*. Using the same set of tissue halftimes and inert gas tension equations above in the DGM, diver staging in the BPM requires the cumulative bubble volume excited into growth by compression-decompression, ϕ , to remain below a critical value, Φ , throughout all points of the dive and in all tissue compartments,

$$\int_t \frac{d\phi}{dt} dt = DS \int_t \int_r n \left[p - P - \frac{2\gamma}{r} \right] dr dt \leq \Phi$$

With D tissue diffusivity, S tissue solubility, and γ bubble surface tension. In applications, the critical phase volume, Φ , is taken near 600 microns^3 and surface tension, γ , is taken around 20 dyne/cm . Diffusivity times solubility, DS , is also fitted to diving data. If Φ is exceeded at any point on ascent, a decompression stop is necessary. Algorithm is used across recreational and technical diving on both OC and RB systems. Staging starts in the deep zone and continues into the shallow zone (deep stops). Ascent rates are also 30 f sw/min.

Oxygen Toxicity (OT)

Both pulmonary and CNS toxicity are tracked by dive computers in a relatively simple way. Pulmonary toxicity is tracked with a dose-time estimator, Γ , written,

$$t_0 = 4140 \exp(-2.7 ppO) \Gamma = \sum_n \left[\frac{ppO - 0.5}{0.5} \right]_n^{0.83} t_n \leq 750$$

with ppO oxygen tension in atm and t the exposure time in min . Dive segments, n , are tallied every 10-20 sec and Γ updated. Central nervous

system toxicity is similarly tallied over dive segments, n , by a CNS clock, Ω , using the oxygen limit points, t_o , for exposure to oxygen partial pressure, pp_o , in *atm* for time, t , in *min*,

$$\Omega = \sum_n \left[\frac{t}{t_o} \right] \leq 1$$

with approximate CNS oxygen time limits in *min*,

$$t_o = 4140 \exp(-2.7 pp_o)$$

In both cases, violations of OT limit points result in dive computer warnings.

Within model implementations and recent practices, dive computers operate in modes consistent with a number of paradigms, support, and are part of a number of developments on the diving scene [4]:

1. reduced nonstop time limits consistent with Doppler bubble measurements;
2. exploding usage of nitrox and enriched breathing mixtures in recreational diving;
3. safe altitude diving extensions of sea level protocols;
4. in recreational diving, computers have supplanted dive tables, in technical diving, computers are backups for wrist carried decompression schedules;
5. deep switches to nitrogen based breathing mixtures are avoided by technical divers, with a better strategy of increasing oxygen fraction with commensurate decrease in helium fraction in the breathing mixture;
6. RB usage is increasing across the full spectrum of diving;
7. wrist dive computers possess chip speeds that allow full resolution and implementation of the most complex diving algorithms; the computer industry, at large, is becoming increasingly interested in marketing new dive computers.

Validation

To validate computer models [2], data is necessary. In the past, data consisted mostly of scattered open ocean and dry chamber tests of specific dive profiles. In such instances, the surface of correlating model and diving data was only scratched. Today, profile collection across diving sectors is proceeding more rapidly. Notable are the efforts [2,4] of Divers Alert Network (DAN) and Los Alamos National Laboratory (LANL). DAN USA is collecting profiles in an effort called Project Dive Exploration (PDE) here and DAN Europe has a parallel effort called Dive Safe Laboratory (DSL). The focus has been recreational dive profiles for air and nitrox. The LANL Data Bank collects profiles from technical diving operations on mixed gases for deep and decompression diving on OC and RB systems. Some interesting features of the data have emerged:

1. profile collection of diver outcomes is an ongoing effort at DAN USA, DAN Europe, and LANL and has aided in model tuning using rigorous statistical techniques;
2. there are no reported spikes in DCS/OT rates for recreational and technical divers using dive computers;
3. statistics gathered at DAN and LANL suggest that DCS/OT rates are low across recreational and technical diving, but that technical

diving is some 10-20 times riskier than recreational diving;

4. data from meter manufacturers and training agencies, reported as anecdotal at recent Workshops, suggests the DCS/OT incidence rate is on the order of 200/3,000,000 dives (underlying incidence) for computer users;

5. the underlying incidences in the DAN and LANL profile data are on the order of 60/190,000 and 23/2,900 respectively.

Profile collection efforts such as these enormously benefit divers and diving science. Without downloadable profile data from dive computers, meaningful algorithm and protocol analysis is very difficult. Profile data banks are important resources for all kinds of diving.

Powerful and useful as dive computers may be, there are some downsides with their usage [1,5].

1. pushing the computer beyond its model limits and correlation envelope;
2. not reading the operating manual;
3. ignoring warnings;
4. violating ascent rates;
5. diving with a computer that is not properly initialized;
6. ignoring ceilings;
7. using one computer for two divers;
8. improperly entering gas mixtures and pp_o set points;
9. twiddling overly liberal correction factors;
10. violating depth restrictions;
11. not performing pre-dive planning;
12. turning the unit off when in ERROR mode (less possible these days).

There are others imbedded, but the above gives the flavor. As with all task loading, risks decline with increasing diver proficiency and computer savvy.

Exercises

1. What are two short descriptors for DGM and BPM dive computers?
 - a) shallow stop; deep stop computers.
 - b) RB; OC computers.
 - c) recreational; technical computers.
 - d) RAM; ROM computers.
2. What are nominal ascent rates in dive computers?
 - a) 10 f sw/min.
 - b) 30 f sw/min.
 - c) 60 f sw/min.
 - d) none.
3. According to a DGM computer, what is the surfacing M – value in the 40 min compartment and what might a diver with inert gas (nitrogen plus helium) tension 70 f sw do?

- a) 72 f sw; proceed directly to the surface.
 - b) 61 f sw; proceed directly to the surface.
 - c) 72 f sw; make a decompression stop.
 - d) 61 f sw; make a decompression stop.
4. Audible and displayed computer warnings issued to divers include?
- a) ascent rate violations, OT violations, missed stops.
 - b) ascent rate violations, unsafe gas mixtures, breathing loop tears.
 - c) unsafe gas mixtures, air consumption violations, missed stops.
 - d) air consumption violations, OT violations, breathing loop tears.
5. If the separated phase volume calculated by a BPM computer is 250 microns³ at 66 f sw, what will be the surfacing value and can a mixed gas diver ascend directly to the surface?
- a) 250 microns³; yes.
 - b) 250 microns³; no.
 - c) 750 microns³; yes.
 - d) 750 microns³; no.

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Author Sketch

Bruce Wienke is a Program Manager in the Nuclear Weapons Technology/Simulation And Computing Office at the Los Alamos National Laboratory (LANL), with interests in hydrodynamics, applied mathematics, particle and nuclear physics, numerical methods, parallel computing, thermonuclear burn, decompression phenomenology and models, radiation and gas transport, bubble dynamics, and phase mechanics, publishing some 240+ technical and research papers in related Journals. He contributes to underwater symposia, educational publications, technical periodicals and decompression workshops, authoring eight monographs (Hyperbaric Physics With Bubble Mechanics And Decompression Theory, Reduced Gradient Bubble Model In Depth, Technical Diving In Depth, Physics, Physiology And Decompression Theory For The Technical And Commercial Diver, High Altitude Diving, Basic Diving Physics And Applications, Diving Above Sea Level, Basic Decompression Theory And Applications). Diving experience includes the Caribbean, South Pacific, Asia, inland and coastal United States, Hawaii, and polar Arctic and Antarctic on OC and RB systems in technical, scientific, military, and research exercises. He functions on the LANL Nuclear Emergency Strategy Team (NEST), above and below water, heading up the C & C Dive Team. Team activities often require coordination with Special Operations Commands (Delta, Recon, SEAL, PJ) in ameliorating WMD threats worldwide.

Wienke is Workshop Director/Trainer with the National Association of Underwater Instructors (NAUI), and served on the Board of Directors (Vice Chairman for Technical Diving, Technical and Decompression Review Board Member). Wintertime he hobbies ski racing, coaching, and teaching. As a Racing Coach and Instructor, he is certified United States Ski Coaches Association (USSCA) and Professional Ski Instructors of America (PSIA), and competes in the United States Ski Association (USSA) Masters Series, holding a 8 NASTAR racing handicap while winning a NASTAR National Championship in his age class in 2002, and Rocky Mountain Masters SL, SG, SG, and DH Championships in 2010 and 2012. He quarterbacked the Northern Michigan Wildcats to an NCAA-II National Championship in 1963, garnering All American Honors. Other pastimes include tennis, windsurfing, and mountain biking.

Wienke received a BS in physics and mathematics from Northern Michigan University, MS in nuclear physics from Marquette University, and PhD in particle physics from Northwestern University. He belongs to the American Physical Society (APS), American Nuclear Society (ANS), Society of Industrial and Applied Mathematics (SIAM), South Pacific Underwater Medical Society (SPUMS), Undersea and Hyperbaric Medical Society (UHMS), and American Academy of Underwater Sciences (AAUS). He is a Fellow of the American Physical Society, and a Technical Committee Member of the American Nuclear Society.

Wienke advises on decompression algorithms across exploration, recreational, technical, commercial, scientific, and research sectors, and developed the reduced gradient bubble model (RGBM), a dual phase approach to staging diver ascents over an extended range of diving applications (altitude, nonstop, decompression, multiday, repetitive, multilevel, mixed gas, and saturation). Many modern dive computers incorporate the modified and iterative RGBM into staging regimens for OC and RB mixed gas diving. In lock step, computer software and platforms offer RGBM for technical dive planning and profile analysis. A number of Training Agencies employ RGBM tables, software, and meters for hands on training and education within their Standards and Procedures. Wienke also brought the RGBM Data Bank online for model and profile analysis and risk assessment. The RGBM Data Bank is similar to the DAN PDE Data Bank but focuses on tec diving data. The RGBM Data Bank presently contains 3000+ mixed gas, OC and RB, decompression profiles with 23 cases of DCS. The Data Bank has been instrumental in RGBM success worldwide and a valued component of C&C dive planning over the past 12 years.

Wienke serves as Reviewer Editor for the Journal of Computational Physics, Physical Review, Transport Theory and Statistical Mechanics, Applied Physics, Nuclear Science and Engineering, Nuclear Fusion, Journal of Quantitative Spectroscopy and Radiation Transport, Nuovo Cimento, and Journal of Applied Physics. He is also an Associate Editor for the International Journal of Aquatic Research and Education, a Contributing Editor of Sources, the NAUI training periodical, and a Contributing Editor of Advanced Diver Magazine, a trade publication for technical diving.

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