Consequently, it was agreed that a dive computer should be both "down-loadable" and compatible with the DAN database.

It is clearly possible to use a dive computer for multi-level diving in such a fashion that the consequent accumulated exposure constitutes a very high risk for decompression illness. The Workshop was unanimous in support of the need to impose "safe" diving practice on computer assisted divers, e.g. dive planning must have priority, only one dive/day to any depth beyond 30 msw etc. see page 204 for the actual Society policy.

There was considerable discussion on the features that a DCC should have and agreed essential features are included in the policy. There was some disagreement on whether there should be a standard format for information display (analogous to that being introduced for anaesthesia equipment). Despite objections that this would constrain developers of dive computers, it was agreed by a large majority that a common display format (ie. specific information, such as elapsed time, would appear in the same "place" in the dive computer display) was needed to improve the reliability of dive computer use/review by novice divers, divers who have recently purchased a dive computer and dive buddies.

Of major concern was the report that 30% of surveyed divers who used a dive computer had experienced a dive computer failure during a dive. Even allowing for improvements in dive computer design since these data were collected, it is clear that sole reliance on a dive computer can not be advocated and that divers must have access to abort procedures. This again underlines the need for dive planning.

The issue of training was raised in the specific context of: the recreational instructor agencies and general training; the obligations of a retailer of dive computers to purchasers of dive computers; and the obligations of purchasers themselves. Consensus statements were possible and these are included in the policy.

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UNDERSTANDING DIVE TABLE AND METER PROCEDURES

Bruce Wienke

Diving model

Decompression sickness results from excessive changes in ambient pressure over a particular period of time. With simple decompression sickness, bubbles, or some related form of free gas phase, are thought to trigger a complex chain of physico-chemical reactions in the body, affecting the pulmonary, neurological, and circulatory systems adversely. Many factors are relevant to the formation of bubbles, such as gas uptake and elimination in the tissues and blood, gas solubility and diffusivity, tissue vascularity and type, breathing mixture, amount of pressure reduction, temperature, presence of preformed nuclei, and individual susceptibility. To prevent decompression sickness, appropriate diving measures limiting depth, time, and repetitions form the basis of diving tables and schedules, more recently encoded into digital underwater computers.

History

Tables and schedules for diving at sea level can be traced to a model proposed in 1908 by the eminent English physiologist, John Scott Haldane.[1] He observed that goats, saturated to depths of 165 feet of sea water (fsw), did not develop decompression sickness if subsequent decompression was limited limited to half the ambient pressure. Extrapolating to humans, researchers reckoned that tissues tolerate elevated dissolved gas pressures (tensions), greater than ambient by factors of two, before the onset of symptoms. Haldane then constructed schedules which limited the critical supersaturation ratio to two in hypothetical tissue compartments. Tissue compartments were characterized by their halftime, τ, that is, the time required for the compartment to halve (loose) or double (gain) dissolved nitrogen. Halftime is also termed halflife generically for exponential (decay) processes. Five compartments (5, 10, 20, 40 and 75 minutes) were employed in decompression calculations and staged procedures for fifty years.

Some years later, in performing deep diving and expanding existing table ranges in the 1930s, Hawkins and Shilling,[2] and Yarborough[3] assigned separate limiting tensions (M-value) to each tissue compartment. Later in the 1950s and early 1960s, Dwyer,[4] Des Granges [5] and Workman,[6] in addressing repetitive exposures for the first time, advocated the use of six tissues (5, 10, 20, 40, 80 and 120 minutes) in constructing decompression schedules, with each tissue compartment again possessing its own limiting tension. Temporal uptake and elimination of inert gas was based on mechanics addressing only the macroscopic aspects of gas exchange between blood and tissue. Exact bubble production mechanisms, interplay of free and dissolved gas phases, and related transport phenomena were not quantified, since they were neither known nor understood. Today, we know much more about dissolved and free phase dynamics, bubbles, and transport mechanisms, but still rely heavily on the Haldane model. Inertia and simplicity tend to sustain its popularity and use, and it has been a workhorse.

Dissolved Gas Exchange

Dissolved gas models limit degrees of tissue supersaturation, assuming gas exchange is controlled by perfusion (blood flow rate) or gaseous diffusion in blood-tissue media. Exchange of inert gas is driven by the local gradient, that is, the difference between the arterial blood and local tissue tension. Obviously the exchange process is very complicated, and models are only approximate. The dissolved gas model emerged early in the Haldane studies of decompression and dominated models for many years, as charted by Behnke,[7] Hempleman,[8] Bühlmann,[9] Crocker,[10] and Workman.[6] Recent application and twists on the Haldane model can be seen in studies by Nishi,[11] Thalmann,[12] Spencer,[13] Weathersby[14] and others.

Perfusion limited gas exchange is modeled in time by mathematical classes of exponential response functions, bounded by arterial and initial tissue tensions. Compartments with 2, 5, 10, 20, 40, 80, 120, 240, 360, and 480 minute halftimes, τ, are employed in applications today, and halftimes are assumed to be independent of pressure. A one-to-one correspondence between compartments and specific anatomical entities is neither established nor implied. For large values of τ, tissue uptake and elimination of inert gas is relatively slow according to the response function. For small values of τ, inert gas uptake and elimination proceed much more rapidly. According to Kety,[15] the major controlling factor is the blood flow rate, $1/\tau$ effectively. Actually, gas uptake and elimination in all tissues is not controlled just by perfusion. Diffusion may dominate in certain tissue types, regions with lesser vascularity and greater distance between capillaries, such as bone and spinal cord. In others, both perfusion and diffusion are rate limiting.

The rate of uptake and elimination of inert gas is symmetrical when the same set of tissue halftimes are employed in calculations. However, this is not always the case. Microbubbles in the circulatory system, particularly venous gas emboli, render gas uptake and elimination asymmetrical. Bubbles in the interstitial areas, or agglutination of red blood cells in reaction to foreign bubbles would have similar effect on local perfusion rates. In such instances, halftimes for uptake are then theoretically shorter than halftimes for elimination.

Critical Tensions

Haldane theory limits degrees of dissolved gas buildup, hypothetically absolute compartment supersaturation, by critical values, M, having a modern range, $122 \leq M \leq 36$ fsw, notably of American origin. Equivalently, critical ratios, R, and critical gradients, G are also employed, with the $R = M/P$ and $G = M - P$, for P, ambient pressure. Critical parameters evolved from self consistent application of assumed tissue response to sets of exposure data, that is, trial and error bootstrapping of model equations to observed exposure time limits. Newer compilations ultimately extend older ones in like manner.

At depth the critical tension is the sum of M_0 and ΔMd, that is, $M = M_0 + \Delta Md$. Such parameters form the basis for most tables and meter algorithms, with a noted recent tendency to reduce critical tensions and (consequenfly) no-stop time limits for safety.

Validation is central to diving, and significant testing of no-stop and saturation diving schedules has transpired. In between, repetitive (more than one dive in a 12 hour period), multi-level (arbitrary depths throughout the course of a single dive), deeper-than-previous (second repetitive dive deeper than first), and multi-day (repetitive dives over days) diving cannot claim the same benefits, though some ongoing programs are breaking new ground. Application of (just) dissolved gas models in latter cases possibly has witnessed slightly higher decompression sickness incidence than in the former ones, as discussed in newsletters, workshops, and technical forums. Some hyperbaric specialists also suggest higher incidence of rash (skin bends) under repetitive loading. While statistics are not yet conclusive, they raise some concerns theoretically addressed by considering both dissolved and free phase gas buildup and elimination in broader based bubble models. Such models often focus on the amount of free phase precipitated by compression-decompression, and contain dissolved gas models as subset. In limiting the volume of free phase in time, they must also limit the growth rate.

Tables and meters

Operational diving requires arbitrary numbers of dives to various depths over periods of hours, and often days. Once a standard set of decompression tables has been constructed, with bounce diving the simple case of no-stop decompression, a repetitive dive procedure is a necessity. After any air dive, variable amounts of dissolved and free residual nitrogen remain in body tissues for periods of 24 hours, and more. Similarly, elevated tissue tensions can promote, or sustain, bubble growth over the same time scales. This residual gas buildup (dissolved and free) will shorten the exposure time for subsequent repetitive dives. The longer and deeper the first dive, the greater the amount of residual tissue nitrogen affecting decompression on subsequent dives. No-stop depth-time allowances for repetitive dives are reduced in such circumstance. Within bubble models, residual free gas phases are also included in procedures, imposing additional constraints on repetitive diving. The many possibilities are easily tracked in continuous time mode by computers, as mentioned, but tables face a more difficult task.

Tables

Considering only dissolved gases, one standard table approach groups combinations of depth and exposure times according to the surfacing tension in the slowest compartment. Then it is possible to account for desaturation during any arbitrary surface interval. The remaining excess nitrogen at the start of the next dive can always be converted into equivalent time spent at the deepest point of the dive. So called penalty time is then added to actual dive time to update appropriate tissue tensions. Surfacing tensions in excess of 33 fsw (absolute) in the slowest compartment are assigned letter designations (groups), A to O, for each 2 fsw over 33 fsw. Any, and all, exposures can be treated in this manner. To credit outgassing, a Surface Interval Table, accounting for 2 fsw incremental drops in tensions in the slowest compartment, is also constructed. Such procedures are bases for the US Navy Air Decompression and Repetitive Surface Interval Tables, with the 120 minute compartment (the slowest) controlling repetitive activity. Standard US Navy Tables provide safe procedures for dives up to 190 fsw for 60 minutes. Dives between 200 and 300 fsw were tested and reported in the exceptional exposure US Navy tables, including a 240 minute compartment. The Swiss tables, compiled by Bühlmann, incorporate the same basic procedures, but with a notable exception. While the US Navy tables were constructed for sea level usage, requiring some safe extrapolation procedure to altitude, the Swiss tables are formulated and tested over a range of reduced ambient pressure. The controlling repetitive tissue in the Buhlmann compilation is the 635 minute compartment.

While it is true that the table procedures just described are quite easily encoded in digital meters, and indeed such devices exist, digital meters are capable of much more than table recitations. Pulsing depth and pressure at short intervals, digital meters can monitor diving almost continuously, providing rapid estimates of any model parameter. When employing exactly the same algorithms as tables, meters provide additional means to control safety beyond table lookup. When model equations can be inverted in time, meters can easily compute time remaining before decompression, time at a stop, surface interval before flying and optimal ascent procedure. Profiles can be stored for later analysis, and the resulting data bank used to tune and improve models and procedures. Considering utility and functionality, meter usage should increase in diving, supported by technological advance in computing power, algorithmic sophistication and general acceptance, though it will probably be some time before tables are supplanted.

Meters

On the heels of growing interest in underwater science and exploration following World War 2, monitoring devices have been constructed to control diver exposure and decompression procedures. Devices, with varying records of success, include mechanical and electrical analogues, and within the past 15 years, microprocessor based digital computers. With inexpensive microprocessor technology, recent years have witnessed explosive growth in compact digital meter usage. All use the simple dissolved tissue gas model proposed by Haldane some 80 years ago, but given the sophistication of these devices, many feel that broader models can be incorporated into meter function today, increasing their range and flexibility. Although the biophysics of bubble formation, free and dissolved phase build-up and elimination is formidable, and not fully understood yet, contemporary models treating both dissolved and free phases, correlated with existing data, and consistent with diving protocols might extend the utility of diving computers. Approaches to treating bubble nucleation, excitation and growth in tissue and blood have been developed. In the industry, such new models are termed bubble mechanical, because they focus on bubbles and their interactions with dissolved gas in tissue and blood.

Decompression computers are fairly inexpensive items these days. Basically a decompression meter is a microprocessor computer consisting of a power source, pressure transducer, analog to digital signal converter, internal clock, microprocessor chip with RAM (random access memory) and ROM (read only memory), and pixel display screen. 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, usually every 3-5 seconds. Results are displayed on the screen, including time remaining, time at a stop, tissue gas build-up, time to flying, and other model flag points, usually Haldanean (perfusion) tissue control variables. 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 (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 in consoles, or even integrated into head-up displays in masks.

Statistics point to an enviable track record of decompression meter usage in nominal diving activities, as well as an expanding user community. When coupled to slow ascent rates and safety stops, computer usage has witnessed a very low incidence rate of decompression sickness, below 0.01% according to some reports.

Patterns of diving

Repetitive and decompression diving probably contend with a greater fraction of separated gas. And this makes extrapolations of bounce diving fits more difficult. In the early days, slower tissue compartments were added to accommodate deeper, prolonged, and decompression exposures. Ostensibly, slower compartments might track a greater proportion of separated gas, possibly dumped from tissues into gas micronuclei. Laboratory studies in decompressed gels bear witness to typical growth and elimination patterns in gas nuclei and bubbles spanning hours. Of course, bubbles and nuclei in the body are both perfused and metabolic, adding to complexity. While not always optimal, tissue response functions with very slow compartments can be coupled to critical tensions for repetitive diving. The approach is more limited for repetitive diving than bounce diving, as possibly witnessed by higher bends incidence in divers embarking on multi-day and repetitive activity, according to DAN. In such repetitive application, tables and meters which do not accommodate slower compartments, those longer than 60 minutes, appear further limited. For that very reason, the US Navy expanded the original set some fifty years ago, replacing the 70 minute compartment with an 80 minute compartment and adding the 120 minute compartment. Yet, the tendency today to add compartments in the several hundred minutes range, while well intentioned, is probably not the best means for tracking separated phases. Very slow compartments, in the several hundred minutes range, cannot really control multi-day and heavy repetitive diving by tracking just dissolved phases. Present consensus thus cautions against 3 or more repetitive dives in any 24 hour period, especially in the deeper categories (beyond 100 fsw), and relaxation periods of at least a day following 3-4 days of repetitive activity.

Repetitive Diving

The Haldane approach to repetitive diving parallels that for bounce diving. Critical tensions again limit permissible degrees of compartment saturation. However repetitive applications of dissolved gas models have not enjoyed the overall successes of bounce diving applications. Free phases in the tissues have had some time to grow between dives, and the next dive then pumps in a fresh supply of dissolved gas, possibly feeding phase growth if elimination has not been effective. Free and dissolved gas phase elimination time scales are generally not equal in any given tissue compartment, which is the root of the concern in multidiving. Some suggest that halftimes for free phase elimination are double those for dissolved phase elimination in the same tissue.

Multi-level Diving

Multi-level diving represents yet another dimension for application of the classical scheme, especially within table application, but less so with digital devices. The reason is not too complicated. Tables generally rely on the slowest tissue compartment to dictate staging and repetitive formats. Repetitive intervals are chosen so that the faster compartments cannot control the exposure upon surfacing, with 10 minutes the usual limit. Tables cannot account for gas uptake or elimination in faster compartments for short time intervals, and so require that short time intervals be added directly to exposure times. In multi-level table application, the 10 minute interval is neglected, and gas exchange in the faster compartments is not considered. At times neglect of the faster compartments causes trouble, especially when their critical tensions are exceeded with the tables blind for some 10 minutes. Because meters continuously monitor activities in all compartments, these table concerns are minimised in multi-level excursions. While such a problem is more an implementation issue than a fundamental issue, foregoing concerns in bounce, repetitive and decompression exposures still carry over here.

Schemes for multi-level diving are employed in the commercial, scientific, sport, and military sectors. One popular approach employs back to back repetitive sequencing, assigning repetitive table groups at the start of each multi-level segment based on the total bottom time (actual plus residual nitrogen) of the previous segment. At times, the method allows critical tensions, other than the controlling 120 minute compartment in the US Navy tables, to be exceeded upon surfacing. In the spirit of the US Navy tables, such circumstance is suspect, at least. But by tightening the permissible exposure window, and accounting for ascent and descent rates, the multi-level technique can be made consistent with the critical tension formulation of the US Navy tables.

In studying this technique, Wienke and Graver drew a line (envelope) across the US Navy Repetitive Group Table, separating multi-level dives violating at least one critical tension in the sequence from those violating no critical tensions. The line simply moves the no-stop time limits back a group from the US Navy no-stop time limits. Ascent and descent rates of 60 fsw/minute were assumed in constructing the multi-level envelope. Applying the back to back repetitive technique only to the safe side of the no-stop time limits maintains tissue tensions in the 5, 10, 20, 40, 80, and 120 minute compartments below the Workman critical values throughout the dive, and upon surfacing. Some 16 million multi-level dives were analysed on a CRAY XMP supercomputer in a few minutes, permitting construction of the envelope. Compared to the standard US Navy tables, the envelope, moving no-stop time limits back a group, also restricts the back to back repetitive method in same measure.

Systematically deeper to shallow diving practices are optimal in all cases. Deeper than previous excursions have the potential to excite smaller, more stable, gas nuclei into growth. Deeper spike and sawtooth diving profiles become more hazardous as repetitive frequency increases, probably due to the presence of growing bubbles and excitable gas nuclei in slower tissues and slingshot effect of higher tensions surrounding them.

Recommendations for safe diving

A set of discretionary protocols, not necessarily endorsed in all diving sectors, might be summarised as follows.

1 reduce no-stop time limits a repetitive group or two below the standard USN limits;
2 maintain ascent rates at below 18 m a minute, preferably slower and requisitely slower at altitude;
3 limit repetitive dives to a maximum of three per day, not exceeding the 30 m level;
4 avoid multi-day, multi-level or repetitive dives to increasing depths;
5 wait 12 hours before flying after nominal diving, 24 hours after heavy diving (taxing, near decompression or prolonged repetitive) diving and 48 hours after decompression diving;
6 avoid multiple surface ascents and short repetitive dives (spikes) within surface intervals of 1 hour;
7 surface intervals of more than an hour are recommended for repetitive diving;
8 safety stops for 2-4 minutes in the 3-6 m zone are advisable for all diving, but particularly for deep (near 30 m), repetitive and multi-day exposures;
9 do not dive at altitudes above 3,000 m using modified conventional tables or linear extrapolations of sea level critical tensions;
10 in short dive conservatively remembering that tables and meters are not bends proof.

Procedures such as those above are prudent, theoretically sound and safe diving protocols. Ultimately they link to free phase and bubble mechanisms.

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