DEVELOPING THE DSAT DIVE COMPUTER MODEL

Ray Rogers

Summary

The modified algorithm computes conventional solutions for typical diver behaviour. It results in dive times and gas loadings similar to those of the Recreational Dive Planner. Calculated gas loadings are consistent with Institute of Applied Physiology and Medicine test data. The algorithm intervenes to restrict profiles of aggressive divers. The degree of restriction increases as diving "aggressiveness" increases.

Background

In the 1980's, the Professional Association of Diving Instructors (PADI) set out, through its corporate affiliate Diving Science and Technology (DSAT), to test decompression systems designed to replace the use of US Navy dive tables by recreational divers. Following successful tests at the Institute of Applied Physiology and Medicine (IAPM), PADI began distribution of the Recreational Dive Planner (RDP), in two formats, a circular slide rule called The Wheel™ and in a tabular format. The DSAT/IAPM research program[1] is the only significant investigation of recreational profiles, and shortly after introduction of the RDP, some of the research data were used in a number of dive computers.

Field experience of the RDP was good and interest grew in adapting the DSAT algorithm itself, not just its supporting laboratory data. DSAT was asked about the use of its algorithm, but said the program was not suitable for direct implementation in computers without extensive modification. These modifications have been made. This paper discusses the changes needed to produce the DSAT Dive Computer Model.

In testing the RDP, the study was limited to profiles allowed by the RDP, which permits only no-stop (no-stop) diving in accordance with long-standing PADI policy. Test profiles were planned to find the beginning of bubble generation while avoiding exposures that might cause decompression sickness. The tests were almost free of DCS but asymptomatic bubbles occurred as expected, suggesting that DCS might be a consequence of exposures that were appreciably more severe, i.e. for deeper or longer. A dive computer if using the identical limiting parameters as the RDP would allow greater dive time than the RDP, and might cause unacceptably high tissue nitrogen pressures. A computer based on DSAT/IAPM research should limit exposures so that compartment pressures are no greater (preferably even less) than the pressures that occurred during testing. Since it is impossible to measure pressures, a table model should be made more conservative to be used in a computer.

A primary goal of the development of the DSAT dive computer model was determination of methods which would result in dive computer profiles that are generally equivalent to DSAT Wheel profiles. Equivalence does not imply equality. Equality would be nearly impossible to achieve, and is not necessarily desirable. Equivalence implies similar gas loadings for similar exposures and further implies that bottom times would be reasonably similar for computer users and Wheel users, if a generally similar dive pattern is followed; slight deviations between the two modalities would be expected.

General description of the DSAT dive computer model

The DSAT computer model includes (among others) the following premises:

1. Haldanian theory does not explain all hyperbaric phenomena,
2. while gas overpressures are responsible for most presentations of decompression sickness, it is likely that manifestations occur with pressures thought to be tolerable,
3. the risk associated with performance of a large number of dives in a short span of time has not been adequately assessed, but when developing a decompression system, it is prudent to assume that this risk exists

A Haldane model calculates theoretical pressures in a series of tissue compartments as a diver is exposed to greater and lesser ambient pressures. Calculation results may be used to determine whether a diver may ascend directly to the surface without a decompression stop, to determine times and depths of decompression stops when needed, to monitor pressures as a diver changes depth in multi-level diving, and to calculate the amount of gas lost at the surface for determination of permissible time on a subsequent dive.

A dive computer based on the DSAT algorithm is in harmony with the philosophy and intent of DSAT and PADI. The restrictions and limitations of the RDP were founded in experience and research, and were incorporated into the computer model, in spirit if not in detail. Cautions, warnings and alerts needed to implement RDP limitations are displayed. Calculations continue even if rule violations occur, but only with visual and/or audible warning. The computer allows continued diving and does not go into error mode, but this continuation is accompanied by appropriate advice against continuing. The theoretical model is basically designed for no-stop diving and discourages intentional stage decompression diving, although the computer displays decompression information when needed.

Modified Haldanian methodology is the basis for monitoring diver status. Gas pressures are computed instantaneously for the 14 RDP theoretical compartments that manifest symmetrical, exponential on-gassing and off-gassing, and adhere to the prescribed limit values. No-stop limits are reached when compartments reach their "M-values".

The provision for safety stops at 5 m for 3 to 5 min is routine for every dive, whether the dive reached a limit or not. If a depth was to more than 30 m, an alert is displayed on later dives when depth reaches 30 m, unless there has been a surface interval of 6 hours. Alerts warn against ascent rates greater than 18 m/min. Slower rates are acceptable. Decompression stops are made at 5 m, unless compartment pressures are too great; in that case, the depth is 8 m. Decompression obligations are stringent: if a no-stop limit is exceeded by 5 min or less, the computer requires a stop at 5 m for at 8 minutes and that the diver cease diving for 6 hours. If a no-stop limit is exceeded by more than 5 minutes, the computer requires a stop at 5 m for 15 minutes (air supply permitting) and that the diver cease diving for at least 24 hours. Flying after diving notice is consistent with the latest internationally accepted guidelines.

Differences between dive tables and dive computers

Dive tables are inherently more conservative than their underlying model because:

1 depths and times are rounded off to the next greater values, and exposures are therefore not as severe as the table calculates them to be, and

2 tables calculate surface off-gassing on the basis of a single compartment, and this compartment is usually slower than the one which actually constrains a dive. Tables cannot make calculations during a dive; they are first calculated as multi-compartment models and modified to be more of a single-compartment model.

Computers do not have this problem, since they do not need to round off or depend on a single compartment.

There is another reason why tables are conservative:

3 recreational divers almost never operate at a single depth; they move freely up and down. The practice is to record the depth as the deepest point of a dive, and the average depth is usually significantly less than the greatest depth. As a result, tissue pressures are less than table determinations. This is in addition to the round-off mentioned above. A dive to a constant depth of 28 m is rounded to 30 m and a dive which was mostly between 24 and 26 m but went for a moment to 28 m, would also be rounded to 30 m.

Testing of dive tables requires use of the most severe exposures possible under the tables, and this means that all tests are at constant depths. A test of a 20 m exposure is conducted at exactly 20 m, which is very different to a dive to 20 m as done by a typical recreational diver. Laboratory tests therefore generate higher tissue pressures than table dives, and the difference is welcome, because some respected scientists think that a dive in open water (for a given time and depth) is more likely to produce decompression sickness than a chamber dive for exactly the same time and depth. Tables have a built-in margin of conservatism (they are always wrong but always conservative).

In contrast computers do not provide the same margin of conservatism; they are able to calculate the theoretical tissue pressures precisely. It is therefore necessary that computers use a slightly different mathematical basis from tables and their calculations must appear to yield lower tissue tensions than tables, which always err on the high side. This is done by programming the computer to determine pressures which seem to be lower than table determinations, so that a computer user will have gas loading similar to a table user.

These details must not obscure the fundamental goal: the development of procedures which maintain tissue pressures within acceptable levels. This is the primary purpose of all decompression systems; ideas such as M-values, no-stop limits, theoretical tissue compartments and half times are only artificial concepts that were created to serve the fundamental goal. They are useful mathematical devices which assist in the process of attempting to prevent injury from inert gas overpressure. They have no demonstrated real basis in physiology. The concepts are probably correct, but we cannot prove or disprove that they are. It probably does not even matter about physiological accuracy; what is more important is whether the ideas can be used to devise successful methods.

Adjustments to the DSAT RDP model

The most important changes in adapting the RDP model for computer use are:

1 active and unrestricted use of the entire range of theoretical compartments,

2 reduction of the M-values for all compartments,

3 progressive reduction of the surface interval credit as dive severity increases.

Active and unrestricted use of the entire range of theoretical compartments

The RDP system of Pressure Groups and surface interval credit are a function of pressure in the 60 minute half time compartment. For many repetitive dives, the RDP is unnecessarily restrictive: its operation assumes that most dives are controlled by that compartment. Because this restriction is conservative it was allowed. Modifications were made when the model was not conservative (multi-level diving and multiple long shallow dives)

These RDP adaptations result from the need to choose a single compartment on which to base the surface interval system for repetitive dives, but a computer can calculate all compartment pressures, and is free from this limitation. Fourteen compartments were used to compute the rules of the RDP. Once the calculations were completed and incorporated into the RDP, these multiple compartments had only a passive role in RDP operation. A computer designer could use these same rules, but would be giving up one of the primary advantages of computers. Using a broad range of compartments allows a computer to be free of these rules that sometimes limit a diver excessively.

Reduction of M-values for all compartments

As discussed before, computers allow more time than tables. A Wheel user who wants to dive to 30 m knows that dive time is 20 minutes. Even though the diver may move in a range of 25 to 30 m, the time is still 20 minutes. The compartment pressures would be less than if the diver stayed at 30 m the entire time; a computer would know that, and would permit a diver to remain at these depths for well over 20 minutes. A carefully determined reduction of compartment pressure limits would cause computer divers and Wheel divers to return to the surface at more nearly the same time.

Progressive reduction of the surface interval credit as dive severity increases

Performance of multiple dives in a day has been identified as a risk factor for DCS. If this type of diving continues for multiple days, the risk factor is thought to be increased. There is no convincing proof for these beliefs, but they are widely accepted. The only significant body of evidence in this area is the Phase IIb testing at IAPM, and it indicates that bubbling increases during a day but multi-day diving did not increase the amount of bubbling; these data appear to indicate that the number of single-level dives is more important.

Yet, there is anecdotal evidence that multi-day diving does cause problems, if only because multi-day divers have more opportunities for trouble; caution suggests that the question should be addressed. Accordingly, it would be prudent to restrict this type of diving by modifying the computer's program. Simple mathematical functions can progressively reduce the apparent surface interval time in certain situations. Higher risk dives become shorter when a diver is aggressive, but cautious divers are unaffected.

The combined effect of these adjustments is that average dives are calculated in a typical Haldanian fashion, but the computer intervenes to restrict aggressive divers.

Preliminary determination of M-values

M-values of the DSAT computer model are derived from a curve of no-stop limits. This curve is a variation of one described by Powell, Spencer and Rogers.[2] It uses different determinants from those of the original curve, to establish a conservative "best fit" to a series of tentative M-values which were empirically derived from a great many simulations of IAPM test profiles. The differences between the two curves result from an effort to harmonise output from static dive tables and dynamic dive computers.

The first step in developing the computer model was deciding the relationship between compartment pressures generated in IAPM tests and the M-values for the model. Extensive analysis with software written for this purpose showed that uniform reduction of DSAT Wheel M-values would serve very well, as long as the reduction was internally consistent and was based in reality. A principle called "random walk" was used to simulate the actions of divers, who seldom stay at a single level but move vertically in the water column. Random walk is a concept that says that circumstances are as likely to remain stable as to change, and that small changes are more likely than large. In modified form, it can describe a diver's movement in the water column and can be a useful tool for desktop computer simulations.

The software used inputs from either a keyboard or reading a data file. Degree of depth variation was specified (10%, 20% and 40% depth variations were examined) and the computer then simulated dives to each chosen depth for the specified time. Compartment pressures were updated every second. Summary and detailed data files were written to store the results for later use. On completing a profile, the process was repeated until a specified number of simulations were done; maxima of all simulations were averaged.

Every test profile conducted at IAPM was simulated many times. Depth variations of 0%, 10% and 20% were used for each profile (the 0% simulations corresponded exactly to actual tests). The IAPM tests were isobaric, equivalent to constant depths, and they produced higher compartment pressures than simulations to lesser depths. These higher pressures provided a useful comparison to the more conservative M-values of the model.

Accumulated data were entered into spreadsheets for a determination of the maximum calculated compartment pressures. The highest pressures generated in each compartment were considered as tentative M-values which served as starting points to generate graphs that could be examined, analysed, rationalised, and perfected. After compiling and examining simulation data and comparing the graphs that resulted from the compilations, the determination was made that the simulations which varied by 10% were sufficiently conservative, relative to isobaric simulations, without being excessively restrictive.

The next step was determining the most suitable curve of no-stop limits. The new curve needed to be more conservative than the original, requiring a rational method of adjustment. As described in Powell, Spencer and Rogers,[2] the curve is determined by three parameters: a deep exposure to its limit, a shallow exposure to its limit, and a depth at which, it is presumed, one may stay indefinitely and return safely to the surface. With addition of appropriate adjustments and modifications, a plot was created to serve as the basis for the DSAT computer model.

An aspect of the DSAT algorithm is internal consistency: all values in the model agree with each other. A curve of no-stop limits might be irregular if derived from empirical data that are irregular, but there is no need for the model to perpetuate these irregularities. This is even more important for a computer, which employs a series of separate compartments that must be coordinated, if it is to yield a smooth and "seamless" flow of information. The best way to eliminate the irregularities was to generate a series of curves by varying the three determinants and fitting the curves to the simulation data, with the goal of deriving M-values directly from the curve and inferentially from IAPM data. The criterion used for curve fitting was: new M-values must be no greater than (or less than) simulation pressures. Tentative M-values were already more conservative than the tests from which they were derived; this step added another level of conservatism.

This no-stop limit curve met desired mathematical and scientific expectations, but additional adjustments were made for the very fast and very slow compartments:

1 The DSAT algorithm has no-stop limits of 39 m (130 ft) for 12 minutes, 36 m (120 ft) for 14 minutes, and 33 m (110 ft) for 17 minutes, which were tested repeatedly during IAPM Phase I. For conservatism, these limits were later reduced slightly to 39 m (130 ft) for 10 minutes, 36 m (120 ft) for 13 minutes, and 33 m (110 ft) for 16 minutes. The pressures of the tests are therefore higher than the M-values that would produce the lower limits. The computer model M-values for the fastest compartments correspond to the pressures that would have developed with the reduced limits, not the higher pressures that actually occurred.

2 For the very slow compartments, the graph uses the maximum calculated pressures that actually developed during the IAPM tests, not the lesser amounts of the random walk variations. Compartments with very long half times are less influenced by rapid and temporary depth changes.

Progressive reduction of surface interval credit

There are many ways to impose an artificial reduction on the activity of the computer in those cases when a diver begins to "push" limits, makes several dives near limits, or both. Many alternatives were considered in search of procedures to address the possibility that slow compartments can gradually accumulate excessive pressures, even in no-stop diving. The method selected acts progressively to restrict the apparent surface interval time during over-zealous diving, resulting in an automatic reduction of time on later dives.

The restrictions operate at several levels:

1 In the calculation of off-gassing, time at the surface is multiplied by a time factor (TF), which is normally 1. If the calculated pressure in the 60 minute compartment on surfacing exceeds a defined threshold level, TF is reduced. In the first occurrence, TF is reduced from 1 to an amount less than 1, and in a later occurrence, it is reduced from its previous level. The amount of reduction depends on the degree to which the threshold level is exceeded. This mechanism reduces the calculated off-gassing during the surface interval.

2 The threshold level is decreased whenever it is exceeded, making it ever easier to initiate the reduction process.

3 If the threshold level has been exceeded previously, TF is decreased directly for each additional time that the level is exceeded.

4 These three reductions apply to all compartments equally, but an additional factor related to magnitude of half time (HT) is also used to reduce TF. This results in a non-linear limitation of the apparent surface interval. The decrement is New TF = Old TF-(HT/constant), and it magnifies the importance of slower compartments. Since the apparent compartment pressures are higher than true pressures, the combined effect of the four adjustments is both synergistic and cumulative.

5 Once the time reduction factor has been activated, it remains in effect until the diver has been at the surface for 6 hours (real time); then it is reset to unity. It is only TF that is reset: the higher-than-customary pressures remain at the last calculated levels

References

1 Hamilton RW, Rogers RE, Powell MR and Vann RD. *The DSAT Recreational Dive Planner: development and validation of no-stop decompression procedures for recreational diving*. Santa Ana, California: Diving Science and Technology Corporation, 1994
2 Powell MR, Spencer M and Rogers RE. *Doppler Ultrasound Monitoring of Gas Phase Formation Following Decompression in Repetitive Dives. Appendix C: The RE Rogers Modifications of JS Haldane's Algorithm*. Santa Ana, California: Diving Science and Technology Corporation, 1988

This paper was prepared as a written submission for presentation at the South Pacific Underwater Medicine Society's Dive Computer Workshop in May 1994. At the time of publication the DSAT dive computer model described above has been used in the SAS DC-II, a Japanese made computer which is only available in Japan.

The address of Raymond E. Rogers, DDS, who developed the Recreational Dive Planner, is P.O. Box 759, Blairsville, Georgia 30512, USA.

ARTICLES OF INTEREST REPRINTED FROM OTHER JOURNALS

AN EPIDEMIC OF DECOMPRESSION ILLNESS

Tom Millington and Bob Izdepski

How do you treat a paralysed diver without a recompression chamber? This was the question asked of me by Dr Benno Marx several years ago. He is a family physician who runs the Clinica Evangelica Morava in Ahuas, Honduras, and he was troubled by the increasing numbers of paralysed Miskito divers who were presenting to his clinic on the Mosquito coast.

The Mosquito Coast (La Mosquitia) is the region of southern Honduras and northern Nicaragua which is on the Caribbean Sea. The coastal marshlands are spider webbed by rivers that recede into low lying rain forests and then snake up into fog whiskered mountains. To this landscape add the Mosquito Indian tribal people with their superstitions and ignorance, who are now able to bring in large amounts of money by diving for spiny lobster using scuba.

The population of La Mosquitia in Honduras is about 45,000 and about 10% of them are lobster divers. The divers are recruited in small villages and taken to the "mother boat," which is about 15 metres long. Typically there are 20 to 25 divers (buzos), none with any training. There are also 20 to 25 men who serve as paddlers for the dugout canoes from which the divers actually perform their dives.

The diving takes place in waters up to 450 km off the coast, and the trips are about 2 weeks long. The divers won't dive unless they smoke marijuana as it "helps them see the lobster better." They frequently drink rum before the dives, for the same reason.

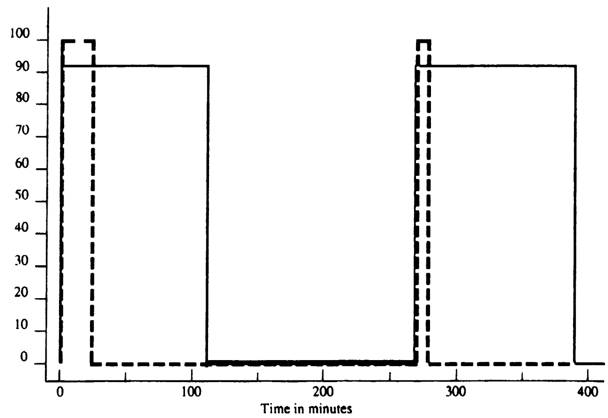

Figure 1. The solid line shows the profile of a typical Miskito daily dive (From a recording made with a Suunto dive computer, courtesy of Richard Dunford). This diver used 4 tanks on each of the two dives, surfacing for less than 6 minutes, bottom to bottom, for each change, as the tank change profiles do not show on the printout. Dotted lines show allowable time using USN no-stop tables, with same surface interval (165 minutes) for comparison.

The canoe leaves the mother boat with the diver, paddler, and 3 or 4 tanks. The diver descends directly to depths of 35 m (120 feet) and deeper (as the resource has been fished out shallower), hooks as many lobster as he can hold, and then ascends directly to the canoe when he is out of air or cannot hold any more lobster. Here he switches tanks and directly descends to depth to continue fishing. They dive a minimum of 8 to a maximum of 20 tanks a day, with bottom times of about 30 minutes, and surface intervals of probably less than 2 or 3 minutes, but surely less than 6 (since they do not show on the Suunto profile, which stores the deepest point every three minutes, in Figure l).