Validation of Dive Computer Algorithms

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Results of a comprehensive effort to analyze commercially available dive computers and PC-based dive planners are reviewed. For this study 234 chamber test dives were carried out with profiles ranging from square to triangular, multilevel forward and multilevel reverse, to a maximum depth of 54 m. Air was the breathing medium for all dives. A first phase considered only no decompression dives, a second phase considered decompression dives at two levels of PRT (pressure root time) and a third phase considered repetitive dives with various surface intervals.

INTRODUCTION

Boycott, Damant and Haldane (Boycott et al., 1908) developed their rather crude decompression model in 1908. The body was divided in 5 compartments, with half times of 5, 10, 20, 40 and 75 minutes, and a decompression schedule was calculated such that the nitrogen pressure in each compartment was never more than twice the nitrogen partial pressure in the inhaled gas (air). More than 100 years later much has changed: the compartments have grown in number (up to 20), a much wider spectrum of half times (from 2.5 to 640 minutes) is considered and the tolerated supersaturation ratio is not constant but rather varies with half time (from 4 for short halftimes to little over 1 for long ones). There are claims of bubble size, volume calculations, adaptations to workload, water temperature and much more being taken into consideration. Indeed, considering the complexity of human physiology and the banality of asymptotic compartment ongasing and offgasing, it is both desirable and optimal to incorporate more physiological parameters into present day decompression models than the three English gentlemen did in 1908.

Diving can be grouped into five categories:

- recreational (dives mostly shallower than 40-50 m, within the no-decompression limits, primarily using the same breathing mix from beginning to end);
- technical (dives pushing depths beyond 100 m and/or dive times to 20 and more hours, using highly dedicated equipment and a multitude of breathing mixes tailored for each part of the dive);
- scientific (dives shallower than 60 m, usually within no-decompression limits, with air or N_2O_2 as breathing mix and computer-controlled dive profiles)
- commercial (dives with a specific goal, e.g., maintenance or inspection of underwater facilities); and,
- military.

The five categories vary in type of exposures and equipment used, but they have in common a rather low decompression illness (DCI) incidence rate and the fact that, by and large, they all rely on decompression schedules evolved from the original compartment model.

In commercial and military diving in particular the use of dive tables is still widespread, and the safety record there is very good. The community of divers relying on tables is, compared to recreational divers, usually more trained and fit and more focused on a particular task with less chance of making errors. Furthermore, when tables are utilized during dives that are not square an intrinsic conservatism is automatically introduced; for the purpose of calculating the decompression, the maximum depth is rounded off to the next value in the table and then applied to the entire duration of the dive.

The alternative to dive tables is dive computers. They track the profile of the dive very closely, but there is no inherent additional conservatism when performing non-square dives. Further, the target market for these instruments are divers who are not always fit people and are less mission-oriented. Therefore, the dive computer models employed are a detuned, more conservative version of the tables (primarily achieved by reducing the tolerated supersaturation levels). Despite the additional conservatism in the algorithms themselves, for most practical uses dive computers will allow for more bottom time because profiles are hardly ever square and only a fraction of the time is spent at the maximum depth.

Dive computers present other very clear and definite advantages. In addition to being able to display a continuously updated decompression schedule, they can warn the diver of unsafe procedures (such as a fast ascent or excessive ppO_2) and also provide a log of the dive itself. This can be useful for monitoring of activities, accident analysis and, ultimately, can represent a database to be used to further our understanding of decompression physiology.

Blind faith in dive computers can certainly be dangerous. Simply because they keep track of pressure over time does not imply that they can be applied to any profile. At the heart of the dive computer there is a mathematical model that wants to mimic human physiology under hyperbaric conditions and any such model has a limited range of applicability. Using a model outside of the validated range carries obvious risk, but even its use within the validated range needs to be addressed with caution. We cannot assume a priori that a multilevel dive computed as an extension of the multi-compartment theory validated via square dives is going to follow the same rules.

The aim of this study was to collect a number of relevant computers from the market and analyze their behavior when subjected to a large number of profiles. Each profile was then also “dived” using two commercially available PC-based dive planners. The profiles ranged from square, no-decompression dives to multilevel long decompression dives. This analysis does not include a judgment about the safety of each product, but rather attempts to assess the range of options and provide a guideline for a separate study including human trials, from which such judgment could be derived.

MATERIALS AND METHODS

Dive computers and PC-based dive planners used in the study

All major manufacturers were asked to participate by submitting the model of their own choosing. We focused on one product per decompression model employed. For example, since all Uwatec computers utilize the same algorithm, one Uwatec product was sufficient for our study. Likewise we used one Suunto and one Mares dive computer.

We contacted, in alphabetical order, Cochran, Delta P Technologies, Oceanic, Mares, Suunto, Uemis, Uwatec. Oceanic and Uemis declined to participate. Suunto did not formally decline but also did not respond affirmatively to our query and did not submit a product; given the wide distribution of Suunto computers we deemed it necessary to purchase one. Cochran, Delta P Technologies, Mares and Uwatec kindly submitted two samples of the same computer: having two allowed us to verify that they were behaving as expected, and in case of a failure we could continue the study without disruption. None of the computers failed during the study.

Our test field comprised the following dive computers:

- Cochran EMC-20H
- Cochran NAVY AIR III
- Delta P VRX
- Mares Puck
- Suunto Vyper Air
- Uwatec Aladin Prime

All dive computers were delivered with PC-interfacing hardware and software, which was used to download and archive all dives. For this purpose we used an HP COMPAQ 6820s running Windows Vista Business SP2.

All computers allowed for some level of conservatism. We only tested the baseline algorithm, i.e. the least conservative setting. Some allowed for salinity setting, typically between fresh water and salt water (Mares, Uwatec). The Cochran computers adjust the salinity automatically by measuring the conductivity between two metal contacts. Delta P and Suunto are calibrated to salt water and this setting cannot be changed.

We intentionally stayed away from special conditions like fast ascent, yoyo diving, cold water or other aspects which, although interesting, should be relegated to a later study when the initial understanding is sound. With enough parameters to deal with, it was important to not introduce additional complexity.

Aside for the VVAL-18 implemented in the Cochran Navy AIR III, which is supported by a wealth of documentation describing the validation performed by the US Navy (Doolette et al., 2012) no real details are provided by any manufacturer about the decompression models. The following is what we were able to gather from manuals, websites and other sources:

- Cochran EMC-20H: 20-tissue Haldanean model.
- Cochran VVAL-18: nine-tissue Haldanean model with exponential ongasing and linear offgasing.
- Delta P: 16-tissue Haldanean model with VGM (variable gradient model, i.e., the tolerated supersaturation levels change during the dive as a function of the profile, but no details are provided as to how this is done).
- Mares: 10-tissue Haldanean model with RGBM; what the RGBM part of the model does is not described in detail anywhere and is not available to the public.
- Suunto: nine-tissue Haldanean model with RGBM; what the RGBM part of the model does is not described in detail anywhere and is not available to the public.
- Uwatec: eight-tissue Haldanean model.

On the PC used for downloading and analyzing all dive computers we also installed V-Planner (version 3.87) by HHS Software Corp. and GAP (version 2.3, build 1665) by Gap Software. V-Planner runs the Variable Permeability Model (VPM; Yount et al., 2000) and allows the choice of VPM-B and VPM-B/E. We chose to use VPM-B/E and for each dive we ran the calculation for all six conservatism levels (baseline plus five incrementally more conservative ones).

GAP allows the user to choose between a multitude of Bühlmann-based algorithms and the full RGBM (Wienke, 2001) in its five conservatism levels (base line, two incrementally more liberal and two incrementally more conservative). For each dive we ran GAP using RGBM in all five conservatism levels. For some dives we also ran the 16-tissue Bühlmann model in GAP for comparison.

Description of the dive profiles and equipment utilized

All dives were carried out in the chamber depicted in Figure 1. The chamber has a usable volume of 30 cm length, 19 cm width and 12 cm height. Effectively, the usable space is the surface of 19x30 cm since we wanted to observe the computers during the dive and thus could not stack them. This area was sufficient for our purposes.

The chamber is fed by the low pressure line off of a scuba tank as can be seen in Figure 2. Maximum pressurization of the chamber is 70 msw, controlled by an overpressure relief valve. In all profiles, a descent speed of 20 m/min and an ascent speed of 10 m/min (unless otherwise specified) was applied.

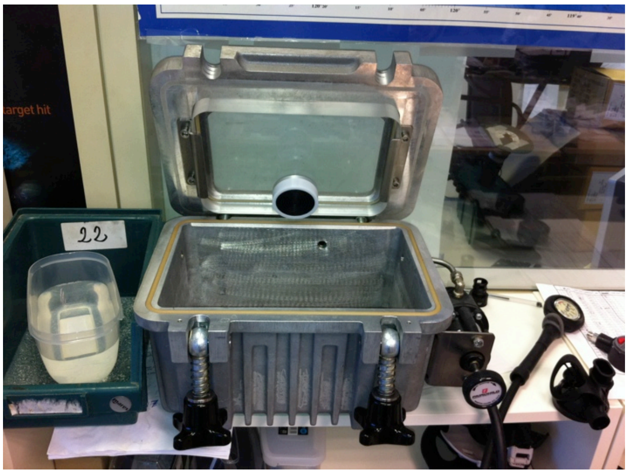

Figure 1. Dive chamber utilized to generate dive profiles.

Figure 2. Dive chamber and source of pressurization.

During a dive, at fixed time intervals, the information displayed by each computer was recorded by hand on a log sheet. This was also done right before and right after each depth change. All computers were also downloaded to PC for archival purposes and for analysis of the dives with the respective PC software packages.

The study itself comprised three main phases:

- Phase one: No-decompression dives with no considerations for repetitive diving effects.

- Phase two: Decompression dives with no considerations for repetitive diving effects. This is split into two ranges of PRT values (PRT: Pressure Root Time is an indicator of the severity of a dive). For square dives, this is the result of multiplying the absolute pressure in bar by the square root of the time at depth. Hence a 40 msw dive for 25 min has a PRT of 5x5=25.
    a. Low to moderate exposures (PRT<25)
    b. Extended exposures (25<PRT<30)
- Phase three: Repetitive dives, covering both no decompression and decompression dives.

Phase 1: No-decompression dives
Phase 1a: SQUARE no-decompression dives. During this first phase, we compared the dive computers and the PC-based dive planners simulating dives to the limit of decompression, for depths between 18 msw and 51 msw, in 3 msw increments.

Phase 1b: TRIANGULAR no-decompression dives. A triangular dive is one in which, after an initial bottom time at maximum depth, the diver maintains a constant, slow ascent to the surface (e.g. 1 m/min). A sample profile is depicted in Figure 3.

Phase 1c: MULTILEVEL no-decompression dives. Here things start to get complex, because of the various possible shapes of a multilevel dive and the multiplying effect of wanting to test various residence times at the various levels. Sample profiles are depicted in Figures 4 and 5.

For these profiles we need to define the depth and the duration of each level. Maximum depth was either 40 or 50 msw, and the other levels were between 15 and 35 msw. For simplicity sake, and because we are still within the realm on no-stop diving, we spent approximately half of the available no-stop time at the first level, then carried the second level to 1 minute of no-decompression time remaining, and then residing at the third level to the limit of the available no-decompression time.

For each of the profiles, we also wanted to test what happens if the first two levels were combined into one level of the same duration and at a depth corresponding to the weighted average of the first two. In other words, we wanted to establish whether, so long as the depth is increasing, a profile can be reasonably approximated with a square dive with the same area.

Phase 2: Decompression dives
Phase 2 covers decompression dives. These are divided into two categories (low to moderate exposure, and high exposure) as defined by the PRT parameter. For each we perform square and multilevel dives as seen in Phase 1, but extended the dive times accordingly. For non-square dives the PRT is less meaningful so we extended the residence times at each level with respect to Phase 1 in order to arrive at total ascent times comparable to the square dives.

Phase 3: Repetitive dives
The complexity grows even more when we attempt to study the effect of repetitive diving. Because a single session is constituted not just by two independent dives but also by the interval of time in between them, the number of possible combinations grows very rapidly. Thus, we chose to limit ourselves to square dives only, repeating the same dive after a given surface interval or performing a different one (for instance, an 18 msw for 62 min followed

by a 42 msw for 18 min and vice versa) in order to gain some insight into the effect of the shape and sequence of the dives in a repetitive series. Surface intervals of 30, 60, 90 and 120 min are used for no-decompression and low-PRT decompression dives, whereas longer surface intervals are used for high-PRT decompression dives (up to five hours).

RESULTS

Phase 1

During this phase, 118 dives were carried out in the pressure chamber. These dives were split in three categories as follows: Square dives (n=34), Triangular dives (n=9), and Multilevel dives (n= 75 total, of which 24 forward and 51 reverse).

Not all computers yield the same results, and because all were tested simultaneously in the same chamber, it is obvious that some computers would have some decompression requirement at the end of the dive while some stayed within the limits of no decompression. The results are then expressed in the following terms:

- for square dives: no-decompression limits. If a computer went into decompression, the bottom time that would have allowed a direct ascent is observed and recorded manually during the dive and then confirmed with the downloaded logbook on the PC;
- for triangular dives: we performed several dives with different residence times at the maximum depth, trying to get some residual decompression at 6 m in order to stress the various models;
- for multilevel dives: we drove the profile so as to get to the limit of decompression on at least some computers, but this would invariably imply that some others would have a decompression obligation while others would still be within the no-decompression limits. Hence in this case we simply reported the status at the beginning of the final ascent.

<u>Square dives</u>

Square dives were carried out in the depth range from 18 msw to 51 msw, in 3 msw increments. Figure 6 summarizes the no decompression times observed during these dives, and also the corresponding results from the GAP and V-Planner PC simulations in their baseline setting.

The two Cochran computers have the longest no-decompression times, with the two models alternating as to which one is the most liberal: the EMC-20H is more liberal at 18 m and 21 m, whereas the NAVY AIR III is more liberal at 24 m and deeper. Mares, Uwatec and Suunto are, in their standard setting, almost identical, whereas the Delta P VRX is a bit more conservative.

<u>Triangular dives</u>

These dives involve a descent at 20 m/min to a target depth, a certain amount of time spent at that depth, then an ascent at 1 m/min, either continuous or discretized in 1 or 2 msw steps. We also performed some dives in which the ascent speed was further reduced, to 0.5 m/min, from a depth of 16 msw to the surface.

Such dives are not very practical for recreational diving, since a great deal of attention has to be paid to maintaining a constant ascent rate. However, they could prove to be very useful in commercial activities such as fish tank cleaning. Primarily, however, these profiles have been introduced in this study because they would represent the greatest challenge for empirical models fitted to square dives. During a slow ascent, the transition from ongasing to offgasing for the various tissues could easily lead to discrepancies between models and might possibly misrepresent the actual human physiology.

In the PC simulations the ascent rate is a user-defined parameter, but for the chamber simulations the ascent is controlled by the operator via an exhaust valve, and hence is very difficult to control to a given speed with certain accuracy. Therefore, in chamber dives we have always applied a discretized ascent in 1 or 2 m steps, performed every 1 or 2 minutes with a quick transition from one depth to the next.

PC Simulations – constant, discretized and variable ascent rates
For a maximum depth of 40 msw, we have run several simulations to determine the longest allowed bottom time which, when followed by the slow ascent, would result in no residual decompression obligation at three msw or six msw ("residual" in the sense that the very slow ascent in itself already represents a very long decompression, so that by the time one reaches six msw, there is no decompression obligation left). The simulations were performed with a continuous straight-line 1 m/min ascent, in 1 msw steps performed each minute, in 2 msw steps performed every 2 min and in 2 msw steps performed every 2 min up to 16 msw, then 1 msw steps every 2 min from 16 msw to the surface.

The findings are as follows:
- RGBM (at setting 0) allows longer bottom times at 40 msw when a discretized ascent in 2 msw steps is used (9 min) with respect to 1 msw steps (6 min) and a continuous ascent (1 min). The allowed bottom time grows to 18 min when a 2 m/2 min ascent rate is employed up to 16 msw, then 1 m/2min from there.
- For ZH-L16 it is the opposite, allowing 19 min for a continuous ascent, 6 min for 1 msw steps and none for 2 msw steps, even when the speed is reduced further from 16 msw onwards.
- V-Planner yields the same results regardless of the ascent method used (2 min at nominal setting), but for the variable ascent rate (1 msw every 2 min from 16 msw to the surface) the allowed bottom time is longer (4 min).

This means that:
- in RGBM offgasing prevails over ongasing when following a discretized ascent rate, the coarser the better. A slower ascent rate in the shallower portion of the profile is very beneficial;
- in ZH-L16 offgasing prevails over ongasing when following a continuous ascent rate;
- V-Planner behaves the same way as long as the overall ascent is similar. A slower ascent rate in the shallower portion is beneficial.

Chamber simulations with dive computers
For a maximum depth of 40 msw, we have performed four dives:
- Dive 16: 6 min at depth followed by an ascent of 2 msw every 2 min;
- Dive 17: 5 min at depth followed by an ascent of 2 msw every 2 min;
- Dive 18: 4 min at depth followed by an ascent of 2 msw every 2 min;
- Dive 21: 6 min at depth followed by a variable ascent rate: 2 msw every 2 min up to a depth of 16 msw, and then 1 msw every 2 min from 16 msw to the surface.

A direct comparison between dives 16 and 21 is very interesting because it shows the effect of slowing down the ascent rate in the shallower part of the profile. The two profiles are depicted in Figure 7. The Mares, Uwatec and Suunto dive computers (Cochran and VRX were not tested in these profiles) show a slight advantage for the split ascent rate, resulting in less remaining decompression obligation at 3 msw (from 8 to 4, 10 to 7 and 8 to 4 min, respectively). RGBM (1 and 0 min remaining decompression time, respectively) and V-Planner (5 and 2 min remaining decompression time, respectively) yield the same trend, whereas ZH-L16 gives the same result for both ascents (1 min remaining decompression at 3 msw).

For a maximum depth of 50 msw, we have performed two dives, each with a two min stay at the bottom, in one case with a 2 msw ascent every 2 min (dive 19), and one employing a variable ascent rate: 2 msw every 2 min up to a depth of 16 msw, and then 1 msw every 2 min from 16 msw to the surface (dive 22). Curiously, RGBM behaves the opposite way than on the 40 m dive: now the slower ascent rate from 16 m to the surface yields longer decompression obligations (20 instead of 9 min), whereas V-Planner still shows an advantage in employing a slower ascent rate in the shallower portion (9 instead of 16 min). The dive computers also show a marked advantage for the implementation of a slower ascent rate (Cochran EMC-20H: 6 instead of 11 min; Cochran Navy: 57 instead of 67 min; Mares: 33 instead of 40 min; Suunto: 24 instead of 35 min; Uwatec: 22 instead of 34 min; VRX: not tested). The wide spread in the results obtained by Gap, V-Planner and the various dive computers shows that these dives are very challenging for the decompression algorithms, especially in light of the otherwise close agreement between some of the computers.

Multilevel profiles

All dives were performed so as to produce near zero decompression obligations on the dive computers, at least on those that are giving very similar results in their nominal setting (Mares, Suunto and Uwatec). We have performed a multitude of dives, with profiles ranging from deepest level first, to deepest level in the middle, to deepest level at the end of the dive. For most dives, we have also repeated the equivalent dive at the average depth of the regular profile at the beginning of the final ascent. All of these permeations were carried out in pursuit of anomalies in order to uncover discrepancies between models, or at least peculiar aspects for specific circumstances.

So as to be able to compare the various decompression calculations in some unbiased way, and highlight things that appear interesting, we have assigned a score to each profile for the two PC-based dive planners, according to the Table 1.

Table 1. Scoring system.

Model/ Score	**0**	**1**	**2**	**3**	**4**
RGBM	only most conservative setting has decompression	only 3 most conservative settings (of 5) have decompression	least conservative setting has 1min of decompression or less	least conservative setting has between 2 and 4 minutes decompression	least conservative setting has 5 minutes or more decompression
V-Planner	least conservative setting has 5 minutes or more decompression	only 4 most conservative settings (of 6) have decompression	least conservative setting has 1min of decompression or less	least conservative setting has between 2 and 4 minutes decompression	least conservative setting has 5 minutes or more decompression

On the table describing the dives, we have included a column for the difference in the score between RGBM and V-Planner: when the difference was 3 or 4, it means that the two models are painting a completely different picture for the dive and they are worth looking into further: for example one computer might say that there is hardly any decompression required, while the other requires a lot of decompression.

Similarly, we wanted to look at dives for which both PC-based dive planners predict very high decompression, since the controlling force of each dive is a no-decompression condition in the dive computers at their nominal setting. It is therefore worth trying to understand what is causing these discrepancies.

Forward profiles

Forward profiles are those in which the maximum depth is reached towards the beginning of the dive, after which the profile gradually evolves towards shallower depths. All profiles are broken into three main sections at constant depths, for instance, 50-35-15 meaning that the chamber is pressurized to 50 msw for some time, then the pressure is reduced to the equivalent of 30 msw and eventually to the equivalent of 15 msw before starting the final ascent to the surface. Figure 8 depicts an example of a forward profile.

For the deepest level we have employed depths of 50 and 40 msw, for the intermediate level 35, 30, 25 and 20 msw, and for the shallowest portion 25, 20 and 15 msw. In all dives to 50 msw, 2 min was spent at depth, hence ascending at 4 min 30 sec dive time. For the dives to 40 msw, 5 min was spent at depth, hence ascending at 7 min dive time.

Table 2 gives the complete overview for these forward profiles in terms of the scoring system described at the beginning of this section.

Table 2. Multilevel forward dives.

Dive no.	Dive descriptor	RGBM	V-Planner	Diff.
23	50-35-20	1	4	3
24	50-35-15	0	3	3
25	50-35-25	2	2	0
26	50-30-15	0	3	3
27	50-30-20	1	4	3
28	50-30-25	2	2	0
29	50-25-25	2	2	0
30	50-25-15	0	3	3
31	50-25-20	1	1	0
32	40-30-15	0	4	4
33	40-25-20	1	1	0
34	40-25-15	0	4	4
35	40-30-20	1	4	3
36	40-20-20	1	1	0
37	40-20-15	0	0	0
45	40-25-20 2step	1	2	1
46	40-25-15 2step	1	4	3
48	50-25-25 1step	2	4	2
49	40-20-20 1step	2	3	1
50	50-35-15 2step	0	4	4
51	50-35-25 2step	2	1	-1
52	50-30-15 2step	0	4	4

What immediately jumps out is the agreement between RGBM and V-Planner for the dives in which the third level is relatively deep, yet a large discrepancy in results when the last level is relatively shallow (24 and 25, 27 and 28, 32 and 33 etc). In other words, RGBM starts to give credit at a deeper depth than V-Planner and hence there are high decompression requirements for those dives in V-Planner and little or none with RGBM. It was also noted that combining the first two levels in one of the cumulative duration and at the average depth, yields, if not the same decompression requirements of the original profile (40-25-20, 40-25-15, 50-35-15), then only a small difference (50-25-25). Only the 40-20-20 profile, when reduced to a unique depth of 23.8 m for the entire duration of the dive, gave appreciable differences in decompression schedule for all models.

Reverse profiles
These are divided into 3 profile types:
- dives in which the deepest portion of the dive is reached at the beginning of the dive, but then a shallower portion follows before a deeper one. An example is shown in Figure 9. A peculiar aspect of these dives is that there is offgasing of some tissues before ongasing starts again;
- dives in which the deepest portion of the dive is in the middle of the dive, as depicted in Figure 10. In these dives, all tissues are ongasing during the first two levels while some may switch to offgasing during the third level;
- dives in which the depth was gradually increasing and the final ascent made from the deepest point (Figure 11). In these dives, all tissues are ongasing until the final ascent.

A summary of all dives is shown in Table 3, in which the score for each is listed. We again find big discrepancies between RGBM and V-Planner when a 15 msw step is at the end of the dive: one model gives credit (RGBM) while another one does not (V-Planner).

As part of these dives we also experimented with profiles in which the sequence of the depth levels were changed without changing the duration at each level, to see what effect this would have on the resulting decompression profile (5 min at 40 msw, 5 min at 30 msw and 14 min at 20 msw). The dive computers showed limited influence (from a minimum of 2 to a maximum of 6 min decompression for the Mares, Suunto and Uwatec; the others were not tested), whereas the V-Planner (minimum of 7, maximum of 18) and RGBM (minimum of 2, maximum of 12) showed bigger changes (dives 35, 91-95, 99).

Table 3. Multilevel reverse dives.

Dive no.	Dive descriptor	RGBM	VPLAN	Delta (R-V)
53	50-15-30	1	0	1
54	50-15-35	2	1	-1
55	50-20-30	2	1	-1
56	40-15-30	1	1	0
57	40-15-35	2	1	-1
58	40-20-30	2	1	-1
59	50-15-30 2step	2	3	1
60	50-15-35 2step	3	4	1
61	50-20-30 2step	2	4	2
62	50-15-30 1step	1	2	1
63	50-15-35 1step	1	2	1

64	50-20-30 1step	2	3	1
66	50-15-35-2step	3	4	1
67	20-50-15	1	4	3
68	20-50-20	2	4	2
69	20-50-25	2	4	2
70	20-50-30	3	4	1
71	25-50-15	1	4	3
72	25-50-20	2	4	2
73	25-50-25	2	4	2
74	25-50-30	3	4	1
75	30-50-15	0	4	4
76	30-50-20	2	4	2
77	30-50-25	2	4	2
78	30-50-30	3	4	1
79	20-40-15	1	4	3
80	20-40-20	2	4	
81	20-40-25	2	2	0
82	20-40-30	3	3	0
83	25-40-15	0	4	4
84	25-40-20	1	1	0
85	25-40-25	2	2	0
86	25-40-30	2	3	1
87	30-40-15	0	4	4
88	30-40-20	1	4	3
89	30-40-25	2	2	0
90	30-40-30	2	2	0
91	40-20-30	2	3	1
92	20-40-30	3	4	1
93	20-30-40	4	4	0
94	30-20-40	4	4	0
95	30-40-20	2	4	2
96	20-50-15 2step	0	3	3
97	20-50-15 1step	1	3	2
98	20-50-20 2step	1	1	0
99	40-30-20 1step	2	4	2
100	20-50-20 1step	2	3	1
101	20-50-25 2step	2	2	0
102	20-50-25 1step	2	3	1
103	20-50-30 2step	2	4	2
104	20-50-30	2	3	1
105	25-50-15 2step	0	3	3
106	25-50-20 2step	1	1	0
107	25-50-20 1step	2	3	1
108	25-50-25 2step	2	1	-1
109	25-50-25 1step	2	4	2

110	25-50-30 2step	2	3	1
111	25-50-30 1step	2	3	1
112	30-50-15	0	3	3
113	30-50-15 1step	1	3	2
114	30-50-20 2step	1	1	0
115	30-50-20	2	4	2
116	30-50-25 2step	2	2	0
117	30-50-25 1step	3	4	1
118	30-50-30 2step	2	2	0
119	30-50-30 1step	2	4	2
120	20m for 50min	1	3	2

Summary of Phase 1

Computers manufactured by Mares, Suunto and Uwatec all produced very similar results. With 118 dives in this first phase and a plethora of profiles and shapes, no-decompression limits or decompression times necessary to complete the dive where always within +/- 1 min, at the most, but very rarely, 2 min. One should note the relevance of this finding, given that these three manufacturers cover more than 50% of the worldwide market.

If one were to expand this study to include human trials, the cost and time required to perform each profile to a statistically relevant extent, makes it paramount to focus on few dives with the most significant impact on our learning and understanding. Table 4 summarizes those dives from which human trials should be picked and the reasoning behind the choices.

Table 4. Relevant dives from Phase 1.

Dive no.	Ref. dive	Description	Profile	Reasoning, notes and comments
1	16	Triangular	40m 1m/min discretized ascent	Effect of ascent rate, trend inversion by RGBM.
2	21	Triangular	40m split ascent	
3	19	Triangular	50m 1m/min discretized ascent	
4	22	Triangular	50m split ascent	
5	26	ML forward	50-30-15	Large discrepancy between RGBM and V-Planner for 26 and 27, trend inversion in 28, validity testing of 2-in-1 in dive 52.
6	27	ML forward	50-30-20	
7	28	ML forward	50-30-25	
8	52	ML forward	50-30-15 2step	
9	33	ML forward	40-25-20	33 yields low decompression in both PC simulations, 34 yields big discrepancy, 45 tests the 2-in-1.
10	34	ML forward	40-25-15	
11	45	ML forward	40-25-20 2step	
12	54	ML reverse	50-15-35	Test 3-step vs 2-step vs 1-step, for which RGBM (2, 3, 1) and V-Planner (1, 4, 3) don't agree.
13	60	ML reverse	50-15-35 2step	
14	63	ML reverse	50-15-35 1step	
15	75	ML reverse	30-50-15	75 has big discrepancy, 78 has both high, 114 both low and 117 both high scores,
16	78	ML reverse	30-50-30	
17	114	ML reverse	30-50-20 2step	
18	117	ML reverse	30-50-25 1step	
19	35	ML forward	40-30-20	Effect of changing sequence when times at depth are left unchanged
20	93	ML reverse	20-30-40	

Phase 2

Phase 2 was further broken down into three parts: square dives between 18 and 51 msw corresponding to a PRT of 22, square dives between 18 and 54 msw corresponding to a PRT of 28, and multilevel dives that were a repetition of those considered the most interesting in phase 1 in which the residence time at the various levels was lengthened. For the square profiles, the depths were chosen to have some difference from one dive to the next, though in some cases the depth was chosen because data existed from human trials for that profile (Ljubkovic et al., 2011; Møllerløkken et al., 2011). For example, the 54 msw for 20 min at a PRT 28 dive was selected instead of a 51 msw dive). Table 5 summarizes the dives performed.

Table 5. Dives in Phase 2.

Depth [m]	Dive time [min]	Descriptor
18	62	Square PRT 22
24	40	Square PRT 22
30	30	Square PRT 22
33	26	Square PRT 22
42	18	Square PRT 22
45	16	Square PRT 22
51	13	Square PRT 22
18	100	Square PRT 28
24	70	Square PRT 28
30	49	Square PRT 28
33	42	Square PRT 28
42	29	Square PRT 28
54	20	Square PRT 28
50-30-15		Multilevel
50-30-20		Multilevel
50-30-25		Multilevel
37.7-15		Multilevel
40-25-20		Multilevel
40-25-15		Multilevel
50-15-35		Multilevel
30-50-15		Multilevel
30-50-30		Multilevel
40-30-20		Multilevel
20-30-40		Multilevel

The analysis is performed on graphs depicting the behavior of the computers and the PC-based dive planners for the given profiles. Due to the desire to keep things clear and understandable, we split the results into two groups so to avoid data overload in each plot. In the first group we compare the two PC-based dive planners at the most liberal and most conservative level (RGBM -2, RGBM +2, V-Planner 0 and V-Planner +5), in addition to the Uwatec standard algorithm L0. In the second, we compare all dive computers at their base setting. The choice of the Uwatec L0 as a main reference was due to the fact that, in absence of yoyo dives, workload and cold water effects, it represents the cleanest Haldanean implementation between the three computers that are in strongest agreement (Mares, Suunto, Uwatec).

Square dives

Figures 12 and 13 show the total ascent time as a function of maximum depth calculated for the square dives between 18 and 51 msw for a PRT of 22. We observe that:

- RGBM -2 shows the shortest total ascent times, the 18 msw dive for 62 min and also the 24 msw for 40 min are even considered no-decompression dives. From 30 msw onwards the trend is for increasing total ascent time as the depth increases until 45 msw, at which point it seems to stabilize.

- RGBM +2 shows total ascent times always longer than the Uwatec computer, save for the 18 msw dive for 62 min. The trend is for increasing total ascent times as the depth increases up to 42 msw, and a decrease after that.
- V-Planner 0 behaves very similarly to RGBM +2.
- V-Planner +5 shows the longest total ascent times, with an increasing trend for depth up to 33 msw and a decrease thereafter.
- The Uwatec computer shows rather constant total ascent times, in a way indicating that for a pure Haldanean model PRT is possibly a good indicator of severity of the dive.
- The Mares, Suunto and Uwatec computers yield practically the same results.
- The VRX is much more conservative for shallow dives but less so at 33 msw and deeper.
- The Cochran EMC-20H is even more aggressive than RGBM -2.
- The Cochran VVAL 18 changes from being the most liberal to being the most conservative computer as depth increases.

Figures 14 and 15 depict the results for the dives between 18 and 54 msw corresponding to a PRT of 28. We observe that:

- RGBM -2 is very liberal, giving the absolute shortest total ascent times. The 18 msw for 100 min dive is considered a no-decompression dive and the trend is for increasing total ascent times with depth throughout the depth range.
- RGBM +2 is always more liberal than the Uwatec computer, save for the 42 msw dive which yields about the same result for the two. The trend is for increasing total ascent time with depth with a slight dip at 54 msw.
- V-Planner 0 is behaving almost identical to RGBM +2, though the trend of increasing total ascent time with depth is more marked.
- V-Planner +5 is giving the longest total ascent times, with a trend of increasing total ascent times with depth, though this appears to be reaching an asymptotic limit.
- The Uwatec computer is also in this case showing that the results are more or less constant when the PRT is kept constant.
- Mares, Suunto and Uwatec behave the same way, the only discrepancy is at 18 and 24 msw where the Suunto is more conservative yet follows the same trend.
- The VRX is also more conservative on shallow dives but approaches the behavior of the other computers as the depth increases.
- The Cochran EMC-20H is showing approximately half the total ascent time of the Uwatec computer and, unlike the case of PRT 22, is now a bit more conservative than RGBM -2.
- The Cochran VVAL18 requires up to three times the total ascent time of the Uwatec computer.
- The PC-based dive planners, claiming a bubble-type model, yield results that are non-linear as the depth increases (in light of a constant PRT), whereas the Haldanean implementation seems to behave in a linear way.
- The most conservative implementation of RGBM behaves rather similarly to the most aggressive implementation of VPM.

Multilevel dives

The dives in this sub-phase do not possess a characteristic that allows a clear order between dives, hence the horizontal axis in the graphs simply represents the sequential dive number. Figure 16 shows that:

- RGBM -2 gives the shortest total ascent times, with six of the dives actually being considered no-decompression dives.
- RGBM +2 is always more conservative than the Uwatec computer.
- V-Planner 0 behaves again very similarly to RGBM +2.
- V-Planner 5 is always more conservative than the Uwatec computer.

From Figure 17 we see that, even with the randomness introduced by these profiles, the Mares, Suunto and Uwatec computers yield once again practically the same results. The VRX gives the same result on most dives and is more conservative on others, while the Cochran duo is once again at the two opposite ends of the spectrum.

The Suunto computer displayed an odd behavior in most dives: it did not credit decompression time at a 1:1 ratio even when the decompression stop depth was perfectly matched (dives 217, 219, 223. In the latter it took 63 min for the Suunto to clear 44 min of decompression while at 3.1 msw).

Phase 3

PRT 22

In the first set of plots we present the total ascent time for an 18 msw dive for 62 min following the same dive and following a 42 msw for 18 min dive. Surface intervals were 30, 60, 90 and 120 min. For the sake of illustration, we placed the data for the desaturated dive at six hours. We observe that:

- RGBM +2 yields the same result regardless of whether the first dive is performed to 18 msw or 42 msw.
- Conversely, V-Planner 0 yields different results, giving longer total ascent times when the first dive was the shallow 18 msw instead of the deep 42 msw dive.
- V-Planner +5 shows a smaller difference between the two, but the trend remains the same, i.e., the 18 msw dive is more punishing than the 42 msw.
- The Uwatec computer shows little difference but also gives longer total ascent times when the first dive was the shallow one.
- Mares and Uwatec behave the same way and are hardly affected by the profile of the first dive.
- Suunto has a stronger repetitive dive effect (probably one of the aspects of their version of RGBM, as emphasized by a warning triangle on the display for surface intervals under one hour) which is affected by the shape of the first dive.
- VRX behaves similarly to the Suunto although the desaturated dive is a lot more conservative.
- The Cochran EMC-20H recovers extremely quickly from the repetitive dive effect.
- The VVAL18 on the other hand has very penalizing repetitive dive effect, more so in light of a first dive that is a no decompression dive.

In the second set of plots, we investigate the results for a 42 msw dive for 18 min with surface intervals of 30, 60, 90 and 120 min when the first dive is the same or when it is an 18 msw for 62 min dive. We observe that:

- RGBM -2 yields the lowest total ascent times, rather constant and thus apparently unaffected by surface interval and the shape of the first dive.
- RGBM +2 is more conservative than the Uwatec computer when desaturated, more liberal when it comes to repetitive dive effect. It also does not distinguish between the shape of the initial dive, but surface interval does play a role.

- V-Planner 0 yields total ascent times that are shorter when the first dive is at 42 msw for 18 min and longer total ascent times when the first dive is to 18 msw for 62 min.
- V-Planner 5 yields the longest total ascent time, with not much differentiation due to the shape of the first dive.
- The Cochran EMC-20H is extremely liberal and does not distinguish between the shape of the initial dive.
- The Cochran VVAL-18 shows a very strong repetitive dive effect.
- The VRX, though a bit more conservative on the desaturated dive, shows less repetitive dive effect than the Uwatec computer and shows no dependence on the shape of the first dive.
- The Mares shows no dependence on the shape of the dive profile and is slightly more conservative than the Uwatec computer.
- The Suunto shows the strongest repetitive dive effect (other than VVAL-18) and a slight dependence on the profile shape.

However, aside from the two Cochran products overall the dive computers once again show a rather good agreement. The two computers that claim an RGBM algorithm seem to show more conservative calculations for repetitive dives.

The next graphs show the results for 18, 30 and 42 msw dives, all for a PRT of 22. The increased amount of data makes the plots more difficult to read, but we can see that the PC-based dive planners do not give consistent results with PRT, whereas the Uwatec computer does. When looking at the same data for computers, we see the following:

- The VRX yields the same results for 18 msw and 30 msw, but is more conservative at 42 msw. This is probably due to the use of profile-dependent gradient factors.
- The Suunto shows the opposite trend, being more liberal as the depth increases.
- Mares and Uwatec show some variation, but much smaller.

PRT of 28

In the first set of plots we present the total ascent time for an 18 msw dive for 100 min following the same dive and following a 42 msw for 29 min dive. Surface intervals were one, two and four hours. For the sake of illustration, we place the data for the desaturated dive at 12 hours. We see that the Uwatec computer is now closer to V-Planner 5 than V-Planner 0, though in absolute terms the differences are quite considerable, going for instance from 85 min ascent of the Uwatec computer to the 110 min of V-Planner 5. Interestingly, V-Planner 0 still agrees with RGBM +2, whereas RGBM -2 considers this a no-decompression dive even after a 30-min surface interval.

When compared to the desaturated case, total ascent times can more than double for short surface intervals (1 hour) and be 50% higher for a two-hour surface interval. In the case of the computers, Cochran again owns the two ends of the spectrum, Mares and Uwatec yield similar results, VRX is more conservative and Suunto even more so.

For the 42 msw dive for 29 min when dived after the same dive and after an 18 msw for 100 min dive, the behavior is repeated, though what is immediately obvious is that the shape of the first dive plays much less of a role, and the same is true for PC-based dive planners and for computers.

When comparing 18 msw, 30 msw and 42 msw dives repeated after the same dive, the first striking evidence is that RGBM loses any recollection of a prior dive at both extremes after a surface interval of three hours. As always, RGBM -2 is the most liberal, V-Planner 0 behaves similar at times very similarly to RGBM +2 and V-Planner 5 is the most conservative. The Uwatec computer once again falls somewhere in between.

Among the computers, the Mares and the Uwatec once again yield remarkably similar results, more so considering that we are in the range of almost 100 min of total ascent time. The VRX is mostly more conservative whereas the Suunto goes out of range (indicating simply more than 99 min of total ascent time). The desaturated total ascent times of the Suunto, however, are very much in line with those of Mares and Uwatec for 30 and 42 msw and much longer at 18 msw.

CONCLUSIONS

There is a very wide offering of dive computers on the market today. We sampled a representative portion and found that whereas some computers are more conservative and some are more liberal, there are several that are in astonishing agreement throughout all tested profiles, especially when it comes to the first dive of a series (non-repetitive dive). Furthermore, the agreement is among the three brands that cover well over 50% of the world-wide market. Most of these dives, however, are very far from stressing the underlying models, so we cannot reach any conclusion as to the actual conservatism, or lack thereof, in any of these computers.

When one considers repetitive dives with short surface intervals (one hour or less), there is less agreement between the various computers, even among the three that otherwise agreed very extensively. One concludes that, whereas a relatively standard Haldanean implementation is at the core of these computers, different types of mathematical manipulations are employed to account for residual nitrogen. This is indicative that the true impact of residual nitrogen is not fully understood. Indeed, repetitive diving has not been researched and validated to an extent that would allow a firm footing in its characterization, in part due to the complexity of approaching a variety of dive profiles combined with a variety of surface intervals, and in part due to the increased complexity of the physiology involved (endothelial damage, pre-existing bubble population at the start of the dive, etc.)

It is worth noting that none of the dive computer manufacturers provide any details as to the inner workings of their models and none have ever performed any substantial validation. It is beyond their means and field of expertise. Rather, they have built upon the experience, published or not, of others (Bühlmann, 1995; Wienke, 2001). The only documentation available comes from the U.S. Navy for the VVAL-18 implemented in the Cochran NAVY AIR III (Doolette et al., 2012). This model was extensively validated, probably more so than any other. Interestingly enough, the VVAL-18 has the most liberal behavior in no-decompression diving, but quickly becomes the most conservative when decompression stops are required. This may indicate that the range of applicability of all other computers on the market is narrower than assumed. The non-linear behavior of the PC-based dive planners for high PRT dives points in the same direction, though until tests are performed, this remains speculation.

The range of applicability may indeed be the key question when assessing dive computers. Since dive tables are of limited range, one cannot extrapolate beyond them. So as long as the tabulated dives have been validated (or at least tested with some measured outcome), using tables should produce a safe or at least known outcome. A dive computer on the other hand continues to calculate and may be well out of its area of competence before an out-of-range message, if any, is displayed.

The final conclusion is that we can only comment on the relative conservatism of dive computers and PC-based dive planners. To go beyond this, one would need to devise a test plan with human trials, possibly drawing from this study when trying to identify which profiles to test.

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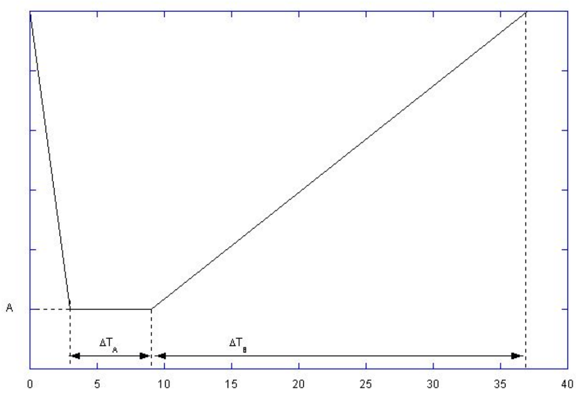

Figure 3. Triangular dive profile.

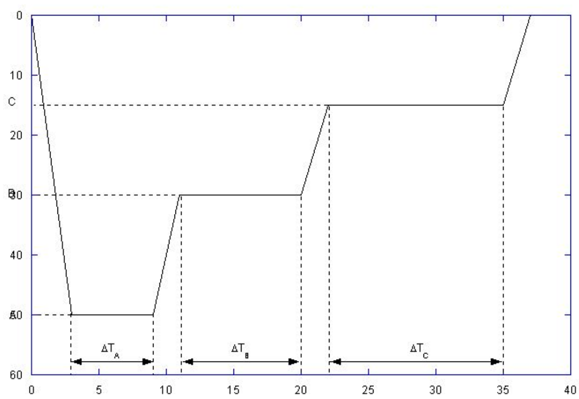

Figure 4. Regular multilevel (ML) dive profile.

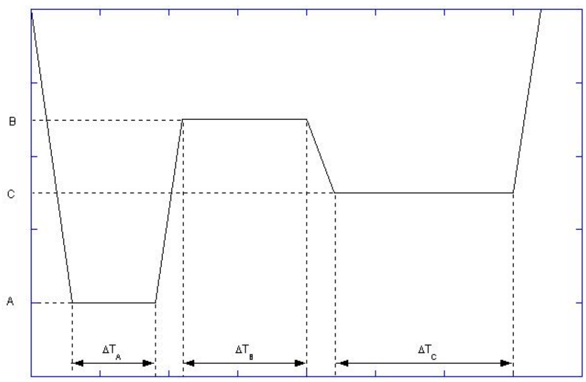

Figure 5. Reversed ML dive profile.

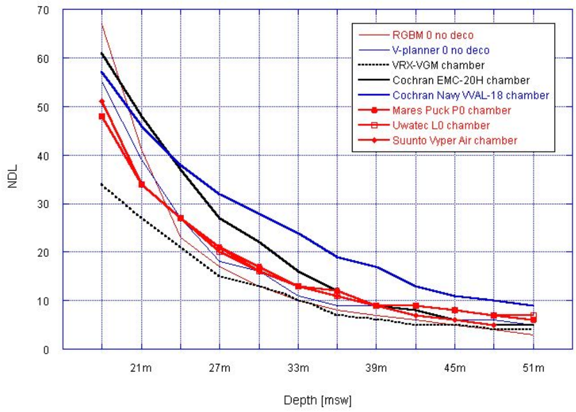

Figure 6. Square dive NDLs.

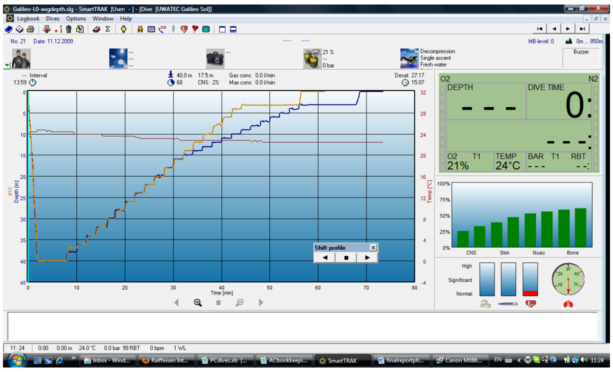

Figure 7. Standard/split ascent rate in triangular dive profile.

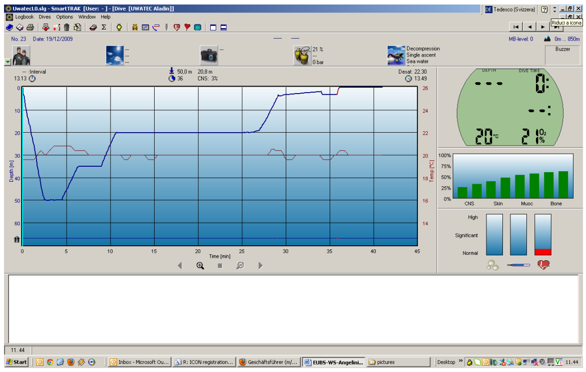

Figure 8. Forward ML profile.

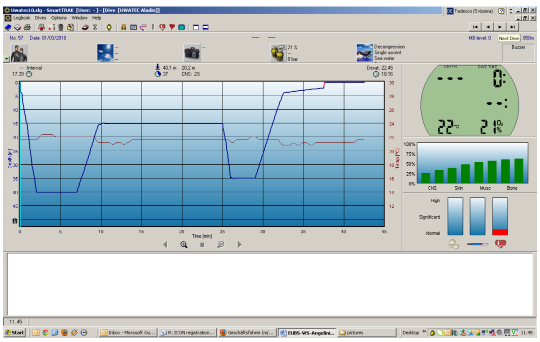

Figure 9. Reverse ML dive, shallowest level in middle.

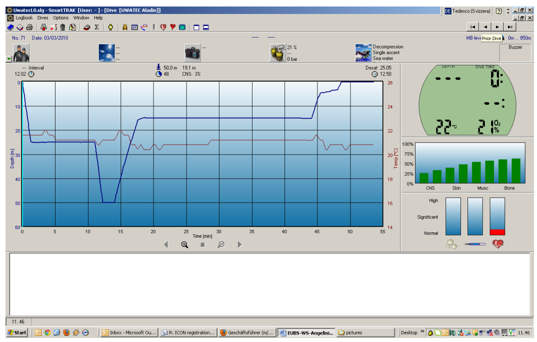

Figure 10. Reverse ML dive, deepest level in middle.

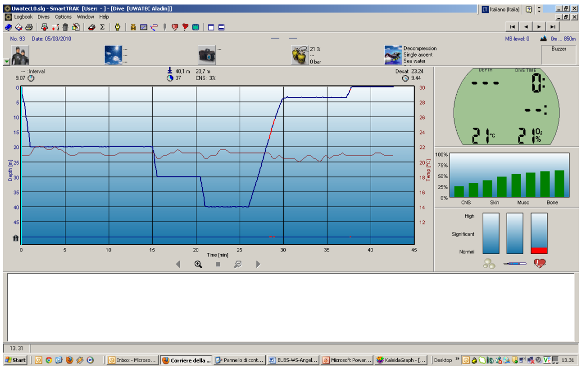

Figure 11. Reverse ML dive with deepest level at the end.

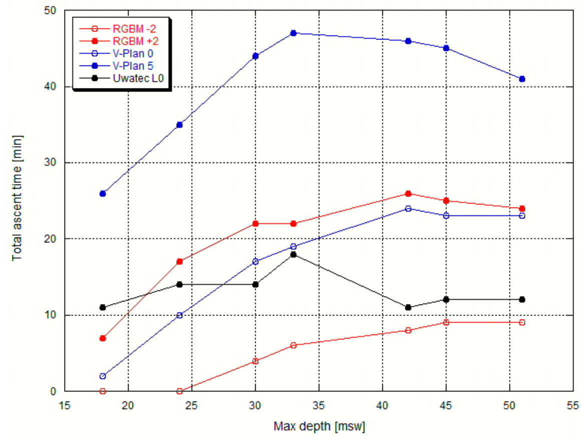

Figure12. Square dives, PRT 22, PC-based DPs.

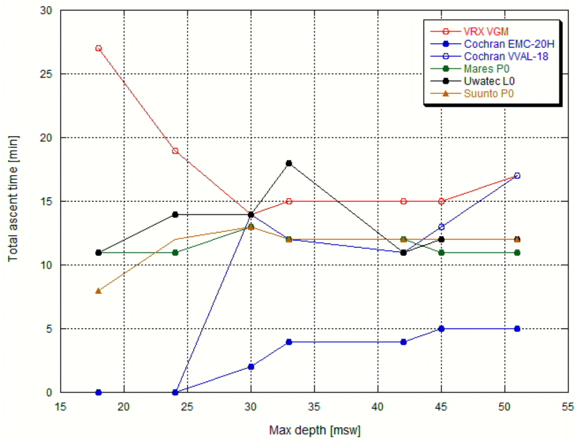

Figure 13. Square dives, PRT 22, DCs.

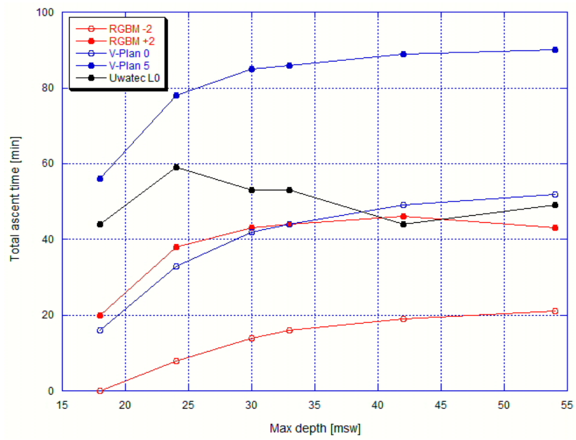

Figure 14. Square dives, PRT 28, PC-based DPs.

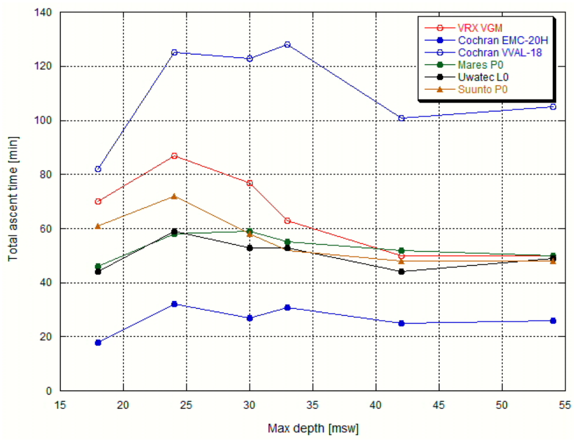

Figure 15. Square dives, PRT 28, DCs.

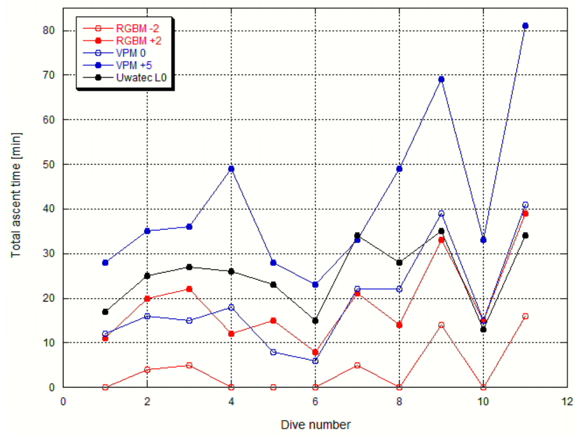

Figure 16. ML phase 2, PC-based DPs.

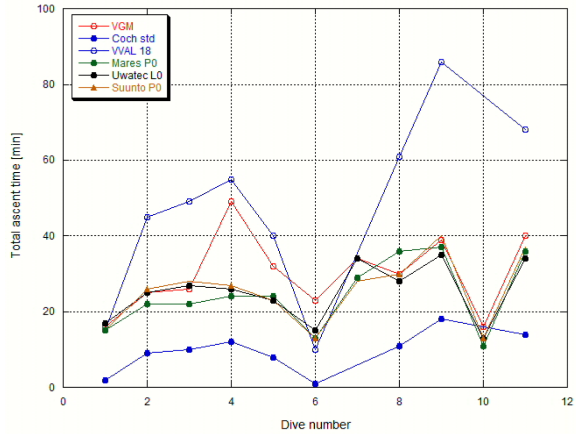

Figure 17. ML phase 2, DCs.

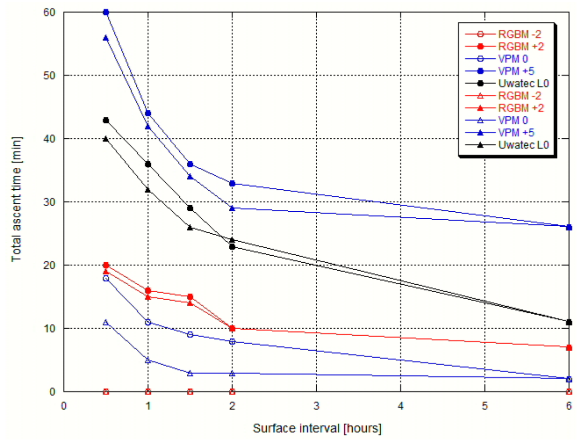

Figure 18. 18m/62 min repet dive, PRT 22, PC-based DPs.

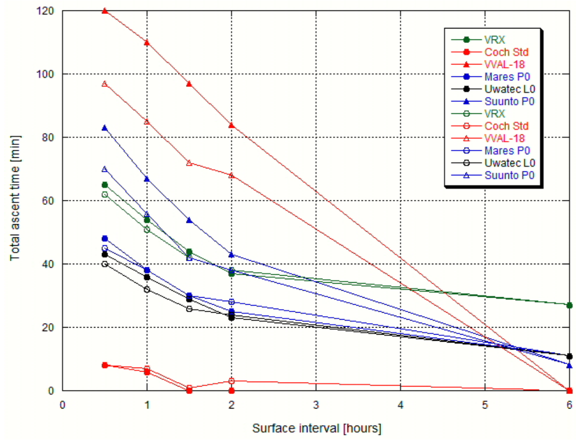

Figure 19. 18m/62 min repet dive, PRT 22, DCs.

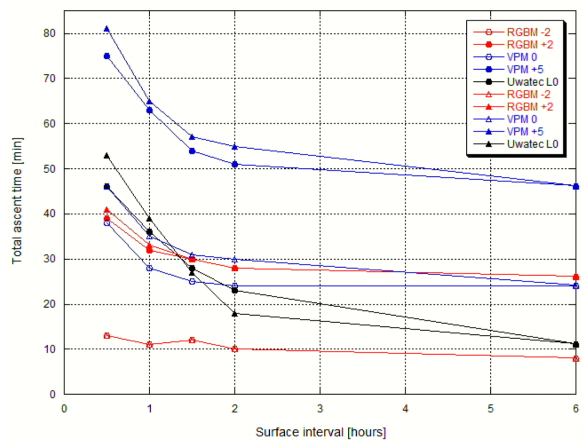

Figure 20. 42m/18min repet dive, PRT 22, PC-based DPs.

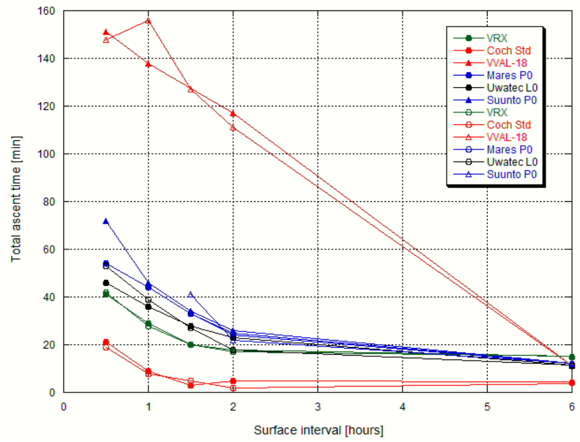

Figure 21. 42m/18 min repet dive, PRT 22, DCs.

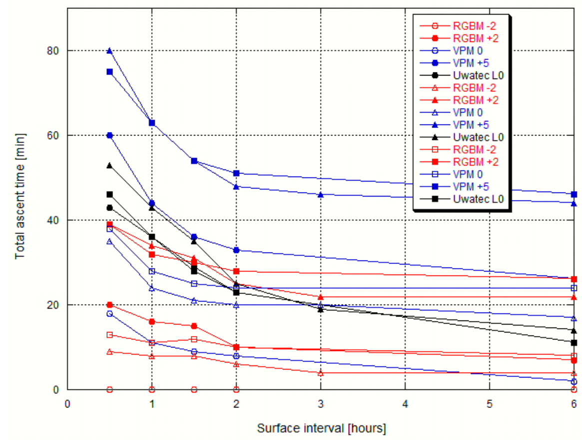

Figure 22. PRT 22 square dives to 18, 30 and 42m, PC-based DPs.

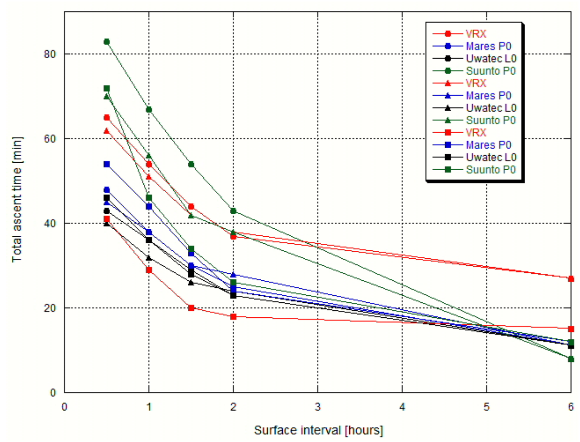

Figure 23. PRT 22 square dives to 18, 30, and 42m, DCs.

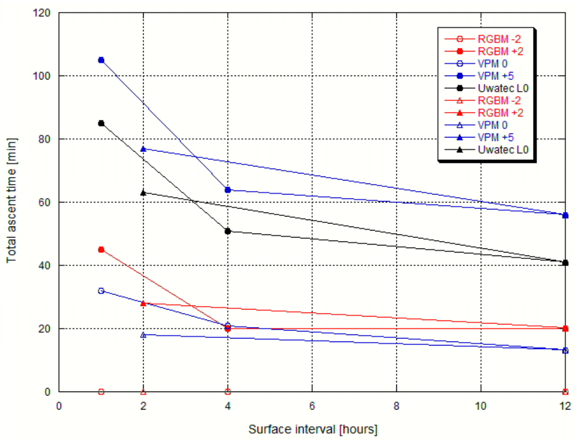

Figure 24. 18m/100 min repet dive, PRT 28, PC-based DPs.

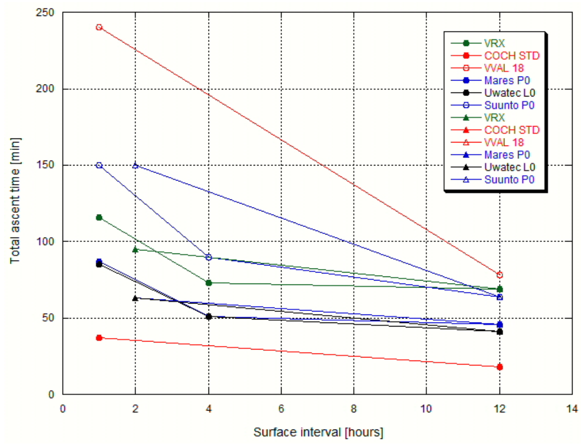

Figure 25. 18m/100 min repet dive, PRT 28, DCs

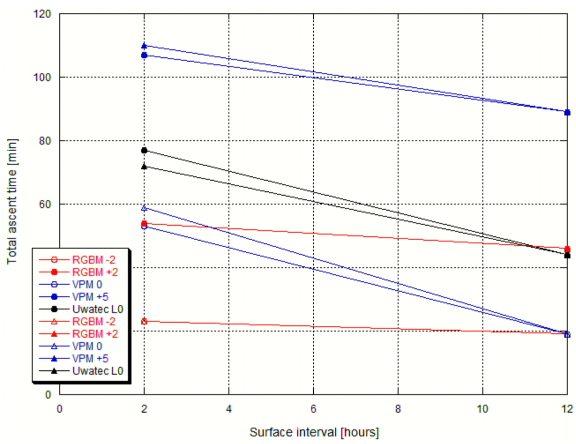

Figure 26. 42m/29 min repet dive, PRT 28, PC-based DPs.

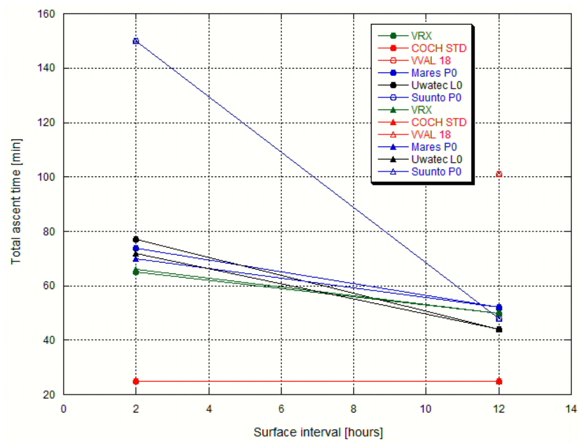

Figure 27. 42m/29 min repet dive, PRT 28, DCs.

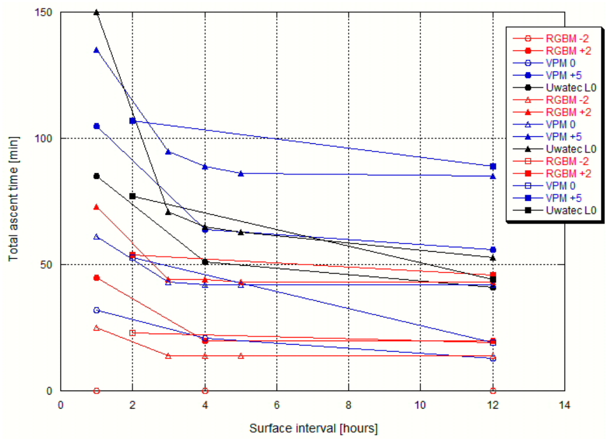

Figure 28. PRT 28, square dives to 18, 30 and 42m, PC-based DPs.

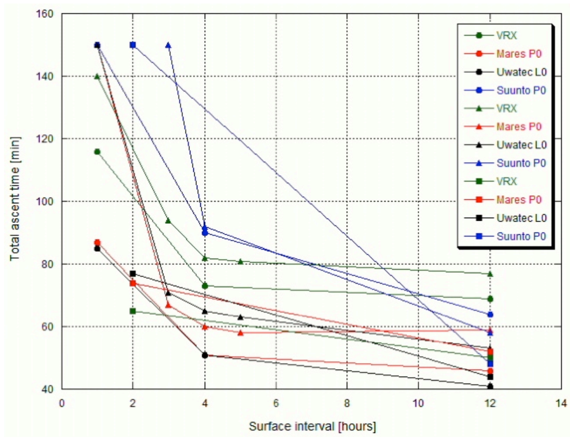

Figure 29. PRT 28, square dives to 18, 30 and 42m, DCs.