The consequences of misinterpreting dive computers: three case studies

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Key words
Case studies, dive computers, models, decompression sickness, recreational diving, diving research

Abstract

(Sayer MDJ, Wilson CM, Laden G, Lonsdale P. The consequences of misinterpreting dive computers: three case studies. *Diving and Hyperbaric Medicine*. 2008; 38: 33-9.)
Three cases are presented where there is a direct link between how the divers used their dive computers and the eventual requirement for their therapeutic recompression. The first case involves a diver with a previous history of decompression incidents making adjustments to their dive computer without understanding the outcomes of those alterations. The second case involves two divers running out of air and surfacing having missed significant amounts of decompression, caused by the dive computer not reducing their decompression obligation in actual time. This effect and performance differences between three models of computers were demonstrated in subsequent compression chamber trials reported here. The final case involves a diver who completed their dive within the indicated limits of their dive computer but subsequently developed serious neurological decompression sickness that left severe permanent residua. Compression chamber trials suggested that a combination of poor measurement accuracy and outdated decompression management in the computer used could have contributed to the diver's eventual poor outcome.

Introduction

For a number of decades, dive computers that calculate and display decompression information for divers have been evolving in their accuracy, complexity and the range of information being manipulated. External features such as gas use, heart rate and gas-mixture changes can now be monitored remotely, and the use of closed- or open-circuit breathing systems included in their calculations.[1–4] These technological advances mean that dive computers are now capable of delivering high-quality information for a diversity of uses.[5–7] In recreational diving, their use is widespread and in this and other diving sectors that predominantly use dive computers, such as scientific diving, decompression illness rates are among the lowest that have been published.[8–13] However, dive computer information may sometimes be open to misinterpretation. Three cases are presented where the misuse of dive computers may have directly contributed to the onset and severity of decompression sickness. Dive computer manufacturers rarely publish technical information sufficient to understand fully how some computers function, and so, in two of the reported cases, compression chamber trials were employed to study their performances.

Case studies

CASE 1

A 33-year-old, female, advanced open-water diver was diving using a *Suunto Vytec*™ dive computer. She completed six dives, two dives a day, maximum depths ranging from 16–27 metres' sea water (msw) and total dive times from 50–55 minutes with surface intervals approximating 2.25 hr. Dive three of the series was to a depth of 24.4 msw for a total time of 53 minutes (Figure 1). The download of that dive showed that the computer went into decompression mode after 21 minutes; the divers ascended from 17 msw 42 minutes into the dive. The ascent was notable for two registered ascent rate warnings, a violation of depth ceiling and a recording of the computer being switched into compass mode. On surfacing, incomplete decompression had been undertaken and the computer locked out into gauge mode (i.e., displayed depth/time information only). An error message was displayed in the form of the letters "Er" on the screen. The divers were confused about this because her buddy's computer had cleared of any decompression obligation on surfacing. None of the dive party understood the relevance of the "Er" display. An attempt was made to unlock the computer by hanging it on a shotline during the surface interval. However, the computer remained in gauge mode and so for her subsequent three dives she used a *Suunto Gecko* computer which had not been dived that week. The *Suunto Gecko* does not have a PC download facility.

On the third diving day, about two hours after her sixth dive, she reported symptoms of probable decompression sickness (DCS). She was transferred to the Dunstaffnage Hyperbaric Unit (DHU) where initial examination showed weakness in the left elbow, poor heel-toe walking and a pronounced unsteady tandem Romberg test. Recompression on an extended Royal Navy Treatment Table 62 (RN 62) started within seven hours of surfacing, and at the end of the treatment she appeared well. She was transferred to Oban Hospital for observation. Later the following day she deteriorated, with pain and weakness in the left arm and shoulder, and her walking and balance were unsteady. Despite three further treatments, complicated by symptoms of pulmonary oxygen toxicity, she became more ataxic

Figure 1
The depth/time profile of the third dive of Case 1. The download shows the computer in decompression after approximately 21 minutes, rapid ascent warnings at 43–44 and 53 minutes, a depth ceiling violation at 47 minutes, a switch to compass mode at 49 minutes and surfacing at 53–54 minutes

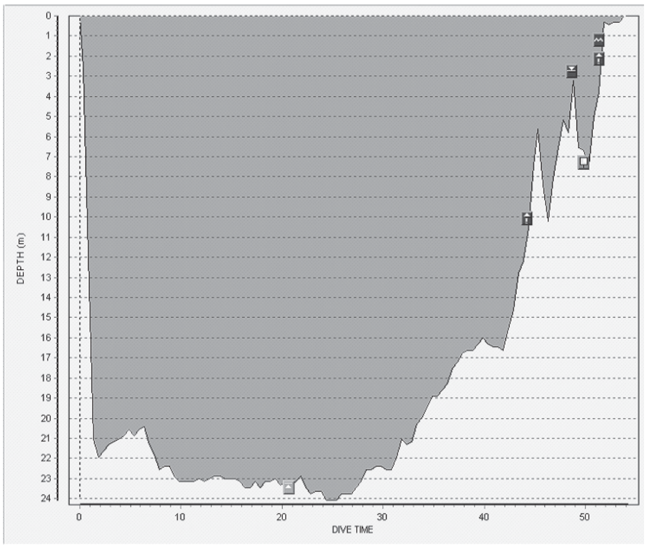
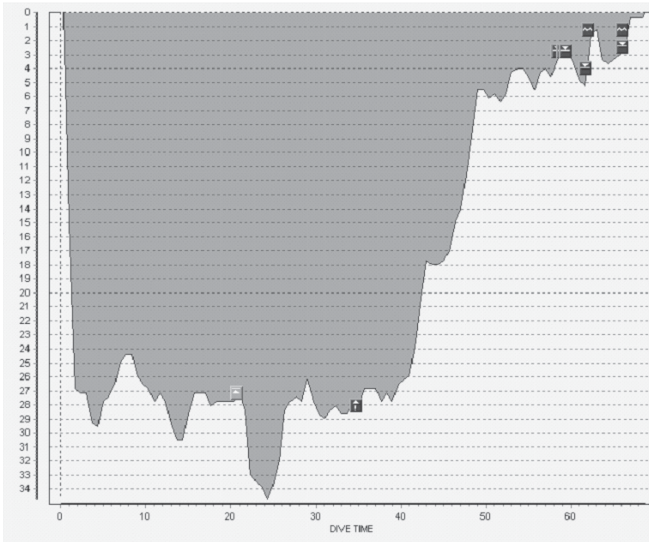


Figure 2
The depth/time profile of the sixth dive of Case 2. The download shows the computer in decompression after approximately 21 minutes, rapid ascent warnings at 33–34 minutes, numerous depth ceiling violations between 57 and 65 minutes, and surfacing at 61 and 66 minutes



and was transferred to the Aberdeen Hyperbaric Unit for further specialist care. In Aberdeen, she received three daily Comex 12 (222 kPa) treatments with some improvement after the first treatment but little after that. An MRI of the brain was normal and, 12 days after the dive incident, she was referred for further rehabilitation to the Glasgow Brain Injury Centre.

During her treatment she reported that two years previously she had been treated for DCS at another Scottish chamber (Orkney). In the month following that treatment, she had an episode of suspected cutaneous DCS that went untreated. Subsequent investigation showed a patent foramen ovale (PFO), which was closed successfully and she returned to diving 15 months later. She purchased the *Suunto Vytec* computer with a view to adjusting its settings to make her decompression management more conservative.

The *Suunto Vytec* is a relatively advanced, new-generation dive computer that can be operated in air, nitrox or gauge modes. There is a facility to switch gases (up to 3 mixes, any one ranging from 21–99% oxygen content), optional wireless pressure transmission, extensive memory functions and a built-in dive simulator. The *Vytec* employs an adjustable *Suunto*-modified reduced gradient bubble model (RGBM) and is PC interface compatible. It is programmed with eight diver-adjustable settings that can be altered singly or in combination to produce many levels of added conservatism, three for altitude, three for personal conservatism and either the full capacity of the RGBM (RGB100) or reduced power (RGB50). In this case, the download indicated that her computer had been set to altitude setting A2 (1,500–3,000 m) and RGB50, but remained at the default personal setting of P0. It was, therefore, unsurprising that on the third dive the altered *Suunto Vytec* had indicated a higher decompression requirement than the dive leader's unmodified computer. The computer had done what it had been programmed to do and produced a more conservative dive profile. However, this was either ignored or not understood, or the consequences of alterations had been forgotten. Further, this was only part of the problem. The decision to use another, undived computer resulted in her basing subsequent decompression management on a computer with no existing nitrogen loading and, possibly, in an unmodified mode.

CASE 2

A 16-year-old, male, advanced open-water diver was using a *Suunto Vyper*™ dive computer. The *Suunto Vyper* carries fewer functions than the *Vytec* but still has air/nitrox/gauge modes and a PC interface, and is controlled using the *Suunto* RGBM decompression model. The diver undertook six dives in three days, with maximum depths ranging from 20–35 msw, total times ranging from 24–68 minutes and with surface intervals of 2–5 hr. The sixth dive was to a maximum depth of 35 msw (Figure 2). For the first 21 minutes of the dive, the maximum depth ranged from 25–30 msw. The computer went into decompression mode after 21 minutes. However, the divers remained at depth and, in fact, reached their maximum depth of 35 msw after 24 minutes. They initiated their final ascent after 40 minutes. At that stage, the download indicated a total ascent time of 29 minutes

Figure 3
Download of the incident dive from the *Buddy Nexus* computer used in Case 3

with a first decompression stop at 5.3 msw. Their ascent was slow and complicated by undertaking a stop for one minute at 18 msw; it took them just over eight minutes to ascend to 5 msw. This slow ascent meant that, on reaching 5 msw, a remaining surfacing time of 29 minutes was still being indicated. Whereas a total dive time of 69 minutes was indicated when the ascent was initiated, on reaching 5 msw, the total dive time was now 78 minutes. The divers attempted to complete the decompression indicated, but had trouble maintaining a constant depth. As a result, by 61 minutes into the dive they still required 21 minutes of decompression. However, they were both running out of air and decided to surface. As they both had 30 bar air left, their group advised them to return to their decompression depth until they had completely run out of air. This they did, but ran out after only six minutes and re-surfaced; the computer locked out, indicating missed decompression; in total, 24 minutes of decompression had been omitted. After surfacing, both divers developed tingling in their lower limbs. They were placed on oxygen and transferred to DHU by lifeboat. They both received an unmodified RN 62 recompression treatment and remained symptom free after surfacing.

CASE 3

A 39-year-old male, described as an “experienced” open-water diver had recently bought a *Buddy Nexus*™ dive computer in order to start mixed-gas diving. At the time, the *Buddy Nexus* was being marketed as “*the first affordable, multi-mode dive computer designed for the full span of your diving career*...”. The *Buddy Nexus* supports a number of diving modes: open-circuit sport (conventional scuba with air); open-circuit technical (nitrox, with up to two mixes); or closed-circuit rebreather (CCR) with a constant inspired oxygen partial pressure (PPO_2). In this case, the diver intended to perform a dive with the computer believed to be set in open-circuit air mode. According to his computer, the diver dived to a maximum depth of 48.7 msw for a total dive time of 50 minutes, breathing air throughout (Figure 3). He completed all decompression stops advised by the computer, but experienced some back pain during ascent. This was eased by breathing oxygen on the boat. Upon returning ashore, he went to his mother’s house nearby and fell asleep exhausted. When he awoke he was unable to stand or pass urine. Diving friends took him to the local emergency department, where they had to carry him in. The relationship of his symptoms to a diving incident was not recognised for several hours, but eventually he was transferred to Hull Hyperbaric Unit where he received a series of treatments over several days. Prior to this accident, he was a fit firefighter. One year after the incident, he had been unable to return to his previous employment and was paraparetic, with both motor and sensory changes in the legs, and bladder and bowel dysfunction. A more detailed account of this case is given by Walker and Laden.[14]

Chamber compression trials

Case 1 required no further investigation as it was clear that the error lay primarily with a misunderstanding of the computer response to the adjustments made. Cases 2 and 3 did require investigation, Case 2 because of inconsistencies in the surfacing times and Case 3 because of the severe outcome caused by a seemingly well-controlled dive.

CASE 2

Three models of dive computer were compared: the *UWATEC Aladin Ultra Pro*™ (an older generation dive computer based on Bühlmann algorithms derived from the Haldane/Spencer tissue compartment principles); the *Mares Nemo*™ (a modern-generation, deep-stopping RGBM-controlled computer); and the *Suunto Vytec*. They were immersed in water in a clear perspex™ tank within the DHU compression chamber to permit direct observation. Where adjustable, the computers were set to their default, least conservative settings.

Trial 1

The previously undived computers were subjected to an approximate simulation of the dive profile of the incident sixth dive in case 2. All three models went into decompression and registered maximum decompression obligations of between 30 and 40 minutes (Figure 4). The simulated profile of Case 2, dive six was allowed to run during the decompression phases of the three models of computer in order to record when they cleared their respective decompression obligations. The *UWATEC Aladin Ultra Pro* cleared after 80 minutes, the *Suunto Vytec* after 90 minutes and the *Mares Nemo* after 93 minutes.

Figure 4
Three models of dive computer were subjected to a single compression profile designed to mimic the incident profile of Case 2 (light grey profile). The y-axis denotes the displayed decompression information of the respective computers; positive values are times remaining before entering decompression; negative values are the decompression times required; values over 99 minutes denote that the computer is clear of any decompression obligation

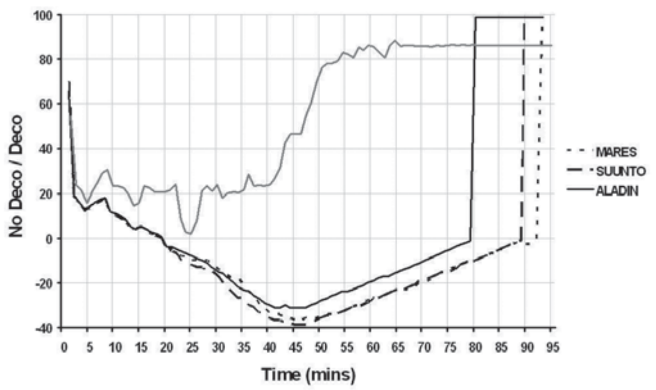
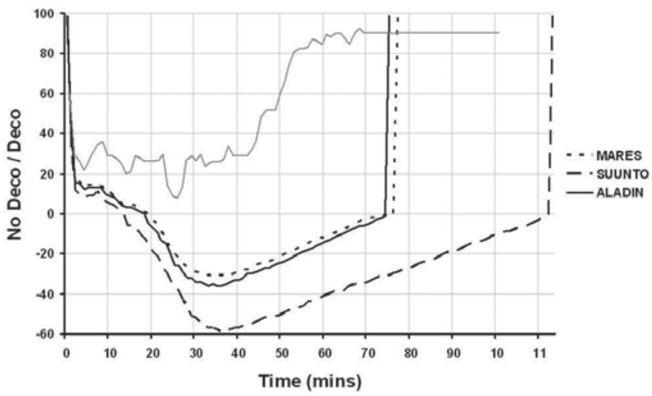


Figure 5
Three models of dive computer were subjected to a compression profile designed to mimic the incident profile of Case 2 (light grey profile) but after 5 other chamber dives over the preceding 3 days. The y-axis denotes the displayed decompression information of the respective computers; positive values are times remaining before entering decompression; negative values are the decompression times required; values over 99 minutes denote that the computer is clear of any decompression obligation



Trial 2

Because the sixth dive had occurred as part of a series, the simulated chamber profile was repeated following five chamber compressions with similar depths, times and surface intervals as indicated from the case downloads. With this gas loading, the decompression profiles of the sixth dive now differed markedly (Figure 5), with the *Suunto*, in particular, accumulating significant decompression obligations. Whereas the *Mares* and *Aladin* accrued decompression requirements of 30–40 minutes and surfaced at about 75–80 minutes, the *Suunto* had a maximum of almost 60 minutes of decompression to carry out and surfaced at 115 minutes (Figure 5).

Of additional note was the rate at which the decompression obligations reduced. From the start of the ascent to surfacing almost 200% in actual against estimated time was taken for the two RGBM models and 150% for the *Aladin* (Table 1). Taken from the time at which the profile reached 6 metres, the RGBM computers took 130% of their indicated time to surface; the *Aladin* about 110%.

Finally, some computer-controlled reduction in decompression can operate on threshold depths. In Figure 6, the same three models of computers described above were held at depths fluctuating between 9 and 11 msw. Where this is a threshold depth range, the information given by some computers ranged wildly and caused large differences in apparent decompression requirements (Figure 6). In a similar way, some dive computers will reduce the decompression in relation to the ascent profile; others will not count down until the threshold depth of the decompression stop is either close or exceeded.

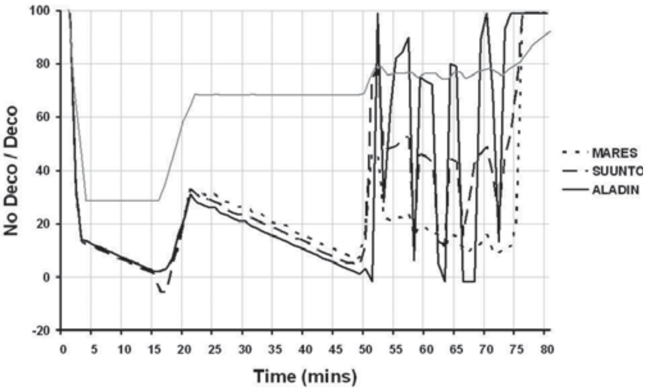
CASE 3

The features of the *Buddy Nexus* dive computer were

Table 1
Reduction rates of displayed decompression times recorded in compression chamber trials for three models of dive computer. Rates are calculated as the display decompression time divided by actual time; a value of 1.00 would be returned if display equalled actual decompression time

Computer make/model	Decompression theory	Decompression reduction from point of first ascent (minute/minute)	Decompression reduction from reaching 6 m (minute/minute)
Mares Nemo	RGBM	0.54	0.77
Suunto Vytec	RGBM	0.55	0.76
UWATEC Aladin Pro Ultra	Bühlmann	0.67	0.89

Figure 6
The reaction of three models of dive computer subjected to a nominal compression chamber dive (light grey profile) of 13 minutes at 30m, 28 minutes at 13m and then 23 minutes varying between 9 and 11m to illustrate the decompression variations caused by travelling through threshold values. The y-axis denotes the displayed decompression information of the respective computers; positive values are times remaining before entering decompression; negative values are the decompression times required; values over 99minutes denote that the computer is clear of any decompression obligation



outdated in quality. The download facility would work only on computers running *Windows 2000*™ or earlier operating systems. Data were recorded only at three-minute intervals; however, it was unclear what the sampling frequency and accuracy actually were. Depth increments were recorded at a resolution of only 0.3 msw; it was unclear how the depth was recorded (e.g., as a threshold or statistically-derived value). These features complicated an accurate recreation of the incident dive.

An initial investigation of the incident dive profile was undertaken using the dive simulation feature of the *Suunto Dive Manager*™ software package. The first run simply employed the dive profile estimated from the download information and failed after 28 minutes because of a staged decompression schedule violation. The second run altered the dive profile to comply with the decompression schedule recommended by the *Suunto* software and stops were 9 minutes at 12 msw, 11 minutes at 6 msw, and 25 minutes at 3 msw. Including travel times between stops, a total of 53 minutes of surfacing time was indicated. This compared with the approximately 23 minutes (at 3 msw) undertaken by the diver in Case 3 (Figure 3).

Trial 1

Compression trials were carried out at the Millport Hyperbaric Unit near Glasgow because the facility better delivers rapid compression and decompression rates necessary for dry-diving trials. The *Nexus* computer from the actual diving incident was used in the trial and the incident profile was reproduced using the downloaded depth profile to inform the chamber depth. A *UWATEC Aladin Ultra Pro* computer was subjected to the same profile; both computers were immersed as before and the *Nexus* performance was videoed. The *Nexus* was clear of any decompression obligation as the chamber surfaced from 3 msw. The *Aladin* had gone into "SOS" mode but, when downloaded, the initial decompression stop for the *Aladin* was at 9 msw after 29 minutes of the dive; at the same time, the *Nexus* was indicating a first stop at 3 msw. As this deeper stop was missed, the *Aladin* recomputed the decompression profile. However, at the point at which the decompression stop was missed, a total of 40 minutes of decompression was being indicated as necessary; the *Nexus* showed 20 minutes of decompression. Throughout the profile, the *Nexus* depth display read between 0.7–1.4 msw shallower than the chamber gauge and *Aladin* download respectively.

Trial 2

To correct for depth differences, a second trial was carried out a few weeks later. The chamber depth reproduced the depth/time profile to match the observed *Nexus* depth. Depth control was slightly compromised because the *Nexus* displayed at increments of only 0.3 m. The *Aladin* again required an initial decompression stop at 9 msw after 29 minutes of the dive, but a total decompression time of 36 minutes; the *Nexus* indicated an initial stop at 3 msw with a total of 19 minutes of decompression.

It was unclear why the *Nexus* permitted a much reduced decompression obligation compared with the *Aladin* for the identical dive profile. The *Nexus* download provided very few secondary data but it was certain that it was set to air and an altitude range of 0–300 m (A0). A recorded 'violation' only highlighted the fact that the computer had entered decompression mode. There was an indication that the computer was set at a PPO_2 limit of 121 kPa (1.2 bar). There was no supporting explanation in the *Nexus* manual as to what this recording referred.[4] Given that the computer could be used both for open-circuit nitrox and constant PPO_2 CCR, the recording could relate to the depth-related maximum permissible PPO_2 limit for open circuit, or the value chosen for a CCR. Given the large differences in decompressions demonstrated, it is possible that the diver in Case 3 was diving on open-circuit air with a dive computer unknowingly set to rebreather mode. Unfortunately, because of the limitations of the download quality for the *Nexus*, it was not possible to determine the mode to which the computer was set.

Discussion

Recreational and scientific diving both depend considerably on dive computers to control decompression. The low published incident rates of DCS[8–13], however, may mask the DCS rates of smaller within-sector groups employing dive computers for deeper and longer dives (e.g., deep wreck diving), or for multi-day diving programmes.[15] Although deep, multi-day diving groups probably carry a higher risk of DCS for many reasons it cannot be discounted that the efficacy of decompression management by dive computers decreases with added diving complexity.[1] It is not suggested that these cases add to any discussion on complexity-affected efficacy of dive computers. However, their dive profiles, primarily through entering decompression, exceed the limits of the computers that their respective manufacturers recommend.[4]

The potential to misunderstand outputs from some dive computers, matched possibly by peer pressure, may be a contributing factor in some decompression incidents. Case 1 was well aware that her previous episodes of DCS, possibly associated with a PFO, meant that to continue diving she needed to dive more conservatively. This she attempted, but then either ignored or forgot about the changed computer settings; both divers should have been aware of the adjusted levels on the computer and modified their dive practices accordingly. That she then swapped to another unused dive computer with no residual nitrogen loading and possibly no altered conservatism settings could have contributed to her subsequent injury and could easily have been avoided.

The newer generation of dive computers vary markedly in terms of complexity, diversity and size. A lack of knowledge of how the computers worked contributed to all three diving incidents. Case 2 demonstrated that large differences in decompression schedules can be generated by different computer models. However, in Case 2, not only did the divers continue their dive after the computer entered decompression mode, but they also dived deeper. This resulted in a decompression obligation when the dive ascent started. In addition, the decompression requirement did not reduce linearly with ascent time, producing an impending predicament of required decompression exceeding the remaining gas supplies, and resulting in the divers surfacing with missed decompression and developing DCS.

This notwithstanding, the related chamber trials show that whereas single, non-decompression dives produced little difference between the computers trialled, there were important differences between them in how decompression was calculated as the decompression obligation increased, and with multi-day diving. In the multi-dive scenario, all the computers tested reduced decompression times at slower than the estimated rates (Table 1) and the *Suunto* model , which is closest to the DCIEM tables model, generated a much greater decompression requirement. This increases the possibility of divers running out of breathing gas before completing their decompression even though with some computer models the decompression obligations may increase disproportionately to those required as more multi-day diving is performed.

Of concern for divers is the difficulty in understanding the performance of some dive computer models new to the market, e.g., the *Buddy Nexus*. This model is manufactured by *Benemec*™ in Finland; other *Benemec* computers are sold under various brand names including *Orca, Zeagle, Ocean Reef* and *Dacor*. What is surprising about a computer model released within the past seven years is the crude levels of measurement resolution, data storage and download information. No information was available on how the computer was controlled and the only mention of the decompression models employed is of “modified Bühlmann’s”. With rebranded computers the decompression algorithms employed may come as a “black box” about which the manufacturers themselves have no knowledge.

During diver training, considerable time is taken teaching decompression tables that are rarely used. Since the majority of recreational diving uses decompression computers, computer-awareness training needs enhancing and divers and treating physicians need to be aware of the limitations of computer performance. Knowledge of how a computer should perform would be enhanced by the provision of better technical manuals by manufacturers. Tame reviews in a diving press dependent on advertising revenue do not help and more independent testing of computers should be encouraged. For a recreation/occupation that is heavily into redundant support systems, it would not be unreasonable to suggest diving with two computers, with the diver always defaulting to the more conservative model.

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