Decompression management by 43 models of dive computer: single square-wave exposures to between 15 and 50 metres' depth

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Abstract

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Introduction: Dive computers are used in some occupational diving sectors to manage decompression but there is little independent assessment of their performance. A significant proportion of occupational diving operations employ single square-wave pressure exposures in support of their work.

Methods: Single examples of 43 models of dive computer were compressed to five simulated depths between 15 and 50 metres' sea water (msw) and maintained at those depths until they had registered over 30 minutes of decompression. At each depth, and for each model, downloaded data were used to collate the times at which the unit was still registering "*no decompression*" and the times at which various levels of decompression were indicated or exceeded. Each depth profile was replicated three times for most models.

Results: Decompression isopleths for no-stop dives indicated that computers tended to be more conservative than standard decompression tables at depths shallower than 30 msw but less conservative between 30–50 msw. For dives requiring decompression, computers were predominantly more conservative than tables across the whole depth range tested. There was considerable variation between models in the times permitted at all of the depth/decompression combinations.

Conclusions: The present study would support the use of some dive computers for controlling single, square-wave diving by some occupational sectors. The choice of which makes and models to use would have to consider their specific dive management characteristics which may additionally be affected by the intended operational depth and whether staged decompression was permitted.

Key words

Computers – diving, occupational diving, decompression, dive profile, decompression tables

Introduction

Dive computers can be accepted in some occupational diving sectors as tools for managing decompression.[1] However, the choice of which dive computer could be used for occupational diving is difficult because the number of models available is considerable. The choice is further complicated by the many different decompression algorithms employed in dive computers, with some being modified by manufacturers in unspecified ways.[2] In Europe, standards and normatives that underpin CE marking for dive computers do not stipulate operational limits for decompression management.[3,4]

There are many potential advantages to using dive computers for occupational diving. They can control diver ascent rates and calculate decompression based on actual (rather than predicted) multi-level pressure exposures. Most have dive profile storage and download capabilities;[5] some have additional features such as: calculating for the use of mixed gases; wireless display of cylinder pressures and heart-rate monitoring, as well as a range of user settings (seawater/freshwater, conservatism, altitude, etc.).[2] However, without a detailed knowledge of how the dive computers are managing decompression, diving supervisors will not have the relevant information on which to base any management choices about which models could be accepted for operational use within a regulated occupational diving environment. Whereas conservatism of decompression schedules may be more important for some diving operations, maximising bottom time safely may be the predominant reason for choice in others.

There have been a number of studies that have compared the performance of dive computers in managing decompression.[6–8] The present study follows previous ones in that it compares the performance of a range of dive computers standardised across a number of pressure/time profiles. However, all the models assessed are relatively modern being either currently on sale or remaining in common use in the UK and Europe.[2,9] Comparisons were made of a series of single, square-wave profile dives for the depth range of 15 to 50 metres' sea water (msw). It is assumed that the square-wave profile is more typical of most occupational diving operations where the divers are working on a single task at a single depth before returning to the surface. The chosen depth range is assumed to be representative of most compressed air scuba diving operations where decompression obligations become apparent.

Methods

Single examples of 43 models of dive computer that are in common use in the UK (Table 1) were set to default settings and all were in sea water mode. The computers were compressed simultaneously to five simulated depths (nominally 15, 20, 30, 40 and 50 msw). In each test, all 43

Table 1
The 43 models of computer employed in the present study, listed alphabetically by brand name

Brand	Model
Apeks	Pulse
Apeks	Quantum
Beauchat	Voyager
Cressi Sub	Archimede 2
Cressi Sub	Edy II
Mares	Icon HD
Mares	Nemo Sport
Mares	Nemo
Mares	Nemo Excel
Mares	Nemo Air
Mares	Nemo Wide
Mares	Puck Wrist
Mares	Puck Air
Oceanic	Atom 2
Oceanic	Datamask Hud
Oceanic	Pro Plus 2
Oceanic	Veo 250
Oceanic	VT 3
Scubapro	Xtender
Seeman	XP 5
Suunto	Cobra 2
Suunto	Cobra 3
Suunto	D9
Suunto	D6
Suunto	D4
Suunto	Stinger
Suunto	Spyder
Suunto	Vyper
Suunto	Vyper 2
Suunto	Vyper Air
Suunto	Vytec DS black
Suunto	Vytec Silver
Tusa	DC Hunter
Tusa	DC Sapience
Uemis	SDA
Uwatec	Aladin One
Uwatec	Aladin Prime
Uwatec	Aladin Tec 2 G
Uwatec	Galileo Luna
Uwatec	Galileo Sol
Uwatec	Galileo Terra
Uwatec	Smart Tec
Uwatec	Smart Com

computers were immersed in fresh water to a depth of 20 cm in a tank located inside a standard two-compartment therapeutic recompression chamber (*Divex* chamber of 2,000 mm diameter). The chamber was compressed with air using manual control to the simulated nominal depth employing the fastest descent rate possible through the compression valve being fully opened each time. Depth was maintained and monitored using calibrated chamber gauges (+ 0.032 msw average error rising (0–50 msw, $n = 5$); + 0.020 msw average error falling (50–0 msw, $n = 5$); calibrated by a UKAS Calibration Laboratory-certified *Druck* MS-022 to the test standard BS EN 837–1:1998); there were some minor manual adjustments for depth (± 0.1 msw) for the effects of temperature changes following compression and before stabilisation occurred as controlled by the chamber's environmental control unit. Barometric pressure before and during the tests was not recorded. The chamber is situated approximately 3 m above sea-level.

The chamber was maintained at nominal depth until it was known that all computers had registered over 30 minutes of decompression. At each depth, and for each model, downloaded data from the computers were used to collate the dive duration at which the unit was still registering "*no decompression*", and the time of the dive at which 3, 5, 8, 10, 12, 15, 20 and 30 minutes of decompression were indicated or exceeded. Each depth profile was replicated three times for most models; intervals between tests were at least 72 h to allow for the effects of the previous test to clear.

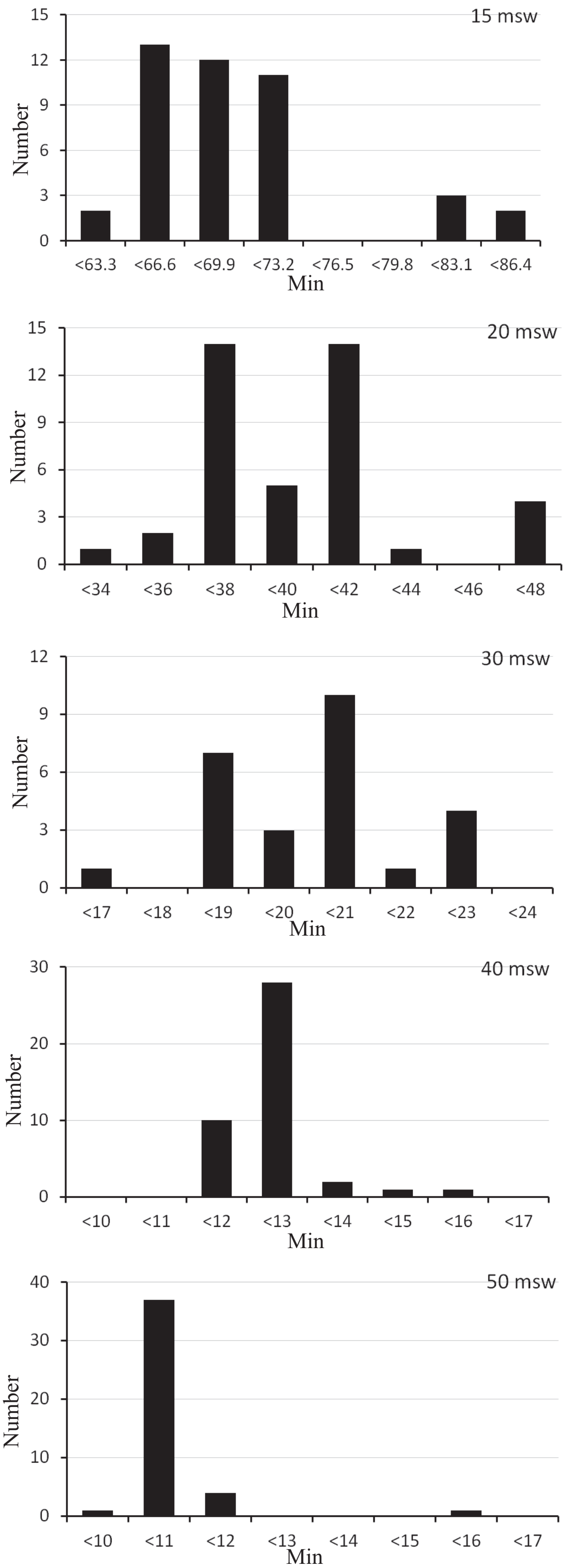
Depth/time isopleth relationships were generated for all the decompression end points examined over a 15 to 50 msw depth range for every model of computer. These were compared against isopleths constructed based on the Royal Navy Physiology Laboratory air decompression table 11 (RNPL 11), the Defence and Civil Institute of Environmental Medicine (DCIEM) air decompression tables, and the Sub-Aqua Association's modified version of the Bühlmann 1986 air decompression tables.[10–12] Linear interpolation was used to provide dive times where table increments did not match the nominal test depths.

Frequency analyses were conducted based on the numbers of computer models falling within the time ranges required to reach designated decompression endpoints. The times recorded to reach all of the decompression/depth endpoints were converted into values of per cent deviation from the overall means. For decompression and non-decompression, the computers and tables were ranked based on their mean per cent deviation values.

The effects of two compression regimes that produced descent rates equivalent to 5.0–7.5 and 16.7–20.0 $m \cdot min^{-1}$, were tested on nine of the computer models (*Uwatec Galileo Sol*, *Uwatec Aladin Prime*, *Mares Nemo Wide*, *Mares Nemo, Suunto D9*, *Suunto Vyper 2*, *Oceanic Atom 2*, *Cressi Sub Edy II*, *Apeks Quantum*) at depths of 20 and 40 msw. The times on the downloaded profiles that indicated the maximum time for no-decompression (the time just before the recording showed a required decompression stop) and those needed to generate 10, 20 and 30 min of decompression were compared between the two descent rates at each depth using Student's *t*-test for paired samples.

The water temperature in all the tests was recorded using an immersed *Gemini Tiny Tag* data logger. A record of any computer malfunctions or failures was maintained.

Figure 1
Frequency analysis of number of tested computer units displaying maximum no-decompression stop times (Min) for square-wave dive profiles to maximum depths of 15–50 msw; for each unit, n = 1–3 for each depth test



Results

Differences between replicated trials were examined for the 0, 5, 10, 20 and 30 minutes of decompression intervals (Table 2). In 95.5% of the comparisons, variation was within 10% of the average time for all tests; variation was zero in 47.4% of the comparisons examined. In 0.4% of comparisons, variation was greater than 25% of the average time. The maximum recorded variations for the five decompression times ranged between 19.0 and 33.3%. There was no consistency in the variations observed in terms of individual units, specific tests or minor depth changes.

A slower descent rate generated significantly longer times permitted before each of the nominal decompression end points (no-stop, 10, 20, 30 min) was reached at both depths tested (20 and 40 msw; $P < 0.01$ and $n = 9$ in all cases). The differences in the times to reach each end point were broadly attributable to the additional time taken during slower descents.

Frequency analyses showed that there was considerable variation in the times recorded by the computer units for all the depth/decompression combinations; an example for no-decompression-stop values is shown in Figure 1. With two exceptions (no stops and 8 minutes of decompression at 50 msw, differences of > 40% recorded) the variances between the maximum and minimum times permitted to reach all the nominal decompression end points at all the five test depths were between 20 and 40% of the maximum recorded times (Figure 2). The largest differences in permitted times were not always attributable to the same computer units. The trends for the 15 and 20 msw tests tended to be more consistent across the range of decompression endpoints tested (Figure 2).

The decompression isopleths generated for no-stop dives indicated that computers tended to be more conservative than standard decompression tables at depths shallower than 30 msw (and particularly at 15 msw), but less conservative between 30–50 msw (Figure 3). However, these differences were not always consistent between computer models. Whereas in some comparisons there were relatively constant differences between the computers at all depths (Figure 4), in others there were quite large differences at shallower depths but these were not evident when the tests were deeper (Figure 5).

Differences in decompression management were also present across the depth range tested in per cent deviation from the mean. For no-decompression dives the *Oceanic Veo 250*, for example, gave times that were less than the mean at 15, 20 and 50 msw, but above the mean at 30 and 40 msw (Table 3). The *Mares Nemo Sport* was among the most conservative computers when tested at 15 msw, but was the least conservative at 40 and 50 msw (Table 3). Similar anomalies were present in the decompression dives; an example is the

Figure 2

The difference in total dive times required to generate decompression penalties of 0–30 min expressed as a % of the maximum permissible time. Values are for 43 computer models tested across a depth range of 15–50 msw (n = 1–3 for each point)

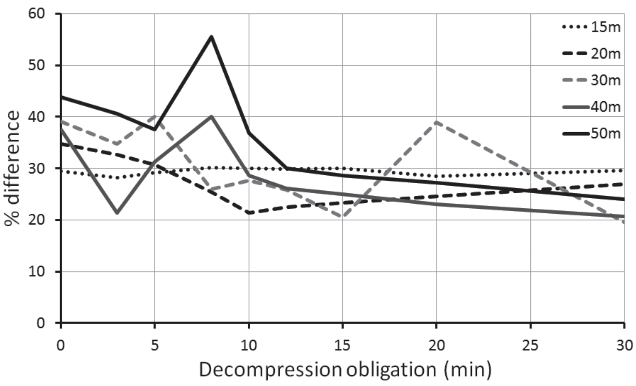


Figure 3

Isopleth relationships for the maximum times permitted by 43 models of dive computer and two air decompression tables before the dive would require any decompression over a depth range of 15 to 51 msw; all dive profiles were square-wave; isopleths for the dive computers are pooled to show maximum (MAX), minimum (min) and median values for all 43 models

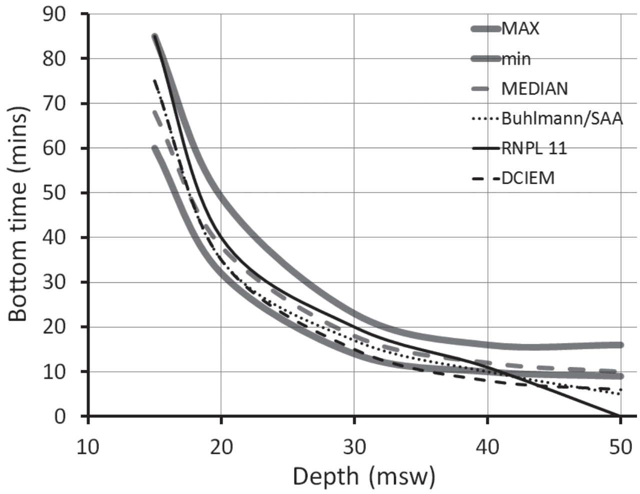


Figure 4

Decompression isopleths for two models of dive computer (*#36 = Oceanic Datamask HUD and #40 = Apeks Quantum*) compared at three levels of decompression stress (no-stops; 15 min of deco; 30 min of deco)

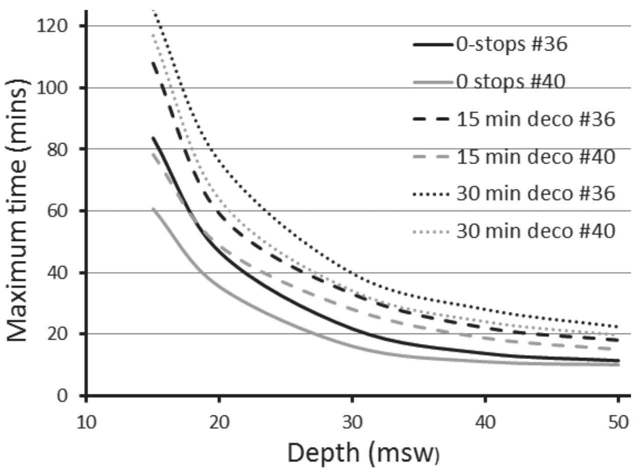


Figure 5

Decompression isopleths for two models of dive computer (*#10 = Mares Icon HD and #42 = Seeman XP5*) compared at three levels of decompression stress (no-stops; 15 min of deco; 30 min of deco)

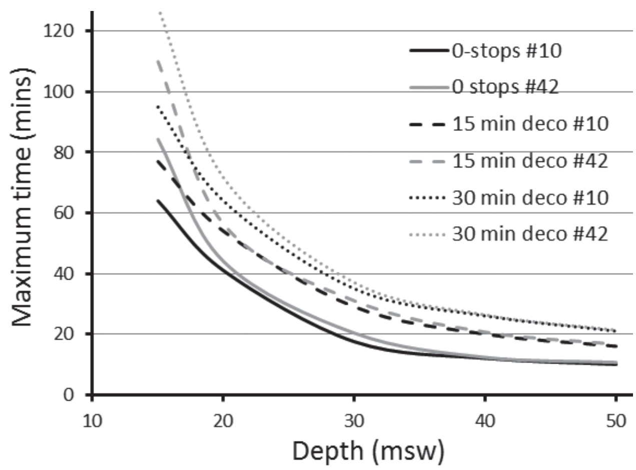


Table 2

Variation in times recorded within three replicate tests for 41 models of decompression computers compared at 25 combinations of nominal depth and decompression interval. Values are for the number of test runs falling within 5% variation groups

	% Variation in times recorded/average time						
Decompression time (mins)	0	0.1–5	5.1–10	10.1–25	> 25	Max	*n*
0	79	51	60	7	3	33.3	200
5	79	60	30	9	1	26.5	179
10	107	70	14	9	0	19.0	200
20	97	79	18	7	0	19.7	201
30	104	84	7	6	0	22.3	201
Total	466	344	129	38	4		981
%	47.5	35.0	13.1	3.9	0.4		

Table 3

Mean maximum times (n = 1–3; n = 3 in 187/215 tests) permitted by 43 dive computers and three decompression tables without having to undertake decompression stops at each of five nominal depths (15–50 msw; the RNPL 11 recommended decompression for any dive to 50 msw). For each depth, the mean no-decompression times were expressed as % deviation from the mean value; the final table ranking is based on the overall mean % deviations; blank cells = missing data

	Mean maximum no-decompression times (min; n = 1–3)					Overall mean deviation (%; n = 2–5)
	15 msw	20 msw	30 msw	40 msw	50 msw	
Decompression table						
DCIEM	75.0	35.0	15.0	8.0	6.0	-19.1
Buhlmann/SAA	75.0	35.0	17.0	10.0	5.0	-15.6
RNPL 11	85.0	40.0	20.0	11.0	0.0	-15.4
Computer model						
UEMIS SDA	70.0	33.3	15.7	11.5	8.7	-9.5
APEKS Quantum	60.7	35.3	16.0	11.0	10.0	-8.9
TUSA DC Sapience	60.0			11.0	10.0	-7.3
TUSA DC Hunter	65.0	37.0	17.0	11.3	10.0	-5.2
SCUBAPRO Xtender	65.3	37.0	17.0	11.3	10.0	-5.1
CRESSI Sub Archimede 2	64.3	38.0	17.0	11.0	10.3	-4.8
CRESSI Sub Edy II	64.7	38.0	17.0	11.3	10.3	-4.1
APEKS Pulse	65.0	38.0	17.0	11.0	10.7	-3.9
MARES Nemo Excel	65.3	37.0	17.3	12.3	10.0	-3.1
OCEANIC Veo 250	65.0	35.0	19.0	12.5	9.7	-2.8
MARES Nemo	66.7	37.3	17.3	12.3	10.0	-2.5
MARES Nemo Wide	66.3	37.7	17.3	12.3	10.0	-2.5
MARES Puck wrist	66.3	37.7	17.3	12.3	10.0	-2.5
MARES Puck Air	65.7	37.3	17.7	12.3	10.0	-2.5
MARES Nemo Air	66.7	37.5	17.3	12.3	10.0	-2.4
MARES Icon HD	64.0	41.0	17.5	12.0	10.0	-1.8
UWATEC Smart Com	66.0	38.0	17.3	12.7	10.7	-0.5
UWATEC Aladin prime	67.3	38.0	17.0	12.7	10.7	-0.5
UWATEC Aladin Tec 2 G	67.3	38.0	17.3	12.7	10.7	-0.1
UWATEC Galileo Sol	67.3	38.3	17.3	12.7	10.7	0.1
UWATEC Galileo Terra	67.3	38.3	17.3	12.7	10.7	0.1
UWATEC Galileo Luna	67.7	38.7	17.3	12.7	10.7	0.3
UWATEC Smart Tec	67.3	38.3	17.7	12.7	10.7	0.4
BEAUCHAT Voyager	69.3	42.0	18.3	11.7	10.0	0.6
SUUNTO Vyper Air	70.3	40.7	19.3	12.0	10.0	1.8
SUUNTO Spyder	72.0	41.7	19.0	11.7	10.0	1.9
SUUNTO Cobra 3	70.0	41.0	19.3	12.0	10.0	1.9
SUUNTO Vyper	70.0	41.0	19.3	12.0	10.0	1.9
SUUNTO Cobra 2	69.3	41.0	19.7	12.0	10.0	2.1
SUUNTO Vyper 2	70.3	41.0	19.7	12.0	10.0	2.4
SUUNTO Stinger	72.3	41.3	19.0	12.0	10.0	2.4
SUUNTO Vytec DS black	69.7	41.0	20.0	12.0	10.0	2.5
SUUNTO D4	70.0	41.0	20.0	12.0	10.0	2.6
SUUNTO Vytec silver	70.0	41.0	20.0	12.0	10.0	2.6
SUUNTO D9	70.3	41.0	20.0	12.0	10.0	2.7
SUUNTO D6	70.3	41.0	20.0	12.0	10.0	2.7
UWATEC Aladin One	68.0				11.0	4.2
SEEMAN XP 5	84.3	44.0	20.3	12.3	10.7	10.5
OCEANIC VT 3	82.3	46.3	21.5	12.0	11.0	12.5
OCEANIC Pro Plus 2	80.3	46.7	21.7	14.0	10.7	14.9
MARES Nemo Sport	65.0	38.3	19.0	15.3	15.3	15.0
OCEANIC Datamask Hud	82.7	46.5	22.0	13.7	11.3	16.7
OCEANIC Atom 2	83.7	46.7	21.7	13.7	11.3	16.7
Mean	69.7	39.5	18.4	12.0	9.9	

Table 4

The mean % deviation (n = 1–3; n = 3 in 561/645 tests) from the mean maximum times taken to generate three levels of decompression (10, 20 and 30 min) at each of five nominal depths (15–50 msw) for 43 models of dive computer and two air decompression tables (shaded); the results are ranked based on the overall mean % deviations; blank cells = missing data

Computer model	15 msw				20 msw				30 msw				40 msw				50 msw				Overall
	10 min	20 min	30 min	mean	10 min	20 min	30 min	mean	10 min	20 min	30 min	mean	10 min	20 min	30 min	mean	10 min	20 min	30 min	mean	mean
APEKS Quantum	-14.54	-12.29	1.17	-8.55	-8.74	-8.70	-8.56	-8.66	-5.27	-6.17	-9.38	-6.94	-16.51	-9.77	-8.83	-11.71	-7.49	-6.13	-5.21	-6.28	-8.43
MARES Nemo Excel	-9.28	-15.29	-15.55	-13.37	-5.34	-6.38	-12.87	-8.20	-9.06	-4.11	-4.05	-5.74	-10.94	0.41	0.03	-3.50	-14.60	-0.61	1.21	-4.67	-7.10
MARES Nemo	-8.06	-14.29	-14.10	-12.15	-4.66	-6.38	-12.87	-7.97	-11.59	-4.11	-5.83	-7.18	-10.94	0.41	0.03	-3.50	-14.60	-0.61	1.21	-4.67	-7.09
OCEANIC Veo 250	-10.90	-11.62	-11.80	-11.44	-8.74	-11.58	-15.26	-11.86	-4.01	-2.05	-6.71	-4.26	2.97	0.41	-1.24	0.72	-5.11	-7.98	-6.82	-6.64	-6.70
MARES Puck Air	-8.87	-14.63	-14.68	-12.73	-4.66	-6.38	-12.87	-7.97	-6.54	-1.02	-4.05	-3.87	-10.94	0.41	0.03	-3.50	-14.60	-0.61	1.21	-4.67	-6.55
MARES Nemo Air	-7.66	-13.96	-14.39	-12.00	-5.00	-6.38	-12.39	-7.92	-6.54	-2.05	-4.05	-4.21	-10.94	0.41	-1.24	-3.92	-14.60	-0.61	1.21	-4.67	-6.55
MARES Puck wrist	-8.47	-14.29	-14.68	-12.48	-3.98	-5.81	-12.39	-7.39	-5.27	-1.02	-4.05	-3.45	-10.94	0.41	0.03	-3.50	-14.60	-0.61	1.21	-4.67	-6.30
MARES Nemo Wide	-8.06	-13.96	-14.39	-12.14	-3.98	-4.65	-11.91	-6.84	-5.27	-1.02	-4.05	-3.45	-10.94	0.41	-1.24	-3.92	-14.60	-0.61	1.21	-4.67	-6.20
MARES Icon HD	-11.30	-16.96	-17.85	-15.37	2.15	-1.18	-8.08	-2.37	-9.06	-2.57	-6.71	-6.11	-5.38	-3.95	-1.24	-3.52	-7.49	-0.61	1.21	-2.30	-5.93
SCUBAPRO Xtender	-8.06	-3.95	11.84	-0.06	-4.66	-4.07	-3.77	-4.17	-2.75	-2.05	-5.83	-3.54	-5.38	-3.95	-5.04	-4.79	-7.49	-37.42	-3.61	16.17	-5.75
TUSA DC Sapience	-13.73	-9.96	3.77	-6.64									-5.38	-3.95	-5.04	-4.79	-7.49	-0.61	1.21	-2.30	-4.57
BEAUCHAT Voyager	-4.01	-8.96	-19.29	-10.75	-1.93	-4.65	-8.56	-5.05	1.04	-4.11	-7.60	-3.56	0.19	0.41	-5.04	-1.48	-0.37	-0.61	-3.61	-1.53	-4.47
TUSA DC Hunter	-8.06	-3.95	11.84	-0.06	-3.98	-4.07	-3.77	-3.94	-1.48	-1.02	-4.05	-2.18	-5.38	-3.95	-5.04	-4.79	-7.49	-4.29	-3.61	-5.13	-3.22
CRESSI-SUB Archimede 2	-8.47	-4.62	11.26	-0.61	-3.29	-2.92	-2.33	-2.85	-1.48	-1.02	-4.05	-2.18	-5.38	-3.95	-5.04	-4.79	-7.49	-4.29	-3.61	-5.13	-3.11
CRESSI-SUB Edy II	-8.87	-4.29	11.26	-0.63	-3.98	-2.92	-2.33	-3.07	-1.48	-1.02	-4.05	-2.18	-5.38	-3.95	-3.77	-4.37	-7.49	-2.45	-3.61	-4.52	-2.95
SUUNTO Stinger	-1.18	0.72	-7.76	-2.74	-1.93	-3.49	-2.81	-2.75	-5.27	-2.05	-3.16	-3.49	-5.38	0.41	-1.24	-2.07	-5.11	-0.61	-2.00	-2.58	-2.72
UEMIS SDA	-0.37	8.05	13.28	6.99	-1.25	1.13	3.89	1.26	-12.85	-2.05	-2.27	-5.72	-8.16	-1.77	-3.14	-4.36	-14.60	-7.98	-8.43	10.33	-2.43
UWATEC Smart Com	-5.63	-0.29	1.17	-1.58	-3.29	-2.92	-1.38	-2.53	2.31	-4.11	-6.71	-2.84	5.76	-2.50	-5.04	-0.59	6.75	-0.61	-3.61	0.84	-1.34
UWATEC Aladin Tec 2 G	-4.42	0.72	1.46	-0.75	-3.29	-2.92	-0.90	-2.37	2.31	-4.11	-6.71	-2.84	5.76	-2.50	-5.04	-0.59	6.75	-0.61	-3.61	0.84	-1.14
UWATEC Aladin Prime	-4.82	1.05	1.17	-0.87	-2.61	-2.34	-0.90	-1.95	2.31	-4.11	-5.83	-2.54	5.76	-3.95	-5.04	-1.08	6.75	-0.61	-3.61	0.84	-1.12
UWATEC Galileo Terra	-4.82	0.72	2.04	-0.69	-3.98	-3.49	-1.85	-3.11	2.31	-4.11	-5.83	-2.54	5.76	-2.50	-5.04	-0.59	6.75	-0.61	-2.00	1.38	-1.11
APEKS Pulse	-7.25	-4.29	11.84	0.10	-3.29	-2.92	-2.33	-2.85	-1.48	-1.02	-4.05	-2.18	-9.09	-6.86	-6.30	-7.42	4.38	8.59	7.64	6.87	-1.10
UWATEC Galileo Sol	-4.82	0.05	1.75	-1.01	-3.29	-2.92	-0.90	-2.37	2.31	-4.11	-6.71	-2.84	5.76	-2.50	-5.04	-0.59	6.75	-0.61	-2.00	1.38	-1.09
UWATEC Smart Tec	-4.01	1.72	2.04	-0.09	-3.29	-2.34	-1.38	-2.34	2.31	-4.11	-5.83	-2.54	5.76	-3.95	-5.04	-1.08	6.75	-0.61	-3.61	0.84	-1.04
UWATEC Galileo Luna	-4.01	1.72	2.04	-0.09	-2.61	-2.34	0.06	-1.63	2.31	-4.11	-4.94	-2.25	5.76	-2.50	-5.04	-0.59	6.75	-0.61	-3.61	0.84	-0.74
SUUNTO Vytec silver	0.85	0.05	-8.34	-2.48	0.11	3.15	4.85	2.70	2.31	-31.95	6.61	-7.68	5.76	1.87	3.83	3.82	6.75	4.91	1.21	4.29	0.13
UWATEC Aladin One	-4.01	0.05	3.77	-0.07													6.75	-0.61	-3.61	0.84	0.39
SUUNTO Vyper Air	0.44	0.38	-8.05	-2.41	0.11	2.86	4.85	2.61	2.31	2.07	5.72	3.37	2.05	0.41	2.56	1.67	6.75	3.07	1.21	3.68	1.78
SUUNTO Spyder	4.09	1.72	-7.19	-0.46	2.15	3.44	3.41	3.00	1.04	0.01	-1.38	-0.11	3.90	3.32	0.03	2.42	6.75	6.75	1.21	4.90	1.95
SUUNTO Cobra 3	1.25	0.38	-7.76	-2.04	0.79	2.86	4.85	2.83	2.31	2.07	6.61	3.66	2.05	0.41	2.56	1.67	6.75	3.07	1.21	3.68	1.96
SUUNTO Vyper	0.85	0.55	-8.34	-2.32	0.11	3.15	4.85	2.70	2.31	2.07	6.61	3.66	2.05	0.41	2.56	1.67	6.75	4.91	1.21	4.29	2.00
SUUNTO Cobra 2	0.04	0.05	-8.34	-2.75	0.11	3.44	4.85	2.80	2.31	2.07	6.61	3.66	3.90	0.41	2.56	2.29	6.75	4.91	1.21	4.29	2.06
SUUNTO Vytec DS black	1.25	-0.29	-8.92	-2.65	2.15	4.02	4.37	3.51	2.31	3.11	5.72	3.71	5.76	1.87	2.56	3.40	6.75	4.91	1.21	4.29	2.45
SUUNTO Vyper 2	1.66	1.05	-7.19	-1.49	1.47	4.02	6.29	3.93	3.57	2.07	6.61	4.08	3.90	1.87	2.56	2.78	6.75	4.91	1.21	4.29	2.72
SUUNTO D4	0.44	0.38	-7.76	-2.31	1.13	4.02	5.57	3.57	4.20	2.07	6.61	4.30	5.76	3.32	2.56	3.88	6.75	4.91	1.21	4.29	2.74
SUUNTO D6	1.66	0.72	-7.48	-1.70	1.47	4.60	5.81	3.96	4.83	2.07	6.61	4.51	5.76	3.32	2.56	3.88	6.75	4.91	1.21	4.29	2.99
SUUNTO D9	1.25	0.72	-7.48	-1.84	1.47	4.02	5.81	3.77	6.09	2.07	7.50	5.22	5.76	3.32	2.56	3.88	6.75	4.91	1.21	4.29	3.06
DCIEM table	**45.80**	**40.07**	**38.36**	**41.41**	**2.15**	**21.35**	**14.90**	**12.80**	**-9.06**	**11.35**	**11.94**	**4.74**	**-22.07**	**-3.95**	**6.36**	**-6.56**	**-35.95**	**-22.70**	**-18.06**	**25.57**	**5.37**
SEEMAN XP 5	20.69	15.39	10.68	15.59	7.60	5.75	2.93	5.43	1.04	4.14	-1.38	1.26	5.76	3.32	0.03	3.04	9.12	1.23	2.82	4.39	5.94
MARES Nemo Sport	-7.66	-3.95	11.84	0.07	-1.93	-1.76	-1.38	-1.69	6.09	4.14	0.39	3.54	13.18	10.60	7.63	10.47	32.84	21.47	18.89	24.40	7.36
OCEANIC VT 3	16.24	12.39	7.80	12.14	11.69	10.37	8.20	10.09	6.09	8.26	3.95	6.10	2.97	0.41	-3.14	0.08	13.86	6.75	6.03	8.88	7.46
OCEANIC Datamask Hud	17.86	13.72	8.67	13.41	12.37	-26.03	9.16	-1.50	7.36	10.32	5.72	7.80	11.32	9.15	6.36	8.94	13.86	6.75	7.64	9.42	7.61
OCEANIC Pro Plus 2	12.59	10.39	6.36	9.78	11.69	10.95	9.16	10.60	7.36	9.29	4.83	7.16	13.18	9.15	5.09	9.14	13.86	6.75	6.03	8.88	9.11
OCEANIC Atom 2	18.67	14.05	8.95	13.89	12.37	10.37	8.68	10.47	6.09	8.26	3.95	6.10	11.32	9.15	6.36	8.94	13.86	6.75	6.03	8.88	9.66
RNPL 11 table	**45.80**	**45.07**	**47.00**	**45.96**	**22.58**	**30.02**	**29.27**	**27.29**	**13.67**	**23.73**	**33.26**	**23.55**	**11.32**	**0.41**	**32.95**	**14.90**	**-28.84**	**-6.13**	**6.03**	**-9.65**	**20.41**

Table 5
The mean overall times needed to generate decompression times of 10, 20 or 30 min of decompression time at each of five nominal depths (15–50 msw) for 43 models of dive computer and two air decompression tables (n = 129–135 for each cell)

	Decompression time (min)		
Depth (msw)	10	20	30
15	82.3	100.0	115.6
20	49.0	57.7	69.6
30	26.4	32.3	37.5
40	18.0	22.9	26.3
50	14.1	18.1	20.8

Uemis SDA which gave longer than mean times at depths of 15 and 20 msw but generated shorter than mean times for the deeper depths (Table 4). Although there was a degree of scatter, there were some general trends within the main manufacturing brands, with *Mares* computers tending to produce the most conservative times, followed in order by *Uwatec* and *Sunto* models (Tables 3 and 4). In both the no-decompression and decompression tests, most of the *Oceanic* computers gave the longest times for many of the exposures (Tables 3 and 4). Overall, but particularly from 30 msw and deeper, the air decompression tables produced the most conservative dive times for no-decompression dives (Table 3); however, in the decompression dives, both of the tables tested (RNPL and DCIEM) were ranked in the lower levels for conservatism (Table 4).

Water temperatures ranged from 12.2–24.5^{O}C (n = 1,467) with a total run time of 1,030.6 computer-hours for all the tests. There were 28 battery changes and 19 computer failures during the trials. Some of the failures were minor and related to being unable to download the dive because of low battery power, or only part of or none of the dive had registered on the download. Some of the failures were where the download information simply did not equate to the dive profile; there was one unit that flooded. Results from any unit displaying any recording anomalies (including low battery readings) were rejected from the analyses. It is unclear whether the download errors were representative of real-time problems that could have affected the ability of the diver to continue to receive valid information and, therefore, could have resulted in a dive being aborted. If it is assumed they could be, then this equates to a battery change or failure every 37 or 54 h of diving, respectively.

Discussion

The results from the present study show numerous scales of variation in how decompression following a single, square-wave exposure is being managed by the dive computers tested. Although 0.4% of all replications showed time differences between sets of greater than 25%, these were in the 40 and 50 msw trials where denominator values are small and so errors are exaggerated. Irrespective of internal variations there were considerable ranges of times permitted to reach each of the depth/decompression end points. The study employed only single examples of each of the dive computer models tested and lack of replication may explain some of the differences that were observed. Although there was a recorded water temperature range of about 12^{O}C, much of that change was linear and temporary, being caused by the heat of compression. Some dive computers are claimed to modify decompression management with changes in ambient water temperature; however, no detail is provided as to the scale of modification and how that would relate to the range in temperatures recorded in this study. The computers were set to sea water mode in all tests as this function (compared with fresh water) was present in all the units. Although the computers were immersed in fresh water, this would not affect comparative decompression computations as the changes in depth were achieved using pressurised air monitored in msw in all cases.

Some of the variation may be caused by the decompression time retrieved from the computer downloads not necessarily being reduced by all computers at similar rates. Previous studies have shown that the decompression penalties displayed on a dive computer at the start of an ascent may not equate to the actual decompression time that is eventually undertaken.[13] Similarly the rate of reduction in the eventual decompression penalty that occurs in most dive computers as the unit travels to the decompression stop depths is not always uniform between computer models.[13] So, although two computers may both be indicating the same duration of total decompression at the point of initiating an ascent, one may take much longer to reach a point where surfacing is permitted than the other. Dive computers that generate longer surfacing times may be compensating in part for the longer times that some units allow to reach the nominal decompression endpoints.

Additional variation in the results obtained may also have been caused by the relatively low resolution of the time units that were displayed in the downloaded profiles (never less than one minute). It is unknown how the displayed information was being controlled and whether threshold values or conventional rounding up was being employed, or if the methods for rounding up were consistent for all models. Relatively small differences in the recording or display methods could generate significant variance in the results.

It is acknowledged that the compression rates of the two chamber compartments used in the present study were much slower than rates that could be employed in profiles where the diver may be attempting to maximise bottom time. Compression rate produced significant differences in the decompression schedules recorded for the same depth. However, these differences were very small and consistent and did not alter the overall rankings; some of the differences almost certainly resulted from the difficulty in retrieving high-resolution data from downloaded information alone.

The present study evaluated performance for single, square-wave dive profiles only. The real advantage of using computers to manage decompression is that they can easily control multi-level, multi-day and multi-dive diving.[6,14] Some of the variation must be attributed to the decompression theories being employed. Examination of Tables 3 and 4 does show approximate groupings for the main manufacturers. This is not surprising as the different manufacturers tend to employ the same form of decompression algorithm over their whole family of computers.[2] However, there is no consistent or predominant decompression model being used and several manufacturers are modifying the algorithms themselves but in the absence of published criteria supporting those modifications.

For example, all the *Oeanic* computers examined in the present study employ modified Haldanean algorithms using the Diving Science and Technology database; the *Suunto* computers use the Suunto reduced gradient bubble model (RGBM); the *Uwatec* computers use versions of the ZH-L8 ADT, which is *Uwatec*'s adaptive 8-tissue algorithm; and *Mares* use their Mares-Wienke RGBM which is not a true RGBM algorithm but a Haldanian model with some additional safety factors.[2,15] Although it could be hypothesised that some algorithms are modifying the test dive decompression management because it is being treated as the initial dive in an anticipated multi-dive series, the differences between the computers are not always consistent across the depth range investigated and so significant theoretical dissimilarities must exist. It is most likely that the computers treat a 'first' dive in isolation and make any subsequent adjustments if the dive series evolves. In that case, differences in how the computers are working are known. For example, the standard Bühlmann model does not penalise consecutive dives whereas the RGBM models from *Suunto* and *Mares* employ a safety factor for repetitive diving that does give a penalty.[15]

The rate of battery failures in the present study was similar to values published previously.[9] The amount and type of warning given to the diver of an impending battery failure varied markedly between models. This, and the relatively high rate of failures recorded that could impact the ability to control decompression, would suggest that carrying two computers should be standard for any occupational diver who is relying on this method for dive management.

The results from the present study are probably only pertinent to the working diver because of the single-dive, square-wave profile employed. In many diving industry sectors, there continues to be a degree of scepticism about using dive computers for managing decompression. Much of that will come from the perceived loss of control over the diver from the surface supervising team. Where the safe control of decompression management can be devolved to the diver, then the present study would suggest that many models of dive computer deliver profiles that are as conservative as standard air decompression tables for non-decompression diving, but considerably more conservative for those dives that involve staged decompression. There is no evidence to imply that the longer exposures being indicated by some of the computers are not adequate although decompression sickness risks and probabilities will probably increase with prolonged bottom time.

In a computer-driven era, it remains disappointing that dive management decisions, needed to balance the operational benefits of longer dive times against the additional risk of decompression sickness, continue to be based largely on subjective assessment. This will remain an issue until there is an accepted 'gold standard' for decompression modelling. As long as no standardised decompression model exists it will remain difficult for there to be any consistent approach to the manufacture of decompression computers.[4]

References

1 Dean M, Forbes R, Lonsdale P, Sayer M, White M. *Scientific and archaeological diving projects*. *Diving at Work Regulations 1997*: *Approved Code of Practice*. Sudbury: HSE Books; 1998. [cited 2014 April 14]. Available from: http://www.hse.gov.uk/pubns/priced/l107.pdf.

2 Azzopardi E, Sayer MDJ. A review of the technical specifications of 47 models of diving decompression computer. *Underwater Technology.* 2010;29:63-72.

3 European Standard EN 13319: 2000 *Diving accessories. Depth gauges and combined depth and time measuring devices. Functional and safety requirements, test methods.* Brussels: European Committee for Standarization; 2000.

4 Sieber A, Stoianova M, Joebstl E, Azzopardi E, Sayer MDJ, Wagner M. Diving computers: the need for validation and standards. In: Blogg SL, Lang MA, Møllerløkken A, editors. *Proceedings of the validation of dive computers workshop 2012*. European Underwater and Baromedical Society Symposium, Gdansk. Trondheim: Norwegian University of Science and Technology; 2012. p. 29-43.

5 Sayer MDJ, Azzopardi E. The silent witness: using dive computer records in diving fatality investigations. *Diving Hyperb Med*. 2014;44:167-9.

6 Lippmann J. Dive computers. *SPUMS Journal*. 1989;19:5-12.

7 Lippmann L, Wellard M. Comparing dive computers. *SPUMS Journal*. 2004;34:124-9.

8 Buzzacott PL, Ruehle A. The effects of high altitude on relative performance of dive decompression computers. *Underwater Technology*. 2009;28:51-5.

9 Azzopardi E, Sayer MDJ. Estimation of depth and temperature in 47 models of diving decompression computer. *Underwater Technology*. 2012;31:3-12.

10 Royal Navy Physiology Laboratory Table 11 (modified). In: *Royal Navy Diving Manual BR2806, volume 2*, London: Her Majesty's Stationery Office; 1972. p. 5-26 to 5-31.

11 DCIEM Table 1: standard air decompression (metres). In: *DCIEM Diving Manual: Part 1, air diving tables and decompression procedures*. DCIEM No. 86-R-35. Richmond, BC: Universal Dive Techtronics, Inc; 1992. p. 1B-3 to 1B-18.

12 Cole B. *Sub-Aqua Association decompression handbook*, 8th ed. Liverpool: Sub-Aqua Association; 2001.
13 Sayer MDJ, Wilson CM, Laden G, Lonsdale P. The consequences of misinterpreting dive computers; three case studies. *Diving Hyperb Med*. 2008;38:33-9.
14 Hamilton RW. Dive computer validation procedures. In: Blogg SL, Lang MA, Møllerløkken A, editors. *Proceedings of the validation of dive computers workshop*. European Underwater and Baromedical Society Symposium, Gdansk. Trondheim: Norwegian University of Science and Technology; 2012. p. 15-18.
15 Powell M. *Deco for divers: decompression theory and physiology*. Essex: AquaPress; 2008.

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Conflict of interest

One author (AS) develops diving computers but only for professional use and is not in competition with the brands employed in the present study.

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