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Estimation of depth and temperature in 47 models of diving decompression computer

Elaine Azzopardi* and Martin Sayer
UK National Facility for Scientific Diving, Scottish Association for Marine Science, Dunbeg, Oban, Argyll, Scotland, PA37 1QA, UK

Abstract

Forty seven models of diving computer were subjected to a range of nominal depths (10, 20, 30, 40 and 50m), in freshwater and seawater, in a simulated temperate environment. The depths downloaded from the computers were adjusted for density and compared to the published limits of the EU standard EN13319:2000 for depth-time measurement. The estimated depths for most of the computer models were close to or within the limits for the standard, but were not always near to the accuracies claimed by the manufacturers. Testing was complicated by the manufacturers' lack of specification of the salinity standards used by most dive computers for the conversion of pressure measured to depth displayed. The mean estimated depths tended toward the simulated nominal test depths; maxima/minima depth differences from nominal were 2.4m/−1.5m and 1.6m/−0.8m for freshwater and seawater tests, respectively. The results from the temperature trials generated a measured range of 5.1°C from nominal values, although the differences in the methods employed either by the computers or the download software to record or display temperature negated standardised comparison. It was concluded that caution should be employed when using displayed and/or recorded depth and temperature data from dive computers in scientific or forensic studies.

Keywords: dive computers, depth, temperature, seawater, freshwater, EN13319:2000

1. Introduction

Diving computers are primarily used as tools to monitor and calculate decompression schedules and have the advantage over conventional tables because they compute decompressions for multi-level dives and in real time (e.g. Angelini, 2012; Huggins, 2012). In a basic form, a dive computer recalculates the cumulative decompression loading based on, in most cases, the near continuous measurement and recording of pressure and time.

The depth displayed on a computer is an interpretation of the pressure measured (Buzzacott and Ruehle, 2009; Sieber et al., 2012). Previous studies have discussed how the conversion of pressure to a depth estimate can be affected by environmental factors such as altitude (Buzzacott and Ruehle, 2009; Sayer, 2010). However, other effects, such as the water standards that are used for computer calibration and the actual ambient temperature and salinity, can also have an influence on the conversion.

Irrespective of what methods and assumptions have been employed to compute the pressure to depth conversion, the computers will generate a downloadable dive profile based on depth against time. For dive computer models that possess a download capability, the dive profile can be a product of varying volumes of stored information displayed at differing rates, increments and resolution of measurement or estimation (Azzopardi and Sayer, 2010).

Dive computers have been applied to studies as diverse as marine biology (Collins and Baldock, 2007); reef measurement (Sayer and Brown, 2010); pathology (Rutty, 2007); decompression modelling (Sayer et al., 2005), in combination with georeferencing techniques (Kuch et al., 2012; Vacchi et al., 2012); and dive accident investigation (Sayer et al., 2008; Denoble et al., 2009). All such studies rely on a relatively accurate conversion from measured pressure to displayed depth. Although the European standard EN13319:2000 addresses depth and time measurement in dive gauges (Sieber et al., 2012), it largely overlooks the fact that total accuracy with regard to depth displayed (and recorded) can only be achieved through converting pressure readings in a combination with measured physical parameters (predominantly water density and temperature). Only *Cochran* computers are capable of adjusting for salinity changes automatically, as they have the capability of measuring the conductivity of the medium in which they are immersed (Angelini, 2012). All the computers in this study do not have this capability, so they possess in-built assumed calibrations for water density with some ability for the user to switch between set points (usually 'freshwater' or 'seawater').

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* Contact author. E-mail address: elaine.azzopardi@sams.ac.uk

Nearly all technical manuals that accompany dive computers upon purchase do not explain the conversion assumptions being made during the transformation of pressure measured to depth displayed (Azzopardi and Sayer, 2010). The present study investigates how dive computers display depth when exposed to a number of nominal pressures and set to seawater and freshwater (where this function was available) at typical operational water densities (full seawater against freshwater). Many models also display water temperature, and since this may be employed in scientific or forensic investigations, temperature recording is investigated in temperate water.

2. Methods

At the time of this investigation there were 47 models of dive computer in common use in the UK made by 14 different manufacturers. An example of each of the models was purchased from independent retail sources. Although all computers were subjected to the following tests, limitations in displays or downloaded information meant that sample numbers varied between tests. Details of all the computers used in this study are given in Tables 1 and 2. Statistical analyses were by Student's *t*-tests following Lilliefors adapted Kolmogorov–Smirnov tests for normality. All data were stored and analysed using Microsoft Excel. A record of any computer malfunctions or failures was maintained.

2.1. Depth

Depth measurement tests were conducted to a simulated nominal maximum depth equivalent of 50msw (metres of seawater) in 10msw increments. Henceforth in this paper, the simulated nominal depths for both seawater and freshwater trials are given only as metres depth irrespective of whether they have been adjusted for respective media densities (discussed later).

In each test, the computers were immersed to 20cm in a tank of either seawater (SW: 33‰S) or freshwater (FW: 1‰S) located inside a standard two-compartment therapeutic recompression chamber (Divex2000). The chamber was compressed on air to a simulated nominal depth equivalent 50m, and then the pressure was released to the depths of 40m, 30m, 20m and 10m before surfacing. The computers were left at each depth for a minimum of 5min to allow for models with slower recording intervals to register the depths displayed. Five to eight replicate trials of each test were carried out in both freshwater and seawater, with the computers set to the correct environment mode (FW or SW), where this function was available. Throughout the tests all other adjustable functions were left on default settings. In addition, Gemini Tiny Talk temperature loggers were immersed with the computers to record water temperature.

Following each depth test, the stored dive profile of each computer was downloaded for analysis. The recompression chamber used in this study was calibrated regularly (every six months or less) to a seawater standard equivalent to 1.02691 kg l^{-1} and within an accepted error of 0.25% of depth. In order to compare the performance of the computers against the simulated depth profiles, the depth (20cm) at which the computers were immersed in the water tank was deleted from the download information. Both the resulting freshwater and seawater depths were then corrected against the chamber gauge depth using the calibration seawater standard density. The height of air above the water surface of the test tank and the take-off for the chamber gauge measurement did not significantly affect any adjustment for depth and so was not considered.

2.2. Temperature

The temperature tests were carried out over a simulated temperate temperature regime (nominally 12–17°C). The data were obtained during the depth tests described earlier with the computers immersed to 20cm depth. Total immersion time usually exceeded 60min. The built-in dive chamber environmental control unit was set to maintain an air temperature of 26 ± 1°C during the temperature fluctuations caused by the actions of compression and decompression. Two or three calibrated temperature loggers were put into each container of computers to provide a reference water temperature.

As before, the computers were downloaded after each test and the readings given in the download profiles or data logs were used in the final analysis. However, for temperature, the downloaded data were not recorded or displayed in a uniform manner between different brands of computer or even between different models of the same brand. For example, not all downloads gave the maximum and minimum temperatures recorded during a dive. A number of brands, such as Mares, Oceanic, Citizen, Beuchat, Seeman Sub, Scubapro and the Aladin Pro Ultra, only gave the minimum temperature recorded during a dive. Suunto downloads gave the temperatures at the start and end of the dive, as well as at the maximum depth, although occasionally supplemental information could be obtained from the temperature readings in the profile list. Cressi Sub, Tusa and Apeks computers only gave the water temperature at the maximum depth. Most of the Uwatec models, with the exception of Pro

Table 1: Mean and range of depth (m) downloaded from 47 models of diving computer immersed in freshwater over a range of nominal depths (10–50m, *n* = 5–7 in each case). Computers with the facility to switch to a freshwater mode are indicated by 'Y'; those without are indicated by 'N'; blanks indicate those where a switch mechanism was not evident (Azzopardi and Sayer, 2010). An asterisk indicates where a computer was tested but no useable data could be recovered from the download

Manufacturer (Brand)	Model		50m	40m	30m	20m	10m
APEKS	Quantum	Y	52.1 (52.0–52.4)	41.9 (41.8–42.1)	31.4 (31.4–31.6)	21.0 (21.0–21.0)	10.4 (10.4–10.6)
	Pulse	Y	51.0 (50.8–51.1)	41.0 (40.9–41.2)	30.6 (30.5–30.7)	20.3 (20.2–20.4)	10.1 (10.0–10.2)
BEAUCHAT	Voyager	N	49.3 (48.8–49.3)	39.5 (39.5–39.5)	28.8 (28.7–29.2)	19.1 (18.9–19.4)	9.4 (9.1–9.6)
BUDDY	Nexus*	Y	–	–	–	–	–
CITIZEN	Cyber Aqualand	N	49.2 (49.0–49.4)	39.5 (39.3–39.6)	29.4 (29.3–29.5)	19.6 (19.5–19.6)	9.7 (9.6–9.8)
CRESSI SUB	Archimede 2	N	49.5 (49.4–49.5)	39.8 (39.6–40.0)	29.6 (29.5–29.8)	19.7 (19.6–20.0)	9.8 (9.7–9.9)
	Edy II	N	49.4 (49.3–49.5)	39.7 (39.6–39.9)	29.6 (29.5–29.7)	19.7 (19.6–19.8)	9.8 (9.8–9.9)
DELTA P	VRX	N	49.4 (49.2–49.6)	39.7 (39.5–39.8)	29.6 (29.5–29.7)	19.7 (19.7–19.8)	9.8 (9.7–10.0)
	VR 3-1	N	49.4 (49.2–49.6)	39.7 (39.5–39.8)	29.7 (29.6–29.7)	19.7 (19.7–19.8)	9.8 (9.6–9.9)
	VR 3-2	N	49.4 (49.2–49.5)	39.6 (39.4–39.8)	29.6 (29.4–29.7)	19.7 (19.6–19.8)	9.8 (9.6–9.9)
MARES	Nemo	Y	50.4 (50.3–50.6)	40.5 (40.4–40.6)	30.3 (30.2–30.4)	20.2 (20.1–20.3)	10.1 (10.0–10.2)
	Nemo Sport		49.7 (49.6–49.8)	39.8 (39.6–39.9)	29.7 (29.6–29.8)	19.8 (19.6–20.0)	9.9 (9.7–10.2)
	Nemo Air	Y	50.3 (50.2–50.5)	40.4 (40.2–40.7)	30.1 (30.0–30.3)	20.1 (19.9–20.3)	10.0 (9.8–10.2)
	Nemo Excel	Y	50.5 (50.4–50.7)	40.6 (40.5–40.7)	30.3 (30.2–30.4)	20.2 (20.1–20.4)	10.1 (10.0–10.3)
	Nemo Wide	Y	50.3 (50.2–50.5)	40.4 (40.3–40.6)	30.2 (30.1–30.3)	20.1 (20.0–20.2)	10.0 (9.9–10.0)
	Puck wrist	Y	50.4 (50.2–50.6)	40.5 (40.3–40.6)	30.2 (30.1–30.3)	20.2 (20.1–20.3)	10.1 (9.9–10.2)
	Puck Air	Y	50.3 (50.2–50.6)	40.5 (40.3–40.8)	30.2 (30.1–30.3)	20.1 (20.0–20.3)	10.0 (9.9–10.2)
OCEANIC	Veo 250	N	49.2 (48.5–50.3)	39.4 (38.9–40.8)	29.5 (29.1–30.3)	19.6 (19.2–20.1)	9.7 (9.4–10.3)
	VT 3	N	49.2 (49.4–49.8)	39.5 (39.3–39.7)	29.6 (29.5–29.7)	19.7 (19.6–19.9)	9.8 (9.7–9.9)
	Pro Plus 2		49.0 (48.8–49.4)	39.3 (38.9–39.5)	29.4 (29.1–29.7)	19.5 (19.2–19.8)	9.8 (9.7–10.0)
	Atom 2		49.2 (48.9–49.4)	39.6 (39.5–39.7)	29.7 (29.6–29.8)	19.8 (19.7–19.9)	9.9 (9.8–10.1)
	Datamask Hud	N	49.3 (49.0–49.4)	39.6 (39.5–39.7)	29.5 (29.5–29.6)	19.7 (19.6–19.8)	9.8 (9.7–9.9)
SCUBAPRO	Xtender	N	49.5 (49.4–49.6)	39.9 (39.8–40.1)	29.9 (29.7–30.0)	19.9 (19.8–20.0)	9.8 (9.7–9.9)
SEEMAN	XP 5	N	49.0 (48.8–49.1)	39.2 (39.2–39.2)	29.2 (29.1–29.4)	19.5 (19.5–19.6)	9.7 (9.7–10.0)
SUUNTO	D9	N	49.5 (49.2–49.6)	39.7 (39.6–39.8)	29.7 (29.6–29.7)	19.8 (19.7–19.8)	9.8 (9.8–9.9)
	D6	N	49.5 (49.3–49.6)	39.7 (39.6–39.8)	29.7 (29.6–29.8)	19.8 (19.7–19.9)	9.9 (9.8–10.0)
	D4	N	49.5 (49.4–49.6)	39.8 (39.7–39.9)	29.7 (29.6–29.9)	19.8 (19.8–20.0)	9.9 (9.8–10.1)
	Stinger	N	49.4 (49.1–49.7)	39.6 (39.5–39.8)	29.6 (29.4–29.7)	19.7 (19.5–19.8)	9.8 (9.7–10.0)
	Spyder	N	49.0 (48.8–49.1)	39.4 (39.2–39.5)	29.4 (29.1–29.4)	19.5 (19.2–19.5)	9.7 (9.4–9.7)
	Vytec DS black	N	49.6 (49.4–49.7)	40.0 (39.8–40.1)	29.9 (29.7–30.0)	19.8 (19.8–20.1)	10.0 (10.0–10.0)
	Vytec silver	N	49.6 (49.4–49.7)	39.8 (39.5–39.8)	29.8 (29.7–30.0)	19.9 (19.8–20.1)	10.0 (10.0–10.0)
	Cobra 2	N	49.6 (49.4–49.8)	39.8 (39.7–39.9)	29.8 (29.7–29.9)	19.9 (19.8–20.0)	9.9 (9.8–10.0)
	Cobra 3	N	49.8 (49.6–50.0)	40.0 (39.9–40.1)	29.9 (29.8–30.0)	19.9 (19.8–20.0)	9.9 (9.8–10.0)
	Vyper	N	49.7 (49.4–50.0)	39.9 (39.8–40.1)	30.0 (29.7–30.0)	20.0 (19.8–20.1)	10.0 (10.0–10.3)
	Vyper 2	N	49.5 (49.3–49.6)	39.8 (39.7–39.8)	29.7 (29.6–29.8)	19.8 (19.7–19.9)	9.8 (9.8–9.9)
	Vyper Air	N	49.8 (49.6–50.0)	40.0 (39.9–40.1)	29.9 (29.8–29.9)	19.9 (19.8–20.0)	9.9 (9.8–10.0)
TUSA	DC Sapience	Y	50.9 (50.8–51.1)	41.0 (40.9–41.2)	30.7 (30.6–30.8)	20.4 (20.3–20.5)	10.1 (10.0–10.2)
	DC Hunter	Y	51.0 (50.8–51.2)	41.0 (40.9–41.1)	30.7 (30.6–30.8)	20.4 (20.3–20.5)	10.0 (9.9–10.1)
UEMIS	SDA	Y	51.4 (51.3–51.5)	41.2 (41.1–41.3)	30.7 (30.7–30.8)	20.5 (20.5–20.6)	10.2 (10.2–10.2)
UWATEC	Galileo Sol	Y	50.4 (50.2–50.5)	40.5 (40.3–40.6)	30.2 (30.0–30.3)	20.1 (20.0–20.2)	10.0 (9.9–10.1)
	Galileo Terra	Y	50.4 (50.2–50.6)	40.5 (40.4–40.6)	30.2 (30.1–30.3)	20.1 (20.0–20.2)	10.0 (9.9–10.1)
	Smart Tec	N	50.4 (50.3–50.6)	40.5 (40.4–40.6)	30.2 (30.2–30.3)	20.2 (20.1–20.3)	10.0 (10.0–10.1)
	Smart Com	N	50.5 (50.4–50.6)	40.6 (40.4–40.8)	30.3 (30.2–30.4)	20.2 (20.1–20.3)	10.1 (10.0–10.2)
	Aladin Pro Ultra	N	50.4 (50.2–50.5)	40.4 (40.3–40.4)	30.1 (30.0–30.1)	20.0 (19.9–20.0)	10.0 (9.9–10.1)
	Aladin Tec2G	Y	50.4 (50.3–50.6)	40.5 (40.3–40.7)	30.2 (30.2–30.3)	20.2 (20.1–20.2)	10.0 (10.0–10.1)
	Aladin prime	N	49.2 (49.0–49.3)	39.5 (39.4–39.6)	29.5 (29.4–29.7)	19.7 (19.5–19.7)	9.8 (9.7–10.0)
	Aladin One	N	49.2 (49.1–49.3)	39.5 (39.4–39.6)	29.5 (29.4–29.6)	19.7 (19.6–19.8)	9.8 (9.7–10.0)

Table 2: Mean and range of depth (m) downloaded from 47 models of diving computer immersed in seawater over a range of nominal depths (10–50m, *n* = 5–7 in each case). An asterisk indicates where a computer was tested but no useable data could be recovered from the download

Manufacturer (Brand)	Model	50m	40m	30m	20m	10m
APEKS	Quantum	51.5 (51.4–51.6)	41.4 (41.3–41.5)	31.0 (30.9–31.2)	20.8 (20.6–20.8)	10.3 (10.3–10.4)
	Pulse	50.3 (50.2–50.5)	40.4 (40.3–40.5)	30.1 (30.1–30.2)	20.0 (19.9–20.0)	9.9 (9.9–10.0)
BEAUCHAT	Voyager	50.1 (50.1–50.1)	40.0 (39.6–40.1)	29.3 (29.2–29.7)	19.3 (19.2–19.7)	9.4 (9.3–9.8)
BUDDY	Nexus*	–	–	–	–	–
CITIZEN	Cyber Aqualand	50.1 (50.0–50.3)	40.1 (40.0–40.2)	29.9 (29.9–30.0)	19.9 (19.8–20.0)	9.9 (9.8–10.0)
CRESSI SUB	Archimede 2	50.5 (50.3–51.2)	40.4 (40.3–40.5)	30.1 (30.0–30.3)	20.0 (19.9–20.1)	10.0 (9.9–10.1)
	Edy II	50.3 (50.2–50.4)	40.4 (40.3–40.4)	30.0 (30.0–30.1)	20.0 (19.9–20.1)	10.0 (10.0–10.1)
DELTA P	VRX	50.3 (50.3–50.5)	40.4 (40.3–40.5)	30.2 (30.1–30.3)	20.1 (20.0–20.2)	10.0 (10.0–10.1)
	VR 3-1	50.3 (50.2–50.4)	40.4 (40.2–40.4)	30.2 (30.1–30.3)	20.0 (20.0–20.1)	10.0 (10.0–10.1)
	VR 3-2	50.3 (50.2–50.4)	40.3 (40.2–40.4)	30.1 (30.0–30.2)	20.0 (20.0–20.0)	10.0 (9.9–10.2)
MARES	Nemo	50.0 (49.9–50.2)	40.1 (40.0–40.3)	30.0 (29.9–30.2)	20.0 (19.9–20.2)	10.0 (9.9–10.2)
	Nemo Sport	50.6 (50.5–50.8)	40.4 (40.2–40.4)	30.2 (30.0–30.3)	20.0 (19.9–20.1)	9.9 (9.9–10.0)
	Nemo Air	50.0 (49.9–50.2)	40.1 (40.0–40.3)	29.9 (29.9–30.1)	19.9 (19.9–20.1)	9.9 (9.9–10.1)
	Nemo Excel	50.0 (49.9–50.2)	40.2 (40.1–40.2)	30.0 (29.9–30.1)	20.0 (19.9–20.1)	10.0 (10.0–10.1)
	Nemo Wide	49.9 (49.9–50.0)	40.0 (39.9–40.0)	29.8 (29.8–29.9)	19.9 (19.8–19.9)	9.9 (9.9–9.9)
	Puck wrist	50.0 (49.8–50.1)	40.1 (39.9–40.2)	29.9 (29.7–30.0)	19.9 (19.7–20.0)	9.9 (9.7–10.0)
	Puck Air	50.0 (49.9–50.3)	40.1 (40.0–40.2)	29.9 (29.9–30.1)	20.0 (19.9–20.1)	10.0 (9.9–10.1)
OCEANIC	Veo 250	50.2 (49.9–51.4)	40.3 (40.1–41.4)	30.1 (29.9–30.8)	20.1 (19.8–20.4)	10.1 (9.9–10.2)
	VT 3	50.2 (50.0–50.3)	40.3 (40.1–40.3)	30.1 (30.1–30.2)	20.1 (20.0–20.2)	10.1 (10.1–10.2)
	Pro Plus 2	49.6 (49.6–49.9)	39.8 (39.8–39.8)	29.6 (29.6–29.9)	19.8 (19.8–19.8)	9.9 (9.9–9.9)
	Atom 2	50.1 (50.0–50.2)	40.3 (40.2–40.4)	30.1 (30.1–30.2)	20.1 (20.0–20.2)	10.0 (10.0–10.1)
	Datamask Hud	50.3 (50.2–50.3)	40.3 (40.3–40.4)	30.2 (30.1–30.2)	20.1 (20.0–20.2)	10.1 (10.1–10.1)
SCUBAPRO	Xtender	50.4 (50.3–50.6)	40.6 (40.4–40.6)	30.3 (30.3–30.3)	20.2 (20.1–20.2)	9.9 (9.9–10.0)
SEEMAN	XP 5	49.8 (49.6–49.9)	39.9 (39.8–40.1)	29.7 (29.6–29.9)	19.8 (19.8–19.8)	9.9 (9.9–9.9)
SUUNTO	D9	50.3 (50.3–50.5)	40.4 (40.3–40.4)	30.1 (30.1–30.2)	20.1 (20.1–20.1)	10.0 (10.0–10.1)
	D6	50.3 (50.3–50.5)	40.3 (40.3–40.4)	30.1 (30.1–30.3)	20.1 (20.0–20.1)	10.0 (10.0–10.2)
	D4	50.4 (50.3–50.5)	40.4 (40.3–40.4)	30.2 (30.2–30.3)	20.1 (20.1–20.2)	10.1 (10.1–10.2)
	Stinger	50.2 (49.9–50.5)	40.2 (40.1–40.4)	30.1 (29.9–30.2)	20.0 (19.8–20.1)	10.0 (9.9–10.2)
	Spyder	50.0 (49.9–50.2)	40.0 (39.8–40.1)	29.8 (29.3–30.2)	19.8 (19.2–20.1)	9.6 (9.2–9.9)
	Vytec DS black	50.5 (50.5–50.5)	40.5 (40.4–40.7)	30.3 (30.2–30.5)	20.1 (20.1–20.1)	10.2 (10.2–10.2)
	Vytec silver	50.4 (50.2–50.5)	40.5 (40.4–40.7)	30.3 (30.2–30.5)	20.2 (20.1–20.4)	10.2 (10.2–10.2)
	Cobra 2	50.5 (50.5–50.7)	40.5 (40.4–40.5)	30.2 (30.2–30.3)	20.2 (20.1–20.2)	10.1 (10.1–10.2)
	Cobra 3	50.7 (50.7–50.9)	40.7 (40.6–40.7)	30.3 (30.3–30.4)	20.2 (20.1–20.2)	10.0 (10.0–10.1)
	Vyper	50.4 (50.2–50.5)	40.5 (40.4–40.7)	30.2 (30.2–30.2)	20.2 (20.1–20.4)	10.2 (10.2–10.2)
	Vyper 2	50.4 (50.3–50.5)	40.3 (40.3–40.4)	30.2 (30.1–30.3)	20.1 (20.0–20.2)	10.0 (10.0–10.1)
	Vyper Air	50.7 (50.7–50.9)	40.7 (40.5–40.7)	30.3 (30.3–30.4)	20.2 (20.2–20.3)	10.0 (10.0–10.1)
TUSA	DC Sapience	50.3 (50.2–50.4)	40.4 (40.3–40.6)	30.3 (30.2–30.3)	20.1 (20.0–20.2)	9.9 (9.9–10.0)
	DC Hunter	50.5 (50.4–50.5)	40.5 (40.4–40.6)	30.2 (30.2–30.3)	20.1 (20.1–20.2)	9.9 (9.9–10.0)
UEMIS	SDA	50.4 (50.4–50.5)	40.4 (40.4–40.5)	30.2 (30.1–30.3)	20.1 (20.1–20.2)	10.0 (10.0–10.1)
UWATEC	Galileo Sol	50.0 (49.9–50.2)	40.1 (40.0–40.1)	29.9 (29.8–30.0)	20.0 (19.9–20.1)	9.9 (9.9–10.0)
	Galileo Terra	50.2 (50.1–50.3)	40.2 (40.1–40.2)	30.0 (29.9–30.1)	20.0 (19.9–20.1)	10.0 (9.9–10.1)
	Smart Tec	51.3 (51.2–51.4)	41.1 (41.0–41.2)	30.7 (30.6–30.8)	20.4 (20.4–20.5)	10.2 (10.2–10.3)
	Smart Com	51.3 (51.3–51.5)	41.2 (41.1–41.2)	30.7 (30.7–30.8)	20.5 (20.5–20.6)	10.3 (10.3–10.4)
	Aladin Pro Ultra	51.2 (51.1–51.3)	41.0 (40.9–41.0)	30.5 (30.5–30.6)	20.3 (20.3–20.5)	10.1 (10.1–10.3)
	Aladin Tec2G	50.1 (50.1–50.2)	40.1 (40.0–40.1)	30.0 (29.9–30.0)	20.0 (20.0–20.0)	10.0 (10.0–10.0)
	Aladin prime	50.1 (50.0–50.2)	40.1 (40.1–40.2)	30.0 (30.0–30.0)	20.0 (20.0–20.1)	10.0 (10.0–10.0)
	Aladin One	50.1 (50.0–50.2)	40.2 (40.1–40.2)	30.0 (30.0–30.1)	20.0 (20.0–20.1)	10.0 (10.0–10.1)

Ultra, gave a temperature profile throughout the dive, as did the Delta P and Uemis computers. No temperature reading was obtained from the Buddy Nexus downloads, although this is not to say that the temperature was not displayed and recorded by the computer during dives.

In some cases there were differences in the values given in the downloaded data. For example, in the Uwatec software program, SmartTrak, temperature readings occasionally differed between the downloaded log book and the download graphic display of the dive profile; this was also the case with some models in the Oceanic series. In order to standardise the results as much as possible, the log book readings were used. Irrespective of how the data were displayed (and recorded), minimum temperature readings were taken in each case for the analyses.

3. Results

3.1. Depth display

During all the depth trials, the temperatures of the test waters (measured by calibrated Gemini Tiny Talk temperature loggers) fluctuated by a mean value of 1.6°C (with a range of 0.9–2.1°C). The mean and range of depth displayed for each computer tested at each nominal depth is given in Tables 1 and 2 (freshwater and seawater, respectively).

In general, the predominant trend (following adjustment) for most computers was to give estimated depths that were close to nominal values (Figs 1 and 2). When tested in seawater, the estimated mean computer depths were deeper than nominal in comparison to depths in freshwater, but with less variance (Fig 3). Taken as a percentage of the nominal depth, the difference for the overall mean estimate values ranged from −0.8% to 0.1% in freshwater and −0.1% to 0.9% in seawater. The overall maximum depth estimates for each nominal depth ranged from 4.7% to 5.9% in freshwater and from 3.2% to 4.1% in seawater. Minimum values were −2.7% to −8.8% in freshwater and −0.8% to −8.4% in seawater.

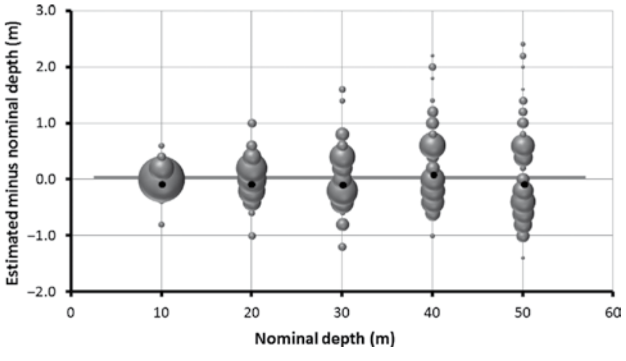

Fig 1: Bubble plot of estimated minus nominal depths (m, mean ● and range; n = 315–320 for each test depth) for all test computers immersed in freshwater and subjected to a nominal depth range of 10–50m. Diameter of bubble represents the percentage of results for each nominal depth

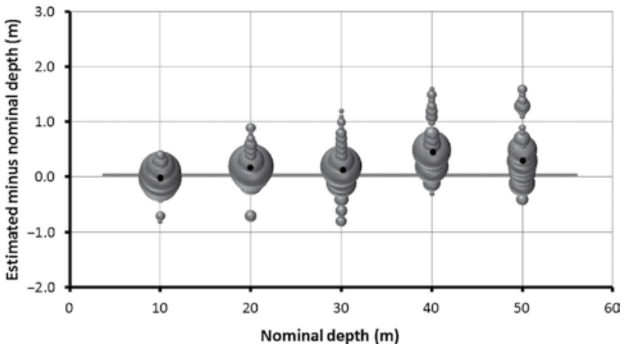

Fig 2: Bubble plot of estimated minus nominal depths (m, mean ● and range; n = 276 for each test depth) for all test computers immersed in seawater and subjected to a nominal depth range of 10–50m. Diameter of bubble represents the percentage of results for each nominal depth

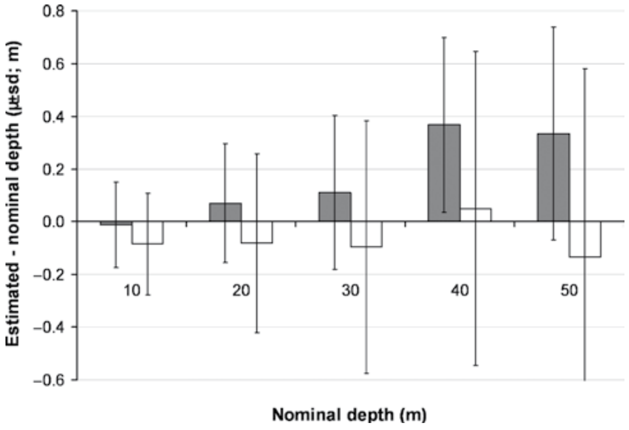

Fig 3: Estimated minus nominal depth (m, μ ± sd; n = 276–320 in each case) for all test computers immersed in seawater (shaded bars) and freshwater (open bars) over a nominal depth range of 10–50m

Although there was a trend for the computers to display deeper depth readings in seawater, this was not significant ($P > 0.05$ in all cases). Computers that could be set to a FW mode tended to give depth estimates that were deeper than those that could not be switched; however, the trend was not significant in any of the nominal test depth groups ($P > 0.05$ in all cases).

Some units gave estimated depth values that were consistently deeper than nominal (e.g. Apeks Quantum); some tended to read low over certain depths (e.g. Beuchat Voyager); but the majority of models produced relatively consistent and accurate results (mostly within 1% of nominal) across the depths tested and between the two water types (see Tables 1 and 2). Although tested in both media, the Buddy Nexus unit tested did not produce useable depth data on download.

The results from the repeated exposures to the same depth in both types of water showed varying ranges of estimated depth from the same model of computer (see Tables 1 and 2). Ignoring how close the estimated depths were to the nominal values, there were a small number of outcomes ($n = 5$–8 in all cases) from replicate trials where the same computer produced identical depth displays for all tests at a single nominal depth (2.6% in freshwater trials; 9.1% in seawater; $n = 230$ in both cases). No model tested produced perfect, repeated depth estimates for every depth/trial combination, as there was always some variation either within depth or between the depths tested.

Overall for the five depths tested, in freshwater trials 41 out of the 46 units that gave depth estimates produced maximum ranges of replicate displayed depths of ≤0.5m, and in the seawater trials, there were 42 out of 46 units. However, of those only one computer model (the Uemis) produced maximum ranges that were ≤0.2m in the freshwater exposures, compared with 22 of the computer models in seawater.

There were four and three computers in the freshwater and seawater trials, respectively, that produced maximum repeat ranges of between 0.6m and 0.9m. Only one computer, the Oceanic Veo 250, was able to produce maximum ranges of the depths displayed more than 1.0m, and did so both for freshwater (maximum = 1.9m) and seawater (maximum = 1.5m). The only instance of a unit producing an overall maximum range of 0.1m was the Mare Nemo Wide, in seawater (see Table 2).

3.2. Temperature

The measured nominal temperature environments representative of temperate regimes had a mean value of 16.7°C, with a range of 10.9–18.9°C (n = 239). The overall recorded temperature information from all the diving computers is shown in Fig 4. The data present considerable variation in the accuracy of temperature measurement: overall variance for the measured nominal values was 5.1°C (with a range of −4.0°C to 1.1°C; Figure 4). Some of this distribution is attributable to the difficulty in establishing a uniform method for extracting the temperature data from the downloaded information.

3.3. Failures and maintenance rates

Including pilot studies, the test computers were subjected to 2401 computer dives, totalling 2008 computer hours. During the tests, 41 battery changes were made at the overall rate of one battery change every 49hr of diving, or 58.6 dives. One unit failed in a way that would have impacted a dive.

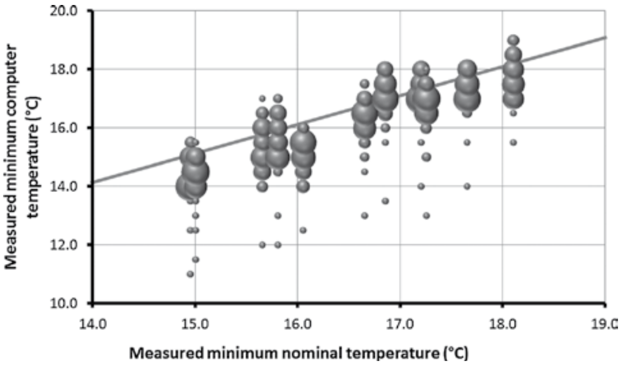

Fig 4: Bubble plot of recorded temperature display against nominal median temperature (°C) for all test computers (total sample n = 800). Diameter of bubble represents the percentage of results for each of the 10 temperature tests

4. Discussion

The present study has demonstrated that, in general, dive computers can vary in their reliability as tools for measuring water depth or temperature accurately. This is not particularly surprising for depth, as the conversion from pressure measured to depth displayed requires the accurate measurement of a number of factors (e.g. water density, temperature) that are outside the operational capability of a relatively limited dive decompression computer. The accurate measurement of depth is not crucial to the predominant function of a dive computer, which is computing decompression obligations (discussed later). However, European standards (e.g. EN13319:2000) do give stated limits for the pressure to depth conversion. Similarly, some of the published technical literature supplied with these computers does state 'accuracy' levels for depth and temperature recording.

With temperature, it is suggested that the display and recording by dive computers is a by-product of some information being generated through having temperature-compensated pressure sensors in the computers. The computers tested did not always produce reliable recorded (downloaded) temperature information. It is therefore suggested that dive computers are not a suitable tool for the measurement of temperature.

Although a total of 47 models of dive computer were employed in this study, it is acknowledged that only single samples of each model were tested. As such, no explicit assertions can be made in relation to any specific model of computer. It is accepted that all recordings relate only to the individual computer model, and even that similar models from the same manufacturer cannot be accepted as true test replicates.

4.1. Depth

Dive computers do not measure depth directly. Instead readings are taken from the pressure sensor at set time intervals, which are then converted into depth readings on the computer display (Buzzacott and Ruehle, 2009; Sieber et al., 2012). The pressure may be measured and recorded at relatively high frequency rates for use in calculating decompression schedules and, it is assumed, at high levels of accuracy. The depth display on the dive computer or in the download on a PC is a product of converting the pressure sensor reading to a displayed depth and is not itself used in any decompression calculations. For example, Cressi Sub computers measure pressure every second, but this is only converted to a depth reading for the download display every 30s (Cressi, pers. comm.). Similarly, the Uemis SDA samples pressure every 625ms, but converts it to a depth download display every 5s (Uemis, pers. comm.).

Much of the disparity between sampling frequency and download recording/display is determined by the data memory, resulting from computational and unit size compromises made when designing a dive computer. The differences in the recording frequencies and techniques employed in the conversion from pressure readings to depth download data may have caused some discrepancies between the models examined. Azzopardi and Sayer (2010) detailed the different methods of displaying depth information (e.g. maximum depth per recording increment; the depth at the point of making the recording; and the average depth over the recording interval) and the resolution of depth displayed (0.1m, 0.3m or 0.5m).

The method of recording should not have made any differences in the present study, because the computers were held at the nominal depths for durations much longer than the display rates of all the computers. However, the methods used to determine when or how the depths changed between the display resolution depths was unclear in all manuals. This should only be a significant issue where the resolution is 0.3m (AP valves Buddy Nexus) or 0.5m (Apeks Quantum, Tusa DC Sapiance, Tusa DC Hunter; see Azzopardi and Sayer, 2010). In these cases, it is unclear what the threshold levels are for changing the depth displayed.

One other possible source of error was that the values given in the downloads were not necessarily the same as those that would have been shown by a computer during a dive. For example, the Delta P computers displayed depth with a resolution of 0.1m during a dive, but only gave this to the nearest 1m in the download (VR Technology, pers. comm.). However, this may only be the case for the graphic representation of a dive profile, as a spreadsheet function listed the depths with a higher resolution (as used in the present study). Finally, some error could have been added into the trials through slight differences in the test pressures, which were monitored using an analogue depth gauge. However, any errors would have been identical for all the computers tested in each run.

Although it was not intended to strictly mimic the test conditions outlined in EN13319:2000, the test pressures, salinities and temperatures in the present study could not be controlled to the levels outlined in the standard. In addition, there is no guidance given in EN13319:2000 on how to incorporate the ability of some dive computers to switch between seawater and freshwater modes into any depth testing.

The ability to switch modes may be meaningless within the context of the present study, as there is a near total lack of information given by manufacturers on the standards used for freshwater or seawater. The mix of computers that could or could not switch between modes (Table 1), plus the lack of published calibration standards for all the test computers, means that there was a number of groups of computers that were being tested less than ideally in the present study.

There was also the issue of trying to determine which dive computers were manufactured to adhere to EN13319:2000. Sieber et al. (2012) discussed the range of standards that can be applied to dive computers and tried to determine from the respective accompanying technical notes which were being employed for each type of dive computer. Five out of fifteen dive computer models or manuals examined by Sieber et al. (2012) did not refer to EN13319:2000. With this in mind, the intention of the present study was to assess the performance of the dive computers in realistic conditions for most types of diving. In general, the models tested were predominantly within the EN13319:2000 limits when corrected for salinity (Tables 1 and 2).

In addition to some operational limits set by the standard, manufacturers also tended to state their own ranges of accuracy in the supporting technical manuals. A number of manufacturers claimed a depth accuracy of ±1% of the full scale, for example all the Oceanic, Seeman Sub and Beuchat computers, and all the Mares computers except the Nemo Sport (Oceanic, 2002a,b, 2005, 2006, 2007, 2009; Beuchat, 2004; Seeman, 2004; Mares, 2005, 2008a–e). Some, namely Suunto and Cressi-Sub, stipulated ±1% of the full scale, but only when at 20°C (Cressi-Sub, n.d. a,b; Suunto, n.d. a,b, 2005, 2006a–e, 2007a–c, 2008a,b). The Uwatec Galileo Sol, Terra and Luna models all claimed to have an accuracy of 2% ±0.2m (Scubapro-Uwatec, n.d. a–c), while the Tusa and Apeks computers claimed an accuracy of ±3% for 0.5m in their depth displays (Apeks, 2003a,b; Tusa, 2004a,b).

No assertion was made about the accuracy of the Scubapro Xtender or the Mares Nemo Sport computers, and no accuracy claims were found for Delta P's VR3 and VRX computers or for the Uemis SDA (Mares, 2007; Scubapro-Uwatec, n.d. d; Uemis, 2009; VR Technology, 2009). Although some accuracy claims were made over the full depth range as a plus/minus percentage of the depth displayed, these were more likely not attained in the present study at the shallower test depths (10m and 20m).

In addition, irrespective of whether the computer had the facility to switch between seawater and freshwater modes, the overall trend was for the computers to be more variable in freshwater. The problems with producing accurate depth estimates in seawater is that its salinity (and hence its density) can only be assumed. Whereas EN13319:2000 suggests a seawater density of 1.0197 kg l^{-1}, manufacturers can use values such as 1.018 kg l^{-1} or 1.025 kg l^{-1} as standard densities for the pressure/depth conversion (pers. comm. various computer engineers).

Temperature also affects density, with water becoming denser at colder temperatures. It is assumed that temperature changes are included in the algorithms estimating depth from pressure, because the pressure sensors are temperature-compensated. However, the fact that dive computers do not measure density means that there will always be some error in depth 'measurement' where the density standards do not match the salinity of the medium being dived in.

Dive computers have been used for depth measurement for a range of differing applications (Sayer et al., 2005; Collins and Baldock, 2007; Rutty 2007; Sayer et al., 2008; Denoble et al., 2009; Sayer and Brown, 2010; Kuch et al., 2012; Vacchi et al., 2012). A general conclusion from the present study is that using a non-calibrated dive computer to give an absolute depth reading cannot be recommended. Measuring relative heights or depth ranges (Sayer and Brown, 2010) may have more credibility, but should still be confirmed with physical measurement. Although working at altitude, Buzzacott and Ruehle (2009) acknowledged the difficulty of obtaining a true water depth using standard dive computers and resorted to physical measurement methods (tape measures) to obtain the nominal water depth.

4.2. Temperature

The lack of uniformity in temperature recording and display methods across the various brands complicated any overall comparison of the results. A number of claimed accuracies for temperature were made by some manufacturers. For example, Tusa, Apeks and Mares computers, with the exception of the Mares Nemo Sport, all claim an accuracy of ±2°C in temperature recording (Apeks, 2003a,b; Tusa, 2004a,b; Mares, 2005, 2008a–e). Suunto also claim accuracy of ±2°C but only within 20min of the temperature changing, whereas the Cressi Sub accuracy claim of ±2°C was for within a 10min change in temperature (Cressi-Sub, n.d. a,b; Suunto, n.d. a,b, 2005, 2006a–e, 2007a–c, 2008a,b). Citizen claimed its computer models were accurate within a ±3°C envelope (Citizen, n.d). In general, there was little if any standardisation in recording or displaying temperature. It can only be assumed that any form of accurate temperature measurement was not a primary design factor for most diving computers.

5. Conclusions

The lack of replication in the computer models used in this study is acknowledged, although it was thought likely that models from the same manufacturer would behave similarly during both the depth and temperature trials. However, this was not the case for many of the manufacturer groups, and so a standard methodology for converting physical measurements to displayed or recorded information cannot be assumed to be manufacturer-specific. This may be caused, in part, by different age groups of computer having different conversion methodologies.

Pressure measurement is the only barometric parameter that is imported into decompression algorithms to calculate and manage dive profiles. This means that totally accurate depth information is not an essential component for decompression monitoring. The accurate conversion of pressure measured to depth displayed is not possible without the concomitant accurate determination of salinity and temperature. The frequency of data storage will always be compromised by factors related to the size and cost of the computers. If the diver is using the computer depth display to compute decompression obligations using decompression tables, then the results from the present study show that, with the majority of depth estimates being in the ±1m range, dive computers should be accurate enough for most table depth intervals (usually 2m or 3m).

In contrast, caution is recommended for the use of dive computers as depth measurement tools in scientific study or underwater surveying. If there is sufficient knowledge of the salinity of the water the computers are being used in and the salinity they are calibrated to, then accuracy levels of ±1% could or should be expected. The acceptability of that level of error will depend on the application of the depth measurements.

From the point of view of forensic examination of diving computers, both depth and temperature records may need to be treated with some caution. Where available the unit should also be calibrated against known pressures and water temperatures if those metrics are important to the investigation. Overall in this study, temperature measurement and display were highly variable in the units examined, and it is concluded that dive computers should not be employed to measure water temperatures for scientific study.

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