Technical report

A novel wearable apnea dive computer for continuous plethysmographic monitoring of oxygen saturation and heart rate

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Key words
Diving, breath-hold diving, transcutaneous oximetry, hypoxia, diving research, physiology

Abstract

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We describe the development of a novel, wrist-mounted apnea dive computer. The device is able to measure and display transcutaneous oxygen saturation, heart rate, plethysmographic pulse waveform, depth, time and temperature during breath-hold dives. All measurements are stored in an external memory chip. The data-processing software reads from the chip and writes the processed data into a comma-separated-values file that can be analysed by applications such as Microsoft Excel™ or Open Office™. The housing is waterproof and pressure-resistant to more than 2.026 MPa (20 bar) (breath-hold divers have already exceeded 200 metres' sea water depth). It is compact, lightweight, has low power requirements and is easy to use.

Introduction

Medical concerns about professional and recreational diving safety stem, in part, from lack of field studies monitoring physiological parameters. This deficiency is primarily because of the lack of instrumentation suitable for underwater measurements of simple but important parameters such as heart rate and arterial blood pressure. With the lack of direct measurements, results from 'models' of underwater diving as well as inferences from the clinical world are commonly adopted in diving medicine. Unfortunately, both processes are intrinsically uncertain and may not be scientifically valid. Thus, the transfer to the underwater environment of routine clinical instrumentation would represent a useful advance, just as it has in space medicine. This task requires the development of novel underwater diagnostic and monitoring instrumentation as well as the elaboration of ad hoc support infrastructure.

The physiological signals that can currently be measured underwater are: heart electrical activity by continuous electrocardiogram (ECG), heart anatomy and function by echocardiography, blood pressure by sphygmomanometer and transcutaneous oxygen saturation ($S_{tc}O_2$).[1–7] However, with the underwater instrumentation currently available, the diver is unable to utilize directly and in real time the information on his physiological status, as the acquisition and communication of physiological data requires the use of more or less complicated devices that are operator-mediated.

The basic idea of the present work was to develop a convenient, small user-friendly apnea diving computer (ADC), which is able to:

- provide continuous recording of two vital parameters such as $S_{tc}O_2$ and heart rate together with water temperature and hydrostatic pressure;
- display the information in real time on a graphical display; and
- store data for at least four hours.

Originality of the device stems from the use of a single sensor for the detection of both $S_{tc}O_2$ and heart rate, which at the same time overcomes the important technical limitations of current fingertip oximeters and continuous underwater ECG recording. Existing finger plethysmographic devices have serious limitations to their underwater use and the recording of the ECG is challenging because of the difficulty encountered in the electrical insulation of the electrodes and the dimensions of the recorder. Without suitable electrical insulation, ECG signal recording on an immersed body is difficult (fresh water) or impossible (sea water), even if the diver uses a neoprene wetsuit, and the recorder is too bulky and uncomfortable to be portable underwater.

Clinical $S_{tc}O_2$ meters (pulse oximeters) are generally based on measurement of the absorption of transmitted light at specific red and near-infra-red wavelengths. The transducer probe is usually placed on the ear lobe or on the finger tip.[8,9] Measurement of $S_{tc}O_2$ in divers has been attempted using standard, finger-transmission pulse oximetry.[10] However, this approach did not produce reliable results probably because of the peripheral vasoconstriction associated with the diving reflex, which is further enhanced in cold water, reducing finger blood flow and preventing correct estimation of $S_{tc}O_2$.

An alternative to transmission pulse oximetry is reflectance pulse oximetry. Using this approach, the light transmitter and receiver are situated a short distance from each other (around 8 mm) in the same probe. Light is transmitted into the underlying tissue and the reflected light is received and measured. In this situation the spectral intensity of the reflected light depends on the O_2 saturation of the arterial blood in the underlying tissues. Importantly, a reflectance transducer probe can be placed on any part of the body surface, in particular on the temple or forehead, a region less affected by vasoconstriction and consequent blood hypoperfusion compared to the fingertip. Additionally it can easily be protected from cold water (e.g., the glabellum or temple by the diving mask). As the pulse oximeter provides a pulsatile waveform synchronous with cardiac contraction, intervals equivalent to the ECG RR interval could possibly be estimated.

Reflectance pulse oximetry probes placed on the forehead were shown to have acceptable agreement with transmittance probes for pulse oximetry within a typical range of $S_{tc}O_2$ in patients undergoing peripheral vascular surgery.[11] $S_{tc}O_2$ values from these methods were compared with oxygen saturation (S_aO_2) measurements of simultaneously collected arterial blood, and S_aO_2 closely matched both $S_{tc}O_2$ probe values. Similar conclusions were reached recently for the use of forehead reflectance oximetry probes versus conventional digit sensors in paediatric patients.[12] The utility of reflectance pulse oximetry beyond the simple measurement of arterial oxygen saturation from the finger or earlobe was recently expanded for use at internal sites such as the oesophagus and bowel; analysis of the photoplethysmographic waveforms produced by these sensors proved useful in providing new physiological data.[13]

Methods

HARDWARE

The core component of the ADC is a low-power 8-Bit RISC microprocessor (Atmega644p, Atmel) with the following specifications:

- 64 kbytes Flash Program Memory
- 4 kbyte SRAM
- 2 kbyte EEPROM
- 8 MIPS @ 8 MHz

The Atmega644p is operated at 7.3 MHz (internal clock). The real-time clock is based on a 32.768 KHz crystal. A combined digital 16-bit temperature/pressure sensor (MS5541B, Intersema) is integrated in the design for depth measurement. It is specified for a maximum pressure of 14 bar (1 bar = 101.3 kPa). In the range 0–5 bar it has an accuracy of +/-20 mbar. A 128x64 matrix display (EA DOG-M, Electronic Assembly) is used to visualize all dive-relevant parameters plus the plethysmography waveform, heart rate and $S_{tc}O_2$. The dive profile and plethysmography waveform are continuously tracked and stored in an external 32-Mbit memory chip (AT25DF321, Atmel), which allows continuous recording and storage of five hours' data (with a plethysmographic sampling frequency of 75 Hz). The pressure sensor, display and external memory are connected to the serial peripheral interface (SPI) of the microcontroller; the SPI is a bus system for serial synchronous data transmission.

In order to provide the $S_{tc}O_2$ signal and heart rate, a commercial pulse oximeter module (OEM III, Nonin) is used. A reflectance probe (8000R, Nonin) was chosen that can be placed on the forehead or on the temple ($S_{tc}O_2$ accuracy +/-3 per cent saturation; heart rate accuracy +/-3 beats per min). It is interfaced to the microcontroller via the universal asynchronous receiver/transmitter (USART1) at 9,600 bits per second.

Two piezo-buttons allow user input. They are connected to the external interrupt INT0. PC communication is done via a serial interface to USB converter (TTL-232, FTDI). The interaction of all hardware parts is shown in Figure 1. The overall low power consumption and the integrated step-up converter (MAX1724, Maxim) allow powering of the whole ADC via a single 1.5V AAA battery.

SOFTWARE

The firmware of the device was developed in the programming language C. As Integrated Development Environment, the IAR Embedded Workbench (IAR Systems) was chosen. It is a set of development tools for building and debugging embedded applications using assembler, C and C++ in Windows 9x/NT/2000/XP/Vista™ environments. The firmware rests upon two major parts. The first part is devoted to measurements, and data pre-processing for storage, and their display on the computer screen. The second part stores all the measurements into the external memory chip.

Continuous tracking of the physiological condition of the diver (including plethysmography) plus parsing, measuring

Figure 1
Hardware diagram for the apnea dive computer

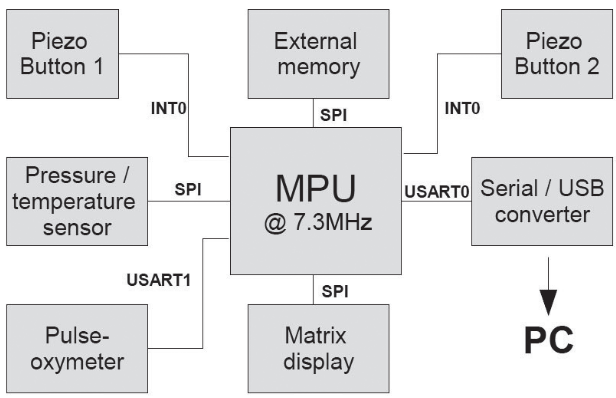
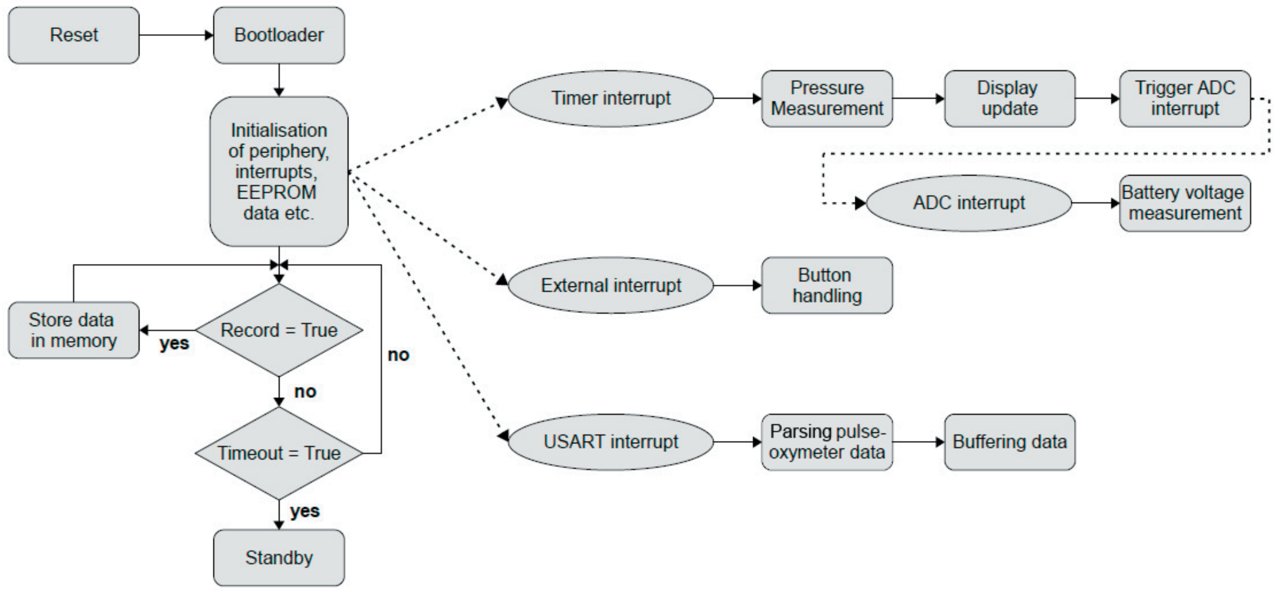


Figure 2
Programme scheduling in the apnea diving computer



and displaying data is time-intensive on a low-power 8-bit microcontroller. Thus a pre-emptive scheduling algorithm with fixed priorities is implemented, which controls everything quasi in parallel. The Nonin OEM III pulse oximeter provides heart rate and $S_{tc}O_2$ (4-beat average values) and the plethysmographic waveform in 25 data blocks, 3 times per second via USART1. Each block has a size of 5 bytes. These data are parsed and stored in a ring buffer whenever an USART1 interrupt occurs. In addition, every 250 ms, depth and temperature are measured and displayed together with $S_{tc}O_2$, heart rate, time and the plethysmographic waveform. To achieve precise timing, this is done using the real-time clock of the Atmega and the timer interrupt. Additionally the battery voltage is measured using the internal analogue-to-digital converter. To prevent data packet loss during USART1 communication, the USART1 interrupt has a higher priority than the timer interrupt. The main loop has lowest priority; it reads the ring buffer and stores its data together with depth, temperature and time into the external memory. The whole programme flow is detailed in Figure 2.

DATA PROCESSING

For visualization and analysis of the recorded data, software was developed under the Eclipse SDK 3.4.1 in Java 1.6 and the Standard Widget Toolkit. The Standard Widget Toolkit is an open-source widget toolkit for Java that provides efficient, portable access to the user-interface facilities of the operating systems. For serial communication with the diving computer, RXTX was chosen. It is a native library, which provides serial and parallel communication for the Java Development Toolkit under the GNU LGPL license. The software reads out the external memory of the ADC at 230400 Baud.s-1 and stores the data in one comma-separated-values (CSV) file per dive. Thus, data can be easily analysed within arbitrary applications like Microsoft Excel™ or Open Office™. After successful data transmission, the memory of the ADC can be erased.

PROTOTYPE

The prototype ADC is wrist-mounted in a square housing measuring 60x60x25 mm (similar in size to some wrist-mounted decompression computers, Figure 3). A single 1.5V AAA battery serves as power supply. The overall power consumption is 60 mA at 7.3 MHz system clock. In sleep mode, the power consumption is reduced to 70 µA. Instead of developing a water- and pressure-proof housing, the internal space of the device is simply encapsulated in

Figure 3
The prototype wrist-mounted apnea diving computer

silicone gel (SilGel 612, Wacker Chemie AG). Further, this measure allows installation of the digital pressure sensor directly on the electronic board, as the ambient pressure is transduced via the soft silicone gel to the membrane of the pressure sensor. Only the battery is housed in a water- and pressure-proof compartment.

VALIDATION AND TESTING

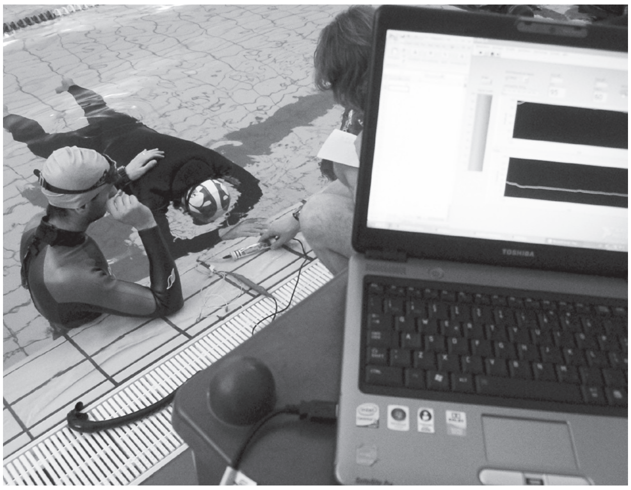
In the first stage of testing, the performance of the ADC was studied on five volunteer apnea divers (height 160–185 cm; weight 50–80 kg; age 27–35 yo) in a swimming pool. All gave written, informed consent for the study, which was approved by the local ethical committee. Measurements obtained with the ADC were compared with measurements from a reference pulse oximeter (ChipOx, Weinmann Medical Technology; accuracy +/- 3 per cent saturation over the physiological range of $S_{tc}O_2$ and +/- 3 beats per min heart rate). Since the reference pulse oximeter uses a transmission sensor on the finger, this is affected by vasoconstriction, and so comparisons were made in warm water with the diver wearing a thin wetsuit. Since the fingertip sensor is only pressure- and water-resistant to a maximum of 1 metre fresh water (mfw), comparative tests were performed during static apnea at the edge of the pool. For direct comparison of the two devices, they were connected to a poolside computer via a USB port and analysed in parallel using LabView software developed ad hoc with a 1 Hz sampling rate.

The ADC was first tested with the subject breath-holding whilst seated poolside, with the two sensors placed on a finger each; the aim of this test was to assess whether the ADC delivered values comparable to those from the reference transducer. Then, with the reference transducer finger-mounted and the ADC placed on the temple, the diver breath-held whilst floating horizontally in the water with the face immersed (Figure 4). During the tests, water temperature was 26^{O}C and air temperature 30^{O}C.

In the second phase, which was carried out in a 10.5 mfw deep research pool, one elite breath-hold diver (male, height 160 cm, weight 55 kg, age 26 yo) and one untrained subject (male, height 185 cm, weight 75 kg, age 28 yo) who nevertheless was able to sustain breath-holds for more than two minutes, were studied. The ADC probe was fixed on the temple with tape, and kept in position by the hood of the diving suit. This arrangement resulted in a clear signal in all cases. Divers performed four breath-hold dives to 1.5 or 10 mfw depth at various times of the day.

Statistical analysis of the collected data was not performed, since it has already been shown that reflectance pulse oximetry probes placed on the forehead have acceptable agreement with transmittance probes for pulse oximetry within typical ranges of $S_{tc}O_2$.[11] Both pulse oximeters used in this study are certified OEM products, and should work accurately according to their specifications. The aim of the current paper is to present the developed system and sample

Figure 4
A subject performing an immersion apnea whilst being monitored with the apnea dive computer



measurement data; a physiological study on apnea divers is ongoing and detailed results, including statistical analysis, are expected later in 2010.

Results

In all the tests, the plethysmographic signal was visualized and heart rate and $S_{tc}O_2$ detected. Table 1 and Figure 5 show $S_{tc}O_2$ values obtained with the ADC and the reference transducer during dry apneas with both sensors placed on the finger. The mean differences in $S_{tc}O_2$ between the reference pulse oximeter and the ADC were less than the quoted accuracies of the two devices.

The results during immersed static apnea were similar, except that at the end of the apnea phase, the fall in $S_{tc}O_2$ recorded with the ADC probe on the temple was greater than that recorded by the reference transducer and recovered slightly more slowly (Table 2 and Figure 6).

In phase two, $S_{tc}O_2$ and heart-rate values were successfully obtained during repeated breath-hold dives at 1.5 or 10 mfw in both divers. Table 3 shows that the fall in $S_{tc}O_2$ was more marked in the untrained diver compared to the elite diver despite apneas of shorter duration. In a typical dive to 10 mfw depth (Figure 7), $S_{tc}O_2$ remained constant up to approximately two minutes of apnea and then started to drop slightly. During the ascent desaturation accelerates rapidly and $S_{tc}O_2$ reached the lowest value (nearly 70%) upon surfacing.

Discussion

This study describes the research and development of a novel wrist-mounted apnea dive computer (ADC), able to provide continuous measurement of $S_{tc}O_2$, heart rate and plethysmographic pulse waveform, water temperature

Table 1
Comparison of the simultaneous measurements of $S_{tc}O_2$ using the apnea dive computer and a reference plethysmograph during dry land breath-holds

Diver	Sex	Apnea time (min)	max $S_{tc}O_2$ Ref	max $S_{tc}O_2$ ADC	min $S_{tc}O_2$ Ref	min $S_{tc}O_2$ ADC	Diff min/max Ref	Diff min/max ADC	Mean diff Ref/ADC
1	m	02:30	98	100	79	81	19	19	3.2
2	f	03:03	99	99	64	66	35	33	1.9
3	m	02:45	99	99	81	79	18	20	2.3
4	m	02:57	100	98	78	82	22	16	3.8
5	m	03:22	97	97	69	71	28	26	3.5

Table 2
Comparison of the simultaneous measurements of $S_{tc}O_2$ using the apnea dive computer and a reference plethysmograph during immersed static apnea with face immersed

Diver	Sex	Apnea time (min)	max $S_{tc}O_2$ Ref	max $S_{tc}O_2$ ADC	min $S_{tc}O_2$ Ref	min $S_{tc}O_2$ ADC	Diff min/max Ref	Diff min/max ADC	Mean diff Ref/ADC
1	m	04:15	100	100	82	63	18	37	3.7
2	f	03:23	100	100	66	53	34	47	6.1
3	m	03:48	98	100	81	69	17	31	4.9
4	m	04:20	100	100	79	65	21	35	4.5
5	m	04:35	100	99	72	59	28	40	5.1

and depth in a simple, user-friendly way. Oxygen is the most essential element to life, its lack having immediate consequences, particularly on central nervous system function. Measurement of $S_{tc}O_2$ is of special interest in breath-hold diving. Under normal conditions, more than 98% of the O_2 in arterial blood is bound to haemoglobin (Hb), the remaining 2% is dissolved in plasma. At a normal arterial pO_2 of 13 kPa, Hb-O_2 saturation is about 97.5%, while in mixed-venous blood, the pO_2 drops to 5 kPa and Hb-O_2 saturation is approximately 75%. Thus, during apnea, $S_{tc}O_2$ will reflect the amount of O_2 that is delivered to tissues and, in turn, $S_{tc}O_2$ depends on the partial pressure of O_2 in the alveoli.[14]

In the dive shown in Figure 7, the rapid blood desaturation during the ascent is because of the rapid decrease in pO_2 in the alveolar space due to the reduction of environmental

Figure 5
Simultaneous recordings of $S_{tc}O_2$ during a dry static apnea using the apnea dive computer and the reference plethysmograph each on a finger; vertical lines delineate the apnea (02:45 min)

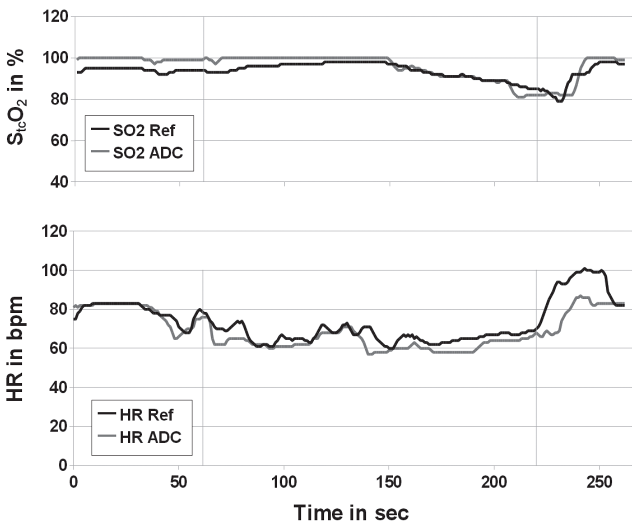


Figure 6
Simultaneous recordings of $S_{tc}O_2$ in the same diver as in Figure 5 during an immersion static apnea with face immersed using the apnea dive computer on the forehead and the reference plethysmograph on a finger; vertical lines delineate the apnea (04:15 min)

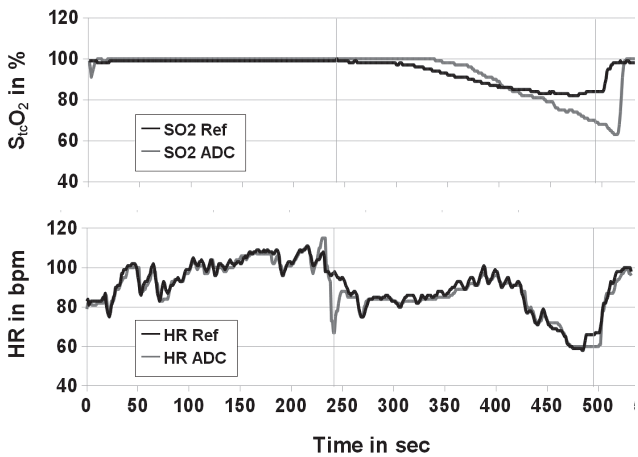


Table 3
$S_{tc}O_2$ measured during repeated dives to 1.5 mfw and 10 mfw depth performed by two divers, one elite and the other untrained in breath-hold diving

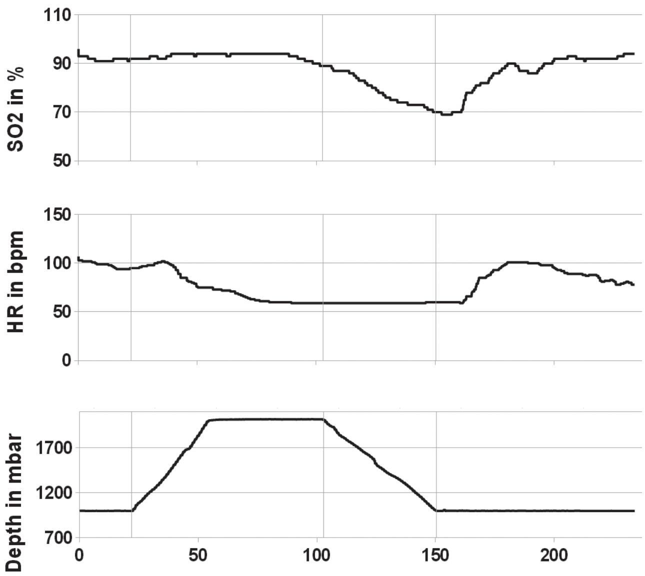
Apnea (min)	Depth (mfw)	Time	min $S_{tc}O_2$	max $S_{tc}O_2$	min Heart rate	max Heart rate
Elite						
02:30	1.5	10:20	96	100	44	91
03:01	1.5	10:40	95	100	45	93
03:12	1.5	13:30	87	100	41	83
02:47	1.5	14:00	85	100	42	85
02:20	10	09:00	95	100	44	96
02:40	10	09:20	96	100	42	96
02:43	10	09:40	97	100	44	97
02:55	10	11:20	95	100	41	95
Untrained						
02:44	1.5	09:42	78	98	54	98
02:45	1.5	10:16	79	99	55	87
03:04	1.5	10:40	69	96	52	96
02:33	1.5	11:18	70	98	55	83
02:07	10	14:36	84	98	70	114
02:29	10	14:58	73	98	58	106
02:13	10	15:30	69	97	59	105
02:34	10	16:37	77	96	58	119

pressure from 2 to 1 bar. This condition is opposite to the descent, when pO_2 progressively increases according to the increase in environmental pressure thus maintaining a constant $S_{tc}O_2$ in spite of continuous oxygen consumption. The fall in $S_{tc}O_2$ during the ascent and its continued drop after surfacing explains why ascent syncope occurs at or near the surface.[15] Continuous monitoring of the $S_{tc}O_2$ screen could help the diver to be more aware of his own limits and provide him with an objective warning of dangerous conditions. In addition, monitoring of $S_{tc}O_2$ during apnea would contribute to a better understanding of underwater physiology. To reach these goals, however, the accuracy of the measurements has to be validated in open-water studies.

In the present work, we utilized a new approach, the use of a reflectance oximetry probe, which can be positioned on a skin region less influenced by vasoconstriction than a digit, and is easily protected from cold water. Preliminary tests of the ADC probe against a reference, finger pulse oximeter showed equivalence of signal during dry apneas but an underestimation of $S_{tc}O_2$ drop in the immersed subject at the end of apnea probably related to vasoconstriction of the finger compared to the temple. A second advance is the utilization of the same pulse oximeter signal for monitoring heart rate. This approach bypasses the difficulties encountered in ECG recording in sea water, i.e., electrical insulation, and makes the device as small and user-friendly as possible.

Although pulse oximetry is used widely to monitor blood oxygenation, it cannot normally determine oxygen consumption. However, in the context of apnea, the sudden and complete interruption of the external O_2 supply leads to a fall in $S_{tc}O_2$ once O_2 consumption has exceeded the initial body stores of oxygen.

Figure 7
Record of $S_{tc}O_2$, heart rate and depth during a 10 mfw dive; vertical lines delineate the apnea and the start of the ascent



The simultaneous display of $S_{tc}O_2$, heart rate and depth profiles allows an accurate analysis of time relationships between physical and physiological parameters. As an example, immersion bradycardia may vary in different subjects depending on pre-dive preparations used by the diver, such as hyperventilation and/or lung packing to modify body O_2 storage.

The main limitation of the present study is the small number of subjects studied. However, the principal objective was to document the technical feasibility and reliability of the new device and its applicability to field studies. From these preliminary results, the device appears capable of providing new information on diving physiology and potentially enhancing diver safety. Further studies on larger cohorts of divers and exploration of a wider range of depths and conditions, especially the impact of thermal (cold) stress, are needed before the performance of the ADC is fully validated. Such studies are currently ongoing. Future studies could also address detailed analysis of the plethysmographic waveform, for instance, to investigate heart-rate variability during diving. However, advanced signal analysis will be required, as the rounded peaks in the plethysmographic waveform are not as clear cut as the R-wave of the ECG.

Conclusion

We present a novel, wrist-mounted apnea dive computer (ADC) capable of measuring and displaying $S_{tc}O_2$, heart rate, the plethysmographic waveform, depth, water temperature and time during breath-hold dives. The measured data are stored in a memory chip, which is read by data-processing software and the processed data are written into a CSV file, for analysis by applications such as Microsoft Excel™ or Open Office Calc™.

Preliminary results give us confidence that the ADC has the potential to provide continuous monitoring of $S_{tc}O_2$ and heart rate for long periods.. Together with depth and temperature monitoring, these measurements may contribute to a better understanding of the complex relationships between physiological cardio-respiratory parameters over time during dives, and to the possible definition of objective criteria for fitness for breath-hold diving, based on simple underwater testing.

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Conflicts of interest: none

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