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

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$_{tcO_2}$). 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$_{tcO_2}$ 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$_{tcO_2}$ 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$_{tcO_2}$ 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. However, measurement of S$_{tcO_2}$ in divers has been attempted using standard, finger-transmission pulse oximetry. 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$_{tcO_2}$. 
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 $StcO_2$ in patients undergoing peripheral vascular surgery. $StcO_2$ values from these methods were compared with oxygen saturation ($S_O_2$) measurements of simultaneously collected arterial blood, and $S_O_2$ closely matched both $StcO_2$ probe values. Similar conclusions were reached recently for the use of forehead reflectance oximetry probes versus conventional digit sensors in paediatric patients. 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.

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 photoplethysmography waveform, heart rate and $S_O_2$. The dive profile and photoplethysmography 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 photoplethysmography 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 $S_O_2$ 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 ($S_O_2$ 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 photoplethysmography) plus parsing, measuring

![Figure 1](http://archive.rubicon-foundation.org)
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 $S_tO_2$ (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 $S_tO_2$, 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...
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 \( S_t O_2 \) 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, \( S_t O_2 \) will reflect the amount of \( O_2 \) that is delivered to tissues and, in turn, \( S_t O_2 \) 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\(_2\) and, in turn, \( S_t O_2 \) depends on the partial pressure of \( O_2 \) in the alveoli.\(^{14}\)
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 $StcO_2$ in spite of continuous oxygen consumption.
The fall in $StcO_2$ during the ascent and its continued drop after
surfacing explains why ascent syncope occurs at or near the
surface.15 Continuous monitoring of the $StcO_2$ 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 $StcO_2$ 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 $StcO_2$ 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 $StcO_2$ once $O_2$ consumption has exceeded the initial
body stores of oxygen.

The simultaneous display of $StcO_2$, 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 $StcO_2$, 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 \(S_O^2\) 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

References


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