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Underwater monitoring system for body temperature and ECG recordings

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Abstract

A new device was developed and tested in a series of diving experiments investigating the physiological effects of immersion on military divers for long periods (8 h to 12 h). During these experiments, the body temperature (core and skin) and electrocardiogram (ECG) of the divers were recorded and monitored in real time. The system developed for this purpose comprised a modified VitalSense temperature monitoring device from Philips Respironics and a one-channel ECG housed in a pressure-proof case. Recorded data were transmitted wirelessly to a PC. The recording and visualisation software was developed under National Instruments LabWindows.

1. Introduction

The French Navy wanted to investigate the physiological effects of long-term (8 h to 12 h) immersion on military divers in moderate water temperatures at depths of up to 20 m (Castagna et al., 2013; Desruelle et al., 2014). The investigation was focused on the divers' electrocardiogram (ECG), skin and core temperature, and required a system capable of monitoring these physiological effects.

In order to identify a suitable design, a number of different approaches in ECG and temperature measurement were evaluated (Baig et al., 2013; Bosco et al., 2014; Sieber et al., 2010). From the evaluation results, the authors derived a new modified device suitable for application in hyperbaric and underwater environments. The system developed was a one-channel ECG device and several temperature measurement sensors. This technical briefing focuses on the technical details of the ECG and temperature recording, as well as the data processing and visualisation.

2. Underwater electrocardiogram

To monitor a one-channel ECG during diving and to access recorded ECG data, a small-sized circuit board was designed and assembled. Fig 1 shows the circuit board (referred to as the monitoring board). The circuit was designed using an instrumentation amplifier (AD632, Analog Devices) to pre-amplify the ECG signal obtained from the electrodes and additional operational amplifiers in series to filter the signal. The filters contained a band pass filter with cut-off frequencies at 1.5 Hz and 100 Hz, and a notch filter to reduce 50 Hz interferences. A microcontroller (ATxmega32A4, Atmel) digitalised the signal, sampling the ECG with a frequency of 250 Hz and 12 bit resolution.

EL502 long-term electrodes from BIOPAC were used as ECG electrodes. Before each dive, a new set

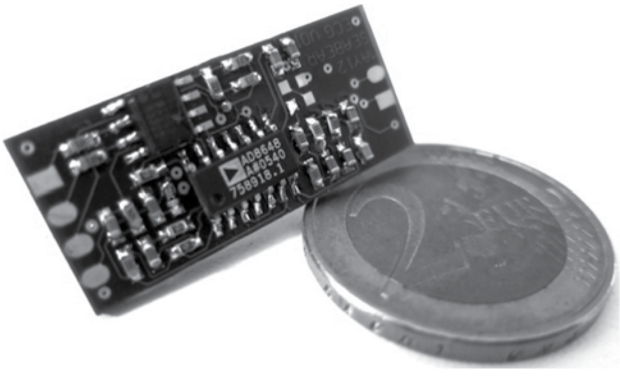

Fig 1: Monitoring board

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of electrodes was soldered to the ECG cables and the contacts were covered with hot glue and further isolated with a self-adhesive waterproof film (Tegaderm, 3M). A rechargeable Li-ion 18500 battery (Trustfire) with a voltage of 3.7 V and 1800 mAh of capacity powered the monitoring board.

3. Underwater temperature monitoring

In addition to the ECG, the French Navy wanted to monitor the divers' body temperature while wearing 7.5 mm thick neoprene wetsuits. Hence, the skin and core temperature in eight different locations needed to be measured for each diver to determine the temperature distribution in different areas of their body. Therefore, a total of nine temperature sensors were applied per diver. To identify the most suitable temperature measurement, different methods were considered.

Wired temperature sensors. One solution to measure the skin and core temperature of divers is to use wired temperature sensors. However, a high number of cables would have been required to be routed along the diver. All the cables would have posed a safety hazard, such as possible entanglement, and seemed to be uncomfortable for the diver.

Ingestible sensor. Another method considered was using HQinc CorTemp® ingestible core temperature sensors, which are little pills (length: 22.4 mm; diameter: 10.9 mm) that can be swallowed. These pills measure the temperature inside the digestive tract and transmit it out of the body via a low-frequency electromagnetic signal (262 kHz to 300 kHz). The advantage of this system is the relatively low cost of the pills. However, only one type of temperature sensor is available. There are no sensors that can be used to measure the skin temperature within this system. In addition, the way the system transmits the data does not allow a discrimination of data sent by the different sensors that have been swallowed.

VitalSense sensors. Philips Respironics provides two different types of body temperature sensor: an ingestible pill to measure the core temperature; and patches that can be attached to the skin to measure the skin temperature. The VitalSense device is capable of tracking ten sensors simultaneously, displaying the data on a screen, and storing the data for later analysis. The VitalSense system has its own internal rechargeable battery.

The VitalSense system from Philips Respironics proved to be most suitable to measure the body temperature of the divers, since it provides a sufficient number of temperature sensors for both skin and core temperature measurement, without the need for a lot of cables. The authors designed a new serial interface on the VitalSense system by modifying the internal transceiver chip's serial connection. This way the system could be read in real time.

4. Data transmission

Several options were evaluated to determine the most suitable system for data transmission between the monitoring device, a PC in the laboratory and open water dive settings. The following options were taken into consideration.

Wired connection. In the hyperbaric chamber, a pressure-sealed cable could be fed through the wall of the chamber to transmit the data through the cable. However, this solution presents two issues: a potential separation between the computer outside of the chamber; and the fact that ECG electrodes were required to be attached to the diver's body. Given the PC is connected to a power outlet, if a malfunction occurred the diver might be directly connected to the power outlet via the data transmission cable and the ECG electrodes. In addition, having a cable from the monitoring system to a fixed connector in the wall of the chamber would be a safety hazard if the divers have to be evacuated.

Electromagnetic signal transmission. Technology such as Wlan, Bluetooth or ZigBee based communication operate on a carrier frequency of 2.4 GHz. Signals of that frequency travel only a few centimetres in fresh water (Lloret et al., 2010) and even less in sea water because of the increased conductivity. Therefore, this type of technology is not a suitable solution for transmitting the data from the diver through the water, out of the chamber and to the laptop. Other wireless communication systems that have previously been employed underwater, for example for the communication between tank pressure sensors and dive computers, rely on low-frequency electromagnetic carriers of 5 kHz to 32 kHz. However, the data rate is only a few bytes/s (Sieber et al., 2010) and therefore too low to transmit an ECG signal.

Acoustic/ultrasonic communication. Ultrasonic communication systems can be used to communicate up to 20 km in water. Even though the transmission range and data rate are sufficient, it does not work well in pressure chambers because of echoes. In addition, ultrasonic modems are bulky, disturbing during experimental dives and very expensive.

Infrared. One option the authors tested used an infrared (IR) transmitter placed close to one of the windows in the hyperbaric chamber and a cable connecting the monitoring system to the IR transmitter. Outside of the chamber, an IR receiver was used for IR remote controls that received and decoded the IR signal. This method was able to transmit the ECG signal and the temperature information, but it relied on the IR transmitter being in line of sight with the IR receiver. This could not be guaranteed in open water conditions, even if the IR transmitter was placed on top of a buoy floating at the surface.

Bluetooth. Another approach to solve the data transmission problem that was tested involved a Bluetooth module that was put into a small buoy that floated at the water surface. A cable connected the Bluetooth module to the monitoring system. The Bluetooth module received the data through that cable and transmitted it to a Bluetooth module inside a laptop outside of the hyperbaric chamber or on a support vessel in the open water setting. Worries arose that the walls of the hyperbaric chamber would block the Bluetooth signal if the module was not close enough to one of the windows. However, in all tests in the hyperbaric chamber of the French Navy in Toulon the system worked without interruption of the Bluetooth link.

In conclusion, the Bluetooth module seemed most likely to possess all requirements for successful application in both the hyperbaric chamber and open water dive settings.

5. Data processing

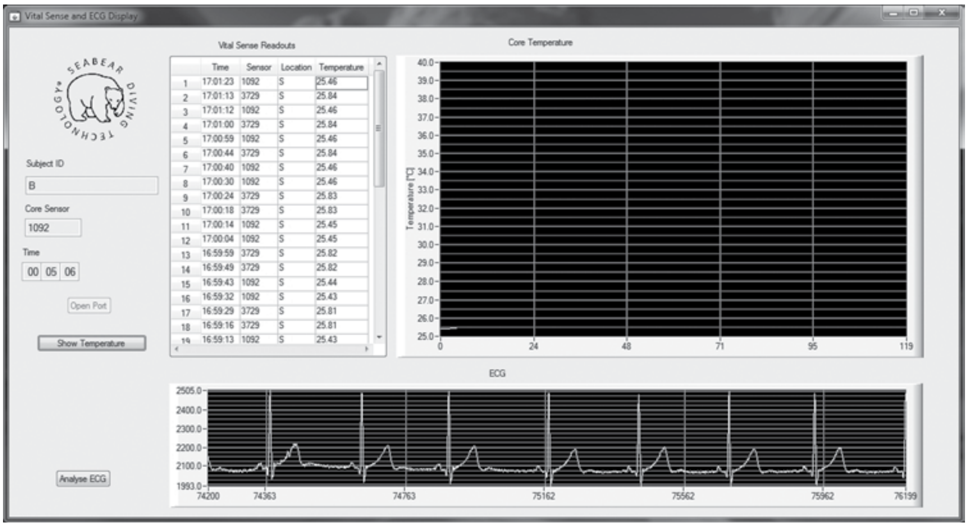
For supervision, real-time monitoring of all measured parameters on a laptop was requested. Since the measurement system was newly developed, there was no software that could use the serial output of the system to display the data in real time and also save it. This meant a program needed to be developed capable of fulfilling the following requirements:

i) Distinguish between different temperature sensors by selecting and assigning each sensor to specific body parts.
ii) Produce a graphical representation of the temperature data to visualise trends.
iii) Plot the ECG signal in real time and save short samples of the signal at different instances during the dive to identify changes that might occur.
iv) Store all measured data in a format that would allow in-depth analysis after the dives.

A graphical user interface (GUI) was implemented using LabWindows^{TM}/CVI from National Instruments to fulfill all those tasks (Fig 2). The user could select the serial numbers of the temperature sensors and assign them to different predefined parts of the body. Furthermore, the user could open the serial ports to the matching Bluetooth receiver. The user interactions with the interface were programmed in C, the same programming language that was used to program the firmware on the microcontroller of the monitoring board. The monitoring board transmitted blocks of 50 ECG samples five times per second. Temperature data from the VitalSense system were distinguished from the ECG data by additional serial string identifiers. Each temperature sensor sent the measured temperature in 30 s intervals.

Once a stable transmission was initiated, the program displayed the ECG signal in the lower graph of the main window. The ECG signal could be analysed in depth by opening a window showing a graph of 5 s intervals. Any of those 5 s intervals that were displayed could be stored and compared to previously saved intervals. The table in the upper left part of the window listed all received temperature data.

In addition, the core temperature was plotted in the graph in the upper right part of the window, and the user could open another window to plot



Subject ID: B
Core Sensor: 1092
Time: 00 05 06

Vital Sense Readouts

	Time	Sensor	Location	Temperature
1	17:01:23	1092	S	25.46
2	17:01:13	3729	S	25.84
3	17:01:12	1092	S	25.46
4	17:01:00	3729	S	25.84
5	17:00:59	1092	S	25.46
6	17:00:44	3729	S	25.84
7	17:00:40	1092	S	25.46
8	17:00:30	1092	S	25.46
9	17:00:24	3729	S	25.83
10	17:00:18	3729	S	25.83
11	17:00:14	1092	S	25.45
12	17:00:04	1092	S	25.45
13	16:59:59	3729	S	25.82
14	16:59:49	3729	S	25.82
15	16:59:43	1092	S	25.44
16	16:59:32	1092	S	25.43
17	16:59:29	3729	S	25.81
18	16:59:16	3729	S	25.81
19	16:59:13	1092	S	25.43

Fig 2: Main window of the data processing software

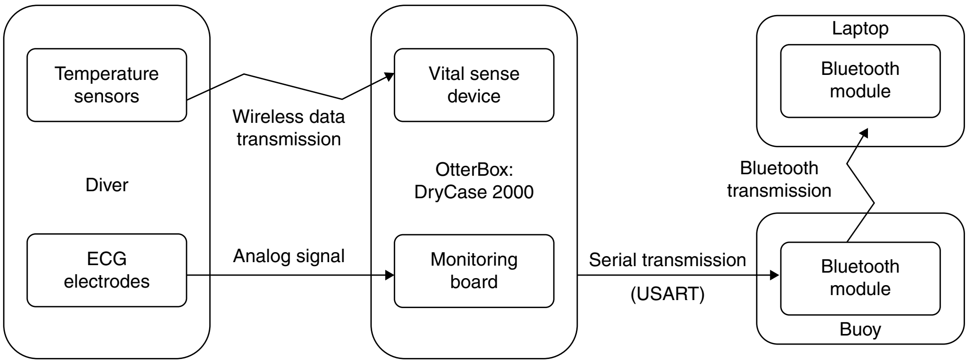


Fig 3: Block diagram of the monitoring system

the temperature curve of any previously selected temperature sensors. This enabled a visual representation of the temperature trend. All data were stored in different csv files. Those files could be accessed with different spreadsheet programs to analyse the data in more detail and plot the different parameters.

6. Underwater monitoring system

The microcontroller on the monitoring board has a total of five universal synchronous/asynchronous receiver/transmitter (USART) interfaces available. One of these was connected to the newly designed serial interface of the VitalSense system. This way the temperature data were also available on the monitoring board and could be sent to a laptop for further data processing.

The monitoring board and a VitalSense device were connected by a short cable and placed in a waterproof DryCase 2000 from OtterBox. Externally the case was equipped with two waterproof connectors, one of which was used for the three ECG electrodes; and the other for data transmission. The Bluetooth module in the buoy was connected to this data transmission connector by a cable. Depending on the dive setting the cable was 2 m or 30 m long. The Bluetooth module received the ECG and temperature data from the monitoring board and transmitted it to a laptop for supervision. Fig 3 shows a block diagram of this setup.

Fig 4 shows the two monitoring systems that were built; one has the ECG cables and Bluetooth buoy attached to it. The outer dimensions of the DryCase 2000 are 14.6 cm by 7.9 cm by 2.5 cm, and it weighs a total of 450 g.

7. Proof of concept and discussion

The French Navy performed a series of dive experiments in a hyperbaric chamber and in the ocean testing the underwater monitoring system. It proved to be capable of collecting the body temperature and ECG data continuously for up to 12 h. The data were transmitted to a laptop outside the hyperbaric chamber or on a support vessel and could be inspected in real time for supervision.

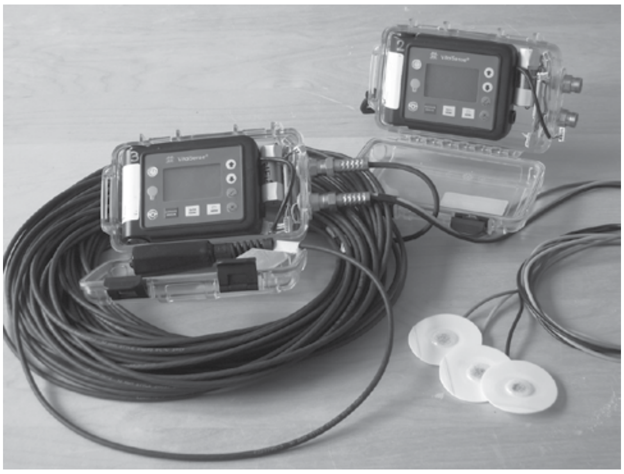


Fig 4: Two assembled monitoring systems

When the infrared data transmission link to transmit the data out of the hyperbaric chamber was tested, the transmitter was connected with rubber bands to a stationary object in the chamber. This was not considered a safety issue in case of an emergency, because this attachment could easily be removed just by pulling on the cable. However, the attachment to that stationary object dramatically decreased the ability to move around freely inside the chamber.

Regarding the open water trials, the cable running from the DryCase 2000 to the Bluetooth module in the buoy was a limitation of the monitoring system. Special attention had to be paid to avoid entanglement.

The case from OtterBox used to house the monitoring system was tested to a depth of 30 m. At this depth it was significantly deformed, but did not break. It is unclear to which depth it can withstand the pressure, but alternative housings can be manufactured easily and cheaply. In cases where only the ECG is needed, the whole device could be assembled to be much smaller since only the monitoring board and a battery are needed inside the waterproof housing.

For a more specific analysis of the cardiac activity, upgrading the ECG to more than just one channel could be considered (Cibis et al., 2015).

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