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Design and Implementation of an Underwater Telemetric Glucose Monitoring System for Scuba Divers

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ABSTRACT

Despite the abundance of telemetric applications for ecology, behaviour and physiology of marine life, few efforts were reported about the use of acoustic telemetry for SCUBA divers. Such systems are required to follow the medical conditions of divers with chronic health problems such as diabetics. This study communicates the details of a study to design, manufacture and test a prototype system that measures the blood glucose while diving and transmit the results in real time to the surface. A subcutaneous glucose sensor placed on the diver transmits wirelessly the glycaemia data to a microcontroller based RF receiver board placed in a custom built waterproof casing. This board works as a relay to transmit the blood glucose value to an acoustic modem SAM-1 (Desert Star Systems LLC, Monterey Bay, CA, USA) via RS232 serial communication. The modem transmits the data to the other modem, which is placed underwater at 1 m depth with a maximum baud rate of 100 bit/sec with ultrasound communication. Finally, the data reaches a portable computer from RS232 serial interface of the acoustic modem. The data is displayed and logged on the computer based at the surface. The whole system is tested to 11 Bar in hyperbaric chamber. The acoustical data link is first established between two computers located at surface to test the reliability of the communication. The acoustical link experiments were successful for 20 minutes of simulated signals for the depth, interstitial glycaemia, breathing frequency and temperature information. The overall efficiency was 80.1%, with 474 bytes sent and 378 bytes received. The bandwidth of the acoustical link is very low (max 4 reading/min) but is adequate for glycaemia monitoring that can be as low as 1 reading every 5 minutes. Finally the system recorded the interstitial glucose of divers in 8 open water dives successfully and will be beneficial for studying diabetic divers. The system has a potential to be used to verify and optimize the existing protocols on diabetic divers. It offers as well an emergency system to monitor the non-diabetic divers during extreme exposures such as saturation diving.

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INTRODUCTION

Insulin-dependent diabetes has been considered for long time as a scuba diving contraindication due to the hypoglycaemia problems potentially exposing the diver to danger. An analysis of Divers Alert Network (DAN) database from 1993 to 2007 has shown that a small percentage of DAN members were diabetic. However, it must be considered that a large proportion of diabetic divers do not declare their condition, increasing the risk for themselves and for their dive buddies. Knowing that that about 10% of world population suffers from diabetes, a workshop was organized to draft the guidelines for diabetes and diving and protocols have been suggested for safe diving [1]. This protocols necessities the frequent measurement of blood glucose (BG). However, in some cases dives can be very long and the measurement of BG during the dive is beneficial. Pieri et al, designed and used a continuous monitoring system for BG underwater [2]. This system can be used by the diver or other members of the team, but in case of emergency it is

also useful that the surface attendants know the hypo/hyperglycaemia conditions in order to take necessary actions. A second benefit of a telemetric system will be to use the transmission signal for geolocatisation of the diver and thereby provide efficient search and recovery in case of emergencies.

Electromagnetic waves are rapidly absorbed by water and acoustic telemetry is the only effective method for wireless underwater monitoring [3]. Despite the abundance of telemetric applications for ecology, behaviour and physiology of marine life, few efforts were reported about the use of acoustic telemetry for SCUBA divers [4-7]. This limited number of studies had been devoted to monitor mainly ECG, temperature, heart rate and respiration frequency of divers using open circuit SCUBA. A monitoring system offers to report technical problems with rebreather equipment underwater using acoustic telemetry [8]. The previous pilot study has recorded the glucose levels of scuba divers while underwater [2]. This study to acquire in real time BG values at surface and is a continuation of this monitoring system while enabling topside bystanders to initiate any rescue in case a dangerous BG level is measured. This system will be used to verify the efficiency of the existing protocols of diabetic divers and has a potential to be used for diver geolocalisation using the single bacon navigation technique [9].

MATERIAL AND METHODS

System Design

A glycaemia measurement system that has a wireless transmitter is selected in order to intercept the signal (Dexcom G4 PLATINUM CGM System, Dexcom Inc., San Diego, CA, USA). Dexcom G4 PLATINUM CGM System consists of 3 parts. A small sensor that measures glucose levels just underneath the skin; a transmitter that is fastened on top of the sensor and sends data wirelessly to the receiver and a receiver that displays glucose trends. The sensor-transmitter pair of the system has been previously demonstrated to have a high performance under hyperbaric conditions [2]. The RF signal range of the transmitter is only 6 metres in the air and few cm in water. In order to transmit the glycaemia sensor data from a diver to the surface or to another diver, it was necessary to use acoustical modems. A pair of low cost/low baud rate (max 100 bit/sec) and relatively high range (1000 m) acoustic modems were selected (SMA-1, Desert Star Systems LLC, Monterey Bay, CA, USA). The acoustic modems accept the RS232 compatible signals, so it was necessary to convert the RF signals of the Dexcom sensor to RS232 using an open source design [10]. An electronic board was designed to accommodate the Wixel board, to pre-process the data and to configure the modems during booting sequence.

System Overview

The system is composed of;

- a G4 Platinum glucose sensor placed on the skin of the diver,
- an electronics board serving as transmitter, based on the open-source RF receiver board inside a water proof housing
- a pair of acoustic modems SMA-1,
- a computer

The main elements of the system and their workflow are represented in Fig. 1. The glucose sensor placed on the diver transmits its measure to the nearby Wixel receiver wirelessly with RF communication, which transmits the measures to an acoustic modem SAM-1 (Desert Star Systems LLC, Monterey Bay, CA, USA) with electrical, serial communication RS232. The modem transmits the measure to the other modem, which is near the surface, with ultrasound communication. Finally, the data is transmitted to the computer with an RS232 communication. The data is displayed and logged on the computer based at the surface.

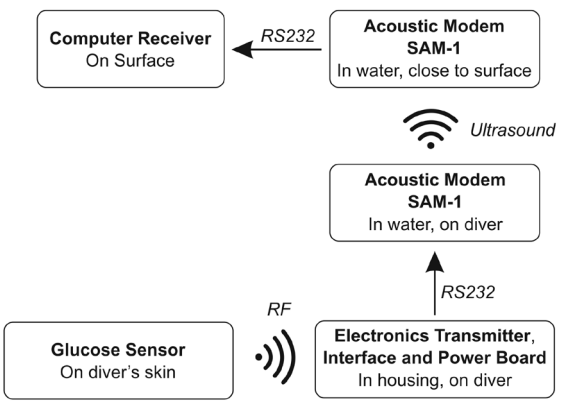


Figure 1. Block diagram of the system's composition and workflow

Glucose Sensor

The glucose G4 sensor is placed on the skin of the diver, as illustrated in Fig. 2. The sensor is made of a needle placed inside the skin, in contact with the subject's blood, a unit containing the electronics and battery, carrying out the measures and transmitting them with RF communication. The sensor measures the glucose every five minutes and transmits the data immediately. PLATINUM CGM System has its own receiver device that displays trends and instantaneous values of glucose and provides alarms. This measurement accuracy of the system under hyperbaric conditions was tested in the earlier study by Pieri et al [2] using capillary blood glucose as reference. BG was monitored every five minutes on every dive, by a dedicated CGM, and the mean of relative difference between CGM and capillary blood glucose was calculated.

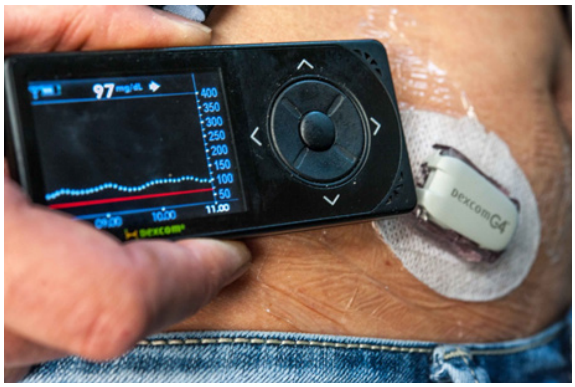


Figure 2. Dexcom G4 sensor placed on the skin of a patient

Measurement accuracy was assessed according to ISO guideline 15197 [11] and by Clarke Error Grid analysis [12] and was found to be adequate.

Electronics Transmitter, Interface and Power Board

The electronics transmitter was designed to serve several purposes;

- supply power to the diver's acoustic modem
- configure the acoustic modem upon power-up
- filter out the data received from the sensor to only transmit the significant data
- serve as an interface between the sensor and the acoustic modem

Fig. 3 details the composition of the electronics transmitter. Wixel is a general-purpose programmable module featuring a 2.4 GHz radio and USB. It is based on the CC2511F32 microcontroller from Texas Instruments, which has an integrated radio transceiver, 32 KB of flash memory, 4 KB of RAM, and a full-speed USB interface [13]. The board has 15 user I/O lines, featuring 6 analogue inputs, 2 USARTs (for serial or SPI), and 7 timer channels (capable of PWM) 4 KB of RAM and 29 KB of application program memory (flash). The Wixel features a built-in USB bootloader that can be used in conjunction with Wixel Configuration Utility software to upload custom programs or precompiled, open-source apps to the Wixel. Based on the previous experience of the firmware development on TI environment [14], the firmware of Wixel was modified to configure the acoustic modem at power-up and to filter the data received from the sensor before transmitting the data to the modem. Both the electronics transmitter and the acoustic modem placed on the diver are powered with a single, rechargeable, 9V battery. While the modem requires a supply of 8V to 16V, the electronics transmitter is powered with 3.3V and requires a step-down converter for power efficiency. An electronics board based on the FT232R chip (Future Technology Devices International Ltd., Glasgow, Scotland) is used to translate the electronic levels from 3.3V UART to RS232 for the acoustic modem.

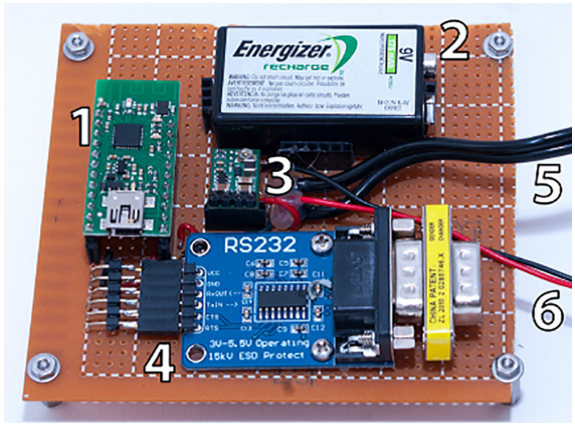


Figure 3. Electronic circuit built for interface, transmission and power. Photograph of the electronics transmitter. 1: Modified Wixel board. 2: battery. 3: step-down converter. 4: UART-RS232 board. 5: power supply to acoustic modem. 6: power supply connector to battery

Waterproof Housing

The electronics transmitter must be placed close to the glucose sensor, because the RF transmission will be very limited in the water. Meanwhile, the electronics must be protected from the water. Therefore, a dry casing was manufactured to embed the electronics transmitter. This casing will contain a single connector to one acoustic modem. The dry casing is designed to be held at the belt of the diver, close to the sensor.

Acoustic Modems

Two identical modems SAM-1 are used for transmission of the data underwater. The SAM-1 is a miniature acoustic modem. It will transmit and receive digital data between underwater stations up to a typical range of 250 meters, with up to 1000 meters possible under ideal (quiet, deep-water) conditions. The SAM-1 features a 5-pin underwater connector through which it communicates with the host and receives power. The connectors on the SAM-1 are models MCIL5F (Seacon, El Cajon, CA, USA). Data exchange is sent to the modem as serial data, converted to an acoustic waveform, transmitted to any modems listening, received, and converted back to serial data format. Data can be exchanged between two or more SAM devices at underwater locations or between an underwater SAM and a SAM lowered by cable from a vessel at the surface. The modem has a data mode and a control mode. Data Mode is used to transmit and receive data. Control Mode is available to change modem operation parameters. The modem will be in data mode after power up. To switch to control mode the user should send '###'. The modem will acknowledge control mode by sending '<CM>'. To return to data mode, send 'D'. The modem will acknowledge data mode by sending '<DM>'. There are 3 important parameters to control the optimal transmission: Sx; Rx and Txx.



Figure 4. Close up picture of the system mounted on the diver

Sx sets the acoustic transmit data speed. Since the blood glucose data is sampled every 5 minutes, this value is set to 3 bits/sec to economise on power.

Rx sets the acoustic receive data speed. For the same reason as Sx, this value is set to 3 bits/sec. The maximum value of Sx is 154 bit/sec while and Rx is 38 bits/sec.

Txx sets the receiver detection threshold. The minimum possible threshold is T01. The modem is at its maximum sensitivity of 85 dB. The maximum threshold is T99, equivalent to a sensitivity 125 dB. The optimal Txx may change according to the medium and was set to T01 within the scope of this work.

A first modem is carried by the diver, and connected to the electronics transmitter. A second modem is near the surface and connected to a PC.

Computer

The computer is the final receiver unit. It is connected to the second modem with a serial, RS232 connection. A terminal application is used to configure the modem and to display and log the received data.

Validation

A validation of the communication between the two modems was carried out in a swimming pool, where the conditions are less ideal due to the reverberation caused by the walls of the pool. The two modems were placed underwater, 5 to 7 meters apart and connected to two separate computers. An application was developed to quantify the quality of communication between two acoustic modems in a given medium. The application, shown in Fig. 5, connects to the modems. It sends simulated packages of 2 bytes representing either a depth, glucose level, breathing rate or a temperature through one modem at regular intervals and counts the proper reception on the second modem. The maximum sensitivity (T01) was used with Sx and Rx set to 3 bits/sec.

RESULTS

During the validation trails at the pool, different positions, threshold levels and communication rates were tested to establish the best configuration for the given conditions. After a total transmission of 398 bytes, 84.3% of the packages were properly received as a worst case. The bandwidth of the acoustical link is very low (max 4 reading/min) but is adequate for glycaemia monitoring that can be as low as 1 reading every 5 minutes.

The first dive is performed in "Istanbul Aquarium" located at Florya, Istanbul, Turkey on May 2017. A Fifty one year old, non-diabetic diver with 21 years of SCUBA diving experience made a dive to 3,8 m for 36 minutes (Fig. 6, 7). He was instructed to follow at all times the safety protocol

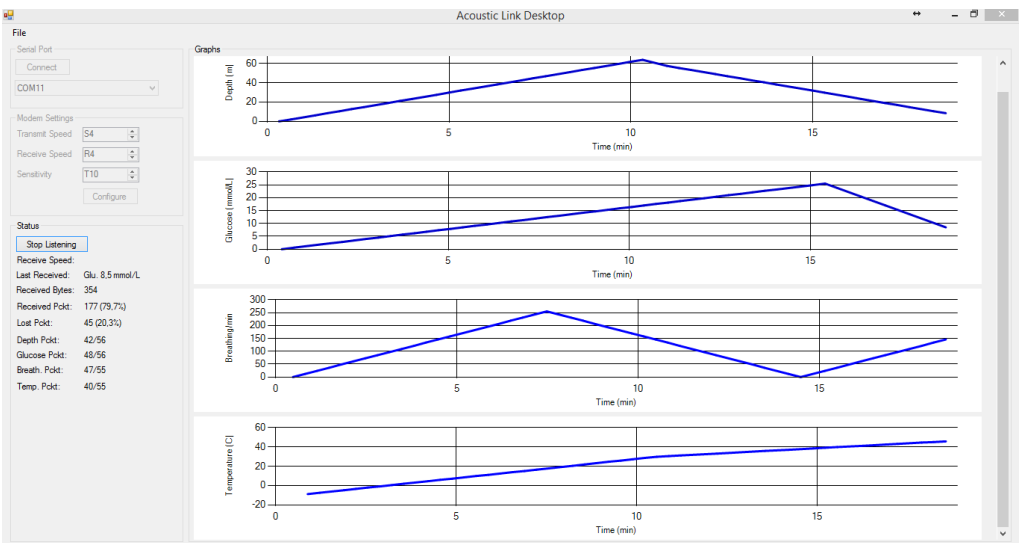


Figure 5. The graphic user interface of the application developed to validate the acoustical communication

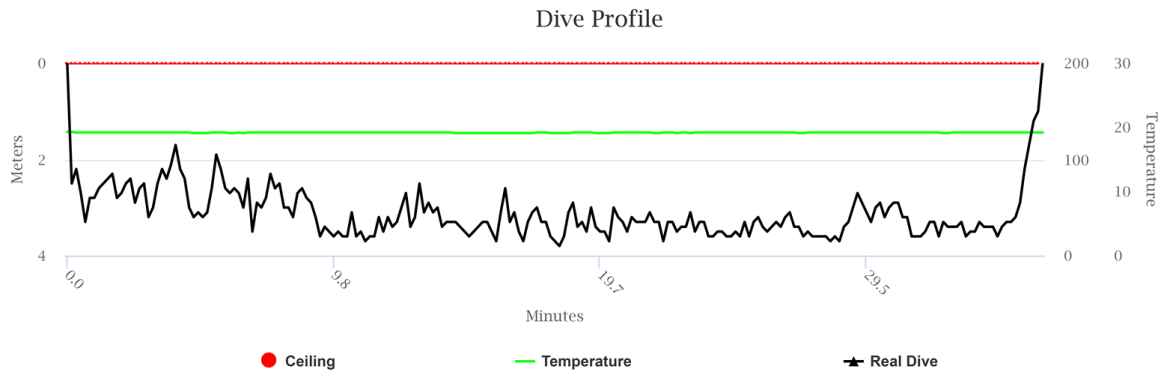


Figure 6. The Depth/Time graphic of the first dive with the acoustical monitoring system

he was trained to, and to abandon the test should any equipment fail and cause to threaten his safety. One hour prior to the dive, a value transmitted by the glucose sensor was recorded. During the dive, the glucose sensor transmitted every 5 minutes. During this dive, 7 BG data have been collected from the water to the surface station and no data was lost. Immediately after the dive, the scuba divers glucose level was measured again.

The system stated to be used to supervise a female diabetic diver, 33 year old, with more than 300 of dives of experience since May 2017. In total, 129 minutes of diving is supervised and 27 BG data is collected while 2 data packages are lost during transmission. The maximum depth of dives was 10.4m.



Figure 7. The telemetric system during the first test dive at Istanbul Aquarium

DISCUSSION

Diabetes, particularly insulin-requiring diabetes mellitus has most commonly been viewed as a condition that should preclude participation in activities during which sudden loss of consciousness may pose a significant risk. Scuba diving is one such activity, as impaired consciousness due to hypoglycaemia underwater would impair the ability to help oneself or a partner and could be fatal [15]. On the other side, The Americans with Disabilities Act [16] was designed to remove barriers and promote equal access for all individuals. A secondary effect was that exclusionary policies were more easily challenged, thus requiring clear and compelling evidence to justify such decisions. The legislation has substantial weight in cases where prohibitions are primarily based on theoretical risk. Subsequent protocols are established to provide recreational diving opportunities for diabetics [1] and were evaluated using pre and post dive data [17]. The study presented in this communication establishes a firm way of supervising the diabetics while diving and shall provide adequate protection for a significant population of world who is diabetics. In fact, World Health Organization guidelines based estimated prevalence of diabetes is very high(12.3%) and includes many individuals for whom no formal diagnosis has been made.

The system needs software and hardware improvements in order to be more useful. The number of lost data during sea dives is even lower than pool trials (93,21% versus 80,1% efficiency) probably due to the challenging reverberation effects at the pool. However, the transmission protocol was decided to be modified such that each BG data should be sent 10 times in expense of reducing the battery life. Therefore, a fresh battery needs to be placed before each dive and will provide autonomy of 75 minutes as a minimum.

The system presented in this study a one-way data flow: from the sensor to the supervisor. However, the acoustic modems enable a two way communication. Such system

could be enhanced with the capability for the supervisor to send messages to the diver. The communication protocol could be improved with an acknowledgement for each package sent, avoiding any data loss in harsh environment conditions and economizing the battery life.

Such system could be integrated in a dive computer to display the glucose levels to the diver while transmitting the same data to surface. In the future, the monitoring system could extend automatic alerts to inform both the surface staff and the diver (sound, vibration and/or light). This system could be extended further to interface with a web server, for remote monitoring and to alert authorities in case of a safety threat. Finally, the supervisor could use such system to send messages to the diver, such as requesting an abortion of the dive and to start the ascent.

CONCLUSION

Today, diabetic divers measure their level before a dive, sometimes twice with a time interval to guess the trend. However, while underwater, it is impossible for them to know whether their glucose is reaching dangerous levels (either high or low).

The prototype of the system presented in this study is fully assembled, programmed, validated and tested on scuba divers at the Istanbul Aquarium, Istanbul, Turkey, in May 2017. The system is in use to collect more data on a diabetic diver since May 2017. Such development participates in making recreational diving a safer activity for the diabetic divers. The system presented in this study brings an extra layer of security while diving and visibility of the trend of the glucose level. Diabetic divers could benefit from real- time blood glucose monitoring during their dives to prevent worsening of hypoglycaemia and to correctly interpret hypoglycaemia-like symptoms whilst diving.

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