HIGH RESOLUTION ECG AND DEPTH DATA LOGGER
A Novel Device to Study Breath Hold Diving Induced Variations of the PQ Interval

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Keywords: ECG, breath-hold, apnoe, diving, PQ interval.

Abstract: Breath hold diving induces several physiological effects. The authors speculate that next to bradycardia, vasoconstriction, splenic contraction and blood shift, the form of the ECG and especially the PQ interval are also affected. Investigations of this effect requires a high resolution ECG monitor which is also capable of recording depth. This paper describes our data logger prototype. It samples ECG data at 1200 Hz, is equipped with three temperature and a pressure sensor that allows depth measurement up to 140 m and stores all the data in an ASCII text file on a SD flash card in FAT 16 or FAT32 file format. The prototype is then encapsulated in a Lexan tube with an outer diameter of 42 mm and an overall length of 18cm that should withstand 20 bar pressure equal to 200 m depth.

1 INTRODUCTION

Freediving or breath hold diving history dates back at least 4500 years ago to pearl divers of the south pacific. In 1911, one of the first freediving competitions was held when a Greek fisherman, Yorgos Haggi Statti, sometimes called "the father of freediving", successfully reached more than 60m depth with a total apnoe close to seven minutes. Today breath hold diving enjoys a wide popularity, both recreationally and competitively. Actual depth record in the breath hold diving discipline No-Limits is already beyond 200m (Nitsch, H., 11.07.2007, 214m No-Limit, Greece). A big stimulus for this sport was and still is Luc Besson's cult film "Le Grand Bleu" or "The Big Blue", which depicts the life of the elite apnoe divers Jacques Mayol and Enzo Maiorca and their life-long competition in freediving. However research on breath hold diving is also shown, where experiments in a mountain lake in gorgeous scenery in Peru are carried out (Mayol, J., 2000) to demonstrate bradycardia during breath hold diving. Other adaptations made by the human body while underwater and at high pressure include (Gooden, B.A., 1994), (Andersson, J.P.A., Line, M.H., Ruenow, E., Schagatay, E.K.A.,2002):

- Vasoconstriction: Blood vessels shrink. Blood stream is directed away from limbs for the benefit of heart, lungs and brain.
- Splenic contraction: Releasing red blood cells carrying oxygen.
- Blood shift: Blood plasma fills up blood vessels in the lungs and reduces residual volume. Without this adaptation, the human lung would shrink and wrap into its walls, causing permanent damage at depths greater than 30 meters.

Recent experiments with a novel underwater Doppler-Echography system also demonstrate cardiovascular changes during breath hold dives at 3 and 10m (Marabotti, C., Scalzini, A., Chiesa, F. Bedini, R., Reale, L., Passera, M. Belardinelli, A. Pingitore, A., Cialoni, D., Data P.G,2005). We speculate that these cardiovascular changes also affect the timing of the ECG. To investigate possible variances of the PQ or the PR interval dependent on the depth, a novel data logger was developed that combines a high resolution ECG (16 bit, 1200 Hz sampling rate) and depth recorder in a small, watertight housing.

Sieber A., Bedini R., Yong X., Navarri A., Dalle Luche M., L'Abbate A. and Dario P. (2008).
HIGH RESOLUTION ECG AND DEPTH DATA LOGGER - A Novel Device to Study Breath Hold Diving Induced Variations of the PQ Interval.
In *Proceedings of the First International Conference on Biomedical Electronics and Devices*, pages 269-275
DOI: 10.5220/0001052102690275

2 METHODS

2.1 Introduction to ECG

The typical ECG signal (Figure 1) is characterized by six peaks and valleys labelled with successive letters of the alphabet P, Q, R, S, T and U (Malmivuo, J., Plonsey, R., 1995).

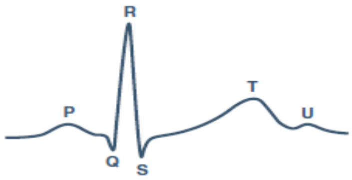

Figure 1: Typical form of a ECG signal.

A typical electrocardiogram (ECG) shows peaks of up to 5 mV. For the proper design of a ECG amplifier DC components up to +-300 mV, resulting from the electrode-skin contact, and a common-mode component of up to 1,5 V, resulting from the potential between the electrodes and ground, have to be taken into account. The bandwidth of an ECG monitoring system, depends on its application. It ranges from 0,5 Hz to 50 Hz in intensive care units up to 1kHz for late-potential measurements (pacemaker detection). A standard clinical ECG application has a bandwidth of 0.05 Hz to 100 Hz.

A typical PQ interval is about 160ms. A correlation is given between heart rate and PQ interval (Atterhög, J., Loogna, E., 1977). Recent studies have shown that this is not always the case, for example directly after a heavy workload (Busse, M., Nißing, A., Tegtbur, U., Miltzow, S., Thomas, M., Fikenzer, S., 2004). To study variances in the PQ interval a high spatial time resolution is required (Ward, S., Shouldice, R.B., Flanagan, M., Heneghan, C.,2004).

2.2 Principle Design of the Module

The prototype consists of two boards: the ECG signal acquisition board including amplifiers and a high resolution AD converter and the data logger board, comprising mainly an 8 bit RISC microcontroller, a display, a Secure Digital memory card slot and a 10 bar pressure sensor to monitor the depth.

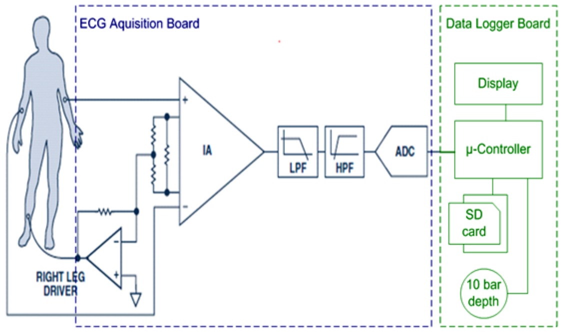

Figure 2: schematics of the developed module.

2.3 ECG Acquisition Board

For the analogue front ECG amplification stage we use the typical approach (Company-Bosch E., Hartmann, E., 2003) with an instrumentation amplifier (IA) and a right leg common-mode feedback op amp. For the IA we have chosen the AD620 [Analog Devices], a low cost, high accuracy instrumentation amplifier, with excellent DC performance: CMRR>>100 dB to nearly 1kHz, 50µVmax offset voltages, low input bias current (1nA max), and low input voltage noise (0.28µVfrom 0.1Hz to 10Hz).

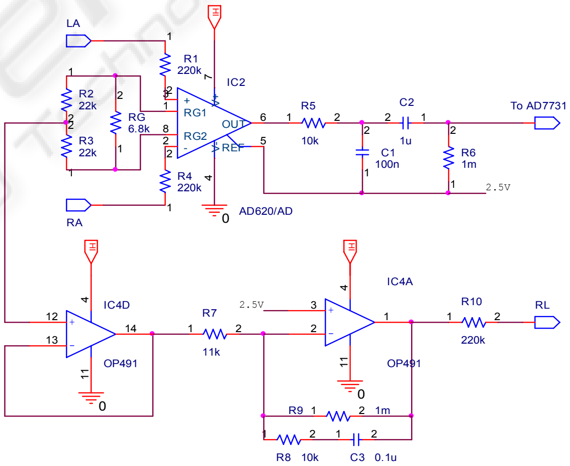

Figure 3: Schematic of the ECG amplifier.

The AD620 requires only a single external gain-setting resistor R_G (figure 3). Resistors R_2 and R_3 change the normal gain equation to:

$$Gain = 1 + 49.4k\Omega / R_G + (49.4k\Omega / 2) / 22k\Omega$$

To avoid output saturation, the usable gain is limited by the output swing and the maximum input voltage to the IA. Here, Gain is conservatively set to 9 by choosing RG=6,8 kΩ.

The OP491 form Analog Devices is used in the right-leg common-mode feedback circuit. It is a high precision operation amplifier with a low power consumption and high common-mode rejection (70 dB minimum). This circuit applies an inverted version of the common-mode interference to the subjects right leg, with the aim of cancelling interferences. The op amp has a voltage gain for the common-mode voltage of 91 (R_9/R_7=1MΩ/11kΩ) with a low-pass cut off at about 160Hz for stability. ($f_{-3dB}=1/2\pi$ x 10kΩx0,1µF)). For simplicity, a passive low-pass filter and a passive high-pass filter are adopted to accomplish both gain and frequency selectivity. The filter will allow all signals to pass through unaffected as long as their frequency is between the low-pass corner frequency at 160Hz and the high-pass corner frequency at 0.1Hz ($f_{-3dB}=1/2\pi$ x 1MΩx1µF)).

The required power for the module is supplied with a battery. The +5V supply required for the AD620 and OP491 is handled through the voltage power regulator TPS76950 [Texas Instruments] which offers the benefits of low dropout voltage, ultra-low power operation and miniaturized packaging (5-pin SOT-23 package). The +2,5 V reference for the AD620 is accomplished with one of the four operational amplifiers integrated in the OP491 (figure 4).

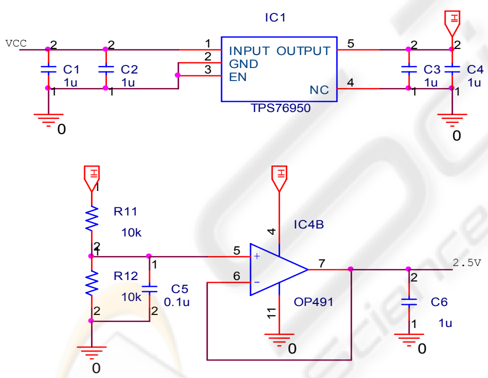

Figure 4: Power supply of the ECG board.

A AD7731 AD converter from Analog Devices follows the analog section. It is a low noise, high throughput 24 bit Sigma-Delta ADC with buffered differential inputs and programmable low pass digital filtering allowing adjustment of filter cut-off, output rate and settling time. The device has a proprietary programmable gain front end that allows it to accept a range of input signal ranges, including low level signals. Figure 5 shows the peripheral setup of AD7731.

JAD is the interface aimed for the communication between AD7731 and Atmega32 which is located on the data logger board.

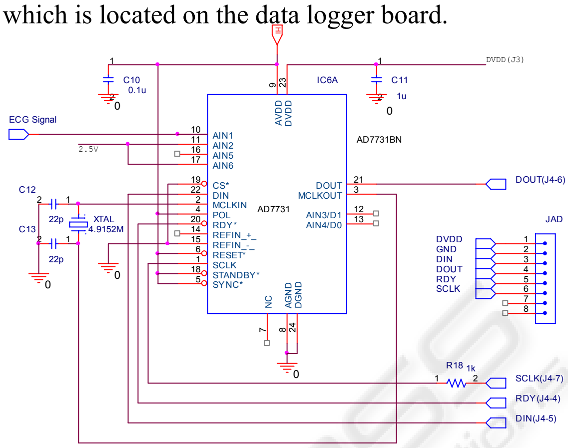

Figure 5: Schematics of AD7731.

2.4 Data Logger Module

The core component of the data logger board is an ATMEL Atmega32 microprocessor with the following specifications:

- 32 kbyte Flash Program Memory
- 2 kbyte SRAM
- 1 kbyte EEPROM
- programmable 8 channel 10 bit ADC
- 16 MIPS @ 16MHz
- TQFP44 housing

The board can be programmed via J1. A Secure Digital memory card connector is connected to the SPI interface of the µ-processor (PB4-PB7). As the SD card is powered with 3,3V, three voltage dividers (R16 – R21) are deployed to decrease the 5V digital output signals to 3,3V. As the Atmega32 interprets digital signals above 2,7V as high, the digital output can be directly connected to the input of the SPI interface (MISO, PB6).

Two low drop low power consumption voltage regulators are used to provide 3,3 V for the SD card and 5V for the rest of the components. Additionally the 3,3 V regulator can be switched in standby mode via dropping the enable pin to ground (via PB2). The EA-DP204 4x20 characters display can be controlled in 4 bit parallel, 8 bit parallel or SPI mode. To simplify the circuit by minimizing the necessary connections we have chosen SPI mode. Therefore the displays clock SCLK and serial input SDI are connected to PB0 and PB1. The ADC's ready pin is interfaced to the external interrupt pin INT1 of the µ-processor (PB3).

To dedicate the µ-processor's inbuilt SPI bus solely to the SD card, the routines for interfacing the

AD converter and the Display are software implemented.

The device mainly addresses ECG recordings in hyperbaric environments like in diving. Therefore a digital pressure sensor needs to be integrated. For this reason the MS5521B 14 bar absolute pressure sensor was chosen [Intersema, Switzerland]. Even if it is not mentioned in the datasheet, the sensor is suitable for pressure measurement up to 33bar. Moreover a digital temperature sensor is integrated in the part.

This sensor requires a 3.3V supply, therefore again voltage dividers (R5-R10) are used to reduce the pins output voltage. The output of the pressure sensor can be directly connected to the microprocessor. For correct operation of the sensor a clock signal is needed (MCLK). This clock signal is generated with the internal Timer 2 from the Atmel ATMEGA32.

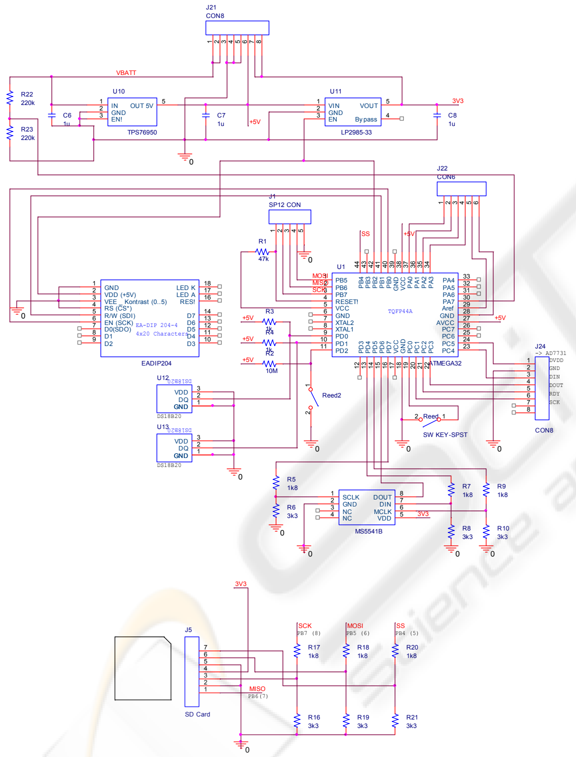

Figure 6: Schematics of the datalogger board.

Body skin temperature and water temperature are parameters that influence the physiological diving response. Therefore two temperature sensors are integrated in the design. These sensors can be for example placed under the diving suit to measure the skin temperature.

As temperature sensors two “one wire” DS18B20 [Maxim] were selected. The “one-wire” feature allows to use just two lines for power supply, communication and ground. In principle the two sensors could be connected to the same port pin, but to increase communication speed by parallel read out, each of the sensors was connected to one separate pin.

2.5 Software

The firmware of the module detailed in figure 7I is developed in C under the Atmel AVR Studio 4 [Atmel] and the GNU C compiler WinAVR (http://winavr.sourceforge.net/).

The implementation of a DOS compatible FAT 16 of FAT 32 filesystem on the SD card requires in total 1,6 kbyte of ROM to mirror the boot sector, the file allocation table (FAT) and to provide a buffer for data storage.

Data storage on SD card in FAT 16 of FAT 32 file system is performed in blocks of 512 bytes each. To enable a high sampling rate of 1200 Hz, it is necessary to treat data storage and read out of the ADC separately, as the data storage of a 512 byte block may last up to 7µs.

Every time an AD conversion is complete, an interrupt is generated via the external interrupt pin INT1.

In the interrupt routine the result is stored in a FIFO buffer. As soon as there are 10 entries in the FIFO buffer, the data is converted in an ASCII string and stored together with the actual depth on SD card.

The “one-wire” protocol [Maxim] is software implemented. Every two seconds the two temperature sensors are read out.

The MS5541B is interfaced via SPI bus. Every two seconds values for pressure and temperature are read out and stored on SD card. Together with 6 calibration parameters stored on the sensor and usually read out at the beginning of the program, pressure and temperature can be calculated. To reduce overall processing time depth and temperature are not calculated on the microprocessor but later under LabView.

A reed contact is used to switch the system on and off via a magnet (in underwater applications magnet switches are preferred as they require no mechanic connection to a switch that needs to be sealed). Once the magnet is removed, the system switches in standby mode. Placing the magnet over the reed contact creates an interrupt on INT0, waking up the module.

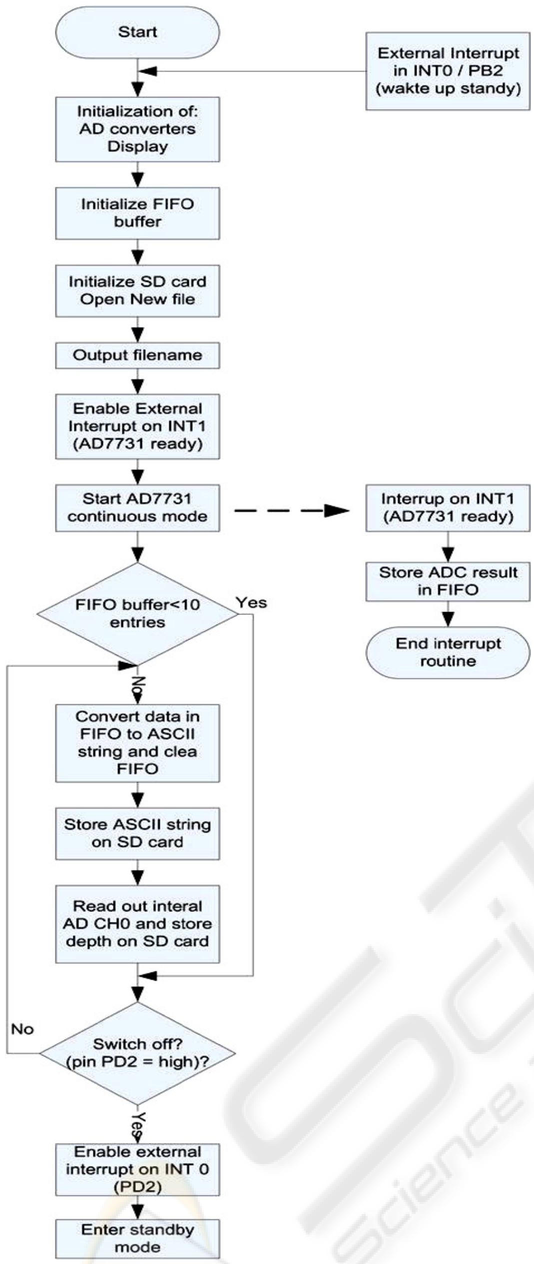

Figure 7: Software flow diagram.

2.6 ECG Data Processing

A software to preview and analyze the collected data software was developed under Labview 7.1 [National Instruments]. To suppress the 50 Hz noise, a optimized Notch filter is implemented (2nd order IIR filter, 45-55 Hz). (Josh, Y.V., Dutta Roy, S.C.,1997), (Chivapreecha,, S., Dejhan, K., Yimman, S., 2005) (see also figure 9A and 9B).

3 RESULTS

A first prototype with the following specifications was build up:

Power consumption[1)]	34 mA
Module size	80x30x25mm³
Battery supply	5,5 … 10 V
Sampling rate ECG	1200 Hz
Resolution ECG	16 bit
Resolution depth sensor	10 bit / 10cm
Sampling rate depth	120 Hz
Bytes / sec	6,4 kbyte/s
File format	FAT16/FAT32
Depth sensor	14 bar (33 bar)
Housing, lexan:	250 m rated

[1)] The power consumption depends also on the SD card (Kingston 256 MB: 34 mA; Lbd, 32MB: 130 mA). In Standby Mode the power consumption drops to 0,3 mA.

Moreover the board is equipped with a second ECG channel with a second AD converter. To enable sampling of low frequency signals a AD8730 AD converter from Analog Devices was additionally integrated in the first prototype. It offers 10 programmable channels with a resolution of 16 bit (application: measurement of skin conductance, breathing sensor, temperature, etc.).

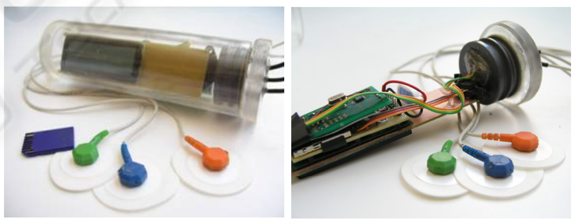

Figure 8A and 8B: First prototype in the double o-ring sealed housing.

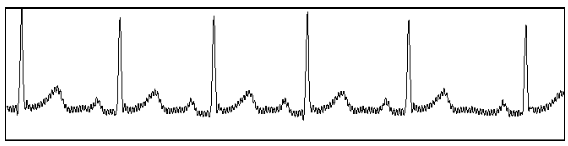

Figure 9A: ECG raw data.

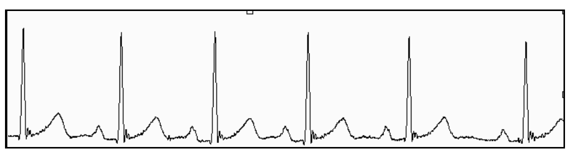

Figure 9B: ECG raw data after filtering with the 50Hz Notch filter.

Figure 8A shows the first prototype encapsulated in the lexan housing. The electronics consist of two boards, one (yellow-brown) with the µ-processor, SD card slot and the display and a second (green) board with the ECG circuit (Figure 8B).

Figure 9A shows a sample ECG recoding. The Notch filter allows an effective suppression of the 50Hz noise signal (figure 9B). This noise suppression is especially necessary when recording the ECG signal on the surface when the diver is preparing for the apnoe immersion. Once under water 50Hz noise signals are usually not seen due to the electrical conductivity of salt water.

Previous experiments have shown that during the first meters of the immersion electrodes with a sponge give bad signals. We speculate that this is due to the small amounts of air next to the sponge that is getting compressed by increasing deph causing electrode movement thus causing also artefacts in the ECG signal. To avoid this problem Kendall Arbo H34SG [Tyco Healthcare] electrodes were selected, as there electrode gel is placed over the electrode without a sponge.

As described earlier (Bedini, R., Reale, L., 2003) recording of an ECG underwater requires a proper sealing of the electrodes. Therefore we use two components impression material (Elite H-D+, Zhermack Hydrphilic Vinyl Polysiloxane)] (Figure 10A). This works well for short dives like breath hold dives. If the electrodes are exposed for longer times like several hours to sea water, we connect the electrode cables directly to the electrode and seal the connection with Epoxy (5 min Epoxy, 155105-1, R&G GmbH, Waldenbuch, Germany).

3.1 Pool Tests

Several tests on apnoe divers were carried out in a 10.5 m deep research pool (Divesystem, Massa Marittima, Italy).

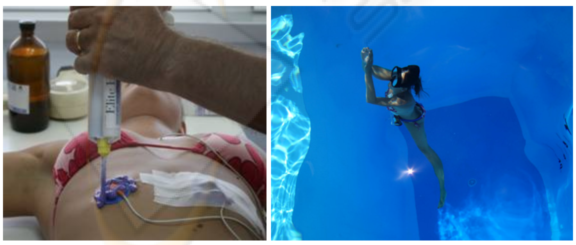

Figure 10A and 10B: 10A: sealing of the electrodes, 10B: test dive in the research pool.

For visualisation and analysis of the recorded data a software was developed under National Instruments Lab View 7.1 which is also offering several data processing utilities.

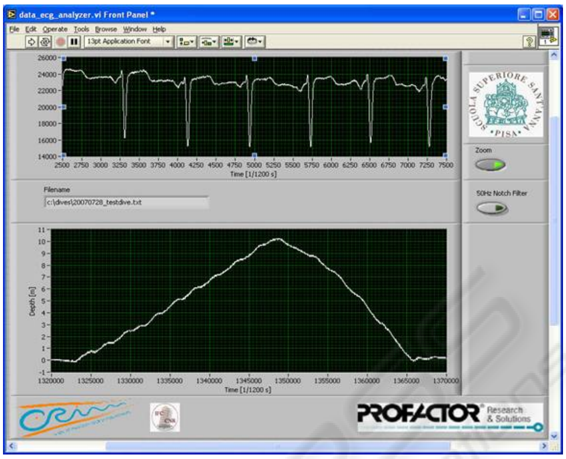

Figure 11: Lab View data visualisation software, in the upper graph the ECG is visualized, down you can see the depth profile.

3.2 Long Term ECG Recordings

An adapted version of the system with a to 250 Hz decreased sampling rate was used to record the ECG of Francesco Colletta during his world record dive in Siracusa, Sicily, Italy on September 8th to 9th. The total dive time was 32h.

Figure 12 A,B: Francesco Colletta after 32h underwater and our especially for this dive adapted ECG measurement device (at the end of each of the two black cables one temperature sensor is encapsulated in epoxy resin).

4 CONCLUSIONS

Research of breath-hold diving induced effects on the ECG requires a high resolution ECG and depth storage device. A novel prototype was developed that is able to store one or two channel ECG with 16 bit resolution at a sample frequency of 1200 Hz on secure digital memory card. This high sampling rate is the basis for a precise estimation of the PQ-interval. The authors are convinced that data gained from elite apnoe divers during the world championship in October 2007 in Egypt will lead to a better understanding of the physiological effects of breath hold diving.

Other applications of this device are ECG, depth and temperature recording during SCUBA dives.

5 FUTURE WORK

4 more prototypes will be fabricated to be then deployed during the AIDA freediving world championship in October 2007 in Sharm el Sheikh.

An enhanced second version of this prototype is planned to address SCUBA diving applications. It will be expanded with the following sensors: breathing frequency, water temperature, skin temperature and skin conductivity.

Software will be developed to allow an automatic measurement of the PQ-interval. This will be based on triggering on the QRS complex and then calculating the time to the beginning of the P wave.

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