Basic biomedical instrumentation for underwater human biotelemetry

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Abstract

Clinical devices used in everyday clinical practice for assessing health status cannot be used underwater, because of a variety of problems related to the liquid environment, its salinity and the hydrostatic working pressure. Thus, underwater medicine is mainly based on the results of a series of 'physiological models' of underwater diving that are considered to be valid surrogate and inferences from the clinical world; this approach, due to the lack of direct physiological measurements in the true environment, induced many drawbacks and/or mistakes in investigating human underwater physiology. Indeed, both processes are intrinsically uncertain and scientifically incorrect.

Thus, the transfer to the underwater environment of routine clinical instruments represents a great improvement, in terms of practice of medicine knowledge, just as it is the case of space medicine.

This task required the design of novel underwater diagnostic and monitoring instrumentation and the development of ad-hoc support infrastructure. In particular, we developed a minimum set of innovative underwater medical instruments to collect data related to heart rate, cardiac electric activity, cardiac morphology and function, arterial blood pressure and oxygen blood saturation, in addition to environmental information on water temperature and hydrostatic pressure.

In the present paper we will briefly describe the devices we designed and manufactured for the underwater assessment of physiological parameters; moreover we report about some important results in terms of advancement of knowledge in underwater physiology, using underwater measurements by novel diagnostic instrumentation. In particular, new acquisitions on blood pressure and cardiac functional responses during different diving activities will be described.

Keywords: physiological measurements, blood pressure, oxygen saturation, ECG, electrodes, underwater medicine, hyperbaric medicine, echography, cardiology.

Introduction

The total absence of instrumentation suitable for underwater measurements of simple but crucial physiological parameters such as heart rate, blood pressure, cardiac function, blood oxygen saturation etc. constitutes the main medical concerns about professional (commercial, scientific, rescue, etc.) as well as recreational diving because. In the lack of direct measurements, the results of series of 'physiological models' of underwater diving are considered as valid surrogate and inferences from the clinical world are commonly adopted, but this approach results in a scanty knowledge of diving physiology and the impossibility of monitoring of vital parameters during diving. Moreover this approach may induce drawbacks and/or mistakes in investigating human underwater physiology and this process appears intrinsically uncertain and scientifically incorrect.

Of course, none of the available clinical devices used in everyday clinical practice for assessing health status can be used underwater because of the problems related to the liquid environment, its salinity and the requested operability in potentially high hydrostatic pressure environment. Thus, with regard to performance of physiological measurements, underwater medicine may appear as to centuries ago.

In developing new instrumentation for underwater biomedical monitoring, the complete compatibility in terms of functional commands, nature of retrieved biomedical information and reporting with routine clinical instruments would represent a must of design and manufacturing. This approach represents a great advancement, in terms of practice of medicine knowledge, just as it is the case of space medicine biomedical instrumentation developments.

Beyond the design of waterproof instruments, special attention must be paid to selecting, placing and protecting the sensors and transducers especially for long term monitoring in the underwater environment.

In this paper we will describe some of the devices we were developed for the underwater assessment of physiological parameters considered crucial for the advancement of knowledge in underwater physiology and for the implementation of measures, able to improve diving related safety. These are heart rate, cardiac electric activity, cardiac morphology and function, arterial blood pressure, skin temperature and oxygen blood saturation in addition to environmental information on water temperature and hydrostatic pressure.

New achievements were then obtained by using our novel instrumentations in the physiology response of cardiac hemodynamic during underwater breath holding and SCUBA diving and they are here reported.

Materials and Methods

Underwater ECG

ECG underwater recording requires special recorder device and electrodes. Nowadays the design and manufacturing of a small and portable ECG recorder to be used underwater is not a big technological problem, both in terms of the protecting case to the water and pressure and the available high performance analog and digital electronics [1]. In the meanwhile the electrodes placement and insulation remain a not yet completely solved problem in underwater ECG data collection due to the effect of short circuits induced by the water environment and its salinity. This mean that without any insulation the recording of significant bio-potentials becomes impossible, even if the diver uses a typical humid neoprene suit. We used not expensive Kendall Arbo H34SG [Tyco Healthcare] electrodes, completely filled with electrode gel and a simple method of insulation by silicon rubber-based two-component material [Elite H-D+, Zhermack Hydrphilic Vinyl Polysiloxane] covered by a second protective layer [Johnson & Johnson, Bioclusive 2463 plaster. This insulation mean assures no off-gassing during the curing period; this propriety is important, as formation of gas bubbles would lead to artifacts in the ECG recording because of bubble compression during immersion, as we noted when using electrodes with a sponge, because the variability of the hydrostatic pressure, during the dives.

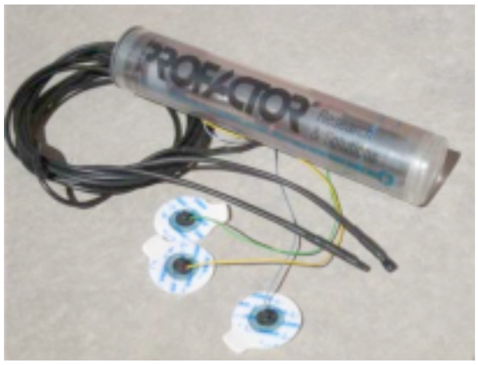


Figure 1. ECG recorder prototype housed in a lexan tube. Two temperature sensors are placed in the diving suit for continuous monitoring of the skin temperature.

Underwater Pulsoxymetry

Another important parameter to be monitored during underwater activity is the blood O2 saturation (SPO2). It is of crucial importance in breath-hold diving, because its fall during the last meter during emersion is related to the possible loss of consciousness. Nowadays, information on SO2 during apnea diving is still scanty just because of the lack of instrumentation suitable for its monitoring [2]. Clinical instrument to detect SPO2 can not be used underwater because the systems, usually based on transmissive light absorbance measurements with red and near infrared light across the ear lobe or the finger tip, fails the measurement due to the temperature of the water, requiring the method a well perfused tissue to be crossed by light.

For these reasons we used a reflectance pulsoxymetry [3], where the light transmitter and receiver are placed in the probe a short distance apart. Light reflected from the underlying tissue is received and measured; its intensity depends on the O2 saturation of tissue blood. By this approach other parts of the body, no or less affected by reflex vasoconstriction and easily shielded from cold water by the diving suit, as the glabellar or the temporal zones of the head may be selected, with good results in SPO2 detection.

A first prototype was developed (figure 2a,b,c), based on an Atmega32 8 bit RISC microcontroller, equipped with a 3x16 characters display for showing data like filename, heart rate, SO2, depth and temperature and a SD card slot for data storage. A pulsoxymeter Module [Nonin, OEMIII] together with a reflectance probe (8000R, Nonin, USA) was chosen for the assessment of the O2 saturation. A MS5541 digital pressure sensor [Intersema, Switzerland] with 16 bit resolution (1,2 mbar) was chosen for depth measurement. Moreover it offers also an integrated digital temperature sensor. This pressure sensor can be used to pressures up to 30 bar, even if in the specifications as maximum pressure 14 bar is stated.

a b c

Figure 2. a: Prototype; b: breath hold diver at 10,5 mfw; c: LCD display

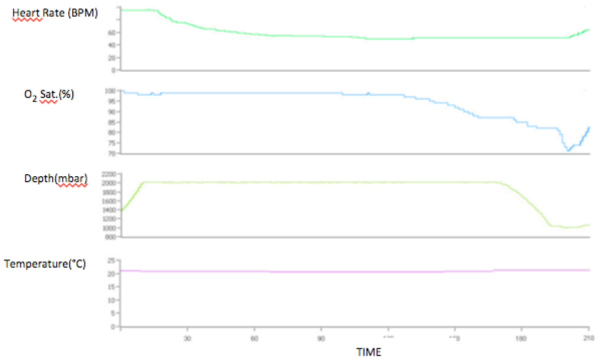


Figure 3. Data from a 3 min breath hold dive to a maximum depth of 10 mfw *Fonts*

Non-invasive underwater blood pressure measurement

The only information on blood pressure changes during diving reported in literature up to 2009 derives from invasive measurements performed during two 45-50m simulated breath hold dives in the hyperbaric chamber [4] and from a study where a digital blood pressure measurement device was used inside an air bell and measurements were performed in a swimming pool [5].

While standard clinical equipment can be used for testing arterial blood pressure in the hyperbaric chamber, any “real” underwater test requires special instrumentation both if invasive and non invasive methods are concerned. Invasive underwater blood pressure measurements were pioneered by Data already in the 1980s [6]. Sensorized catheters have the highest accuracy and assure a good signal quality; however, invasiveness and ethical reasons prevent the use of such an approach for investigations on a statistical significant number of subjects.

Nowadays, no instrument on the market enables underwater non-invasive measurement of arterial blood pressure. We developed a system for non invasive intermittent blood pressure measurement [7], based on the oscillometric methodology, because standard method based on Korotkoff-sounds is not usable underwater.

In the oscillometric systems, algorithms are used to calculate systolic, diastolic and mean arterial pressure, simply analyzing and processing the signal (purposely digitalized) related to the pressure oscillations (see figure 4b) in an inflated cuff [5]. To be used underwater the digital sphygmomanometer electronics has been designed for underwater usage, water resistant and withstanding water pressure. Moreover the normally used air pump for filling the cuff with air from the environment has been substituted by a proper pneumatic circuit derived by a high pressure air bottle. The pressure sensor has been located inside the housing posed at the same water depth of the cuff, to avoid the errors induced also by small water height differences (for example a depth difference of 25cm will result in an 18,75 mmHg offset).The device consists of three core components (figure 4a).

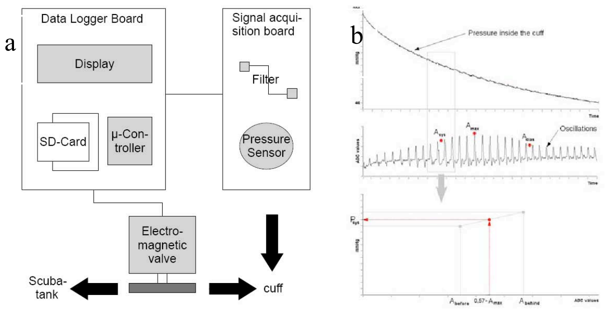


Figure 4. a: outline of the underwater blood pressure meter; b: raw data and calculation of systolic and diastolic pressures

The data logger board incorporates an Atmega32L [Atmel]. Moreover the board is equipped with an SD card for data storage and a 4x20 characters display [EA-DP204, Electronic Assembly] for visualization of the measured blood pressure values.

The analog board includes a 500 mbar differential pressure sensor [Motorola, MPX5050DP].

The third major component of the device is a solenoid valve [Sirai, Italy] that is used for inflation of the cuff with air from a SCUBA tank. a

b

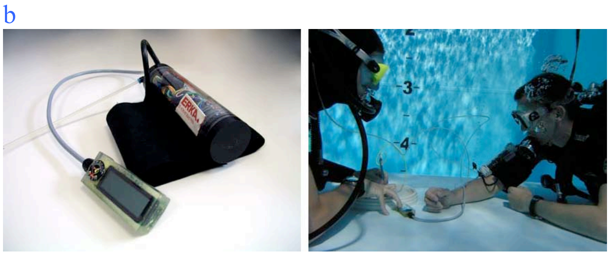


Figure 5. a: first prototype of the blood pressure meter b: tests at 4 m depth Underwater

Underwater Echocardiography

Research on cardiovascular adaptations to breath-hold and SCUBA diving would largely benefit from modern cardiac imaging.

Modern echography provides real-time detailed imaging of anatomical, and in some instances, functional characteristic of several organs including the heart and vessels. Theoretically, for underwater applications, it would be possible to prolong the cable and seal the probe against the hydrostatic pressure. However modification of the tuned multi coaxial wire of the "phased shift array" US probe would be unpractical and expensive. Moreover, as the echograph has to remain in a dry environment on the surface, the examining physician would face the lack of visual feedback (which is mandatory for clinical echography). A different approach is based on the idea of sealing the whole echograph for its immersion [8].

The authors decided for an echograph housing operating at environmental pressure (namely the pressure corresponding to the operating depth) to avoid the large amount of the necessary mechanical interfaces that would imply a very complicated design from the mechanical arrangement point of view requested by a design for normobaric operation.

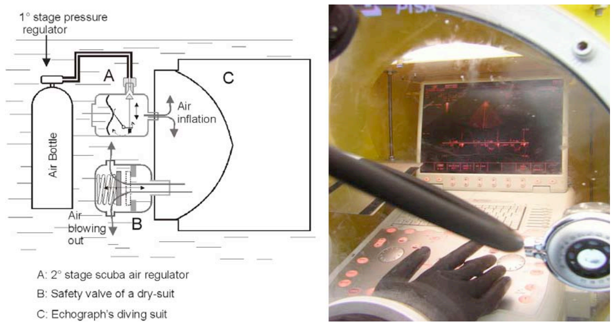
Keeping the pressure inside the housing at ambient pressure has many advantages. First of all by integrating a glove into the housing, the user can handle the echograph keyboard and the trackball like on the surface. Moreover, the housing does not need to withstand high pressures, as the differential pressure will always be close to zero (+- 30 mbar). A special pneumatic circuitry automatically regulates the pressure inside the housing to ambient level. As far as the instrumentation is concerned, a Mylab 30 [Esaote, Genova, Italy] Doppler-Echograph was chosen, as it is equipped with a with a 17" colour TFT screen, is able to record an adequate number of cardiac cycles for post analysis outside the water and has suitable memory storage capacity allowing the collection of an adequate number of cases. Tests with devices equipped with a small display demonstrated that a 14 inches screen represents the minimum worthwhile screen dimension.

The selected sealed battery is specified for normal operation up to pressures of 4 bar absolute pressure limiting the system maximum operational depth to 30m. The battery allows continuous operation up to 3h, thus no off-board power supply and cable connection to the surface are required.

The housing is basically constituted by a 60 cm steel tube T- flange. The top and the front port are covered with two 20mm thick plexiglas covers/windows. These windows are radially sealed with an O-ring with 6mm diameter. Waterproof connectors are installed for eventual interfacing the Echograph. A special plug was designed to pass through the probe cable – sealing is assured with an o-ring washer and an internal epoxy filling.

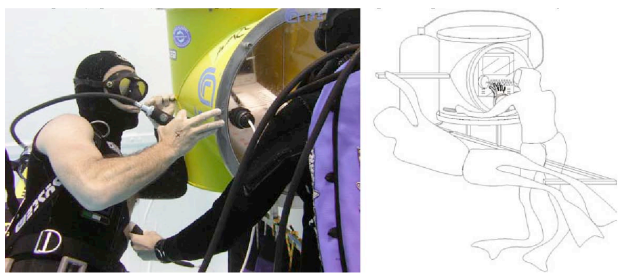
The pneumatic system for assuring continuous and automatic internal vs external pressure balance at any water depth is based on the following components [13]:

- a first pressure reduction stage with an intermediate pressure of 9,5 bar over ambient is attached to a standard 15 l SCUBA steel tank (200 bar).
- a modified standard second stage air regulator (Scubapro R) is attached at medium height in the front window (figure 6a, A). During descend, the ambient pressure increases, thus the regulator will inject air into the housing (figure 6a, C) for pressure equalization.
- recovering and surfacing the system will lead to gas expansion. A standard drysuit exhaust valve (Sitech, Sweden) (figure 6a, B) is used to ventilate the waste air into the water. Its position is 15 cm lower than the inflating air regulator (fig 6a, A). In the forced vertical positioning of the system, which is held by a rope on an external davit and properly ballasted at the bottom, a positive pressure gradient greater than 15 mbar is assured between the inside and the outside of the system preventing any possible water infiltration.



a b

Fig. 6. a: pneumatics of the Echograph housing; b: echograph operated at 5m depth



a b

Figure 7. a: diver gets examined at 5m depth; b: positions of the diver and of the cardiologist during examinations

Results & Discussion

In the present paper we described some technological advancements reached by our group in the last few years in the field of medical underwater instrumentation aimed to the assessment and monitoring of the essential vital parameters during diving.

Very important results were obtained also by the first underwater investigation using the developed devices.

We performed the first report on dynamic imaging of the heart during breath-hold diving in human beings. Underwater echography, confirms and extends previous reports indicating that breath-hold diving at depth induces a reduction of cardiac output secondary to a concordant decrease in ventricular stroke volume and heart rate. It also indicates that these changes are already appreciable during shallow diving and do not significantly increase when diving depth is doubled. More importantly, our study documents for the first time that underwater re-expansion of the chest is able to reverse cardiac function to normal. This finding is consistent with the hypothesis of a constrictive effect on the heart exerted by chest squeeze, although the contribution of other factors remains to be evaluated [9]

Moreover our study reports that shallow-depth SCUBA diving induces LV enlargement and left ventricular diastolic functional changes [10]. Interestingly enough, the first effect is opposite to the one previously observed during breath hold diving while the second is common to both conditions. These findings, in addition to their physiological meaning, have relevance in clinical perspectives. Several Authors, mainly on the basis of the effect of diving on blood redistribution, have raised concerns about the safety of immersion in patients with previous myocardial infarction and mild congestive heart failure (Meyer 2006). In conclusion, we underline that direct underwater evaluation by Doppler-echocardiography could be an appropriate tool for identifying subjects with subclinical or even overt cardiovascular diseases who may be at risk for underwater-related accidents.

Arterial blood pressure has been previously reported to reach dramatic high values during simulated apnea diving [4]. On the contrary we demonstrated coming from the first experiments on breath hold divers at 10, 15 and 20 msw, only slightly increased values by direct underwater measurement [11].

Monitoring the SO2 underwater might also be suitable for enhancing training efficiency and safety of apnea diving.

For example in breath-hold diving we reported and measured the pO2 dramatic drop at the end of diving blood, resulting in potentially sudden blackout (also called shallow water blackout. This is one major reason for fatalities in deep breath-hold diving.

Conclusions

Scientific knowledge on adaptation of the human body to underwater environment is substantially hampered by the lack of technological facilities suitable for surveillance of the basic vital physiological parameters. Most of the knowledge on human diving physiology has been extrapolated either from data obtained in dry apnea in subjects with or without face immersion, in head-out immersed subjects , or during simulated dives in the pressure chamber. Thus, the development of dedicated underwater instrumentation represents a research priority in diving medicine and physiology. Developed monitoring equipment for physiological variables might become part of the standard diving equipment, be available at diver training facilities, and contribute to the culture of safely-diving at the level of individual divers and organizations involved.

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