An underwater blood pressure measuring device

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Key words
Blood pressure, equipment, immersion, diving, cardiovascular, physiology

Abstract

(Seiber A, Kuch B, L'Abbate A, Wagner M, Dario P, Bedini R. An underwater blood pressure measuring device. *Diving and Hyperbaric Medicine*. 2008; 38: 128-34.)
Measurement of arterial blood pressure is an important vital sign for monitoring the circulation. However, up to now no instrument has been available that enables the measurement of blood pressure underwater. The present paper details a novel, oscillometric, automatic digital blood pressure (BP) measurement device especially designed for this purpose. It consists mainly of analogue and digital electronics in a lexan housing that is rated to a depth of up to 200 metres' sea water, a cuff and a solenoid for inflation of the cuff with air supplied from a scuba tank. An integrated differential pressure sensor, exposed to the same ambient pressure as the cuff, allows accurate BP measurement. Calculation of systolic and diastolic pressures is based on the analysis of pressure oscillations recorded during the deflation. In hyperbaric chamber tests to pressures up to 405 kPa, BP measurements taken with the prototype were comparable to those obtained with established manual and automated methods. Swimming pool tests confirmed the correct functioning of the system underwater. The quality of the recorded pressure oscillations was very good even at 10 metres' fresh water, and allowed determination of diastolic and systolic pressures values. Based on these results we envisage that this device will lead to a better understanding of human cardiovascular physiology in underwater and hyperbaric environments.

Introduction

Arterial blood pressure (BP) is a vital sign as well as a routine diagnostic marker. It reflects the ability of the heart to supply the vascular network with blood. The coupling of the contractile activity of the left heart with the mechanical characteristics of the arterial vascular tree (compliance and resistance) generates the pressure existing inside the arterial vascular network. In large arterial branches, pressure oscillates at each contraction (systolic and diastolic pressures). BP is strictly controlled by several neuro-humoral factors that modulate cardiac stroke volume, heart rate, arterial and arteriolar vascular resistance and circulating blood volume. BP is confined within a relatively narrow normal range (100–140 mmHg systolic; 70–90 mmHg diastolic). Low values may impair tissue perfusion, while high pressures may damage vascular integrity and increase left ventricular afterload.

BP MEASUREMENT TECHNIQUES

There are various non-invasive methods of measuring BP, for example manual techniques using a cuff, an aneroid or a mercury manometer, and a stethoscope to listen for the Korotkoff sounds or automatic techniques using digital sphygmomanometers mainly based on the oscillometric method. Unfortunately BP estimation based on the Korotkoff sounds is not possible underwater.

The principle of digital sphygmomanometers is based on the measurement of pressure oscillations (see Figure 3b later) in an inflated cuff, which are caused by pulsations of the compressed brachial artery. Algorithms are used to calculate systolic, diastolic and mean arterial pressure. Schematically a digital sphygmomanometer consists of an inflatable cuff which is connected to a pneumatic system for controlled inflation and deflation, an integrated pressure sensor, a manual or an electrical pump and a microcontroller unit. To detect the oscillations, the signal of the pressure sensor is usually passed through a bandpass filter (2–20 Hz) and then amplified. A central processing unit (CPU) uses the cuff pressure (derived from the pressure sensor) and the oscillation signal to calculate the systolic and diastolic BP.[1] In this sense, digital sphygmomanometers do not allow a direct measurement of BP.

A standard digital sphygmomanometer is not suitable for underwater usage because:

- the systems are not water or pressure resistant
- a pump is used to fill the cuff with air from the environment (in principle, this can be solved by using the instrument in an air-filled bell, which is not a robust and reliable solution and is not suitable for field tests)
- the pressure sensor is located inside the housing instead of close to and at the same water depth as the cuff.

Previous attempts by the authors to use a standard BP meter in a separate housing underwater proved unsuccessful.

Currently the only information on BP changes during diving derives from invasive measurements performed during a few simulated dives in the hyperbaric chamber and from a study performed inside an air-bell in a swimming pool.[2,3] The experiments performed in the hyperbaric chamber involved breath-holding at 45–50 metres' sea water (msw) depth while immersed in cold water. Two subjects showed an early, rapid and dramatic increase in BP with values as high as 280–300 mmHg systolic and 150–200 mmHg diastolic. When encountered in the clinical setting, such values are considered of particular concern and potentially life-threatening. The study in the swimming pool was based on a commercially available, electronic sphygmomanometer mounted inside an air-filled bell, 1.7 msw below the surface. Neither technique is suitable for field tests; the latter device is bulky and damageable (to ensure that the pressure inside the bell is equal to the ambient pressure, the bell needs to be open; thus the electronic instrument is close to the water). Moreover, small differences between the cuff and the bell working depths may induce difficulty in inflating and deflating the cuff (every 10 cmH_2O corresponds to approximately 7.5 mmHg).

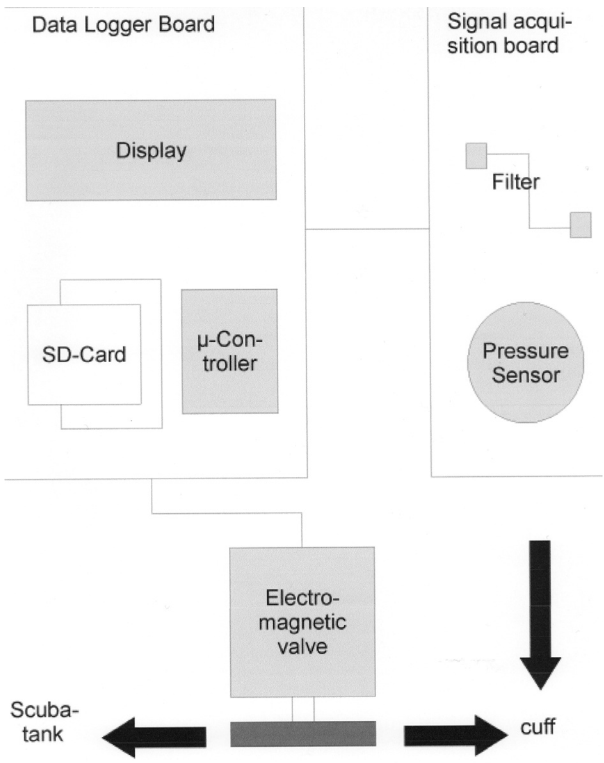
Non-invasive assessment of arterial pressure in divers would be of great interest in human diving physiology and the development of effective safety guidelines. The present study describes the development of a digital sphygmomanometer, sealed in a pressure-resistant housing rated to 200 msw, for BP measurements underwater in scuba and breath-hold divers.

Methods

PRINCIPLE DESIGN OF THE BP MODULE

The prototype consists of a BP signal acquisition board, a data logger board, an adjustable exhaust valve, an electromagnetic inflator valve (solenoid) and a cuff (Figure 1). The cuff can be inflated automatically with air supplied from a first stage regulator mounted on a standard scuba tank with an intermediate pressure of 950 kPa over ambient.

Figure 1
Principle design of the module



DATA LOGGER MODULE

The core component of the data logger board is an Atmel™ ATmega32L 8 Bit RISC microprocessor with the following specifications:

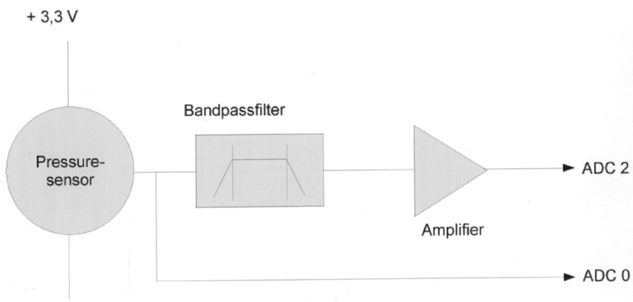
- 32 Kbyte Flash Program Memory
- 2 Kbyte SRAM
- 1 Kbyte EEPROM
- programmable 8-channel 10-bit ADC
- 8 MIPS @ 8 MHz

A secure digital memory card (SD card) connector is connected to the serial peripheral interface (SPI) of the microprocessor. Low-drop, linear regulators are used to provide 3.3 V. For visualization of the data a 4 x 20 characters electronic assembly display is integrated on the board and interfaced via SPI software to dedicate the microprocessor's inbuilt SPI solely to the SD card. For analogue signal acquisition purposes, eight 10-bit programmable analogue-to-digital converter channels are integrated in the ATmega32L. To inflate the cuff a 6 V Sirai solenoid with a 1.1 mm orifice is used. It is controlled via Pin PC4 and an N-FET NDS355. Maximum differential operational pressure of the valve is 1.52 MPa.

BP SIGNAL ACQUISITION BOARD

The main component of the BP signal acquisition board is a calibrated Motorola™ MPX5050DP silicon pressure sensor. It offers a differential pressure range of 50 kPa together with a nominal output from 0.2 to 4.7 V at 5 V supply. A 1 ms response time is fast enough to record oscillometric pressure signals. Furthermore, inbuilt temperature compensation allows operation from -40°C to +125°C. The MPX5050DP is used to measure the differential pressure between inside the cuff and outside/ambient. According to its specifications, the sensor requires a 5 V supply. However, previous tests showed accurate results with a 3.3 V power supply, allowing the pressure sensor to be powered through one of the output pins

Figure 2
Main components of the signal acquisition board



(Port C, Pin 7). To reduce the overall power consumption during standby mode, the pressure sensor and the display are switched off by setting port pin PC7 to low.

Figure 2 shows all the main components of the BP signal acquisition board. The output of the pressure sensor is directly connected to an analogue input pin of the microprocessor (ADC 0). The relatively small oscillations cannot be derived directly from the analogue output signal from the pressure sensor mainly because of the low resolution of the inbuilt analogue to digital converter (10 bit). Thus additional hardware is necessary. A bandpass filter cuts off frequencies below 2 Hz (static signals and slow pressure changes because of deflation of the cuff) and above 20 Hz (noise). A low-noise, rail-to-rail operational amplifier is set to a gain of 500. The output signal is connected directly to another channel of the microcontroller (ADC 2).

SOFTWARE

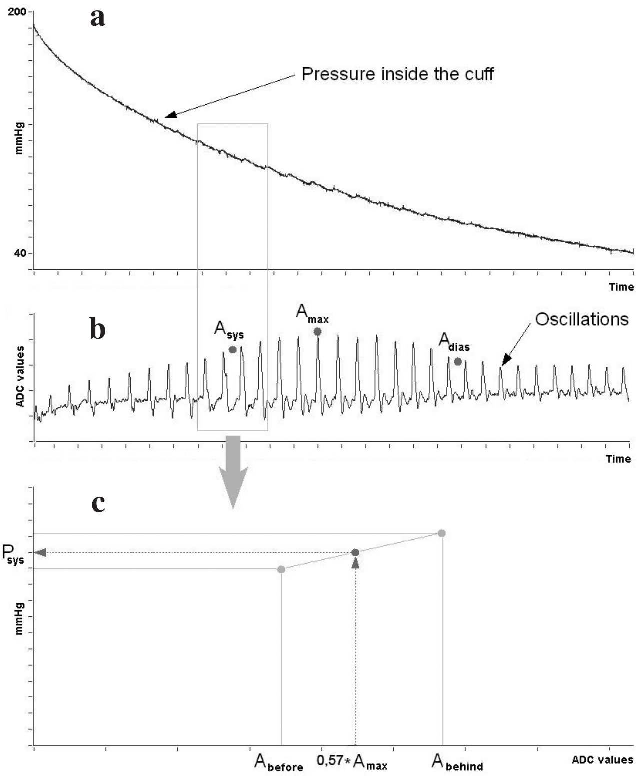
The firmware of the module is developed in C (GNU C compiler WinAVR) under the Atmel™ AVR Studio 4.13 [Atmel]. AVR Studio is a powerful, integrated development environment (IDE) for development and debugging of applications for Atmel microcontroller in Windows® 9x/NT/2000/XP/Vista environments. The firmware comprises two major parts. One part stores all recorded analogue values on SD card in file allocation table (FAT) 16 or FAT 32 file system. Data storage is performed in blocks of 512 bytes each. The implementation of a DOS-compatible FAT 32 file system on the SD card requires in total 1.6 kbyte of RAM to mirror the boot sector, the FAT and to provide a buffer for data storage.

Accurate BP measurement in relation to its harmonic content requires a sampling rate of around 100 Hz. As the input channels are multiplexed, a synchronous read out of the channels is not possible. Thus the two analogue signals on ADC0 and ADC2 are sampled in 5 ms intervals one after the other (2 x 5 ms = 10 ms, 100 Hz sampling frequency, Figure 3).

To achieve precise timing and to avoid resource conflicts between the complex data storage and the analogue sampling, the AD conversions are interrupt-controlled. The internal Timer0 of the ATmega32 is triggered every 5 ms and creates an interrupt. The last converted ADC value of one channel is then read out and stored in a FIFO buffer. Then the conversion of the other channel is initiated. As soon as there are 10 entries in the FIFO buffer, the data is converted into an ASCII string and stored in a text file on the SD card (Figure 4). Column 1 in the text file represents ADC channel ADC0 and column 2 the oscillation signals from ADC2.

The second major part of the firmware controls the solenoid and calculates and visualizes the systolic and diastolic BP from the raw values. After inflation of the cuff to 200 mmHg

Figure 3
Algorithm to detect systolic and diastolic arterial BP. Figure a) shows the raw differential pressure, b) the oscillations inside the cuff and c) shows the algorithm and how it combines the two measured values



(user definable), it is deflated at about 2–3 mmHg per second. During deflation, an algorithm detects all positive peaks of the oscillations inside the cuff. These peaks are stored in a two-dimensional array together with the pressure inside the cuff. Additionally every peak is shown on the display, in combination with the actual pressure inside the cuff in mmHg.

After the cuff is deflated to 38 mmHg, the calculation of the pressure values is performed. First, the maximum oscillation peak A_{max} is picked out of the array. A_{max} multiplied by the empirically estimated value of 0.57 leads to A_{sys}, a value which usually lies between two peaks A_{before} and A_{behind} (Figure 3b). P_{sys} is then calculated by linear interpolation (Figure 3c) of the corresponding pressure values (Figure 3a). The estimation of the diastolic pressure value is performed in the same way, but using 0.74 as multiplication factor.[4 5] After calculating the systolic and diastolic arterial BP and storing the measured data on the SD card, the device turns into standby mode. A reed contact together with a magnet is used to activate the system and start a new measurement (via an internal interrupt). In underwater applications magnetic switches are preferred as they require no mechanical connection to a switch thus avoiding o-rings. A flow diagram of the whole software is shown in Figure 4.

Figure 4
Software flow diagram

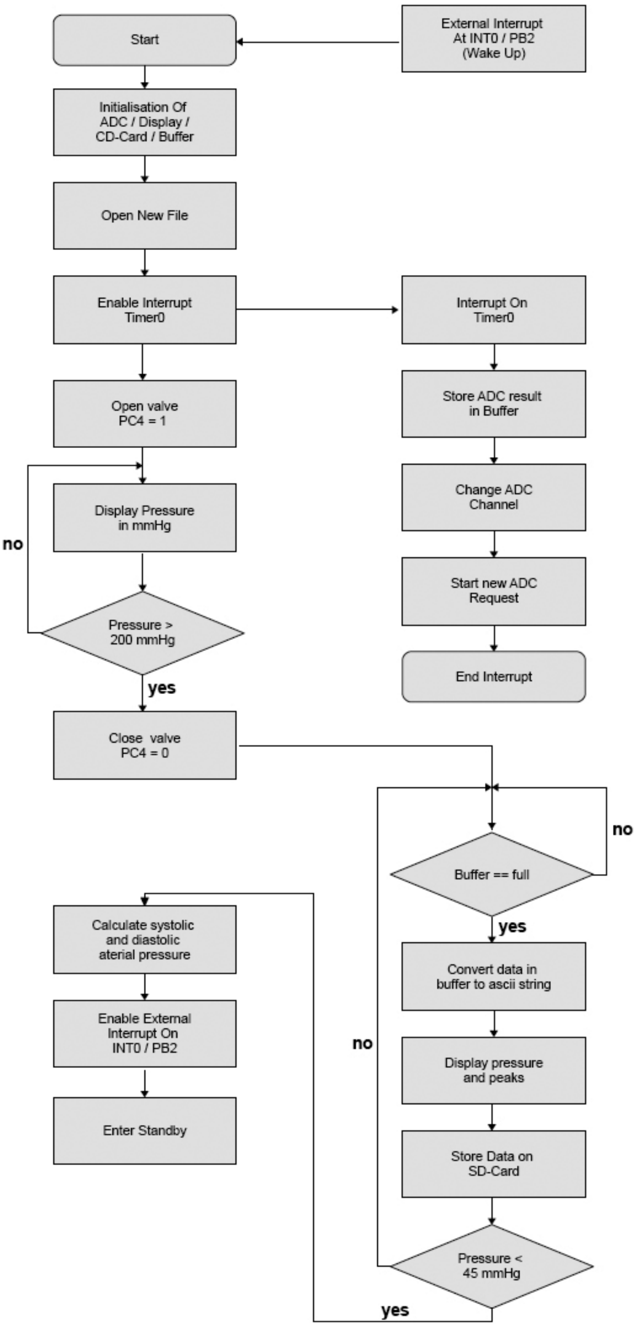


Figure 5
Software display of the logged data

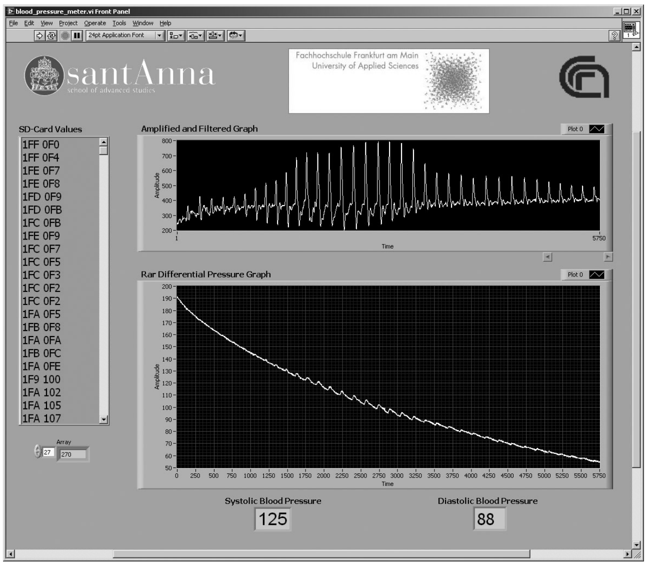
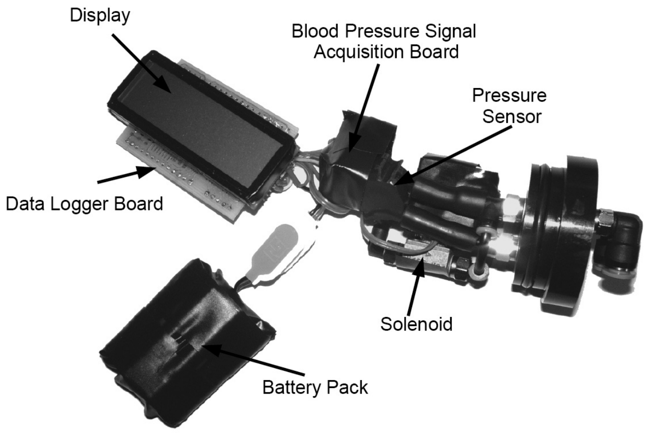


Figure 6
Prototype BP monitor dismantled to display its component parts



DATA PROCESSING

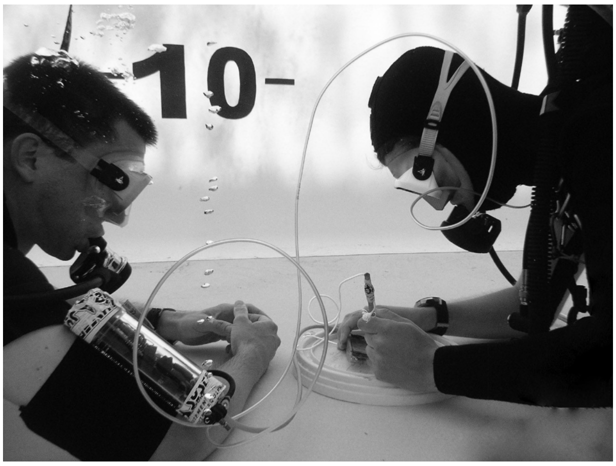
For visualization and analysis of the recorded data, software was developed under National Instruments™ Lab View® Version 8.5. Lab View is a platform and development environment for a visual programming language. It is commonly used for data acquisition and instrument control in industrial applications on a variety of platforms.

Figure 5 shows a screen shot of the software. On the left-hand side, one can see the raw data in hexadecimal format, which are read from the SD card. The upper graph of the right-hand side shows the oscillations inside the cuff. The lower graph represents the differential pressure inside the cuff.

FIRST PROTOTYPE

The first prototype is shown in Figure 6, disassembled into its component parts and, in Figure 7, mounted in position on a diver. The input of the solenoid is connected to the first stage of the scuba regulator. The regulator is mounted on a 1.5 L scuba tank with a filling pressure of 200 bar. The regulator reduces the tank pressure to an intermediate pressure of approximately 950 kPa above ambient pressure. Previous experiments had shown that the orifice of the solenoid was too large. The inflating air produced an excessive pressure wave, closing the electromagnetic valve before reaching the predefined value of 200 mmHg. To avoid this problem, a needle valve is placed between the regulator and the

Figure 7
The prototype being tested in a swimming pool at 10.5 mfw depth



electromagnetic valve to reduce the airflow. The cuff is deflated via a second needle valve. The housing is located directly on the cuff, thus the differential pressure sensor is always at the correct level.

Specifications of the first prototype:

- Module size: 120 mm length, 40 mm diameter
- Battery supply: 6–8 V
- Sampling rate: 100 Hz
- Pressure sensor: 0 to 50 kPa
- System clock: 8 MHz
- Data storage on SD card
- File format: FAT16 / FAT32
- Measurement data volume: 800 bytes per second
- Housing: lexan, 200 msw rated

TESTS

To validate the prototype, several tests were performed in parallel with either one of two other BP measurement methods: manually with a stethoscope, listening for Korotkoff sounds, or with a digital BP measurement device (Pabisch TOP-MATIC™). The Pabisch TOP-MATIC is a C.S.IMQ N.J1332-certified digital sphygmomanometer which measures mean arterial pressure and then utilises an algorithm to calculate systolic and diastolic values.

All recordings were performed under the following conditions:

- Main condition: same diver, each arm one cuff
- Timing: both measurements were done at the same time
- Cuff: fitting tightly and equally
- Deflation velocity: steady at 2–3 mmHg per second
- Body position: seated/upright or lying/horizontal
- Arm position: perpendicular, cuff at height of the heart
- Interval: 1 min

Firstly tests were performed in a swimming pool, the subjects fully immersed on the surface except for the head, and then at 3 mfw. Secondly, tests were performed in a dry hyperbaric environment. Several measurements were taken at the surface and at pressures equal to 30 msw, 20 msw, 10 msw and 5 msw, on surfacing and repeated after 15 min post-dive. Finally further in-water tests were conducted in a public swimming pool, and in a 10.5 mfw-deep research pool (Divesystem, Massa Marittima, Italy) at the surface (head-out), 3 mfw and 10.5 mfw.

STATISTICAL TESTS

The statistical software package R, an Open Source GNU Project which is similar to the S language and environment developed at Bell Laboratories (formerly AT&T, now Lucent Technologies), was chosen. R is a language and environment for statistical computing and graphic display. To compare BP data from the prototype and other BP measurement techniques in various environments, in both dry and wet conditions, a Mann-Whitney U test with a significance level of 0.05 was used.[6]

Results

In all pool tests, oscillations in the cuff were reliably detected and pressure values were able to be calculated. Figure 8 details the measurements comparing the prototype with the clinical instruments. BP values measured with this device were not significantly different from those using the manual or TOP-MATIC methods. The predicted value (Mann-Whitney U test) resulted in 0.86 for systolic and 0.80 for diastolic BP.

Figures 9 and 10 show the results of the tests in the hyperbaric chamber. Table 1 displays the measurements obtained in the public swimming pool. Table 2 shows the results of the tests in the 10.5 mfw research pool.

Discussion

The prototype BP-measuring device we have developed has passed several tests in a normobaric environment, in a hyperbaric chamber at pressures up to 405 kPa and underwater to a depth of 10.5 mfw. In a normobaric air environment, the BP measurements were very similar to those obtained using established manual and automated sphygmomanometry techniques. In the chamber, the device produced more reliable and more constant values (lower variance) than did the Pabisch TOP-MATIC, which faced serious cuff deflation problems under pressure, as it deflates the cuff much more slowly at increased pressure, in marked contrast to the prototype whose deflation rate can be adjusted to the ambient pressure.

The prototype and the Korotkoff sounds techniques produced similar values of BP, though those obtained with the stethoscope were slightly lower than those from the

Figure 8
Comparison of prototype and Pabisch TOP-MATIC BP measurements on the surface

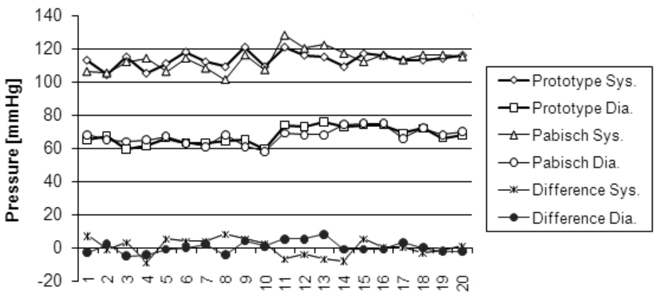


Figure 9
Hyperbaric chamber: prototype vs Pabisch

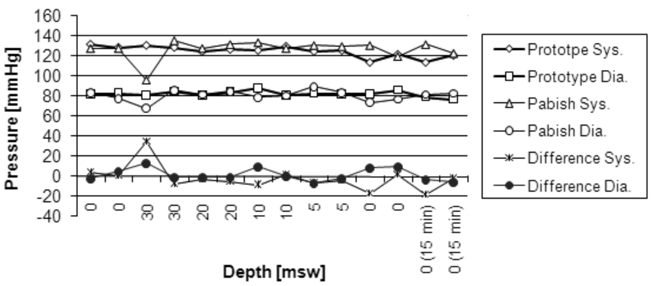


Figure 10
Hyperbaric chamber: prototype vs stethoscope

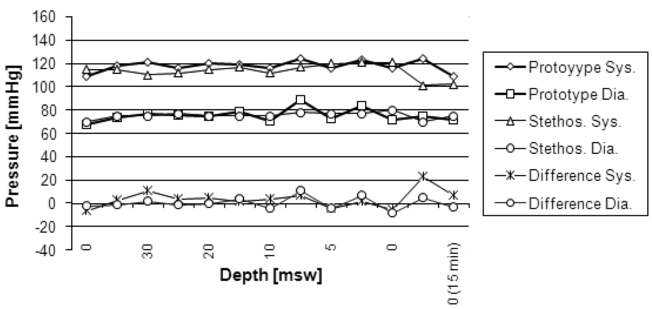


Table 1
BP measurements (mmHg) during swimming pool tests; measurements were taken at each depth in lying and sitting positions (mean values and ranges shown)

Depth	Systolic	Diastolic
0 msw	126	83
(N = 3)	(120–130)	(81–85)
0 msw underwater	131	75
(N = 5)	(127–136)	(68–85)
3 msw sitting	142	86
(N = 5)	(136–149)	(81–91)
3 msw lying	137	87
(N = 5)	(134–140)	(82–91)

prototype. This is likely caused by the environmental noise in the hyperbaric chamber, which makes it difficult to detect the Korotkoff sounds accurately.

The pool tests demonstrated clearly that the prototype device is capable of performing reliably underwater to a depth of 10 mfw. However, at 10.5 mfw depth the measurements on Diver 1 and Diver 2 were less constant. This was most likely due to the fact that after one hour of testing in the pool at 20°C, Divers 1 and 2 were already quite cold and shivering. In such conditions, oscillometric measurements may be distorted. At this point, Diver 3 still felt warm and measurement results were more constant. This effect of cold immersion may be a limiting factor in the application of this technique for BP measurement.

Conclusion

Research on the cardiopulmonary effects of diving in humans has been limited by the lack of a device capable of non-invasive BP measurement underwater. In this study, we describe the principles and development of an automated underwater sphygmomanometer and its validation under dry and immersed hyperbaric conditions. Measurements with the prototype were comparable to those obtained using established clinical techniques. We conclude that the new device is capable of accurate non-invasive measurement of BP underwater and will be a useful tool in studying the human cardiovascular response to hyperbaric environments.

Table 2
Field test in the 10.5 mfw research pool in lying position (blood pressure mean values and ranges shown; mmHg)

	Diver 1		Diver 2		Diver 3	
	Systolic	Diastolic	Systolic	Diastolic	Systolic	Diastolic
Surface	133	87	130	87	121	82
(N = 4)	(127–139)	(80–92)	(129–131)	(81–92)	(119–122)	(77–85)
3 msw	121	81	128	83	118	78
(N = 4)	(120–123)	(71–89)	(125–131)	(79–88)	(112–123)	(76–79)
10 msw	134	92	121	87	127	87
(N = 5)	(130–137)	(81–101)	(112–137)	(70–107)	(125–130)	(82–93)

Future work

Several pool and field studies are planned with elite breath-hold and scuba divers at various dive sites, including at the 2008 freediving world championships. Professional scuba divers from military and/or civil rescue organizations will be involved in the scuba tests.

Acknowledgements

We would like to thank the Italian Apnea Academy and Dive System for their support and the ERASMUS initiative of the European Union for enabling the collaboration between the Scuola Superiore Sant'Anna and the University of Applied Science, Frankfurt.

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Submitted: 11 April 2008
Accepted: 16 August 2008

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