Underwater study of arterial blood pressure in breath-hold divers

Arne Sieber,1,2 Antonio L’Abbate,1,3 Mirko Passera,1,3 Erika Garbella,3 Antonio Benassi,1,3 and Remo Bedini1,3

1Institute of Clinical Physiology, National Research Council, Pisa, Italy; 2Profactor Research and Solutions, Seibersdorf, Austria; and 3Scuola Superiore Sant’Anna, Extreme Centre and Master of Underwater and Hyperbaric Medicine, Pisa, Italy

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Sieber A, L’Abbate A, Passera M, Garbella E, Benassi A, Bedini R. Underwater study of arterial blood pressure in breath-hold divers. J Appl Physiol 107: 1526–1531, 2009. First published August 20, 2009; doi:10.1152/japplphysiol.91438.2008.—Knowledge regarding arterial blood pressure (ABP) values during breath-hold diving is scanty. It derives from a few reports of measurements performed at the water’s surface, showing slight or no increase in ABP, and from a single study of two simulated deep breath-hold dives in a hyperbaric chamber. Simulated dives showed an increase in ABP to values considered life threatening by standard clinical criteria. For the first time, using a novel noninvasive subaquatic sphygmomanometer, we successfully measured ABP in 10 healthy elite breath-hold divers at a depth of 10 m of freshwater (mfw). ABP was measured in dry conditions, at the surface (head-out immersion), and twice at a depth of 10 mfw. Underwater measurements of ABP were obtained in all subjects. Each measurement lasted 50–60 s and was accomplished without any complications or diver discomfort. In the 10 subjects as a whole, mean ABP values were 124/93 mmHg at the surface and 123/94 mmHg at a depth of 10 mfw. No significant statistical differences were found when blood pressure measurements at the water surface were compared with breath-hold diving conditions at a depth of 10 mfw. No systolic blood pressure values >140 mmHg or diastolic blood pressure values >115 mmHg were recorded. In conclusion, direct measurements of ABP during apnea diving showed no or only mild increases in ABP. However, our results cannot be extended over environmental conditions different from those of the present study.

underwater sphygmomanometer; apnea; diving

CURRENT KNOWLEDGE of underwater arterial blood pressure (ABP) derives from a few reports on surrogate measurements performed at the water surface, in air with face immersion, or during simulated dives. In addition to different experimental conditions, different equipment has been used to explore ABP. For noninvasive measurements, a standard arm sphygmomanometer (21), a Korotkoff sound-based automatic sphygmonanometer placed in a watertight bell at the same height as the cuff (1), a pho- toplethysmometer with a finger cuff (2, 3, 10, 18), and an aneroid manometer on the upper arm (6, 10) have been used. Invasive methods were based on the cannulation of the radial (7, 8, 10) or brachial artery (13). Some studies were performed before and during apnea in air either at rest (5, 18, 21) or during steady-state exercise on a cycle-ergometer (1–3, 22), most of them also during apnea with the subject’s face immersed in thermoneutral or cold water (1–3, 10, 21, 22). They all showed moderate increases in blood pressure during apnea with an augmented response to face immersion. Studies in wet conditions measured ABP either during head-in and/or head-out breath-hold full body immersion (6, 9, 16) or during breath-hold midchest immersion (5). They showed a small increment in ABP during apnea compared with predive breathing conditions and a greater rise in ABP during face-in compared with face-out apnea. No or only a moderate increment in ABP has been observed during breath holding just below the surface (6, 19).

A single scientific reference concerning ABP in deep breath-hold dives is available. In 1997, Ferrigino et al. (8) described the blood pressure response to breath-hold diving in two elite free divers during simulated diving to 50 m of freshwater (mfw) in a wet compartment of a hyperbaric chamber. ABP was invasively measured with a fluid-filled catheter and continuously recorded together with ECG and depth during the simulated dives. The highest blood pressure values, 280–300 mmHg for systolic blood pressure and 150–200 mmHg for diastolic blood pressure, were recorded during descent at 10–20 mfw. Until now, this finding has been the only available reference on the ABP response to breath-hold diving. A number of clinical circumstances are characterized by crises of severe hypertension, such as malignant hypertension, pheochromocytoma, postoperative hypertension, cocaine use, and others. These conditions are all considered at high risk of serious acute events, such as pulmonary edema, myocardial infarction, retinal hemorrhage, severe epistaxis, or stroke, and require rapid treatment (12). If severe hypertension accompanies breath-hold apnea, a high frequency of serious side effects would be expected. Actually, pulmonary and cerebral side effects can be observed in apnea divers; however, these are fortunately infrequent. Thus, a simple epidemiological consideration seems to be in contrast with the common view of a harmful increase of blood pressure during apnea diving. In addition, the cause-effect relationship of reported health disturbances in divers with hypertension is only speculative.

Recent developments in underwater research have included a novel underwater sphygmomanometer (20) that allows, for the first time, the easy and noninvasive assessment of ABP without the need for bulky and fragile housings. The aim of the present study was to obtain underwater ABP measurements in a group of breath-hold divers to test the hypothesis of a normal or near to normal response of blood pressure to breath-hold diving by a series of statistically significant underwater measurements.

MATERIALS AND METHODS

Characteristics of the subaqueous sphygmomanometer. A noninvasive oscillometric blood pressure meter for underwater use has been developed and validated as previously described (20). In brief, in this instrument, the upper arm cuff is automatically inflated via an electromagnetic valve with air supplied from a scuba tank. A microcontroller board, the differential pressure sensor, and a display are incorporated in a waterproof housing situated directly on the cuff and
designed to withstand pressures up to 10 bar. The calculation of systolic and diastolic blood pressures was based on the oscillometric method. Measurement data were stored on a SD card. The system has been previously validated both in the normobaric air environment and in the hyperbaric chamber (from 0 to 30 mfw). In both conditions, blood pressure was measured in the same subject simultaneously, at the two arms, the novel system and either a manual sphygmomanometer or a clinical automatic unit (Pabisch TOP-MATIC). Testing values were not significantly different from those obtained with either the manual or TOP-MATIC method (Mann-Whitney U-test for the null hypothesis). In addition, the prototype was tested in scuba divers at 1.5, 3, 5, and 10 mfw to optimize the duration and quality of pressure reading. The time required for one ABP measurement was reduced to 50–60 s.

Study population. In the present study, we enrolled 10 well-trained breath-hold divers. All divers were male with a mean age of 34 yr (range: 25–47 yr) and were instructors of the Apnea Academy, the international school of free diving, founded by the pluri-world champion Umberto Pelizzari. All of them were free of known cardiovascular, pulmonary, or other diseases and were free of cardiovascular risk factors. Each diver had performed at least 300 breath holds and had good sport experience. The study protocol was approved by the Ethical Committee of the Consiglio Nazionale delle Ricerche Institute of Clinical Physiology.

Study protocol. At the beginning of the protocol, ABP was measured at rest in dry conditions, after a minimum resting time of 15 min, while subjects sat in a shady corner close to the swimming pool. Within the next 15 min, ABP was then assessed during body immersion while subjects had normal breathing and with their head out of the water. The athletes then had 20 min of time to “warm up” during several predives. Immediately afterward, ABP measurements were performed at 10 mfw. The measurement at 1 m was repeated after a 20-min break at the surface. Each breath-hold dive used a special neoprene 5-mm suit without the left sleeve. An assistant with a scuba gear performed the measurements on the subjects. During the measurement, the diver sat up, leaning against the pool wall in a comfortable position. The free diver wore a small air volume face mask during the dives, which covered the forehead together with part of the hood.

Free divers followed standard breath-hold diving procedures. They performed two warm-up shallow dives at “constant weight” (i.e., without any ballast) followed by 2–3 min of deep breathing in the absence of hyperventilation or glossoptaryngeal insufflation and then by the “variable weight” testing dive. The variable weight dive consisted of descending with the use of the ballast along the guiding rope, stopping at the depth for ABP measurement, and then ascending by normal fin swimming. The use of ballast allowed the diver to reach the depth with minimum effort.

Experiments on the first eight subjects were performed in a 10.5-mfw research pool with a water temperature of 26°C (Divesystem, Massa Marittima, Italy). Additional experiments on two subjects (7, 12) took place in seawater at Asinara Island, Italy (25°C water temperature, no waves). The mean descent speed variable weight was 1 m/s. Blood pressure measurements were performed within <1 min immediately after the descent. The typical diving time was <90 s.

Although 10 m of depth is relatively shallow compared with the simulated dives studied by Ferrigno et al. (8), this measure was considered appropriate for this study since during simulated dives, the highest ABP values were just recorded between 10 and 20 mfw.

Statistical analysis. Values are expressed as means ± SD. Comparison between mean values was performed by a paired-samples two-sided t-test. Statistical significance was defined as P values of <0.05.

RESULTS

After subjects had entered the water, ABP measurements were performed at the surface with the head out (baseline condition) and then twice at 10 m of depth (10-m condition). The double measurement of ABP at 10 m of depth was performed on all subjects without any complications or side effects. Two measurements at 10 mfw were excluded due to technical reasons (incorrect readings of the pressure sensor). Table 1 shows single values obtained in dry conditions, at the surface with the subject’s body immersed and head out, and at 10 m of depth as well as the computed mean values for each subject together with the reference pressure obtained in dry and head-out conditions. As expected, a trend toward a small increase in ABP was observed during head-out immersion

Table 1. Recorded ABP values

<table>
<thead>
<tr>
<th>Subject</th>
<th>SBP (Dry Condition)</th>
<th>DBP (Dry Condition)</th>
<th>Dive Type</th>
<th>SBP</th>
<th>DBP</th>
<th>Measure 1 (Basal Head-Out Condition)</th>
<th>Measure 2 (Depth of 10 m)</th>
<th>Measure 3 (Depth of 10 m)</th>
<th>Mean (Depth of 10 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>226</td>
<td>70</td>
<td>FW</td>
<td>113</td>
<td>89</td>
<td>126</td>
<td>123</td>
<td>109</td>
<td>116</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
<td>70</td>
<td>FW</td>
<td>124</td>
<td>87</td>
<td>147</td>
<td>140</td>
<td>130</td>
<td>138</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>70</td>
<td>FW</td>
<td>119</td>
<td>90</td>
<td>115</td>
<td>114</td>
<td>113</td>
<td>114</td>
</tr>
<tr>
<td>4</td>
<td>117</td>
<td>75</td>
<td>FW</td>
<td>123</td>
<td>95</td>
<td>123</td>
<td>120</td>
<td>120</td>
<td>121</td>
</tr>
<tr>
<td>5</td>
<td>115</td>
<td>80</td>
<td>FW</td>
<td>126</td>
<td>94</td>
<td>132</td>
<td>130</td>
<td>130</td>
<td>131</td>
</tr>
<tr>
<td>6</td>
<td>120</td>
<td>80</td>
<td>FW</td>
<td>124</td>
<td>84</td>
<td>Error</td>
<td>116</td>
<td>116</td>
<td>116</td>
</tr>
<tr>
<td>7</td>
<td>125</td>
<td>75</td>
<td>FW</td>
<td>124</td>
<td>94</td>
<td>Error</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>8</td>
<td>120</td>
<td>85</td>
<td>FW</td>
<td>123</td>
<td>104</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>9</td>
<td>110</td>
<td>70</td>
<td>SW</td>
<td>130</td>
<td>80</td>
<td>138</td>
<td>136</td>
<td>136</td>
<td>136</td>
</tr>
<tr>
<td>10</td>
<td>120</td>
<td>85</td>
<td>SW</td>
<td>140</td>
<td>115</td>
<td>130</td>
<td>130</td>
<td>130</td>
<td>130</td>
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<tr>
<td>Mean</td>
<td>119</td>
<td>76</td>
<td></td>
<td>124</td>
<td>93</td>
<td>127</td>
<td>127</td>
<td>127</td>
<td>127</td>
</tr>
<tr>
<td>SD</td>
<td>4.6</td>
<td>6.1</td>
<td></td>
<td>8.1</td>
<td>10.1</td>
<td>8.8</td>
<td>9.9</td>
<td>10.7</td>
<td>9.7</td>
</tr>
</tbody>
</table>

P value 0.9505568 0.7272428

Values are recorded arterial blood pressure (ABP) values (in mmHg) at rest before subjects entered the water (dry condition), at rest at the surface with the subject’s head out (basal head-out condition), and during breath holding at a depth of 10 m. SBP, systolic blood pressure; DBP, diastolic blood pressure; FW, freshwater; SW, saltwater. Student’s t-test was used to compare SBP and DBP in the two conditions: at a depth of 10 m of SW and in the head-out condition.
compared with the dry condition (difference was not significant).

Considering the 10 subjects as a whole, mean ABP values of 124 ± 8.1/93 ± 10.1 mmHg at the surface (head out) and 123 ± 9.3/94 ± 9.1 at 10 m of depth were found. No statistical significant differences in systolic and diastolic blood pressure values (P = 0.95 and P = 0.73, respectively) were found between the surface and 10 m of depth. No significant differences were found when ABP values at 10 m and out of the water were compared.

On an individual basis, diastolic blood pressure values of >100 mmHg were recorded in two subjects at surface and in four subjects at 10 m of depth (2 subjects had high diastolic blood pressure values in both conditions). Systolic blood pressure did reach 140 mmHg in only one subject at the surface. A greater variability was present at 10 m of depth relative to the surface for both systolic and diastolic blood pressures. In post hoc analysis, the outlier represented by both systolic and diastolic blood pressures of subject 10 was probably related to the physical effort of preparing the equipment for variable weight dives just before the test.

As a corollary of the study, we also succeeded in testing the ABP response to breath-hold diving at 20 msw in two divers. Although anecdotal, this further test did not show any increment in ABP at 20 msw compared with normal values recorded at the surface (data not shown).

**DISCUSSION**

For the first time, our study succeeded in measuring the ABP of breath-hold divers underwater at a depth of 10 mfw. This achievement was made possible by the development of a novel subaquatic sphygmomanometer (20).

The main result of the study is reassurance regarding the “normal” response of ABP to exposure of the human body to the underwater hyperbaric environment during breath holding.

Our study was performed in 10 well-trained free divers at the surface as well as at a depth of 10 m. In no instance did we find systolic blood pressure values >140 mmHg and diastolic blood pressure values >115 mmHg. In addition, when ABP values during breathing on the surface were compared with ABP values in breath-hold diving to a depth of 10 mfw or msw, we did not find any statistically significant differences.

The above experimental results contradict the alarming results of the study by Ferrigno et al., which showed large increases in both systolic and diastolic blood pressure (reported values up to 300 and >200 mmHg, respectively) in two healthy elite free divers during breath-hold simulated diving in a hyperbaric chamber (8). To explain this discrepancy, one must take into account the differences in the experimental setup, in the methodologies used for ABP assessment, and, finally, in the individual diving response to psychophysical

**Table 2. ABP trend values shown in original record 5B of Fig. 1**

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Condition</th>
<th>ABP Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>5–35</td>
<td>Descent at -1 m/s</td>
<td>Increased blood pressure values</td>
</tr>
<tr>
<td>35–39</td>
<td>Constant at -30 mfw</td>
<td>Normal blood pressure values</td>
</tr>
<tr>
<td>39–49</td>
<td>Descent at -1 m/s</td>
<td>Increased blood pressure values</td>
</tr>
<tr>
<td>49–53</td>
<td>Constant at -40 mfw</td>
<td>Normal blood pressure values</td>
</tr>
<tr>
<td>53–63</td>
<td>Descent at -1 m/s</td>
<td>Increased blood pressure values</td>
</tr>
<tr>
<td>68–80</td>
<td>Constant at -50 mfw</td>
<td>Normal blood pressure values</td>
</tr>
<tr>
<td>80–140</td>
<td>Ascent</td>
<td>Decreased blood pressure values</td>
</tr>
</tbody>
</table>

[Data were obtained from Ref. 8.]
stressors. Although the variance in the ABP response to substantially different environmental conditions (free underwater diving vs. restrained semiprone immersion in the wet compartment of the hyperbaric chamber) as well as differences in depth profile, prestudy physical activity, lung volume, involuntary breathing movements (4, 17), and other factors cannot be excluded, the high ABP values could also be the consequence of a technical artifact. The careful examination of the ABP traces in Ref. 8 supports this hypothesis.

Figure 1 shows the recordings of ECG, ABP, and depth from one of the two divers studied by Ferrigno et al. (8). The visual analysis of ABP during descent testifies to the following remarks, as shown in Table 2.

It is noticeable that the increased blood pressure values occurred only during descent, whereas they suddenly decreased to normal values during the periods of constant ambient pressure (marked by the vertical dashed lines in Fig. 1). Finally, during ascent, the reverse effect occurred with ABP becoming lower than at 50 mfw.

To explain these observations, it should be considered that a pressure-strain gauge for invasive blood pressure measurement normally incorporates a differential pressure sensor, like the one schematically detailed in Fig. 2.

The pressure difference between the measurement side and the reference chamber causes a membrane deflection that is transformed into an electrical signal. The measurement side is in continuation with the fluid-filled catheter. When the ambient pressure changes, as occurs during descent in the simulated dive, air passes through the equalization opening to keep the

![Fig. 2. Schematization of the differential pressure sensor used in many medical devices (such as the CDXIII sensor from Argon Medical).](image)

**Fig. 2.** Schematization of the differential pressure sensor used in many medical devices (such as the CDXIII sensor from Argon Medical).

![Fig. 3. Production of pressure artifact recording by delayed equalization of the strain gauge reference chamber with ambient pressure in the hyperbaric chamber.](image)

**Bottom:** actual ambient pressure in the hyperbaric chamber during the simulation of a dive to a depth of 25 m. **Top:** pressure reading of the tested sensor pressure. Note the similarity of the upper pressure profile with the one shown in Fig. 1.
reference chamber at ambient pressure. The time required for complete equalization depends on the size of the equalization opening and the volume of the reference chamber. During the equalization process, the pressure sensor reads values higher than real, as the pressure inside the reference chamber is lower than that in the measurement side. Thus, the use of a differential pressure sensor in an environment where pressure changes rapidly requires knowledge of the device’s response to different steady pressure values as well as its response to dynamic pressure changes.

To confirm the hypothesis that the alarming values recorded in simulated diving were the result of a technical artifact, a CDX III sensor [like the one used by Ferrigno et al. in 1997 (8)] was ordered from Argon Medical and characterized in a 50-liter pressure chamber. The 2008 model of the CDX III sensor showed no significant discrepancies with actual values during the rapid increase in ambient pressure. After consultation with Argon Medical, it turned out that the design of the current CDX III model is different from the 1997 model. As matter of fact, in the old model, the reference chamber was equalized through a tiny hole along the cable of the device. This sort of assemblage is compatible with a significant delay in pressure equalization during rapid ambient pressure changes, particularly in a humid environment, where water droplets can impede the entrance of air into the reference chamber. Unfortunately, this possibility could not be challenged, since a 1997 model of the CDX III sensor could not be found at Argon Medical in either the United States or Europe. Thus, a different approach was used, i.e., the reproduction of the mechanical condition existing in the old model of the CDXIII sensor, using a MPX5500DP differential pressure sensor (Motorola), whose reference side was connected with a 1-m long cable of 2.5-mm diameter. The device was placed in the hyperbaric chamber together with an absolute pressure sensor (MPX5700, 7 bar absolute, Motorola). The sensor signals were read out with a commercial analog-to-digital converter card (NI USB-6800, National Instruments) and processed with LabView 8.5 software (National Instruments). Figure 3 shows a screenshot of the graphical user interface. The progressive linear increase in ambient pressure (Fig. 3, depth) resulted in a bell-shaped increase in the differential pressure sensor readings (Fig. 3, top). To more closely reproduce the depth profile of Fig. 1, two short periods of constant ambient pressure were performed: the first at 10 m and the second at 20 m. During these periods, the differential pressure reversed to “prediving” values. The similarities of the pressure profile with the one of Fig. 3 are obvious.

On the basis of the above results, we feel confident that a technical artifact in the invasive measurement of ABP in the hyperbaric chamber is a possible reason for the discrepancies between our results and those previously reported by Ferrigno et al. (8) in 1997. To reinvestigate the divergence, invasive ABP measurements during a simulated dive should be repeated with sensors dynamically characterized in the hyperbaric environment.

In a previous study (14), using a novel underwater ECG, we were able to document that both stroke volume and heart rate decreased at a depth of 10 m during apnea. In the present study, we obtained the complementary information that no or only a mild increase in blood pressure occurred in similar environmental conditions. Thus, arbitrarily pooling the results of the two separate studies suggests that systemic vascular resistance (SVR) increased in these conditions. However, to draw any firm conclusions regarding the quantitative response of SVR to breath-hold diving, simultaneous ECG and blood pressure measurements would be required.

Study limitations. One limit of our study might be the relatively small size of the reference sample. However, with a SD of 10 mmHg (see Table 1), we can exclude a blood pressure difference of 10 mmHg with 99.9% confidence; this is due to the paired-sample design of the study.

These results are limited to our experimental conditions and cannot be extrapolated to different environmental conditions or to subjects who are not well-trained elite divers or who may have comorbidities such as hypertension.

A final limitation includes the lack of verification of our device against invasive arterial pressure measurements.

Conclusions. In conclusion, we can state that in our sample of elite free divers only mild changes in ABP were detectable during breath-hold diving. Of course, these results are limited to our experimental conditions.

However, further studies are needed to confirm the results of the present study in a larger number of divers, although the practical difficulty of enrolling on a voluntary basis a large number of well-trained breath-hold divers able to rest for few minutes at a depth of 10 m should be considered. Further studies are also required to answer additional relevant questions such as the ABP response to repeated diving [paradigmatic is the case of free diver spearfishers and Japanese and Korean ama women divers (11)] to prolonged scuba diving as well as the response of ABP in recreational or professional divers with cardiovascular risk factors, borderline hypertension, or even treated hypertension. Answers to the above questions could considerably modify the medical guidelines for apnea diving safety. Finally, the possibility of measuring blood pressure now offered by the subaqueous sphygmomanometer, especially when associated with the subaqueous ECG (14, 15), may greatly contribute to a better understanding of diving physiology.

REFERENCES


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