

# Original articles

## Cardiac function and oxygen saturation during maximal breath-holding in air and during whole-body surface immersion

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### Abstract

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**Introduction:** The magnitude of the oxygen-sparing effect induced by the diving response in humans is still under debate. We wished to compare cardiovascular changes during maximal breath-holding (BH) in air and during whole-body immersion at the surface in a group of BH divers.

**Methods:** Twenty-one divers performed a maximal static apnea in air or during whole-body immersion. Doppler echocardiography, arterial blood pressure and haemoglobin saturation ( $S_aO_2$ ) were obtained at the beginning of, and at 1/3, 2/3 and maximal BH time.

**Results:** BH time was on the average  $3.6 \pm 0.4$  min, with no differences between the two conditions.  $S_aO_2$  significantly decreased during BH in both conditions, but was significantly higher during immersion as compared to the dry ( $P = 0.04$ ). In both conditions, BH induced a significant linear increase in right ventricular diameter ( $P < 0.001$ ), left ventricular (LV) volumes ( $P < 0.001$ ) and LV stroke volume ( $P < 0.001$ ) but a significant linear decrease in LV ejection fraction ( $P = 0.033$ ). In both conditions, Doppler diastolic parameters showed changes suggesting a constrictive/restrictive left ventricular filling pattern (i.e., an increase of early diastolic left ventricular filling velocity,  $P = 0.005$ , and a decrease in the deceleration time of early diastolic left ventricular filling.  $P < 0.001$ ).

**Conclusion:** BH induces progressive LV enlargement both in air and whole-body immersion, associated with reduced LV ejection fraction and progressive hindrance to diastolic filling. For a similar apnea duration,  $S_aO_2$  decreased less during immersed BH, indicating an  $O_2$ -sparing effect of diving, suggesting that interruption of apnea was not triggered by a threshold critical value of blood  $O_2$  desaturation.

### Key words

Breath-hold diving, physiology, diving reflex, cardiovascular, echocardiography, Doppler, hypoxia

### Introduction

Prolonged interruption of respiration enables mammals to dive. Maximal duration of voluntary breath-holding (BH) is conditioned by the amount of oxygen carried from the surface, by its rate of consumption during diving and by hypoxaemic tolerance, and varies enormously, from hours in some marine mammals to seconds in typical terrestrial animals.<sup>1</sup> Cardiac effects of prolonged BH in humans, evaluated in a magnetic resonance (MRI) study, showed that prolonged BH in air produced no changes in heart rate and peripheral vascular resistance, but rather a progressive depression in cardiac contractility paralleled by left ventricular dilatation with maintained stroke volume and cardiac output.<sup>2</sup>

The diving response is a well-known phenomenon that has an oxygen-sparing effect and may prolong BH duration, as demonstrated in instrumented aquatic mammals and in diving birds.<sup>3,4</sup> The diving response has also been documented in humans during whole-body immersion at surface with face immersion and during in-air experiments.<sup>5,6</sup>

Elicitation of the diving reflex by face immersion during in-air apneic dynamic exercise reduced lung oxygen depletion and increased anaerobic metabolism, thus suggesting an oxygen-sparing effect.<sup>7,8</sup> Body immersion entails environmental changes that significantly affect the cardiovascular system. During head-out immersion, a blood shift from the peripheries to the thorax has been observed, leading to an increase in central blood volume.<sup>9</sup> As a consequence of the increased ventricular preload, an increase in both stroke volume and cardiac output has been reported in head-out immersed humans.<sup>10</sup>

The overall haemodynamic changes induced by whole-body immersion and diving response elicitation are an increase in central blood volume and a reduction and redistribution (in favour of heart and brain) of cardiac output. Therefore, immersion, because of haemodynamic changes and diving response activation, might modulate the cardiovascular response to maximal BH and, due to the oxygen-sparing effect of the diving response, could also favorably influence the time-course of hypoxic depression of cardiac function. The aim of this study was to evaluate the influence of whole-

body immersion on haemodynamics and arterial oxygen saturation ( $S_aO_2$ ) in humans during maximal BH in air and during total-body immersion.

## Materials and methods

### SUBJECTS

A group of 21 subjects (18 male, 3 female; age  $35 \pm 4$  years, range 26–51 years) was studied. All subjects were high-level recreational free divers with at least three years of apnea diving experience, performing at least 3 h per week of BH diving training; no subject was engaged in regular physical activity besides underwater training. All subjects were able to reach a depth of at least 30 metres' sea water (msw) under constant weight (i.e., with no ballast aid for descent). No subject had a history or clinical evidence of hypertension or other cardiac or pulmonary disease. All subjects were non-smokers and had been fasting for at least 2 h before the study. The local University Hospital Ethics Committee approved the study protocol (approval number 2085). All participants received information about the aims and procedures of the study and gave their written consent.

### BREATH-HOLD MANOEUVRE

The study was performed during a free diving meeting at Sharm El Sheikh, Egypt, in a swimming pool (air temperature 27°C; water temperature 29°C) in a single session. Each subject, lying in left lateral decubitus, performed a maximal duration ('peak') apnea the day before the study (mean apnea time  $3.7 \pm 0.5$  min, range 3.0–5.1 min). For each athlete, we designed a personalised schedule for Doppler-echocardiographic acquisition, dividing the pre-determined BH duration into thirds (1 min or more each) and acquiring physiological signals at four epochs:

I – early BH;

II – end of the first third;

III – end of the second third;

IV – 'peak' (near end) of apnea.

In this way, the four epochs were equally spaced within the apnea period in all the athletes. At peak epoch, recording was continued up to the end of apnea.

On the day of the study, each athlete performed two apneas, once in air and once during whole-body immersion. Both tests were performed with subjects lying in left lateral decubitus during maximal inspiration. Before both tests, athletes had a period of 2–4 minutes of relaxation and preparation. During the immersion test, subjects entered the water and spent this preparation period in the upright position beside a metal stretcher held by two assistants. When they were ready to start the test, they lay on the stretcher, made a maximal inspiration and immersed their face. The comfortable water temperature and the period of preparation before immersed apnea minimized the possible

acute influence of immersion on the data acquired at the first epoch. The two tests were done 2 h apart; between tests, subjects were allowed drinking water or soft drinks but no food or exercise or breath-hold training. The order of the two tests was assigned randomly.

### DOPPLER-ECHOCARDIOGRAPHY

Doppler-echocardiography was performed using a commercially available instrument (MyLab 30, Esaote SPA, Florence, Italy). This technique has proved to be reliable for dynamic and non-invasive assessment of cardiac anatomy and systolic and diastolic function of the left ventricle during diving.<sup>11,12</sup> During immersed apnea, the instrument was placed beside the pool while the operator stood in the water on the left side of the subject being studied.

An apical four-chamber view loop (4 s duration) and a pulsed-wave Doppler tracing of trans-mitral blood flow were recorded. Analysis was made offline, according to the American Society of Echocardiography recommendations, by an expert in Doppler-echocardiography, unaware of the identity of the subject or the experimental conditions.<sup>13</sup> From the four-chamber view, the following parameters were obtained: end-systolic and end-diastolic left ventricular volumes (ESV and EDV respectively) by the area-length method, and right ventricular internal dimension (RV, i.e., maximal diastolic distance from the right side of the interventricular septum to the right ventricular free wall).<sup>14</sup> From the same view, maximum transverse (from inter-atrial septum to the opposite atrial wall, LALL) and supero-inferior (from the mitral valve plane to the opposite wall, LASI) dimensions were calculated for the left atrium during ventricular systole. Early (E) and late (A) peak trans-mitral diastolic flow velocities, as well as deceleration time of E velocity (DTE), were obtained from pulsed-wave Doppler tracings, by sampling blood velocities at the level of the mitral valve tips; E-to-A ratio (E/A) was then calculated.

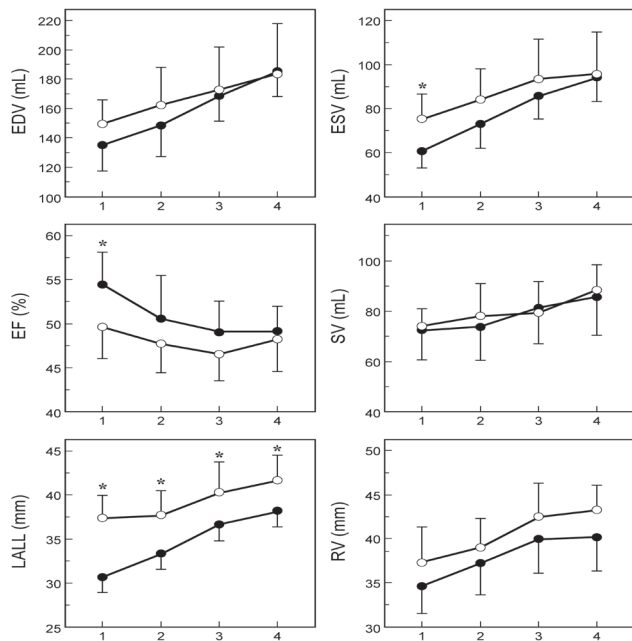
Duration of cardiac cycle (R–R interval) was measured as the time interval between two consecutive mitral A-peaks; heart rate (HR) was then calculated ( $60/R-R$  interval expressed in seconds). The mean value of three consecutive cardiac cycles was considered. Left ventricular stroke volume (SV) was calculated as the difference between diastolic and systolic left ventricular volumes. Cardiac output (CO) was obtained as the product of SV and HR. Finally, left ventricular ejection fraction (EF) was calculated as  $100 \times (SV/EDV)$ .

### ARTERIAL BLOOD PRESSURE AND $S_aO_2$

In a subgroup of six subjects, systolic and diastolic blood pressure (SBP and DBP) were measured at the same time as echocardiography acquisition by a submersible sphygmomanometer; mean arterial pressure (MAP) was calculated as  $DBP + (SBP - DBP)/3$ .<sup>15</sup> Total peripheral resistance (TPR) and the rate-pressure product (RPP) were

**Figure 1**

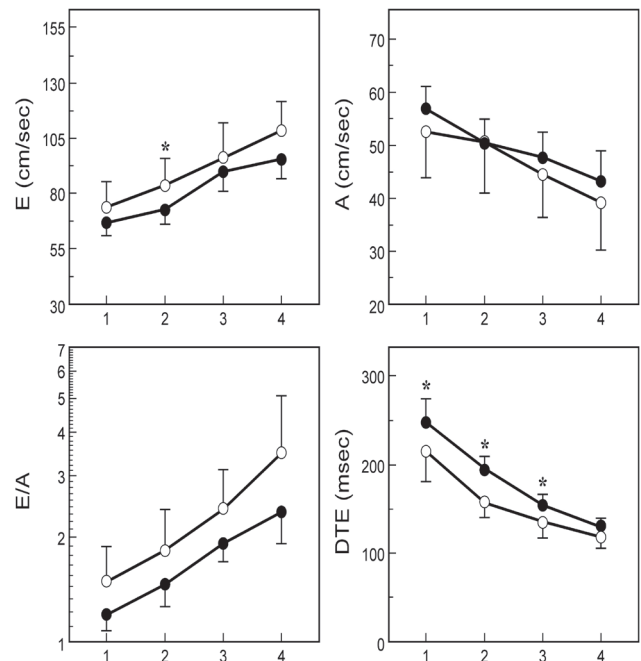
Changes in end-diastolic volume (EDV, upper-left panel), end-systolic volume (ESV, upper-right), ejection fraction (EF, middle-left), stroke volume (SV, middle-right), maximal transverse dimension (LA LL, lower-left) and right ventricle dimension (RV, lower-right) during the four epochs of maximal breath-hold in air (solid dots) and during surface immersion (open dots). See text for detailed explanations. \*  $P < 0.05$  (wet vs. dry at each epoch)



**Figure 2**

Changes in early (E, upper-left panel) and late (A, upper-right) peak trans-mitral diastolic flow velocities, E-to-A ratio (E/A, lower-left) and deceleration time of E velocity (DTE, lower-right) during the four epochs of maximal breath-hold in air (solid dots) and during surface immersion (open dots). See text for detailed explanations.

\*  $P < 0.05$  (wet vs. dry at each epoch)



also calculated as  $MAP/CO$  and  $SBP*HR$  respectively. In the same subgroup, percentage of saturated haemoglobin ( $S_aO_2$ ) was measured simultaneously with echocardiography by means of an oximeter OEM III (NONIN Medical, Inc., Plymouth, MN, USA) placed over the right temporal artery.

**STATISTICAL ANALYSIS**

Student's paired t-tests were used to evaluate changes in selected parameters at the different times during apnea and to assess differences between apnea conditions (i.e., in air or immersed).

A mixed model analysis was conducted to explore:

- impact of apnea duration ('effect of time');
- impact of apnea condition (dry or immersed; 'effect of condition');
- impact of interaction between time and apnea condition after taking into account the repeated measures (i.e., intra-subject variability).

Logarithmic transformations were applied for skewed variables having a non-Gaussian distribution according to the Kolmogorov-Smirnov test; post-hoc comparisons were performed using the Bonferroni correction in case of a significant result.  $P$ -values  $< 0.05$  were considered statistically significant. Data are presented as mean  $\pm$  standard deviation (SD).

**Results**

**APNEA DURATION**

Apnea lasted  $3.6 \pm 0.4$  min (range 2.9–5.3 min). No difference was detected between the two BH conditions.

**CARDIAC CHANGES DURING BH (EFFECT OF TIME AND COMPARISON BETWEEN CONDITIONS)**

Parameter values (mean and SD) obtained at each epoch during dry and wet BHs are reported in Table 1. No significant interaction effect between apnea duration and apnea condition (immersed or dry) was found for any of the analyzed parameters, meaning that changes relative to each parameter were concordant (i.e., showed the same pattern in the two conditions).

*Doppler-echocardiographic parameters*

Both EDV and ESV linearly increased from epoch I to IV in both conditions ( $P < 0.001$ ). Immersed apnea, as compared to dry, showed higher ESV at epoch I ( $P = 0.015$ ; Figure 1). EF showed a linear as well as a quadratic negative correlation with time ( $P = 0.033$  and  $0.039$  respectively) in both conditions (Figure 1) in epoch I, being lower in immersed as compared to dry apnea ( $P = 0.003$ ). SV linearly increased from epoch I to IV in both conditions ( $P < 0.001$ ;

**Table 1**

Parameters (mean (SD) shown) at each epoch during dry and total-body immersion during a maximal breath-hold (see text for detailed explanations); *n* – number of subjects; \* – *P* < 0.05 (immersed vs. dry at each epoch); † – *P* < 0.05 (effect of time during apnea)

Parameter	<i>n</i>	Condition	Epoch I	Epoch II	Epoch III	Epoch IV
<b>Left ventricular end-diastolic volume (ml)</b>	21	Immersed †	145.5 (31.9)	162.5 (46.3)	168.5 (48.3)	183.9 (62.0)
		Dry †	135.8 (40.1)	150.0 (45.8)	169.5 (45.2)	185.2 (32.9)
<b>Left ventricular end-systolic volume (ml)</b>	21	Immersed †	74.5 (19.6) *	84.3 (22.5)	90.5 (29.7)	95.5 (34.7)
		Dry †	60.3 (16.5) *	73.2 (23.1)	85.0 (25.8)	94.6 (22.0)
<b>Ejection fraction (%)</b>	21	Immersed †	48.7 (5.9) *	47.5 (6.3)	46.7 (5.3)	48.3 (6.7)
		Dry †	55.1 (6.9) *	51.0 (8.7)	49.9 (6.8)	49.2 (4.7)
<b>Stroke volume (ml)</b>	21	Immersed †	70.9 (17.7)	78.2 (27.6)	78.0 (21.5)	88.4 (32.2)
		Dry †	75.5 (27.8)	76.8 (28.4)	84.5 (24.7)	85.6 (25.8)
<b>Heart rate (bpm)</b>	21	Immersed	57.1 (10.0)	54.9 (10.1)	57.0 (10.8)	55.5 (10.6)
		Dry	62.0 (8.2)	58.8 (8.5)	57.5 (13.1)	56.5 (18.1)
<b>Cardiac output (L min<sup>-1</sup>)</b>	21	Immersed	4.04 (1.21)	4.17 (1.38)	4.30 (1.04)	4.42 (1.15)
		Dry	4.61 (1.51)	4.46 (1.56)	4.68 (1.45)	5.14 (2.05)
<b>Left atrial latero-lateral dimension (mm)</b>	21	Immersed †	37.2 (5.1) *	37.2 (5.0) *	40.5 (5.2) *	41.9 (4.9) *
		Dry †	31.0 (4.7) *	33.0 (3.7) *	36.4 (3.5) *	38.2 (3.6) *
<b>Left atrial supero-inferior dimension (mm)</b>	21	Immersed †	40.3 (4.6)	40.8 (4.4)	43.3 (3.8)	45.0 (4.5)
		Dry †	39.2 (4.4)	39.6 (3.5)	41.3 (4.1)	43.4 (4.6)
<b>Right ventricular dimension (mm)</b>	21	Immersed †	36.9 (6.5)	38.7 (5.1)	39.9 (11.4)	43.3 (4.5)
		Dry †	34.6 (5.1)	36.9 (6.0)	39.9 (6.5)	40.1 (6.7)
<b>Early trans-mitral flow velocity (cm sec<sup>-1</sup>) (ET-MV)</b>	21	Immersed †	72.4 (17.2)	83.3 (17.2) *	94.8 (20.5)	108.4 (21.2)
		Dry †	66.4 (11.6)	71.6 (11.7) *	89.6 (12.8)	95.8 (17.6)
<b>Late trans-mitral flow velocity (cm sec<sup>-1</sup>)</b>	21	Immersed †	53.6 (13.1)	50.1 (12.7)	45.7 (11.5)	38.9 (13.9)
		Dry †	56.3 (11.4)	50.8 (9.6)	48.0 (7.2)	43.1 (10.7)
<b>Early/late ratio</b>	21	Immersed †	1.4 (0.5)	1.8 (0.8)	2.3 (1.0)	3.5 (2.5)
		Dry †	1.2 (0.2)	1.5 (0.3)	1.9 (0.4)	2.4 (0.8)
<b>Deceleration time of ET-MV (msec)</b>	21	Immersed †	196.5 (53.6) *	155.1 (31.4) *	126.4 (25.9) *	119.0 (22.0)
		Dry †	240.7 (51.5) *	191.8 (32.4) *	154.9 (22.0) *	130.8 (13.0)
<b>Systolic BP (mmHg)</b>	6	Immersed	138.1 (22.4)	138.3 (14.5)	150.7 (21.1)	158.8 (31.9)
		Dry	120.5 (18.2)	124.7 (18.0)	122.9 (47.6)	143.3 (11.7)
<b>Diastolic BP (mmHg)</b>	6	Immersed	78.6 (16.6)	86.4 (6.8) *	90.1 (9.5)	100.2 (14.1) *
		Dry	68.8 (16.8)	72.8 (9.2) *	83.1 (11.7)	81.7 (11.3) *
<b>Mean BP (mmHg)</b>	6	Immersed †	97.0 (10.6)	108.2 (6.1) *	112.0 (14.2)	111.2 (7.7) *
		Dry †	76.9 (11.1)	83.3 (10.5) *	86.6 (16.0)	104.3 (4.3) *
<b>Total peripheral resistance (mmHg*min L<sup>-1</sup>)</b>	6	Immersed	26.6 (8.5)	31.4 (8.4)	26.1 (4.7)	28.6 (1.2)
		Dry	20.5 (7.0)	24.8 (9.7)	24.9 (12.0)	21.3 (5.3)
<b>Rate-pressure product (bpm*mmHg)</b>	6	Immersed	7,660 (1,882)	7,283 (1,475)	8,683 (1,676)	8,249 (1,669)
		Dry	7,315 (1,122)	7,086 (1,037)	6,783 (2,933)	8,433 (2,235)
<b>Haemoglobin saturation (%)</b>	6	Immersed †	98.2 (2.1)	96.3 (3.3)	91.7 (4.8)	91.5 (5.2)
		Dry †	98.2 (1.6)	96.9 (1.8)	90.0 (4.2)	84.6 (7.4)

Figure 1). No significant difference was present between the two conditions at each epoch.

Left atrial dimensions, as assessed by latero-lateral and supero-inferior diameters in the four-chamber view, increased linearly with time in both conditions ( $P < 0.001$  and  $P = 0.001$  respectively). Latero-lateral diameter was greater in immersed compared with dry apnea at all epochs ( $P = 0.001$ ; Figure 1).

Right ventricular transverse diameter increased linearly with time in both conditions ( $P < 0.001$ ) with no significant difference between conditions (Figure 1). The E-wave peak velocity of the left ventricular filling rate increased with time in both conditions ( $P = 0.005$ ) without any difference between the two conditions except at epoch II (Figure 2). The A-wave peak velocity decreased linearly with time in both conditions ( $P < 0.001$ ) without any difference between the two conditions (Figure 2). The E/A ratio linearly increased with time in both conditions ( $P < 0.001$ ) without any difference between the two conditions (Figure 2). Finally, DTE showed significant linear and quadratic decrease with time in both conditions ( $P < 0.001$  for both) with significantly lower values during immersed apnea at epochs I, II and III as compared to dry apnea ( $P = 0.012$ , Figure 2).

#### *Haemodynamic parameters*

HR and cardiac output did not change with time in either condition and no differences were found between conditions. MAP increased with the duration of apnea during both conditions, while a similar trend in systolic and diastolic arterial pressures did not reach statistical significance. Increase in both diastolic and mean arterial pressure during immersed compared with dry apnea reached statistical significance at epoch II (DBP  $P = 0.003$ ; MAP  $P = 0.011$ ) and at epoch IV (DBP  $P = 0.038$ ; MAP  $P = 0.015$ ). Systemic vascular resistance tended to increase with time ( $P = 0.06$ ). Moreover, TPR showed higher values at peak apnea than at the onset of apnea ( $26.7 \pm 8.7$  vs.  $21.0 \pm 5.7$  mmHg\*min L<sup>-1</sup>;  $P = 0.005$ ) during both conditions but no significant difference between conditions. RPP, an index of external cardiac work, did not change with time.

#### *Oxygen saturation*

In both conditions, S<sub>a</sub>O<sub>2</sub> remained constant at epochs I and II, but progressively decreased at epochs III and IV (Table 1). Significantly higher values of S<sub>a</sub>O<sub>2</sub> were observed during immersed compared with dry apnea ( $P = 0.040$ ); at peak apnea, mean S<sub>a</sub>O<sub>2</sub> was higher in water than in air, although the difference did not reach statistical significance ( $P = 0.13$ ).

## **Discussion**

### **CARDIAC ANATOMY AND SYSTOLIC FUNCTION**

In the current study, prolonged apnea (whether dry or immersed) induced a progressive increase in left ventricular

systolic and diastolic volumes with reduced left ventricular EF but increased stroke volume and no changes in cardiac output. These findings substantially confirm the pattern previously documented with MRI during maximal dry apnea in elite apnea athletes.<sup>2</sup> In that study, progressive increases in left ventricular diastolic and systolic volumes, impairment of LV systolic function as shown by reduced maximal left ventricular elastance and ejection fraction, but maintained stroke volume and cardiac output, likely through the activation of the Frank-Starling mechanism, were seen.<sup>2</sup> The finding of progressive LV enlargement is also in agreement with previous studies on animals with either mechanical airway obstruction or with respiratory paralysis and artificial ventilation, showing that prolonged hypoxia impairs left ventricular systolic function and induces left ventricular dilatation.<sup>16,17</sup>

In contrast, comparison of the present findings with previous ones at depth is made difficult by the fact that available observations at depth are limited to the early period of apnea.<sup>11,12,18</sup> Nevertheless, if comparison is confined to the early phase of apnea, enlargement of LV volume and increase in SV observed during both dry and shallow immersion apnea, contrast with LV volumes and SV reduction at depth. As compared to diving at depth, shallow immersion is characterized by mildly increased environmental pressure (approximately 40 cm of water). Although sufficient to exert compression on the venous system, this hydrostatic pressure is unable to reduce pulmonary gas volume, thus preventing the significant pulmonary blood shift and chest volume reduction occurring at greater depth that could affect central haemodynamics and, therefore, explain the different changes in LV volumes observed during shallow and at-depth immersion.<sup>9,19</sup>

### **LEFT VENTRICULAR DIASTOLIC FUNCTION**

A progressive increase in early diastolic trans-mitral velocities and reduction in deceleration time of E velocity was observed during BH in both conditions. These changes resemble a constrictive/restrictive left ventricular diastolic pattern.<sup>20</sup> A similar diastolic pattern was previously described during breath-hold diving at depth.<sup>11</sup> This pattern could be reversed to normal after chest re-expansion at depth by means of a single maximal inspiration from a scuba device.<sup>18</sup> However, at variance with the present study, the above pattern was not observed during shallow immersion.<sup>12</sup> This discrepancy might be explained by the spot nature of previous observations limited to the early phase of apnea rather than to the entire period of apnea including peak maximal apnea, when the additional effects of hypoxia become apparent. The diastolic dysfunction observed with shallow immersion, in the absence of hydrostatic chest compression, might be explained by the combined effect of the positive transthoracic pressure induced by breath-holding at total lung capacity (with relaxed respiratory muscles) and of the reduced compliance of the dilated left



ventricle. Alternatively, or in combination, the progressive increase in right ventricular volume during maximal BH may also support the hypothesis that right ventricular dilatation hampered left ventricular filling (ventricular interdependence).<sup>21,22</sup> The more pronounced constriction observed during immersed apnea might be related to the shift of blood from the peripheral venous pool to the thorax, increasing the amount of incompressible blood in the thorax. Whatever the case, left ventricular diastolic impairment may explain the observed progressive left atrial enlargement during apnea.

#### HAEMODYNAMICS

As previously observed during dry maximal apnea, MAP increased slightly during breath-hold, both in dry and immersed conditions.<sup>2</sup> Previous papers reported large increases of arterial pressure during prolonged BH in man, sitting in air with face immersed in cold water.<sup>23</sup> This discrepancy may be due to differences in BH protocols between studies, in particular to the different environment of evaluation (medical laboratory vs. swimming pool, the latter being likely perceived as familiar by divers) and to the different water temperature (6–8°C vs. 29°C).

Recent data have shown that divers have a greater sympathetic and pressor response to apnea as compared to matched non-diver controls, suggesting that BH dive training may affect the autonomic response to hypoxia.<sup>24</sup> In that series, the vasoconstrictor response correlated with the duration of apnea, indicating a possible contribution of sympathetic tone to the oxygen-sparing effect. The observation in our study of significantly higher MAP values in the late stages of immersed BH, as compared to the dry, suggests that, in diving-trained subjects, immersion may drive the sympathetic flow contributing to coping with prolonged apnea.

#### OXYGEN SATURATION

In previous studies of human BH diving, elicitation of the diving response decreased the rate of oxygen desaturation, and face immersion attenuated cardiovascular depression.<sup>7,25–27</sup> On this basis, we expected higher  $S_aO_2$  during immersed apnea compared to dry. Whilst  $S_aO_2$  decreased during both conditions it was significantly higher during immersed apnea compared with dry. In particular, at peak apnea,  $S_aO_2$  was on average 83% in dry as opposed to 92% in immersed apnea. Interestingly, duration of maximal apnea was similar in wet and dry conditions suggesting that interruption of apnea was not triggered by a threshold critical value of blood  $O_2$  desaturation.

#### DIVING RESPONSE

Heart rate did not significantly change with time during either condition, nor was it different in immersed as compared to

dry apnea. Similarly, no significant difference was found in total vascular resistance between BH conditions. This behaviour was in line with recent results showing that cardiovascular autonomic control in breath-holding humans does not show significant changes until the hypoxic BH phase.<sup>28</sup> In spite of the lack of the main hallmarks of the diving reflex (possibly due to the warm water), a higher  $S_aO_2$  was observed in immersed apnea compared to dry. This finding could indicate that, in trained subjects, immersion by itself has an oxygen sparing effect, possibly owing to a higher level of relaxation and, hence, to a reduction of metabolic requirements.

#### Conclusions

In conclusion, the present study confirms that in-air maximal voluntary BH leads to progressive left ventricular dilatation with increased stroke volume and maintained cardiac output. Whole-body immersion induced similar haemodynamic changes but significantly less oxygen desaturation, suggesting an oxygen-sparing effect of immersion even in the absence of increased hydrostatic pressure and thus of significant pulmonary blood shift. The similar apnea duration in dry and immersed BH, in spite of different  $S_aO_2$  levels, suggests that apnea interruption is not driven by blood oxygen desaturation. Finally, hindrance to left ventricular filling was observed in both dry and immersed apnea, resembling that described at depth and compatible with a constrictive-restrictive effect of chest squeezing. The mechanism underlying this pattern in maximal apnea may be related to increased right ventricular volume (ventricular interdependence), in turn linked to increased venous return to the heart.

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