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Abolition of the Postural Autonomic Requirements for Cardiovascular Control during Water Immersion

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Abstract

The cardiovascular status and its autonomic regulation were studied in 10 healthy men (25.5 ± 1.2 years; mean ± SEM) in the supine and upright positions in air (AIR) and in water (WI).Changing from supine to upright in AIRposture decreased stroke volume (SV, from 89.9 ± 5.3 to 81.1 ± 5.0 mL; p<0.05) and significantly increased heart rate (HR, from 56.5 ± 5.6 to 81.2 ± 2.7 bpm), systolic (SBP, from 132.4 ± 5.2 to 140.8 ± 4.7 mmHg) and diastolic (DBP, from 72.1 ± 3.0 to 89.8 ± 2.8 mmHg) blood pressure. Also, plasma catecholamines and the sympathetic indicators derived from spectral analysis of HR and BP variability increased (p<0.05), while parasympathetic indicators of cardiac control decreased (p<0.05). During supine WI, SBP (112.8 ± 4.2 mmHg) and DBP (61.1 ± 1.9 mmHg) were lower (p<0.05) than during supine AIR with higher HR (67.0 ± 2.9 bpm; p<0.05).Contrary to AIR, no or only minor cardiovascular and autonomic changes were observed with posture change. Thus, compared to upright AIR, SV was higher whereas HR and BP were lower (p<0.05)during upright WI. Also, parasympathetic indexes were higher and sympathetic indexeswere lower (p<0.05).It was concluded that the hydrostatic pressure gradient applied on the body during WI maintained the venous return and nearly suppressed the gravitational cardiovascular orthostatic challenge in air. The very peculiar postural hemodynamic stability during WI might be of interest in patient rehabilitation.

Keywords: *spectral analysis, catecholamines, cardiac baroreflex, heart rate, arterial blood pressure*

Introduction

The change from supine to the erect posture decreases the effective circulating blood volume. One half to one litre of blood contained in the thorax is transferred to the legs and the abdomen, triggering several cardiovascular and autonomic nervous system changes that have been well assessed. Briefly, the decrease in central venous pressure (CVP), stroke volume (SV) and pulse pressure (PP) reduces the afferent baroreflex traffic through unloading cardiopulmonary and arterial baroreceptors [1,2]. Cardiac output (CO), blood pressure (BP) and cerebral perfusion are maintained through a decreased cardiac parasympathetic activity and an increased cardiac and vascular sympathetic activity, which increase heart rate (HR) and heighten vasoconstriction.

During head out water immersion (WI), about 85% of the hydrostatic pressure exerted on the skin is transmitted to the adventitial side of the vessels [3], through tissues with density closed to that of water, as e.g. muscles, liver or kidney. The hydrostatic pressure compresses superficial and profound veins and reduces the venous capacitance. The blood is shifted from the periphery into the highly compliant intrathoracic vascular bed, due to the low density of the surrounding lung tissue (airway and alveolar gas) [4,5]. Therefore, changes in the repartition of blood volume in the thoracic and lower limb beds likely mirror the alterations occurring with upright tilting in air. The central blood volume was found to increase by 700 mL during upright immersion up to the neck, as compared with upright in the air [4]. Therefore, the cardiovascular and autonomic adjustments observed when changing from supine to upright position in air should be dampened during WI. But, to our knowledge, these opposed effects have not been clearly assessed.

Also, during WI, both low- and high- pressure baroreceptors are loaded [6]. Aspecific pattern of autonomic control of cardiovascular activities should be observed, but this one has not been clearly emphasized. Indeed, during WI an expected decrease in vascular and cardiac sympathetic activity and an increase cardiac parasympathetic activity have been reported [7,8], but not always found [9,10]. The reported effects of WI on HR and arterial blood pressure (BP) arenot consistent. Either a decrease [11,12], or nochange[13,14] in HR have been observed. While most investigators have failed to observe changes in BP [8,11,13,15],a decrease [14,16] and an increase [12] have also been reported. These discrepancies might have resulted from different experimental body positions (i.e., supine, sitting or upright) [8,9,12,14]. The hydrostatic pressure applied on the body is depth-graded (the deeper the body, the greater the pressure), which must trigger different blood displacements and autonomic adjustments according to the position.

The aim of the present study was to assess the effects of body position on the cardiovascular status and the setting of the autonomic nervous system during resting head out water immersion. For that purpose, 10 healthy subjects were studied in both upright and supine positions on land (in air) and in water. We hypothesized that, due to hydrostatic pressure, water immersion would blunt the cardiovascular and autonomic adjustments to change from supine to upright posture.

Materials and Method

Subjects

Ten physical education students (age 25.5 ± 1.2 years mean ± SEM; height 179.1 ± 1.4 cm; and weight 69.8 ± 1.0 kg) participated in the study. Their medical history and a medical examination were used to discard subjects with cardiovascular, pulmonary, or metabolic diseases. The subjects were normotensive and none was taking any medication. The study protocol complied with the Helsinki declaration for human experimentation and was approved by the local ethic committee. The possible risks and benefits were explained and written informed consent was obtained from each subject prior to testing.

Study protocol

Each subject performed two tests, at the same time of the day (between 9:00 AM and 16:00 PM), 7 days apart. The subjects were instructed to fast for at least 3h before testing, and were asked to refrain from ingesting beverages containing caffeine and alcohol and not to exercise during the 24h proceeding the test sessions. For each subject, the test in air (AIR; 24-25°C) was performed before the test in water (WI; 35-36°C).

For the AIR test, a classic tilting board with a foot support was used. After a resting period of 20 min in supine position, data acquisition was initiated for 15 min and subsequently, the subjects were set upright at 60° for another 15 min period.

For the WI test, the subject was lying down on a submersible bed which could be inclined at 60°. After an adaptation period of 20 min in the supine position in the air, data acquisition was initiated for 10 min. Thereafter, the bed was submerged for two 15- min periods: 1) in supine position (5-10°) with the subject immersed as deep as possible (with the restriction that the head remained out of water), and 2) at 60° upright with water up to the axillae.

During each period, venous blood samples from an antecubital vein, electrocardiographic data (ECG), thoracic impedance measurements of stroke volume (SV), and measurements of systolic (SBP) and diastolic (DBP) blood pressure were taken.

Plasma catecholamines and ArgininVasopressine (AVP)

Blood samples were drawn at the end of each epoch, i.e. between the 14th and 15th min. Plasma concentrations of noradrenaline and adrenaline were determined by a specific radio-enzymatic method, as already described [17]. Radioimmunologicalassay was used to assess the plasma concentrations of AVP (Nichols Institute Diagnostics, CA, USA).

HR and BP measurement and analysis

To study heart rate variability (HRV), blood pressure variability (BPV) and the sensitivity of the baroreflex, the duration of RR-intervals and beat by beat BP (SBP and DBP) were recorded and analysed. R-R interval was obtained continuously from a standard four-lead electrocardiogram (ECG). Blood pressure was obtained by the non-invasive finger cuff method (Finapres model 2300, Ohmeda, Englewood, Co). The photoplethysmographic cuff was placed on the third finger of the right hand during the data collection period. To keep the finger cuff dry, the arm of the subject was supported 10 cm above the level of the left ventricule by an arm rest attached to the tilt bed. Special precautions were taken to ensure that the position of the pressure cuff relative to the heart was not changed during the experiments and the height difference between the finger cuff and the left ventricule was corrected. The Finapres®servoreset mechanism was turned off to permit uninterrupted observations.

For each cardiac cycle, the peaks of the QRS complexes (R waves) in the ECG data were subsequently used to produce R-R interval. SBP and DBP were determined from the maximum and minimum BP, respectively that occurred during an R-R interval. Duration of R-R interval, SBP and DBP were stored on a microcomputer via an analogue-to-digital converter (Metrabyte DAS-16).

Spectrum analysis of heart rate (HRV) and blood pressure (BPV) variabilities

Analyses were performed on a time series of 5 consecutive minutes manually selected over the 20 min recordings. All the R-R intervals, SBP and DBP values were edited initially by visual inspection to exclude all the undesirable beats (i.e., to ensure that each analysis for the segment was free of movement artefact and/or sharp transient in the signal due to premature beats) which counted for <1% in every subject. At least 256 cycles were used for each analysis. Spectrum analysis was performed with the coarse graining spectral analysis (CGSA) method [18] to quantify the total harmonic power (TP) and the power of spectral components in the low- (LF: 0.04-0.15 Hz) and high- frequencies (HF: 0.15-0.50 Hz). The very low frequencies (0-0.04 Hz) were not addressed in the present study. With HRV spectral analysis, HF_{HRV} power is almost entirely mediated by the parasympathetic activity to the sinus node directly associated with respiratory activity, whereas LFHRV power reflects the mixed modulation of parasympathetic and sympathetic activities [19]. Parasympathetic and sympathetic nervous system activities were also evaluated by HF_{HRV}/TP_{HRV} and LF_{HRV}/TP_{HRV}ratios, respectively [18]. Changes in the ratio LF_{HRV}/HF_{HRV} were taken as an indication of changes in sympathetic activity [18]. With BPV spectral analysis, it has been showed that the LF_{BPV} region is mediated by sympathetic modulation of the vascular tree and other neurohumoral mechanisms while the HF_{BPV} is related to respiration [20].

Spontaneous Baroreflex (SBR) activity

Sequences of three or more beats in which the SBP and the following RR-interval changed in the same direction (either increasing or decreasing) were considered as spontaneous baroreflex (SBR) since they reflect the heart rate response to spontaneous variations in BP [21]. Sequences were only accepted for analysis if the correlation coefficient (r) between RR-interval and BP was higher than 0.80. A linear regression was calculated for each of these sequences, and an average regression slope was calculated for all such sequences detected during each chosen recording epoch. This slope is considered as depicting the sensitivity of the cardiac SBR in $ms.mm\ Hg^{-1}$ and has a high agreement with other methods used for baroreflexevauation such as transfer function [21]. Separate analyses of the number of sequences and slope of SBR were carried out for each 5 min epoch.

Cardiac output measurements

Values of HR, SV andCO were assessed non-invasively with a thoracic impedance device (PhysioFlow®, Manatec, and Paris, France) [22]. For immersed measurements, the ECG and impedance electrodes were protected with surgical tape to prevent wetting, as described in other studies [8,23]. The recorded values of HR, SV and CO were averaged for periods of 10 consecutive minutes.

Arterial pulse pressure (PP, mmHg) was calculated from SBP minus DBP. Mean blood pressure (mmHg) was calculated as DBP plus one third of PP. Total peripheral resistance (TPR, $mmHg.L^{-1}.min$) was calculated as the ratio of mean blood pressure minus central venous pressure to cardiac output. Central venous pressure was assumed to be 6.6 mmHg during supine posture in AIR, + 2.6 mmHg during upright posture in AIR [2] and + 12.8 mmHg during WI [5].

Statistical methods

Results were expressed as mean ± SEM. Paired t-test (supine vs. 60° and AIR vs. WI) were performed using SigmaStat® software (SPSS Inc, Chicago, USA). Statistical significance was accepted at $p<0.05$.

Results

Baseline

The two experimental days, the baseline cardiovascular and autonomic status was not significantly different. Indeed, before WI, at baseline in air in the supine position, HR was 58.2 ± 2.6 bpm, SV was 90.3 ±3.7 mL, SBP was 128.5 ± 4.1 and DBP was 73.2 ± 3.3 mmHg. Also, TP_{HRV} was 2377 ± 319 ms² and HF_{HRV} was 249.5 ± 38.0 ms². These values were not significantly different compared to supine AIR (Tables 1 and 2).

Position change: AIR

In AIR, changing from supine to upright position significantly reduced R-R interval, SV and PP and significantly increased SBP, DBP and plasma concentrations of AVP, adrenaline and noradrenaline (Figures 1 and 2) (Tables 1 and 2). Upright tilting significantly decreased TP_{HRV} (NS), HF_{HRV} and HF_{HRV}/TP_{HRV} and significantly increased LF_{HRV}, LF_{HRV}/TP_{HRV} and LF_{HRV}/HF_{HRV}.

		AIR			WI			
		0°	60° HUT		0°		60°HUT	
HR	(ms)	56.5 ± 1.6	81.2 ± 2.7	***	67.0 ± 2.9	###	67.8 ± 2.7	#
SV	(mL)	89.9 ± 5.3	81.1 ± 5.0	**	90.1 ± 4.1		88.4 ± 3.3	#
PP	(mmHg)	60.3 ± 2.6	51.0 ± 2.7	***	49.8 ± 3.2	#	50.8 ± 3.6	
TPR	(mmHg.L-1. min)	18.5 ± 1.2	16.3 ± 0.9		10.5 ± 0.9	#	9.8 ± 0.9	#

Table 1. *Changes in hemodynamic values during supine (0°) and 60° head-up tilt (HUT) positions, in AIR and during water immersion (WI)*

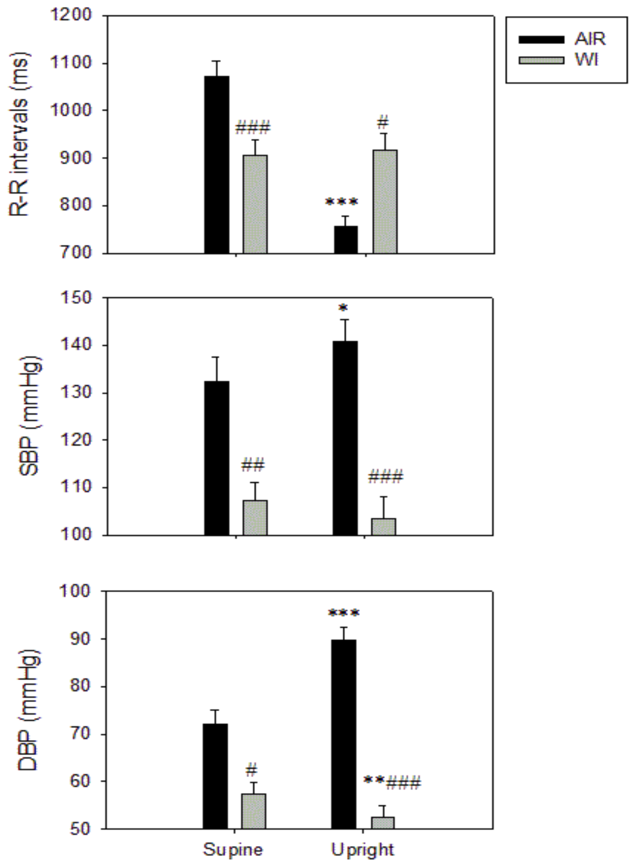
HR: Heart Rate, SV: Stroke Volume, PP: Pulse Pressure, TRP: Total Peripheral Resistance; *compared to supine posture under each condition, #compared with AIR in each posture, *, **, and *** or #, ##, and ### = p<0.05, p<0.01 and p<0.001, respectively

			AIR			WI			
			0°	60° HUT		0°		60° HUT	
HRV	R-R intervals	(ms)	1072 ± 33	757 ± 21	***	906 ± 33	###	918 ± 33	#
	TP	(ms²)	2105 ± 397	1796 ± 722		1315 ± 355	#	2143 ± 598	
	LF	(ms²)	517.2 ± 145.4	774.8 ± 323.6	*	592.7 ± 238.7		960.0 ± 304.4	
	HF	(ms²)	256.5 ± 82.1	70.4 ± 42.2	**	108.6 ± 30.8	#	176.1 ± 65.9	#
	LF/HF		15.10 ± 11.16	18.69 ± 7.24	**	7.71 ± 2.68		9.61 ± 3.53	#
	LF/TP		0.26 ± 0.06	0.39 ± 0.03	*	0.38 ± 0.05	#	0.39 ± 0.04	
	HF/TP		0.13 ± 0.03	0.03 ± 0.01	***	0.22 ± 0.11		0.07 ± 0.02	#
SBPV	SBP	(mmHg)	132.4 ± 5.2	140.8 ± 4.7	*	107.2 ± 3.8	##	103.5 ± 4.5	###
	TP	(mmHg²)	28.3 ± 10.8	29.7 ± 6.4		16.2 ± 4.1	#	25.3 ± 5.2	*
	LF	(mmHg²)	6.7 ± 2.8	9.9 ± 2.6		9.0 ± 2.7		8.9 ± 2.5	
	Number of SBR Sequences	17.9 ± 4.1	40.3 ± 2.4	***	25.9 ± 4.4		24.1 ± 3.6	##	
	SBR Slope	(ms.mmHg-1)	22.3 ± 1.9	9.4 ± 1.0	***	17.5 ± 2.2	##	20.6 ± 3.3	##

Table 2. *Changes in the indicators of spectral analysis variability of heart rate (HRV), systolic (SBPV) blood pressure during supine (0°) and 60° head-up tilt (HUT) postures, and in baroreflex indexes in AIR and during water immersion (WI)*

TP: Total Power, LF: Low-Frequency Power, HF: High-Frequency Power, SBR: Spontaneous Baroreflex; *compared to supine posture under each condition. #compared with AIR in each posture. *, **, and *** or #, ##, and ### = p<0.05, p<0.01 and p<0.001, respectively.

Also, the SBR slope was significantly lower and the number of SBR sequences was significantly higher in upright than in supine position.



*compared to supine posture under each condition. #compared with AIR in each psture. *, **, and *** or #, ##, and ### = p<0.05, p<0.01 and p<0.001, respectively.

Figure 1: *Change in R-R intervals, systolic (SBP) and diastolic (DBP) arterial blood pressures during supine and upright positions, in AIR and during water immersion (WI).*

Position change: WIN

Contrary to AIR, no significant changes were observed with posture change during WI.

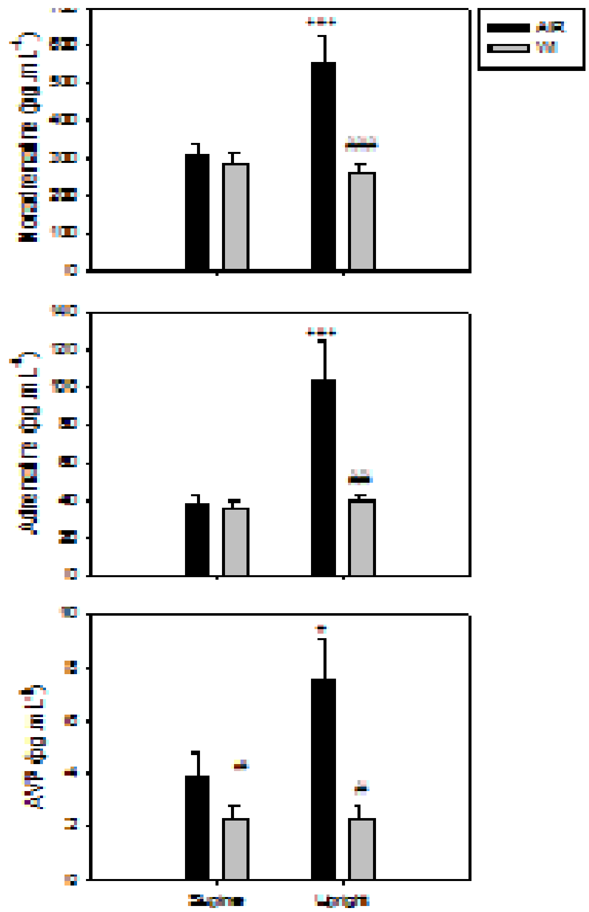
WIN vs. AIR: supine

During supine WI, R-R interval, BP, PP and TPR were significantly lower while CO was significantly higher than during AIR. On the contrary, catecholamine and AVP concentrations were not different from AIR. TP_{HRV} and HF_{HRV} were significantly lower than during supine AIR while LF_{HRV}/TP_{HRV} was significantly higher. Also, supine TPS_{BPV} and SBR slope weresignificantly higher than during AIR.

WIN vs. AIR: Standing

During upright WI, R-R intervals were significantly longer, SV was significantly greater and BP, plasma catecholamines and AVP were significantly lower than during upright AIR.

Upright HF_{HRV} and HF_{HRV}/TP_{HRV} were significantly higher during WI than AIR, and LF_{HRV}/HF_{HRV} was significantly lower. During upright WI, the SBR slope was significantly higher than during upright AIR, and the number of sequences was significantly lower.



*compared to supine posture under each condition. #compared with AIR in each posture. *, **, and *** or #, ##, and ### = p<0.05, p<0.01 and p<0.001, respectively.

Figure 2: *Change in the plasma concentration of noradrenaline, adrenaline and arginin vasopressin (AVP) during supine and upright positions, in AIR and during water immersion (WI).*

Discussion

The cardiovascular and autonomic nervous alterations observed with change from supine to upright posture in AIR in the present study were in line with the established literature. The decrease SV and PP [2] likely reflected a lowered CVP and contributed toreduce the afferent baroreflex traffic [1], which triggered in turn a decrease in cardiac parasympathetic activity (HF_{HRV} and HF_{HRV}/TP_{HRV}) and an increase in sympathetic tone(LF, LF/TP and LF/HF values HRV, plasma catecholamines). As a consequence, HR and BP were higher during upright AIR than supine AIR [1,2,17,20]. The reduction of the SBR slope when the subjects were upright tilted was another evidence of parasympathetic tone withdrawal [1,17,24].

During WI, at variance with the AIR condition, the postural-linked cardiovascular and autonomicresponses were almost completely abolished. Indeed, HR, SV,BP and TPR remained unaltered with the posture change. The parasympathetic indexes (slope of cardiac SBR, HF_{HRV} and HF_{HRV}/TP_{HRV}) were not reduced with upright tilting during immersion, pointing to a steady parasympathetic activity in the two immersed positions. The sympathetic involvement in cardiac and vascular settings remained also stable as assessed through the similar plasma catecholamine levels and LF_{HRV}/TP_{HRV}, and LF_{HRV}/HF_{HRV} values. Finally, the stable plasma AVP and number of baroreflex sequences reflected very similar conditions of blood pressure control whatever the position. According to our hypothesis, these results highlighted that the autonomic activities involved in hemodynamic control were minimally challenged during WI postural changes and emphasized that the hydrostatic pressure gradient counteracted the gravity-linked postural changes in hemodynamic conditions.

During immersion, the hydrostatic pressure behaved as a restraining system and likely blunted the CVP alterations which occurred with the postural changes, in a way similar to lower body positive pressure (LBPP). Fu et al. (2001) reported that 30 mmHg LBPP dampened the orthostatic lowering of venous return and CVP andattenuated the reduction of SV with achievement of upright posture. It reduced the baroreflex-mediated enhancement in sympathetic activity and the increase in HR [25]. During supine WI, an average 15-20 mmHg hydrostatic pressure could be assumed to apply around the body. We are not abreast of any assessment of CVP during supine head-out WI, and we did not perform this measurement in the present study. However, in the supine posture, 11 and 20 mmHg LBPP heightened CVP bycirca 2 and 6 mmHg [26,27]. Accordingly, it may be hypothesized that in supine position WI increased CVP to 8-13 mmHg at least(from 6-7 mmHg during AIR) [2,26]. Since during upright WI CVP has been measured as 7-13 mmHg [5,28,29], this would be consistent with the absence of a conspicuous CVP change between the two immersed positions. All in all, the present study highlighted a great stability of the cardiovascular status and of its control throughout the postural changes from supine to upright during head out WI.

To our knowledge, the cardiovascular and autonomic effects of water immersion during supine posture have been scarcely studied. Nishimura and Onodera (2001) reported lower BP and similar HR during floating, compared to supine posture in air. In agreement with this report, we also found a lower BP. However, we observed a significantly higher HR. As already mentioned, the immersion-linked decrease in vascular capacitance is functionally similar to volume loading, and leads to a rise in CVP [5,28,29]. The chronotropic response to this increase depends on the concomitant change in aortic diameter, volume or pressure[30]. An increase in cardiac parasympathetic tone and a slowing of HR is evoked by an increase in CVP leading to a rise in aortic baroreceptor activity. On the contrary, an increased in cardiac sympathetic tone and a rise in HR follows whenever the increase in CVP fails to trigger the baroreflex [30] or when a marked peripheral vasodilation develops and eliminates the stimulation of arterial baroreceptors [31]. In accordance with these authors, the higher HR and cardiac sympathetic predominance (decrease of TP_{HRV} and HF_{HRV} and increase of LF_{HRV}/TP_{HRV}) we observed during supine WI could be explained by both a lower baroreflex stimulation (PP was significantly lower and SV and the number of spontaneous baroreflex sequences were unchanged) and a vasodilation (lower DBP, TPR). Also, thehigher HR might be due to a reduced SBR sensitivity evidenced by the significantly decreased SBR slope [32,33].

Contrary to supine posture, the upright position has been more attentively described during immersion, and our results are in accordance with the literature. In this posture, CVP is more than two-fold higher during immersion (between 7 and 13 mmHg) [5,6,34] than in air (about 2-3 mmHg) [2]. Our observations during upright WI were consistent with the involvement of a classic reflex response to baroreceptor loading [30]. Indeed, SV was increased [8,23] likely stimulatingthe aortic baroreceptors [6]. Thus, the parasympathetic activity to the sinus node predominated (higher HF_{HRV} and HF_{HRV}/TP_{HRV} and lower plasma catecholamines and LF_{HRV}/HF_{HRV} values) [7,8], which led to a decreased HR [11,12,34]. Also, during this condition of well replete vasculature, and consistent with lower BP control requirements, the need for a vascular sympathetic activity maintaining smooth muscle tone was lessened, as indicated by the lower BP, TPR, and plasma noradrenaline values [7,8,14-16].

Conclusion

The well documented cardiovascular and autonomic alterations observed during postural change in AIR were almost abolished during WI, suggesting that the gravity-dependency in the body vessels is offset by the external hydrostatic pressure gradient. The WI environment promoted an outstandingstability of cardiovascular settings as well as narrow requirements of their autonomic control. Because of these particular conditions, we suggest that WI could be of interest for rehabilitation procedures in patients with limited cardiovascular autonomic ability.

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