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DOI 10.1055/s-0033-1345136
Int J Sports Med 2013; 34: 1043–1050

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Rüdigerstraße 14
70469 Stuttgart
ISSN 0172-4622

The Underestimated Compression Effect of Neoprene Wetsuit on Divers Hydromineral Homeostasis

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Key words
- diving wetsuit
- body compression
- fluid balance
- urine output
- plasma volume

Abstract

This study aimed at demonstrating that the neoprene wetsuit provides not only thermal protection. Compression it exerts on the diver's shell significantly impacts hydromineral homeostasis by restraining the systemic vascular capacity and secondarily increasing urine output on dry land and during scuba diving. 8 healthy divers underwent five 2-h sessions: sitting out of water in trunks (control situation), sitting out of water wearing a wetsuit, and 3 wetsuit scuba-immersed sessions at 1, 6 and 12 msw depth, respectively. Urine volumes and blood samples were collected. Hemoglobin (Hb), hematocrit (Ht) and plasma sodium concentration were measured. Interface pressure between the garment and the skin was measured at 17 sites of the body shell, with a pressure transducer. Mean interface pressures between wetsuit and skin amounted to: 25.8±2.8 mm Hg. Whatever the depth, elastic recoil tension of wetsuit material was unchanged by immersion. Weight loss was respectively 2 and 3 times greater when wetsuit was worn out of water (430 g) and during immersion (710 g) than when divers did not wear any wetsuit out of water (235 g; $p<0.05$). Urine volume accounted for 85% of weight loss in either session. Weight loss and urine volume were similar whatever immersion depth. The decrease in plasma volume amounted to 8% of urine volume when divers did not wear any wetsuit out of water, and to 30% when wetsuit was worn out of water or during immersion. Diving wetsuit develops a pressure effect that alters diver's hydromineral homeostasis. During immersion, the wetsuit pressure merges into the larger main effect of hydrostatic pressure to reduce water content of body fluids, unrelated to immersion depth.

accepted after revision
March 27, 2013

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DOI http://dx.doi.org/10.1055/s-0033-1345136
Published online: June 18, 2013
Int J Sports Med 2013; 34: 1043–1050 © Georg Thieme Verlag KG Stuttgart · New York
ISSN 0172-4622

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Introduction

Head-out water immersion causes diuresis and plasma volume changes [14,19,28]. Similar diuretic effect and plasma volume changes occur during whole body immersion and scuba diving without and with wetsuit [4,13]. During water immersion, the external hydrostatic pressure is largely transmitted to interstitial pressure [10,25]. In turn interstitial fluid is driven into plasma, and peripheral vascular capacitance is also restrained, leading to increases in thoracic blood volume and intravascular pressures [1,27]. The cardiopulmonary and arterial baroreceptors are loaded [9] and trigger autonomic changes [5,25]. Together with changes in endocrine settings this in turn elicits diuresis and natriuresis, and reduces plasma volume [14]. Whereas the effects of water immersion on water balance have been widely studied, the effects of the elastic recoil tension of the wetsuit material and of the pressure applied on the skin by the suit have never been assessed, even though the foam neoprene is widely used for diving and swimming. The neoprene wetsuit is designed to strongly reduce heat loss from body to water [2] and is fully efficient only if tightly fitted to the body. Therefore, this suit likely behaves as an elastic compression on the whole body. Compression garments and elastic stockings have been long used for to assist venous return and reduce peripheral swelling in patients with vascular diseases [24,30]. In addition, the effects of lower body compression through military anti-shock trousers have been assessed [32].

This study was designed to assess the effects of wetsuit wearing on body mass, urine output and plasma volume in healthy subjects on dry land and during quiet dives at depths of 1, 6 and 12 m. We hypothesized that wearing the diving wetsuit imposes a pressure on the skin and in turn limits the peripheral vascular capacity so as to lead to plasma volume lowering. We also wanted to assess how this effect combines with hydrostatic pressure at different immersion depths. This question is of interest since hydration status might be related to the hazard of venous gas emboli at the time of decompression after a dive [3,8,22].

Subjects and Methods

Organization of the study

Each subject underwent 5 experimental sessions: sitting out of water in trunks (C-air), sitting out of water while wearing a diving wetsuit (WS-air) and 3 scuba immersed sessions in tropical sea water while wearing the wetsuit at depths of 1 m, 6 m and 12 m (msw). During every immersion, subjects were simply resting without significant exercising. During each session, urine flow and urine sodium concentration were assessed, and blood samples were collected. Hemoglobin (Hb), hematocrit (Ht) and plasma sodium concentration were measured. The compression effect applied by the wetsuit was assessed through both assays of the elastic tension of WS material and direct measurements of interface pressure between skin and WS. All participants in this study have read, understood and respected IJSM's ethical standards document as proposed by Harriss DJ and Atkinson G in 2011 [11].

Subjects

8 healthy experienced male divers (age 35.3±4.8 [SE] yrs, height 173.2±4.3 cm, weight 72.9±4.8 kg, body surface area 1.91±0.12 m²) participated in the study after a medical examination. None of them had any history of cardiovascular, pulmonary or metabolic disease. None had ever experienced decompression sickness. The university's Institutional Review Board approved the study, and each subject signed an informed consent form before inclusion.

Organization of the 5 experimental sessions

In each session, the time schedule was divided in 2 periods A and B (**Fig. 1**). The subject arrived at the medical facility at 07:00 h in a rested, fasted and hydrated state. He emptied his bladder, then ingested a standardized breakfast comprising carbohydrates 150 g, lipids 11 g, proteins 30 g (790 kcal) and 1 L of mineral water. The subject was then not allowed to drink from the beginning of period A to the end of period B (i.e., 190 min).
During period A, subjects remained at rest 1 h sitting in the shade. The air temperature was 27±2.5 °C and the flow of an air fan was directed on the subjects. Each subject was clothed with a cotton T-shirt and bathing trunks.
Subjects were weighed (BW) on an electronic device (Tanita®, Hoofddorp, The Netherlands; precision ±20 g) immediately before and within the first 15 min following immersion, or immediately before and within the first 15 min following period B for C-air and WS-air conditions.
During period B (2 h duration) a control condition and 4 experimental conditions were tested. In the C-air condition, subjects remained in a setting identical to period A (i.e., at rest, sitting, wearing T-shirt and trunks, in the shade). In the 4 other experimental conditions the subjects were clothed with a complete wetsuit (WS) and remained seating on dry land (WS-air) or immersed themselves at 3 different depths (WS-1 m; WS-6 m; WS-12 m) with a scuba equipment. In this tropical sea, the water temperature was 28 °C at each of the 3 depths. The main features of the experimental conditions are described in **Table 1**. The order of the 5 experimental sessions was randomized for each subject.
Between C-air and WS-air, only the clothing was different (cotton T-shirt vs. wetsuit).
Core temperature (Tco) and mean skin temperature (Tsk) were controlled during all conditions respectively with an ingestible telemetry pill for Tco and with waterproof dermal temperature

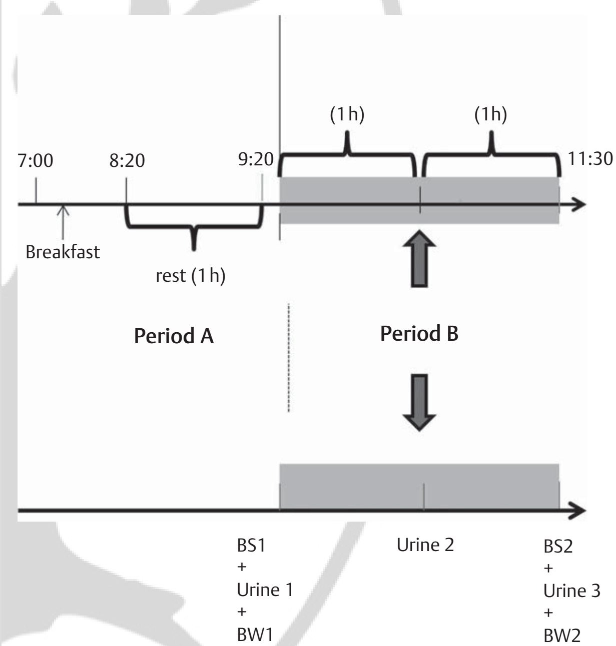

Fig. 1 Time course of each experimental session. BS = blood sample; urine = urine collection; BW = body weight measurement.

Table 1 Experimental conditions.

conditions	environmental conditions	equipment	immersion depth (m)	environmental temperature	duration (min)
C-air	dry condition	short & T-shirt	out of the water	27 °C	120
WS-air		wetsuit (5 mm)	out of the water	27 °C	120
WS-1m	wet condition	wetsuit (5 mm)	1	28 °C	120
WS-6m		wetsuit (5 mm)	6	28 °C	120
WS-12m		wetsuit (5 mm)	12	28 °C	120

WS = wetsuit; m = meter, °C = Celsius degrees, min = minutes patches for Tsk (VitalSense® Telemetric, Mini Mitter Co., USA). Mean skin temperature (Tsk) was calculated according to the Ramanathan Formula [31].

The wetsuit was similar for all subjects: a 5 mm thick neoprene wetsuit "Balance-Comfort®" (Aqualung, Carros, France) covering the entire body except the hands, feet and head. All suits were new, and the appropriate individual size was chosen.

In the 3 immersed conditions with the WS, the subjects performed a very quiet air-breathing dive for 2 h in open sea conditions at each of the 3 depths. The subjects were mostly lying prone or supine. They used a diving computer (Suunto® D9, Helsinki, Finland).

Blood and urine biology

A baseline blood sample (BSl) was taken during the last minutes of period A (9:20 am). A second blood sample (BS2) was taken immediately after the end of period B (11:30 am).

Each blood sample (70 µL) taken from the earlobe was immediately processed on an I-Stat® analyzer (Abbott Point of Care Inc., Illinois, USA). 3 biological variables were assessed: sodium [Na^+]; hematocrit (Htc), and hemoglobin (Hb). Percent of plasma volume changes over time (ΔPV) were calculated from changes in hematocrit and hemoglobin concentration according to the equation by Dill and Costill [6]. We then used the formula published by Sawka et al. [40] to express ΔPV in volume units (mL) from percent changes.

Body surface area was estimated according to the formula proposed by Mosteller [23]:

$$BSA = \sqrt{\frac{H \times W}{3600}}$$

where BSA is body surface area (m^2), H is height (cm) and W is weight (kg).

3 urine collections were performed. U0 was collected at the end of period A as a reference point. Then, the subjects donned a penis sheath connected to a 2 L urine collection bag with a no back-flow valve (Coloplast A/S, Humlebaek, Denmark). The urine bag was emptied after the first hour of immersion (U1) and immediately after the end of immersion (U2). Urinary volume was measured and urinary sodium concentration (UNa) was measured with the ion-specific electrode method (Prolyte, Diamond Diagnostics, USA).

Assessment of elastic recoil tension of the wetsuit material and of the pressure applied on the skin by the suit.

Test bench

A test device was built to assess that the tension developed by elastic recoil of the wetsuit material did not change when the ambient pressure spanned from 1 to 9 bars both in gaseous atmosphere and when the material was immersed. This was indeed verified in several WS fabric samples for each of the 2–7 mm thick materials. The details of the testing procedures are not reported here.

Measurement of interface pressure between WS and skin

Interface pressure between the garment and the skin was measured (in air and during lower limb immersion in water at ambient atmospheric pressure) at multiple sites of the body shell, with a Picopress* device (Microlab, Padua, Italy). Linearity, variability and accuracy of this device have been recently confirmed [24,29]. The pressure transducer consists of a flat plastic pressure probe (diameter 5 cm) that is filled with 2 ml of air for the pressure measurement. Fluctuations of pressure on this probe are transformed into electronic signals (Statham-element) that can be recorded continuously.

After the pressure sensors had been placed on the skin, subjects donned the neoprene wetsuit. Each subject used the WS that was the best fitted to his own morphology, i.e., comfortable, without any fabric fold. Each WS was made of 5 mm thick neoprene. To further scale the compression effect of the wetsuit, we also measured the pressure exerted on 6 points by commercially available lower limb stockings. These garments were class II Sigvaris® (St.Gallen/Switzerland) stockings individually chosen to fit each subject. In dry ambiance, interface pressure measurements were performed on 17 points with the diving suit (► **Fig. 2a**). During immersion of the lower limbs up to the navel

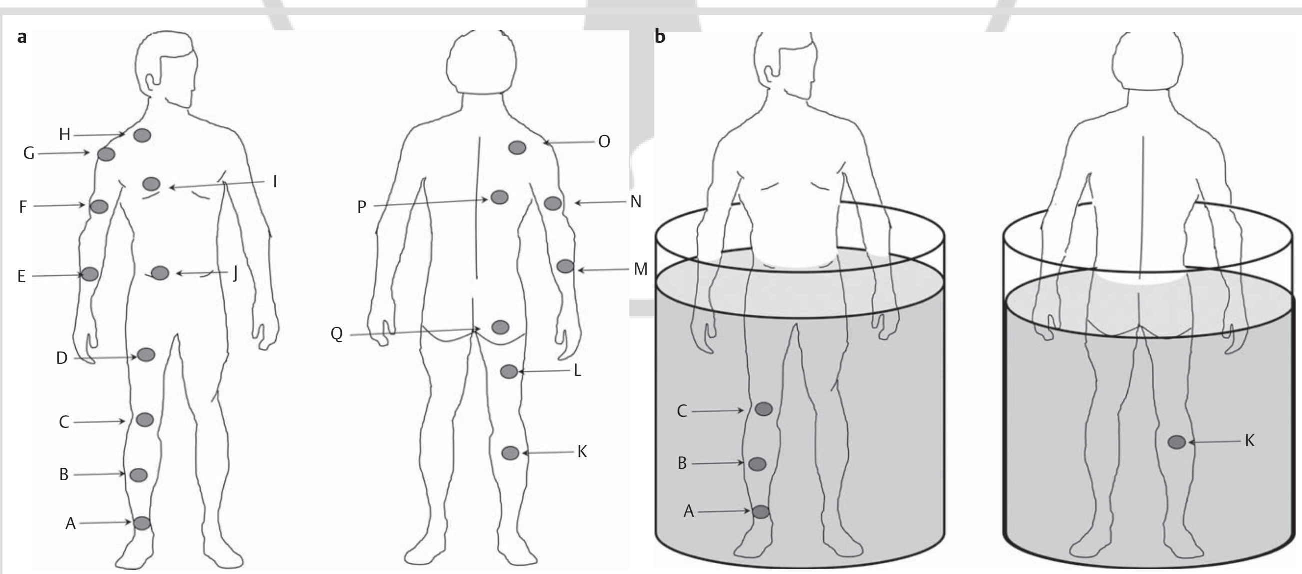

Fig. 2 **a** Pressure probe positions in air conditions. When wearing wetsuit, all pressure probes were used. When wearing compression stocking, only A, B, C, D, and K probes were used. **b** Schematic presentation of interface pressure measurement, during lower limb immersion.

in a tub (33 °C water), only 5 pressure probes were used both with WS and with compression stockings (▶ **Fig. 2b**). At each measurement point 5 consecutive measure runs were performed. The 2 extreme values were discarded and the average of the 3 remaining values was then considered.

Statistical analysis

Statistical tests were run on Sigma Stat 3.0 software. Each subject served as his own control. Data distribution was assessed using a Kolmogorov-Smirnov test. To compare values recorded at 2 different times, a t test for paired data was used when the data were normally distributed. If not, the Wilcoxon's paired signed rank test was used. For values obtained at 3 time points, one-way repeated-measures analysis of variance was performed (with the post-hoc Holm-Sidak test) when the data were normally distributed. For abnormally distributed data, comparisons relied on a Friedman's test and on the post hoc dichotomous comparisons with a Dunn's test. Differences between groups were considered significant at $p<0.05$.

Results

▼

Effects of wetsuit on urinary output and plasma volume.

Whole body fluid balance and plasma volume

The group average changes over 2 h in body mass, urine volume and plasma volume are shown in ▶ **Table 2**.

Mass loss and 2h urine volume were significantly higher in all WS conditions than during the C-air session ($p<0.05$). In addition, mass loss and 2 h urine volume were greater during the 3 immersed session than during WS-air ($p<0.05$). On average, urine volume accounted for about 82 % of mass loss during C-air and for 85 % during the 4 WS sessions (NS).

Plasma volume was lowered during WS-air by more than 6 times the slight decrease assessed during C-air ($p<0.01$). Plasma volume was further lowered during the 3 WS-immersed sessions (about twice as much than during WS-air; $p<0.01$).

Decreases in plasma volume amounted to 8 % of urine volume during C-air and to about 30 % during all the WS-sessions ($p<0.05$). During the 4 WS sessions, 70 % of urine volume hence originated from fluids that were initially non-plasmatic.

There was no significant change in plasma sodium concentration during any session (range 139.57 ± 0.32–141.72 ± 0.51 mmol/l).

Kinetics of urine output and natriuresis

The amounts of urine volume and urine sodium concentration at each sampling time are given in ▶ **Table 3**. A graphical display of the changes over time is given in ▶ **Fig. 3**.

At baseline, urine volume and urine sodium concentration were similar in each session. During C-air, values after 1 and 2 h were not different from baseline. During WS-air urine volume was larger than baseline after 1 and 2 h ($p<0.05$) but not different between the last 2 samples. During immersed WS, urine volume was larger than baseline after 1 h and again significantly larger after the second hour than after the first one. There was no significant difference due to immersion depth. The average urine flow rate amounted to 3 mL/min during each hour of the WS-air session and for the WS-immersed sessions to 4 ml/min during the first hour and to 6 mL/min during the second hour.

During WS-air, urine sodium concentration was lower than baseline after 1 and 2 h ($p<0.05$) and not different between 1 and 2 h. During immersed WS, urine sodium concentration decreased after 1 h and additionally after the second one.

The total amount of urinary sodium during the 2-h session was 0.52 ± 0.03 g during C-air, 0.75 ± 0.04 g during WS-air ($p<0.05$ vs. C-air). During immersed WS, the amount of urinary sodium mass was respectively 1.02 ± 0.04 g at 1 m, 1.04 ± 0.08 g at 6 m, 1.01 ± 0.07 g at 12 m (NS). Urinary sodium output was larger during immersed sessions than during C-air ($p<0.05$) and WS-air ($p<0.05$).

Table 2 Mean values (± SEM) of weight loss and fluid loss in the 2 air conditions and in the 3 underwater conditions, over 2 h.

conditions	weight loss (g)	2h UV (mL)	2h ΔPV (%)	2h ΔPV (ml)	2h ΔPV/UV (%)	2h non-PUV (mL)
C-air	235 ± 17*	193 ± 14*	−0.52 ± 0.18*	−16 ± 3*	8.3 ± 0.7*	−177 ± 12*
WS-air	434 ± 38$^{\$}$	374 ± 35$^{\$}$	−3.47 ± 0.98$^{\$}$	−105 ± 14$^{\$}$	26.8 ± 1.6$^{\$}$	−269 ± 23$^{\$}$
WS-1m	713 ± 10	599 ± 11	−5.77 ± 1.36	−179 ± 22	29.5 ± 1.8	−420 ± 18
WS-6m	703 ± 17	604 ± 20	−6.01 ± 1.12	−187 ± 18	30.2 ± 1.7	−417 ± 21
WS-12m	715 ± 12	602 ± 12	−5.98 ± 1.18	−184 ± 20	30.4 ± 1.9	−418 ± 15

UV = urine volume; ΔPV = change in plasma volume; ΔPV/UV = part of plasma volume loss in urine volume; nonPUV = part of urine volume besides the amount equal to plasma volume decrease; C-air = control session in air without the WS; WS-air = wetsuit worn in the air; WS-1m wetsuit and immersion at 1 m depth; WS-6m = wetsuit and immersion at 6 m; WS-12m = wetsuit and immersion at 12 m. * significant difference between Ref-air and all other conditions ($p<0.05$); $^{\$}$ significant difference between WS-air and respectively WS-1m; WS-6m; WS-12m ($p<0.05$)

Table 3 Successive amounts of urine volume and sodium urinary concentration at baseline and after each of the 2 experimental hours.

	Urine volume (mL)			Urine Na concentration(g/L)		
conditions	**UV0**	**UV1**	**UV2**	**UNa0**	**UNa1**	**UNa2**
C-air	96 ± 14	95 ± 12*	98 ± 13*	2.71 ± 0.14	2.72 ± 0.12*	2.71 ± 0.13
WS-air	100 ± 18	182 ± 21$^{\$\#}$	192 ± 23$^{\$}$	2.73 ± 0.18	2.11 ± 0.15\$$^{\#}$	1.91 ± 0.12$^{\$}$
WS-1m	102 ± 11	241 ± 26$^{\#}$	358 ± 25$^{¥}$	2.69 ± 0.11	1.82 ± 0.18$^{\#}$	1.65 ± 0.15$^{¥}$
WS-6m	95 ± 15	242 ± 28$^{\#}$	362 ± 27$^{¥}$	2.72 ± 0.15	1.78 ± 0.16$^{\#}$	1.64 ± 0.16$^{¥}$
WS-12m	98 ± 12	238 ± 23$^{\#}$	365 ± 26$^{¥}$	2.71 ± 0.12	1.79 ± 0.13$^{\#}$	1.66 ± 0.14$^{¥}$

UV = urine volume; UNa = urinary sodium concentration; 0 = baseline; 1 = end of the first hour; 2 = end of the second hour; C-air = control session in air without the WS; WS-air = wetsuit worn in the air; WS-1m = wetsuit and immersion at 1 m depth; WS-6m = wetsuit and immersion at 6 m; WS-12m = wetsuit and immersion at 12 m. * significant difference between Ref-air and all other conditions ($p<0.05$); $^{\$}$ significant difference between WS-air and respectively WS-1m; WS-6m; WS-12m ($p<0.05$)
$^{\#}$significant difference between urine1 and urine2 ($p<0.05$); ¥ significant difference between urin2 and urin3 ($p<0.05$); \$ significant difference between WS-air and respectively WS-1m; WS-6m; WS-12 m ($p<0.05$); $^{\#}$ significant difference between urin1 and urine2 ($p<0.05$); ¥ significant difference between urine2 and urine3 ($p<0.05$)

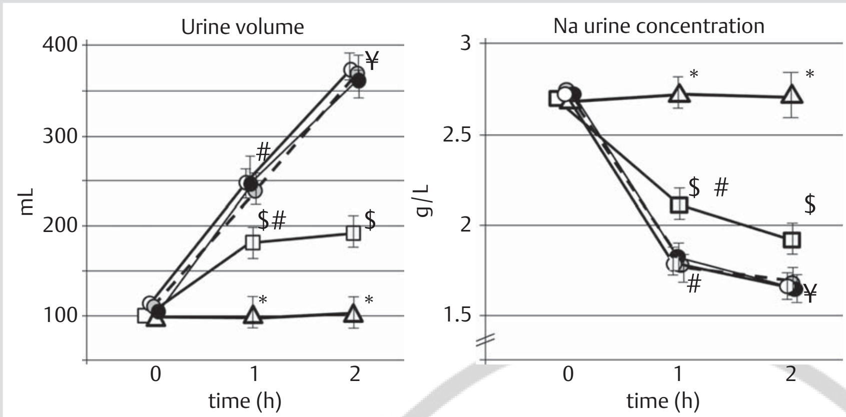

Fig. 3 Urine volume and urinary sodium concentration at baseline and after each hour of the test sessions. Empty triangle = C-air; Empty square = WS-air; Empty circle = WS-lm; Grey circle = WS-6 m; black circle = WS-12 m. * = significant difference ($p < 0.05$) between C-air and all the other conditions; $ = significant difference ($p < 0.05$) between WS-air and the 3 immersed WS sessions (1, 6 and 12 m depth); # = significant difference ($p < 0.05$) between values at baseline and after l h; V = significant difference ($p < 0.05$) between values at l h and at 2 h.

Assessment of wetsuit's compression effect

Elastic recoil tension of the wetsuit material

There was no difference between the recoil forces produced by the wetsuit test samples in normobaric atmosphere (42 ± 3 mN), in normobaric immersion (38 ± 7 mN), in hyperbaric gaseous ambience dry (44 ± 5 mN) and immersed (40 ± 3 mN).

Interface pressure between the skin and compression garment

Since there were only minute differences between pressure values on different measurement points of the same limb segment (upper limb, lower limb and trunk) interface pressure values were averaged for each limb segment.

Out of water, interface pressure between the wetsuit and the skin were as follow – upper limb: 24.5 ± 4.3 mmHg; trunk: 25.8 ± 2.8 mmHg and lower limb: 25.1 ± 3.2 mmHg. In similar conditions, the interface pressure created by compression stockings on lower limb was 17.6 ± 3.8 mmHg ($p < 0.05$ vs. WS). The interface pressure measured with compression stockings was in line with the labeled performance according to the manufacturer grade (grade II).

During immersion up to navel, the interface pressure on each lower limb probe was the sum of the compression pressure created by a garment (either WS or compression stocking) and hydrostatic pressure as resulting from the probe depth.

Discussion

The study led to 3 main results. First, it was found that wearing the neoprene diving suit out of water caused significant changes in whole body fluid balance, an effect that was strengthened during water immersion, leading during the second immersed hour to a value of urine flow previously described during head-out water immersion performed without wetsuit. Secondly, during quiet scuba diving with the neoprene suit the fluid balance effects were not different at 1, 6 and 12 m water depth, i.e., within the 1.1–2.2 bar range of ambient hydrostatic pressure. Thirdly, the estimated lowering of plasma volume averaged 30 % of the amount of urine volume during each session in which the neoprene suit was worn out of water and during immersion in the ambient and quiet conditions of the study.

Although the effect of the neoprene wetsuit was expected, it had not been assessed previously, to the best of our knowledge. Compression stockings are used to oppose blood pooling and plasma extravasation in the lower limb tissues and to bolster venous return. Anti-g suits and shock trousers have similar and greater effects that increase cardiac preload [32]. Head-out water immersion also limits peripheral blood pooling [36] and increases thoracic blood volume [1]. Additionally, during graded immersion, the intravascular blood pressures increase later than cardiac preload and stroke volume beyond a threshold amount of immersed body volume [16,27]. The immersion hydrostatic pressure triggers plasma uptake of interstitial fluid [13,25], which together with changes in autonomic and endocrine controls [16,25] lead to an increased urine flow [13].

In subjects sitting out of water, the measurement of a higher urine flow rate while wearing the diving wetsuit was consistent with a compression effect of the garment in a smaller range than hydrostatic pressure during head-out water immersion. The wetsuits worn were standard garments carefully chosen to fit the individual morphology of each subject, as is usual to ensure the thermal efficiency of the wetsuit. It was established that the elastic recoil tension of neoprene garment was not significantly modified in markedly increased ambient pressure either dry or immersed. Since a 9 bar pressure with immersion had no significant influence on the elastic tension exerted by the material, the circumferential compression exerted by the wetsuit garment (on the limbs, torso, trunk) was unlikely significantly different on dry land out of water and at the 3 immersion depths. On the lower limbs, the magnitude of the wetsuit compression amounted to that of middle range compression stockings (between class II and III), which have conspicuous hemodynamic effect [18]. The wetsuit compression concerns a much larger portion of body surface than stockings.

Prolonged wetsuit wearing on the land (in WS-air condition) could restrain heat loss and lead to increasing T core and T skin. Such a heat strain may in turn trigger sweat production able to increase water loss and somewhat limit urinary output [12]. In our WS-air condition the subjects rested sitting in the shade at 27 ± 2.5 ° C air temperature with an electric fan directed on them, their core temperature remaining unchanged during the 2 h, while their mean skin temperature rose only slightly from 34.3 ± 0.5 °C to 35.1 ± 3 °C ($p < 0.05$). It is therefore unlikely that sweat production, if any, was significant, differing from the results in the study of Hope et al. When subjects removed the WS, the inner fabric of the suit was not wet.

During all immersed sessions (whatever the depth), no significant changes occurred in Tco between the beginning and the end of the dive. At each of the 3 depths, the mean Tsk decreased from 34.5 ± 0.4 °C to 31.8 ± 0.5 °C ($p < 0.05$), which confirmed the efficient thermal insulation provided by the wetsuit even at a 2.2

bar ambient pressure. This still high Tsk also made unlikely the occurrence of a significant peripheral vasoconstriction reflex, which conversely had been triggered with skin exposure to 27 °C water [26]. Thus, significant cold-induced changes in autonomic and endocrine settings able to affect body fluid balance were unlikely during these immersed sessions [13,26].

During immersion, the wetsuit pressure and hydrostatic water pressure combined in a directly additive pattern as evidenced when subjects were standing immersed to the waist both without and with the wetsuit. Like cuff pressure [10], hydrostatic immersion pressure is directly linked to water depth and is fully transmitted to the adventitial side of vessel walls. However, the interstitial fluid pressure accounts for about 85 % of the pressure applied to the skin regardless of the pressure reached in the vascular compartment [21]. Thus, according to the experimental assays and to the measures recorded in standing subjects, the pressure effect of wetsuit likely remained constant at every immersion depth.

During the dives at 1, 6 and 12 m, the ambient hydrostatic pressure can be estimated to respectively 836, 1 216 and 1 672 mmHg, and at each depth the diver skin also received the 23 mmHg pressure created by the wetsuit elastic recoil. The wetsuit pressure clearly remained low compared to ambient hydrostatic pressures. Thus the proper pressure developed by the neoprene wetsuit rapidly merges in ambient hydrostatic pressure with increasing depth.

During the 2 h of each session, urine flow increased with the increase in pressure applied on the subject's skin. On average, wearing the wetsuit out of water doubled urine volume compared to control sitting, and the urine flow rate was not significantly higher during the second hour than the first, reflecting a roughly steady effect of skin pressure and the renal response it triggers. However urine volume was 1.6 times greater during immersed sessions with the wetsuit than when the wetsuit was worn out of water (◉ **Table 2**). During all the immersed WS session, urine flow rate increased more during the first hour than during WS-air and significantly further during the second hour to reach 6 mL/min during the second hour, which was 1.5 greater than during the first hour. The further significant increase during the second hour did not occur during the WS-air session. Former results of measures in dogs and humans support that the different urinary flow rates between the immersed sessions and WS-air reflect the difference in skin pressures, plasma fluid intake and the ensuing renal response [14,18,20]. In this study, the observed flow rates during the first and second hours are similar to values repeatedly measured during head-out immersions [14].

Converting percent changes in plasma volume into absolute volumes feeds the comparison with overall mass loss and urine output – at least as magnitude orders. It was found that over 2 h changes in plasma volume displayed the same relative patterns as changes in urine output. Wearing the neoprene wetsuit out of water significantly lowered plasma volume, which was decreased by a larger degree during the 3 immersed sessions. Both plasma volume decrease and enlargement in urine volume resulted from the compression effects of the wetsuit on dry land and the wetsuit plus hydrostatic pressure during whole body quiet immersions. The 3 immersion depths led to the same decrease in plasma volume amounting to an average 30 % of the overall urine volume. This result throws light on several points. It first supports the alleged weakness of thermal strains during the study. Indeed, when heat strain is high, both plasma volume and urine volume are significantly lower than in thermoneutral conditions [12]. When a cold strain is present, urine volume is higher and plasma volume lowering is deeper than in thermoneutral condition [13]. The similar degree in the drop of plasma volume as compared to urine volume and to overall mass loss in the 4 WS sessions of the study is indirect evidence that the increase in urine flow rate was driven primarily by the pressure effect and the fact that urine output responded to the plasma uptake of interstitial fluid during each 2 h session with WS [13]. Another main point is that during the WS sessions dry and immersed, urine volume comprised a large part of fluids originally located in interstitial and possibly also intracellular volumes [35]. No comparable effect occurred during the control session on dry land without any wetsuit during which the plasma volume decrease amounted to only 8 % of urine volume. Indeed, while the kidney extracts urine volume from plasma during immersion, the intravascular pressure is only slowly and slightly reduced despite a persistently high urine flow [34]. The immersion-linked diuresis seems mostly dependent on the pressure-driven entry of interstitial fluid into plasma [13,19], which implies that the overall volume of interstitial, and perhaps also intracellular fluid, continuously decreases during immersion [10,35]. When the kidney subtracts plasma fluid from the blood, interstitial fluid is likely driven into plasma either directly because of high tissue pressure or through lymphatic flow [20]. While the plasma concentration of sodium did not change during any session, the amount of urinary sodium increased, reflecting the plasma fluid renewal and the lowering of the overall extracellular water volume. The amount of urinary sodium was not different between the 3 immersed sessions. Natriuresis is supported by the decrease in sympathetic renal control [5,25] and by the dampening of aldosterone release during whole body immersion [13] as well as during head-out water immersion [16,34].

The similar urine output and decrease in plasma volume at the 3 immersion depths is puzzling. According to Miki et al. [21] at each dive depth the interstitial pressure reached about 85 % of the pressure applied to the skin. It might be expected that the increase in the adventitial pressure with immersion depth progressively reduces the peripheral vascular capacity. In turn, urine output volume might also be expected to increase with rising ambient hydrostatic pressure. At the same time, the intravascular pressure is balanced with central venous pressure [19]. In the thorax, the average airway pressure is close to the pressure surrounding the body, either atmospheric when breathing on dry land, or determined by the breathing regulator during dives. Thus, during respiratory and cardiac cycles, the airway pressure around heart chambers and thoracic vessels fluctuates around the hydrostatic pressure of the instant depth [17]. Therefore, the transmural pressure operating on the low and high pressure thoracic baroreceptors remains roughly constant when the depth increases. Baroreceptor stimulation elicits changes in autonomic activity, which modulates in turn glomerular and tubular blood flow and urine output [5,21]. These baroreceptors also control the release of antidiuretic hormone [27]. Thus despite different dive depths, similar transmural cardiac and thoracic vascular pressures likely lead to similar urine flows. In addition, body posture has no significant influence during immersion, since being upright, seated or lying leads to similar autonomic nervous and endocrine settings, all roughly equivalent to supine on dry land [7,26].

Implications

The dive depths chosen for the study did not lead to nitrogen tissue loading likely to carry a significant decompression risk. If similar water balance changes were to occur at greater diving depth (e.g. 30, 40, 60 m…), which seems likely according to the physiological hypothesis of a main role for pressure difference between blood in the thoracic compartment and the airways, then the lowered plasma volume may suddenly change tissue blood flow when the external compression disappears at a time during which inert gas is being washed out, i.e., when the diver emerges from the water and the neoprene suit. This sudden change in blood tissue perfusion might support a rapidly impaired inert gas washing out, leading to a decompression hazard after the end of the dive per se.

Limitations of the study

Detailed assessment of renal function was not achieved in this study, as e.g. creatinine clearance, osmotic clearance, free water clearance, glomerular filtration rate. The renal function has been well described during several head-out water immersions studies [27,28], and recently in 6 h quiet whole body immersions either thermoneutral and with 2 stages of cooling [13]. The body of results describing the immersion effects on renal function and urine flow appeared sufficiently sound and reproducible to allow addressing the questions of this study by using the already gathered body of knowledge.

We directly compared the magnitude orders of urine volumes and plasma volumes with rough mass loss. The mass figures corresponding to urine and plasma volume are larger than the volume figures, according to density of the respective fluids. These densities were not measured in the study. However, the differences in mass and volumes taken into account for delineating the main results of the study had by far much greater magnitude than the mass corrections which would have resulted from applying density factors to urine and plasma volumes.

The partitioning of the effects on water balance of hydrostatic pressure and of the neoprene wetsuit would be more precisely delineated with an experimental situation in which subjects would perform the same immersion without any neoprene suit. However, with the water temperature of our study (28 °C), superficial cutaneous vasoconstriction would quickly appear and add another influence on body water balance.

Although only male subjects were used in our studies, there is no reason to expect that changes in overall mass, urine volume and plasma volume would be significantly different in female subjects.

In conclusion, it was assessed that the neoprene wetsuit commonly used in diving activities produces a compression effect independent of ambient pressure and wetness. The suit-generated pressure on skin alters fluid balance to a lesser degree but in the same way as water immersion, i.e., an overall fluid loss through increased urine output and a lower scaled decrease in plasma volume. With submersion, the proper effect of wetsuit became minor and eventually merged in the degree effects of hydrostatic pressure. It was also observed that the cumulated effects of the wetsuit and water immersion during quiet scuba diving had identical ranges when the ambient pressure was doubled, i.e., at depths between 1 and 12 msw, which reveals minor effects of depth per se on fluid balance during regulator breathing dives. Finally during 2 h quiet scuba diving with a wetsuit, the plasma volume was decreased by 30% of urine volume and similarly at either 1, 6 and 12 msw.

Competing interests: None. This study has no funding sources, no conflicts of interest.

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