Time and Temperature Effects on Body Fluid Loss During Dives with the Open Hot-Water Suit

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Background: Bodyweight (BW) losses up to 5 kg have been observed during diving with the open hot-water suit (HWS). The objective of these dives was to study the hormonal, hematological, and renal effects of dehydration during shallow HWS diving. ***Methods:*** In series 1, four divers dove for 3.5 h each day for 7 d. In series 2, 12 divers dove to 6–8 msw for 1, 2, and 4 h. Blood and urine samples, BW measurements, oral temperature, and thermal stress indices were collected. ***Results:*** Average ΔBW (± SD) for the 28 dives in series 1 was 1.5 ± 0.8 kg, and the largest BW reductions were 3.2 and 3.0 kg, corresponding to 3.7 and 4.7% of BW. Changes in thermal stress, hemoglobin, hematocrit, aldosterone, and electrolyte excretion correlated with BW reduction. In series 2, average BW reductions were 0.46 ± 0.27, 0.96 ± 0.38, and 1.55 ± 0.59 kg during 1-, 2-, and 4-h dives. BW reduction correlated significantly with thermal stress ($p < 0.01$). Aldosterone increased after 1 and 2 h and plasma renin activity was unchanged. Atrial natriuretic peptide increased in all dives ($p < 0.01$) and arginine vasopressin increased in the 4-h dives ($p < 0.05$). The 7.2% decrease in plasma volume, the increases in hemoglobin, hematocrit and serum proteins, and an unchanged plasma osmolality indicate an isotonic dehydration after the 4-h dives. ***Conclusions:*** BW loss during HWS diving is mainly caused by sweating. Dives of 4 h produce an isotonic dehydration and a break for fluid intake is, therefore, recommended.

Keywords: osmolality, aldosterone, atrial natriuretic peptide, arginine vasopressin, plasma volume, hemoglobin, immersion.

COLD IS FREQUENTLY a problem for the working diver and may affect comfort and work performance. To avoid cooling during diving in cold water, systems for active heating have been developed. The only diver heating system in use during saturation diving in the North Sea today is the open hot-water suit (HWS). With this equipment cooling is avoided by the surface-heated seawater delivered via an "umbilical" through a series of perforated hoses sewn into the suit. Water of 37–40°C thereby continuously perfuses the diver's skin.

Hertig et al. (4) observed that head out immersion in warm baths, especially after adding salt to the water, resulted in significant fluid loss by sweating. These findings were confirmed during immersion experiments using warm seawater, which also revealed that moderate increases in skin and core temperatures induced significant sweat production and fluid loss (7). HWS diving may be considered as immersion in warm seawater and the diver will, therefore, be vulnerable to fluid loss and dehydration. This was confirmed by bodyweight (BW) measurements—the only measured parameter—before and after 128 saturation HWS dives and 129 shallow HWS dives, where BW losses up to 5 kg, or 6% of BW, were observed (6).

It should be emphasized that during a normal saturation "lock out" dive lasting for up to 4 h, the diver normally receives no fluid replacement. If the diver loses body fluids equivalent to more than 3% of his bodyweight, his physical as well as his mental performance may be impaired at the end of the dive (12,13). Severe fluid imbalance may not only affect divers' comfort and performance, but also endanger their safety.

The main purpose of the present study was to test our hypothesis that sweating in the HWS may result in hypohydration, and to establish that heat is an important environmental factor to control during HWS diving. Thus, the purpose of this investigation was to verify and extend previously published observations on body fluid loss during HWS diving (6) by determining changes in bodyweight, body temperatures, hormonal, hematological, and renal function, as also determined in a head-out immersion study (7).

METHODS

The experimental protocol was approved by the Regional Ethics Committee at the University of Bergen, and the study was performed according to the Helsinki declaration. The subjects signed a written informed consent form after the purpose of the study and the experimental procedures had been explained.

Series 1—Pool Diving

Four male divers averaging 28 yr of age (range 25–30 yr) with a mean BW of 76 kg (range 65–86 kg) dove

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with the HWS for 3.5 h daily, for 7 consecutive days. Two and two divers dove together at the same time each day—either between 08:00 and 12:00 or between 12:00 and 16:00. The temperature of the seawater in the 4-m deep pool was kept at 10°C. The divers worked on a steel frame test rig by mounting and dismounting pipeline valves ("nuts and bolts"), watching video films, and playing a kind of soccer/underwater rugby ball game. Neither activity was physically demanding. The subjects did not ingest any fluids during diving, or between the two blood samplings on days 1, 4, and 7 (see below). No alcoholic beverages were allowed from 24 h before the first dive and during the whole test period. All other kinds of hot and cold beverages were permitted and the subjects carefully logged their total fluid intake (type and volume) for the entire 7-d experimental period.

Venous blood was sampled from the cubital vein before and after diving on days 1, 4, and 7 and analyzed for the parameters described below. The post-dive samples were taken 15 min after diving, of which 5 min were in a seated position just prior to sampling. Similarly, urine was voided and the bladder voluntarily emptied prior to and about 15 min after the dive. Diuresis and electrolyte excretion during each dive were also determined.

Series 2—Sea Diving

The 12 male subjects were experienced commercial divers. Average age was 38 yr (range 21 to 55 yr) and BW 81 kg (range 65 to 106 kg). All divers performed three dives with the HWS to 6–8 msw lasting for 1, 2, and 4 h. These open water dives, with water temperatures around 10–12°C, were performed in randomized order with at least 48 h between each dive. Two divers dove together starting at 09:00 in the morning. No subjects had to void during the dive and, therefore, diuresis was calculated from the urinary volume obtained after the dive and the time elapsed between this and the pre-dive sample. Venous blood and urine was sampled before and after each dive in a similar manner, and at the same time, as described above for Series 1.

Diving Equipment

All experiments were performed with standard diving equipment as used by the offshore saturation divers in the North Sea. This included surface-supplied breathing gas (air) as the primary system and a rigid diving helmet (Superlite 17B, Kirby Morgan Diving Systems International Inc., Santa Maria, CA) or a Kirby Morgan Band Mask 18 (a full-face mask). A speaker inside the helmet and a microphone in the oro-nasal mask facilitated communication with each diver. Each subject used the same suit, underwear, and helmet in all dives.

The individually fitted HWS were perfused with 38°C seawater. The HWS system consisted of a thermostatically controlled seawater heater, a 12.7-mm (0.5-in) diameter and 30-m long water hose, and the diving suit (FCO hot-water suit, F.C. Olsen, Bergen, Norway, or DUI hot-water suit, Diving Unlimited International Inc., San Diego, CA). Approximately 10 $L \cdot min^{-1}$ surface-heated seawater delivered via perforated hoses in the suit continuously perfused the skin surface. The diver controls the temperature within the suit by either requesting warmer water or by reducing the flow rate of warm water by using a dump valve at the suit inlet. The divers were all familiar with the equipment. All dive procedures were conducted according to the regulations given by the Norwegian Petroleum Directorate. No special experimental situation was induced and the diving conditions were optimal with respect to equipment function and comfort.

Physiological Measurements

A series of measurements and analyses were performed in order to characterize the fluid loss resulting from the use of the HWS. BW was measured to the nearest 0.1 kg before and after diving on a balance (Soehnle S10 2720, Soehnle-Waagen GmbH, Murrhardt, Germany).

Sweat loss (SL) was calculated as the difference between measured BW loss (ΔBW) and the sum of urine volume (VU), estimated insensible fluid loss through the skin and respiration (IF), and estimated metabolic weight loss (MW): $SL = \Delta BW - (VU + IF + MW)$. Since the skin was continuously flooded with water the diffusion gradient through the skin is zero and this insensible fluid loss is, therefore, negligible. The water content of saturated expired air at 37°C is about 44 $g \cdot m^{-3}$ (1). With a dry breathing gas and an estimated average ventilation of 20 $L \cdot min^{-1}$, the maximum respiratory fluid loss is approximately 53 $g \cdot h^{-1}$. Together with a metabolic weight loss of about 20 $g \cdot h^{-1}$ (8), the total insensible weight loss was estimated to be maximally 0.3 kg during a 4-h dive.

In all dives thermal stress was scored on a scale from 1 to 5 where 1 = very cold, 2 = cold, 3 = comfortable, 4 = warm, and 5 = very warm. In Series 2 four skin thermistors (EUS-U-V5–0, Grant Instruments, Cambridge, England) were taped to the skin with Blenderm Surgical Tape (Medical Products Division, 3M Company, St. Paul, MN) on the right forearm, chest, thigh, and dorsal aspect of the right foot. Mean skin temperature (T_{skin}) was calculated as: $T_{skin} = (0.4 \cdot T_{chest} + 0.4 \cdot T_{thigh} + 0.2 \cdot T_{arm})$. In Series 2 oral temperature was measured with a digital thermometer ("Memory," Citizen Watch Co. Ltd., Tokyo, Japan) 2–5 min before dive start and immediately after surfacing. The wires from the thermistors were collected in a common cable that penetrated the suit through a rubber collar in the right hip region. The cable was taped to the main umbilical (Silvertape, 3M Company, St. Paul, MN) and connected to a data logger on the surface (Grant Squirrel Series 1000 and Series 1200, Grant Instruments, Cambridge, England). The skin temperatures were recorded at 1-min intervals. Diuresis and electrolyte excretion were calculated from the timed urinary output. Heart rate and systolic BP were measured before and after diving in Series 2.

Hemoglobin and hematocrit were analyzed on an

automatic hematology analyzer (Coulter STKS, Coulter Company, Miami, FL). Total serum protein and albumin, serum and urine electrolytes, and osmolality were measured by standard techniques on a Technicon Chem-1 instrument (Technicon Instruments Corp. Bayer, New York, NY). Percent changes in volumes of blood, plasma, and red cells were calculated according to Dill and Costill (2). Arginine vasopressin (AVP) was analyzed using a radioimmunoassay method that includes extraction on a SEP-PAK C 18 column. The normal values are 0.9–9.2 pmol · L^{-1} and the sensitivity of the method is 0.5 pmol · L^{-1}. Renin activity was measured as angiotensin I generation in plasma under standardized conditions using an angiotensin I kit (RIANEN Angiotensin I [^{125}I] RIA Kit, DuPont de Nemours, Germany). The precision of the assay, expressed as a coefficient of variation between assays, was 10.3–10.6% in the measured range. Plasma levels of atrial natriuretic peptide (ANP) were measured as described by Omland et al. (11). The method uses a radioimmunoassay kit from Nycomed Amersham Plc., Buckinghamshire, UK, and includes an extraction step on a C18 octadecyl minicolumn system. The limit of detection is 5.0 pmol · L^{-1}. The precision of the assay (the interassay coefficient of variation) is 12% at the level of 22 pmol · L^{-1} and 6.2% at 82 pmol · L^{-1}. Aldosterone was determined using a radioimmunoassay kit from Diagnostic Products Corporation, Los Angeles, CA. The method has a detection limit of 44 pmol · L^{-1} and a sensitivity (interassay coefficient of variation) of 9.5% for the entire concentration range from 88 to 1550 pmol · L^{-1}.

Statistical Analysis

Student's *t*-test was used for paired comparisons between pre- and post-dive measurements in Series 2. With an unpaired *t*-test, sweat loss differences in Series 2 dives were evaluated. Linear regression analysis was done to evaluate the relation between calculated sweat loss and thermal stress for pooled data from Series 1 and 2. For all statistical analyses, $p < 0.05$ was considered significant. Values are presented as means ± SD or ± SEM (**Fig. 1**).

RESULTS

Series 1—Pool Diving

Average BW reduction was 1.5 kg · $dive^{-1}$ (range 0.5 to 3.2 kg) and the largest BW losses were 3.2 and 3.0 kg · $dive^{-1}$, corresponding to 3.7 and 4.7% of BW. Average ΔBW was 2.0% of pre-dive BW and average thermal stress index was 3.2. In 7 of the 28 dives ΔBW was greater than 3%. A correlation was observed between BW reduction during diving and total fluid consumption during the following 20.5 h before the next dive. The sum of metabolic weight loss and respiratory fluid loss was estimated to be 0.28 kg. Calculated sweat loss averaged 0.96 kg ± 0.82 (SD) and average urine volume was 0.29 L ± 0.18.

The small post-dive increases in hematocrit, hemoglobin, and serum protein concentration, and the calculated percentage decrease in blood volume, plasma volume, and red cell volume were not statistically significant. Also the aldosterone increase from a pre-dive value of 415 ± 195 (SD) to 573 ± 458 pmol · L^{-1} determined shortly after the dive was not statistically significant.

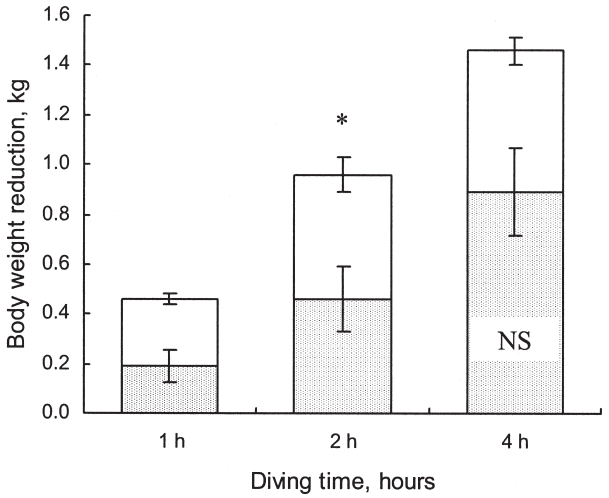

Fig. 1. Average values (± SEM) of total weight loss as the sum of sweat loss (hatched bars) and urinary, metabolic, and respiratory fluid loss (open bars) as a function of diving time in series 2. * $p < 0.05$: Total weight loss vs. the 1- and 4-h dives. NS: Sweat loss vs. the 2-h dives.

The 7-d dive period did not result in changes in BW or any venous blood parameters. BW was 75.7 ± 10.2 (SD) and 75.3 ± 10.8 kg, hemoglobin was 14.6 ± 1.0 and 14.4 ± 0.8 g · L^{-1}, serum sodium was 142 ± 1.2 and 140 ± 1.9 mmol · L^{-1}, and serum protein was 68.0 ± 4.2 and 71.2 ± 4.7 g · L^{-1} before diving on days 1 and 7, respectively.

Series 2—Sea Diving

Mean values and standard deviations for the pre- and post-dive measurements are given in **Table I**. Significant differences are also indicated. The lower diuresis in the 4-h compared with the 2-h dives corresponds to a higher thermal stress index, smaller oral temperature reduction (Table I), and an insignificant higher mean skin temperature [35.3 ± 1.3 (SD) vs. 34.2 ± 2.6°C]. In accordance with this, calculated sweat loss was 0.19, 0.46, and 0.89 kg in the 1-, 2-, and 4-h dives, respectively. The corresponding total BW reductions were 0.46, 0.96, and 1.47 kg ($p < 0.05$, Fig. 1).

The significant increases in hemoglobin, hematocrit, and serum protein concentration after 4 h, but not after 2 h and less, clearly indicates an increasing hypohydration with increasing diving time (Table I). A significant correlation was observed between calculated sweat loss and thermal stress ($p < 0.01$, **Fig. 2**). Only minor and insignificant changes were observed in serum electrolytes and osmolality. ANP and AVP increased, aldosterone decreased, and renin activity was unchanged (Table I). No significant changes in systolic BP and heart rate were observed when comparing pre- and post-dive measurements. The 7.2% decrease in calculated plasma

TABLE I. MEASURED AND CALCULATED VALUES (MEANS ± SD) BEFORE AND AFTER DIVING WITH THE OPEN HOT-WATER SUIT FOR 1, 2, AND 4 H IN SERIES 2.

Parameter		1 h		2 h		4 h	
		Before	After	Before	After	Before	After
Aldo	pmol · L^{-1}	316 ± 80	235 ± 81*	343 ± 127	213 ± 97**	305 ± 80	305 ± 183
Renin	mg · L^{-1} · h^{-1}	1.86 ± 1.16	1.94 ± 0.77	1.56 ± 0.68	1.8 ± 1.01	2.41 ± 0.94	2.89 ± 1.39
ANP	pmol · L^{-1}	5.22 ± 4.30	11.13 ± 5.46**	6.68 ± 3.53	11.00 ± 4.41**	6.42 ± 4.36	9.75 ± 3.96**
AVP	pmol · L^{-1}	2.44 ± 1.13	3.00 ± 1.00	4.40 ± 2.70	5.41 ± 3.63	3.30 ± 3.46	5.63 ± 4.15*
Hb	g · dl^{-1}	14.88 ± 0.61	14.82 ± 0.58	15.02 ± 0.67	14.89 ± 0.82	14.81 ± 0.71	15.16 ± 0.61**
Hematocrit	L · L^{-1}	0.435 ± 0.018	0.437 ± 0.017	0.438 ± 0.019	0.434 ± 0.022	0.433 ± 0.023	0.444 ± 0.02*
S-Prot	g · L^{-1}	74.11 ± 3.76	76.25 ± 3.62	75.64 ± 4.68	76.91 ± 3.73	73.73 ± 3.26	79.08 ± 3.99**
U-Vol	L		0.203 ± 0.084		0.362 ± 0.251		0.374 ± 0.137
Diuresis	ml · min^{-1}		1.31 ± 0.41		1.80 ± 1.29		1.05 ± 0.51†
T_{oral}	°C	36.7 ± 0.3	36.1 ± 0.6*	36.6 ± 0.3	36.2 ± 0.3**	36.6 ± 0.4	36.5 ± 0.5
T_{stress}	scale: 1–5		2.92 ± 0.52		2.98 ± 0.56		3.15 ± 0.26
BW	kg	78.2 ± 8.9	77.8 ± 8.9**	80.9 ± 11.6	79.9 ± 11.7**	80.8 ± 11.6	79.3 ± 11.5**

Aldo = aldosterone, ANP = atrial natriuretic peptide, AVP = arginine vasopressin, Hb = hemoglobin, S-Prot = serum protein, U-Vol = urine volume, T_{oral} = oral temperature, T_{stress} = thermal stress index, and BW = bodyweight.
†Compared to the 2-h dives: $p < 0.05$.
Compared to pre-measurements (Students *t*-test): *$p < 0.05$, **$p < 0.01$.

volume correlates with the 7.1% increase in serum protein concentration in the 4-h dives.

DISCUSSION

Several studies indicate that the body fluid loss during HWS diving relates to thermal conditions (6,7,10). Observations in the present Series 1 and 2 show that thermal stress above thermoneutral conditions results in an increased sweat fluid loss (Fig. 2). In agreement with our findings, dry-suit dives in warm (34–42°C) water resulted in a sweat loss of approximately 1.0 kg · h^{-1} and a rectal temperature increase to 39°C (5).

In 128 operational saturation dives performed by 22 divers the thermal stress index was 3.3 and the average

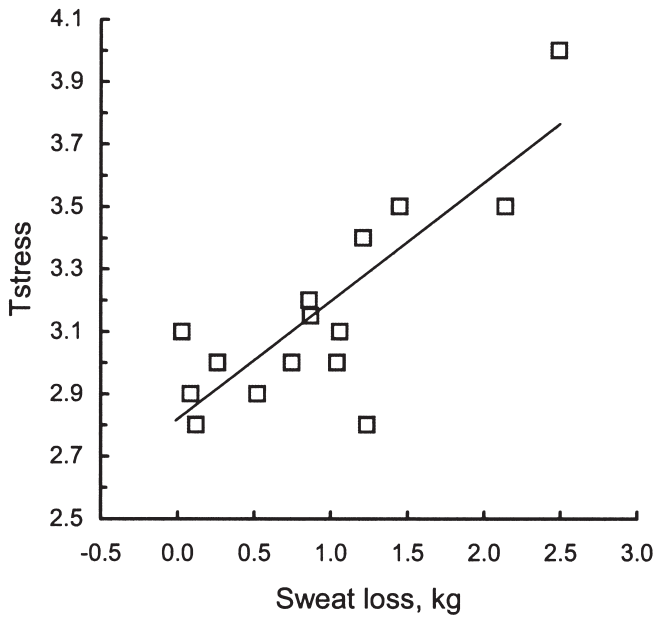

Fig. 2. Linear regression of calculated sweat loss vs. thermal stress based on individual subjective evaluation of cold/heat ($p < 0.01$). The data presented are from the 4 divers on day no. 6 in series 1 and from the 4-h dives for 11 divers in series 2.

BW loss was 0.5 kg · h^{-1} (6). In that study, several dives resulted in BW losses greater than 3.5 kg and 5% of BW. Four divers had four dives or more with BW losses greater than 3% of BW, whereas seven divers had no dives with weight losses greater than 2%. One possible explanation for the large individual differences in BW reduction observed in these operational dives (6) could be a non-uniform distribution of the hot water in the suit. Improper suit fitting and/or restriction at tube outlets probably cause this uneven hot water flow. A diver who is cold on one foot due to an inadequate hot water flow in that part of the suit will ask for warmer and more water. He will probably get warmer feet, but his needs may also result in a higher temperature on the rest of his body surface. Thus, both skin and core temperature may rise, both being stimuli for sweat production. A better performing suit with respect to warm water distribution would, therefore, require less warm water at a lower temperature.

Furthermore, evaporation of the sweat is rendered impossible since the diver's skin is continuously flushed with water during HWS diving. In addition to the lack of evaporative heat loss, the temperature gradient will actually favor heat absorbance to the blood vessels in the vasodilated skin and thereby increase core temperature. In support of this view, oral temperature increased by 0.6°C from a pre-dive value of 37.4°C during operational saturation diving (10). In addition, fluid intakes of more than 1.5–2 L have been reported after diving (personal communication with the diving company Stott Offshore, 2001). Anecdotal reports of exhaustion without having performed hard work also indicate that dehydration and hyperthermia may occur in HWS diving. That the hyperosmotic seawater may have an additional osmotic effect was confirmed in a recent study where we observed a significantly greater sweat loss when the subjects were immersed for 4 h in warm (38°C) seawater compared with freshwater (7).

The higher total sweat loss in the 4-h dives compared with 2 h may be explained by body temperature differ-

ences (Table I). The lower diuresis in the 4-h compared with the 2-h dives may also be explained by the fact that these dives were on average warmer than the dives with shorter duration (Table I). Thus, the increased sweat production is probably compensated for by decreasing the total urinary output in the 4-h dive series. Alternatively, one could argue that the higher diuresis in the 2-h compared with the 4-h dives might be due to the colder conditions stimulating to peripheral vasoconstriction followed by a cold diuresis. However, the major part of the urine produced in all dive series is probably caused by the immersion effect (3). The hydrostatic pressure changes will result in a redistribution of peripheral blood toward central parts of the body and central blood volume will increase. This again stimulates stretch receptors in the atrial walls that in turn induce release of ANP resulting in increased natriuresis (3,9). This mechanism responds rather fast and could explain the insignificant differences in urine volume between the 1-, 2-, and 4-h dives (Table I).

The significant increases in hemoglobin, hematocrit, and total serum proteins observed after the 4-h dive, but not after 1 and 2 h, clearly indicate an increasing dehydration with diving time (Table I). The unchanged plasma osmolality and the significant reduction in plasma and blood volume, but not in erythrocyte volume, support the view that the dehydration is isotonic and extracellular. Since the venous blood samples were taken about 15 min after the divers surfaced the blood results may rather reflect an opposite immersion effect where a surplus of centrally located blood now returns to the extremities and peripheral tissues. This direction of the fluid fluxes would result in a hemoconcentration (Table I), and thereby reflect hydration changes induced by the dives.

In general, a dehydration and reduction in plasma volume would normally decrease natriuresis by increasing aldosterone and decreasing ANP plasma levels (3). However, in all dives in Series 2, ANP increased, whereas aldosterone decreased (Table I). It may well be that the immersion effect still prevails 15 min after the dive for the slowly responding aldosterone (3). The post-dive ANP and aldosterone values will, therefore, reflect the immersion situation in addition to dehydration induced by the sweat loss. On the other hand, AVP responds faster and may, therefore, reflect the post-dive situation at the time of blood sampling (3). This would also apply for hemoglobin, hematocrit, and serum proteins, which change fast and in parallel to the movement of plasma fluids back to the interstitial spaces. In the present experiments the hypohydration is isotonic and should not induce significant changes in AVP. Even if osmolality is the most sensitive stimulus for AVP changes, this hormone may also be stimulated by plasma volume reduction and may explain the small increase observed in the 4-h dives (Table I).

Previous observations show a significantly greater sweat loss in seawater compared with freshwater immersion. The explanation could be that when the sweat channels are open, the osmotic effects of the hyperosmotic seawater will increase the transport of the hypotonic sweat through the channels (7). This is in accordance with observations made by Hertig et al. (4), who found that sweating during freshwater immersion increased significantly when salt (5% NaCl) was added to the water.

Based on the present results in shallow depth diving with the open hot-water suit, and also from results obtained in previous studies (6,7), we conclude that the great weight losses of more than 3% of bodyweight are mainly caused by sweating. However, the divers in Series 1 recovered fast, as ascertained by bodyweight measurements every morning, and by the almost identical individual blood values prior to diving on days 1, 4, and 7. Thus, perceived thirst seemed to stimulate adequate ad libitum fluid intake, and no indications of progressive voluntary dehydration were observed during the 7-d dive period.

The fluid loss depends on the hot water temperature and correlates to core and skin temperature changes, and to subjective thermal stress. It is, therefore, recommended that the temperature of the hot water must be better controlled and regulated by the topside personnel, and not by the diver's subjective feeling. A better suit fit should be aimed at improving the hot water distribution. If a dive is planned to last for more than 4 h, a mandatory rest and refreshment period with fluid intake is recommended. The amount and what to drink should be determined by individual needs and perceived thirst. Since the hyperosmotic seawater obviously has an effect on fluid loss (4,7), the use of dry suits with active heating as an alternative to the HWS should be considered.

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