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Depth of Immersion as a Determinant of the Natriuresis of Water Immersion (38147)

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Water immersion to the neck results in a significant natriuresis in normal seated subjects (1, 2). Although the natriuresis is thought to be mediated in part by the redistribution of blood volume induced by immersion (3–5) the precise mechanism whereby water immersion exerts this effect remains unclear. Previous studies from this laboratory have demonstrated that the increase in sodium excretion in supine subjects undergoing water immersion did not differ from supine controls, supporting the hypothesis that the natriuresis of water immersion is mediated in part by an immersion-induced hydrostatic pressure gradient (6).

The current study was undertaken to further assess the contribution of an immersion-induced hydrostatic pressure gradient on the redistribution of blood volume. Since the pressure exerted on body surfaces increases with increasing depth of immersion, it was anticipated that studies of renal sodium handling in subjects immersed at varying depths, would permit a more quantitative assessment of the relationship between the hydrostatic pressure gradient and the magnitude of the resultant natriuresis.

Material and Methods. Nine healthy male subjects between the ages of 18 and 42 years were studied. None had a history of hypertension, cardiovascular disease or diabetes. Significant renal disease was excluded by documenting a normal urine sediment and creatinine clearance and negative urine cultures. The subjects were housed during the study in an environmentally controlled metabolic ward at a constant temperature. Each consumed a diet containing 150 mEq sodium, 70 mEq potassium and 2,000 ml water, the composition of which remained unchanged throughout the study. Daily 24 hr urine collections were made for determination of sodium, potasium and creatinine. Following dietary equilibation, control studies were carried out on day 4, followed by immersion to the level of the umbilicus (waist immersion), immersion to the level of the nipples (chest immersion) and by immersion to the level of the sternoclavicular notch (neck immersion). To preclude the bias of the ordering sequence, the order of the experiments was varied. Four subjects initially underwent waist immersion, followed by chest immersion and then neck immersion. The order of the experiments was modified in the remaining five subjects as follows: neck immersion followed by chest immersion (2 subjects); neck immersion followed by waist immersion (2 subjects) and chest immersion followed by waist immersion and then neck immersion (1 subject). On study days, identical protocols were carried out as follows:

The subject was awakened at 0700 and instructed to void. After completely emptying his bladder, he was given a 700 ml oral water load and then assumed a seated position for 5 hr (0800–1300). During control studies, the subject sat quietly outside the immersion tank for the 5 hr period. During immersion, the subject sat in the study tank immersed in water for 4 hr (0900–1300), preceded by 1 hr of quiet sitting outside the tank (Pre-Immersion).

Each subject stood briefly every hour to void spontaneously. To maintain an adequate urine flow, 200 ml water was administered orally every hour during each study. Sodium was measured in aliquots of the hourly urine collection. All subjects were weighed every

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morning at 0730 after voiding, and before and after each study.

Immersion was carried out in a waterproof tank described in detail in a previous communication (1). A constant water temperature of 34 ± 0.5° was maintained throughout each immersion study.

Sodium and potassium were analyzed with a IL flame photometer. Creatinine was measured by an automated adaptation of Jaffee's picric acid reaction (7). In the presentation of the data, mean values are followed by the standard error of the mean as an index of dispersion. Data were evaluated statistically by two-factor analyses of variance procedure for experiments having repeated measurements in the same subject (8). If a significant effect was detected, the Duncan's new multiple-range test was used to determine which treatment means were significantly different (8). Nonsignificant differences were those with $P > 0.05$.

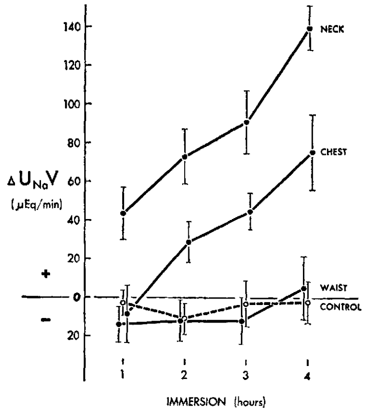

FIG. 1.

	Significance levels Time, Hours			
	1	2	3	4
Control vs. waist	N.S.	N.S.	N.S.	N.S.
Control vs. chest	N.S.	$< .05$	$< .01$	$< .01$
Control vs. neck	$< .01$	$< .01$	$< .01$	$< .01$
Waist vs. chest	N.S.	$< .05$	$< .01$	$< .05$
Waist vs neck	$< .01$	$< .01$	$< .01$	$< .01$
Chest vs. neck	$< .01$	$< .01$	$< .05$	$< .05$

Alterations in the rate of sodium excretion ($U_{Na}V$) during water immersion at varying depths. Data are expressed in terms of the absolute changes from the preimmersion hour ($\Delta U_{Na}V$). The increment in $\Delta U_{Na}V$ during chest immersion exceeded the changes during control and waist immersion during hours 2 through 4. Neck immersion was associated with an even greater increment in $\Delta U_{Na}V$, exceeding the values encountered during waist and chest immersion during every hour of study.

Permission was obtained for the study from each subject after a detailed description of the procedure and potential complications. The protocol was aproved by the Human Experimentation Committees of the University of Miami School of Medicine and the Miami Veterans Administration Hospital. No complications occurred.

Results. The effect of 4 hours of water immersion on sodium excretion are shown in Fig. 1. During control, the mean rate of sodium excretion ($U_{Na}V$) was constant, ranging from 50 to 57 μEq/min. Immersion to the waist did not significantly increase $U_{Na}V$ compared to the preimmersion hour ($\Delta U_{Na}V$). In contrast, water immersion to the mid-chest resulted in a significant increase in $\Delta U_{Na}V$ compared to both control and waist immersion, beginning with hour 2 of immersion. Immersion to the neck resulted in a further increase in $U_{Na}V$,—that increase ($\Delta U_{Na}V$) exceeding the $\Delta U_{Na}V$ induced by chest immersion during each hour of the study.

The rate of potassium excretion (U_KV) was significantly increased during chest immersion (hr 2) and neck immersion (hr 3 & 4) (Fig. 2). As a consequence, there was a significant increase in $U_{Na}V + U_KV$ during chest (hr 2) and neck immersion (hr 2–4) compared to control ($P < 0.05$).

Creatinine clearance (C_{Cr}) remained constant throughout all studies and did not differ one from the other except for a small decrease during hour 1 of chest immersion compared to neck immersion.

Discussion. Water immersion to the neck has previously been shown to produce a profound natriuresis in normal subjects in balance on an identical diet (1, 2). Although several lines of evidence have suggested that these effects are mediated by a redistribution of circulating blood volume with a relative increase in central blood volume (3–5), the mechanism whereby water immersion mediates such a redistribution is not clear. Gauer has suggested that an immersion-induced hydrostatic pressure gradient acting on the vascular columns of the body is responsible for the shift in the distribution of circulat-

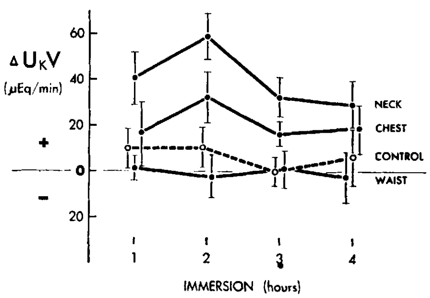

FIG. 2.

Significance levels

	Time, Hours			
	1	2	3	4
Control vs. waist	N.S.	N.S.	N.S.	N.S.
Control vs. chest	N.S.	$< .05$	N.S.	N.S.
Control vs. neck	N.S.	$< .01$	$< .01$	N.S.
Waist vs. chest	N.S.	N.S.	N.S.	N.S.
Waist vs. neck	N.S.	$< .01$	$< .01$	N.S.
Chest vs. neck	N.S.	N.S.	N.S.	N.S.

Alterations in the rate of potassium excretion (U_KV) during water immersion at varying depths. Data are expressed in terms of the absolute changes from the preimmersion hour (ΔU_KV). The natriuresis of water immersion was associated with a maintained or increased U_KV, suggesting an increased delivery of sodium from the proximal tubule.

ing blood volume from a more peripheral to a more central partition (3, 9). Recent studies from this laboratory have attempted to assess this postulate by studying the effects of water immersion on sodium homeostasis during recumbency, an experimental condition which would tend to minimize the hydrostatic pressure gradient (6). The demonstration that $U_{Na}V$ during immersion did not differ from control in recumbent subjects is consistent with the hypothesis that an immersion-induced hydrostatic pressure gradient participates in the natriuresis of immersion.

In an attempt to further assess the relationship between the hydrostatic pressure gradient and the natriuresis of immersion, the current study of renal sodium handling during graded immersion was undertaken. It was anticipated that increasing the depth of immersion would increase the hydrostatic pressure gradient acting on the vascular beds of the lower extremities and body trunk, and thus enhance the rate of sodium excretion during immersion.

Although a previous study from this laboratory has demonstrated that water immersion to the waist did not alter renal sodium handling compared to control (10), differences in experimental design preclude inferences regarding the effect of varying the depth of immersion on the resultant natriuresis. Thus, in the former study (10), the subjects were studied while in balance on a 10 mEq sodium diet. Since dietary sodium restriction has been shown to markedly blunt the natriuresis of water immersion (1), it is conceivable that the failure of waist immersion to augment sodium excretion in the earlier study may have reflected the limitations imposed by the sodium-depleted and volume contracted state of the subjects (1). Furthermore, the effect of water immersion to the mid-chest was not examined.

The present studies demonstrate that immersion to the level of the mid-chest in normal subjects in balance on a 150 mEq Na

TABLE I. Effect of Immersion on Urinary Excretory Patterns
(Results are Mean ± SE of 9 subjects).

	Group	Pre-Immersion	Time, Hours			
			1	2	3	4
C_{Cr} ml/min	Control A	116 ± 10	114 ± 6	99 ± 9	106 ± 13	113 ± 7
	Waist B	114 ± 10	116 ± 8	113 ± 6	107 ± 10	123 ± 12
	Chest C	124 ± 17	105 ± 10	120 ± 8	117 ± 5	124 ± 3
	Neck D	113 ± 9	136 ± 7	118 ± 9	115 ± 10	132 ± 8
Significance levels	A vs B	N.S.	N.S.	N.S.	N.S.	N.S.
	A vs C	N.S.	N.S.	N.S.	N.S.	N.S.
	A vs D	N.S.	N.S.	N.S.	N.S.	N.S.
	B vs C	N.S.	N.S.	N.S.	N.S.	N.S.
	B vs D	N.S.	N.S.	N.S.	N.S.	N.S.
	C vs D	N.S.	$< .05$	N.S.	N.S.	N.S.

diet produces an increase in $U_{Na}V$ compared to both control and waist immersion. Immersion to the neck produced an earlier (hr 1 vs. hr 2) and more profound increase in $U_{Na}V$ compared to chest immersion.

The demonstration that U_KV increases during chest and neck immersion is consistent with previous data (1, 2), suggesting an increase in proximal sodium rejection. Finally, the demonstration that creatinine clearance during chest and neck immersion did not differ significantly from that during control is consistent with previous data (1, 2), and suggests that the increase in $U_{Na}V$ during chest and neck immersion was not attributable to a concomitant increase in filtered sodium load.

The current study suggests that volume contraction did not account for the previous inability to demonstrate an effect of waist immersion on renal sodium handling (10). It seems more likely, as suggested by Gauer and Thron, that immersion to the level of the diaphragm merely cancels the intravascular hydrostatic pressure gradient by providing an identical external gradient (11). However, increasing the depth of immersion above the level of the diaphragm results in an increasing water pressure which tends to favor a shift in volume from the lower extremities.

The current observations are consistent with the hypothesis that an immersion-induced hydrostatic pressure gradient participates in mediating the increase in central blood volume reported during immersion with a resultant natriuresis (6). It is probable that the increase in central blood volume is attributable to a redistribution of circulating blood volume. Alternatively, it is possible that with increasing depth of immersion, there is an increasing tendency for fluid to redistribute from the interstitial compartment to the plasma compartment of the total extracellular fluid volume with a resultant increase in circulating blood volume. Such a mechanism may interact in an additive manner with a redistribution of blood volume *per se*, to induce the resultant natriuresis. Unfortunately, the absence of serial determinations of plasma hematocrit and plasma protein at frequent intervals during immersion precludes inferences regarding this possibility.

Summary. Water immersion to the neck has been demonstrated to produce a profound natriuresis in normal seated subjects. Since an immersion-induced hydrostatic pressure gradient with a resultant redistribution of circulating blood volume has been postulated to produce this natriuresis, it was of interest to examine this postulate by sequentially assessing renal sodium handling at varying depths of immersion. Renal sodium handling was assessed in nine normal subjects on four occasions while in balance on a 150 mEq Na diet; control, waist immersion, chest immersion and neck immersion, under identical conditions of diet, posture and time of day. Immersion to the mid-chest was associated with a significant increase in $U_{Na}V$ compared to waist immersion ($P < 0.05$). Immersion to the neck resulted in a further increment in $U_{Na}V$ compared to chest immersion ($P < 0.05$).

These data are consistent with the hypothesis that the immersion-induced hydrostatic pressure gradient acting on the vascular beds of the lower extremities and body trunk participates in mediating the natriuresis of water immersion.

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