Role of thermal and exercise factors in the mechanism of hypervolemia

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CONVERTINO, V. A., J. E. GREENLEAF, AND E. M. BERNAUER. *Role of thermal and exercise factors in the mechanism of hypervolemia.* J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 48(4): 657–664, 1980.—Our purpose was to determine whether the chronic increase in plasma volume (PV), resulting from heat exposure (HE) and exercise training (ET), was due only to elevated rectal temperature (T_{re}) or whether there were additional nonthermal factors related to the exercise. Eight men were divided into two groups. The HE group sat for 2 h/day (T_{db} = 42°C, 93% rh) for 8 consecutive days; T_{re} was raised by 1.72 ± 0.04°C to 38.5°C each day. The ET group rode a bicycle ergometer for 2 h/day for 8 days (T_{db} = 25°C, 60% rh) at a load (60–65 $\dot{V}O_{2\ max}$) that gave the same area under their T_{re} curve. PV increased by 177 ml (4.9%, $P < 0.05$) in the HE group and by 427 ml (12.0%, $P < 0.05$) in the ET group. This exercise-induced hypervolemia was associated with thermal factor(s) that contributed 40% and nonthermal factors that accounted for the remaining 60%. Some nonthermal, exercise-induced factors were twofold greater increases in plasma osmotic and vasopressin levels during exercise, and a fivefold increase in resting plasma protein (albumin) content.

plasma volume; rectal temperature; plasma proteins; plasma renin activity; arginine vasopressin; plasma osmolality

PLASMA VOLUME (PV) expansion (hypervolemia) of 10–23% (1, 36, 40) and isotonic expansion of the interstitial fluid volume (1) have been observed as an adaptive response to both natural and artificial acclimatization (acclimation) to heat. This hypervolemia is associated with increased sweat rate, increased evaporative heat loss, and decreased skin temperature during heat exposure (1, 14, 25, 40). Cardiovascular responses include decreased heart rate, increased stroke volume, and a possible increase in cardiac output (1, 36, 40). These thermoregulatory and cardiovascular adaptations correlate highly with PV (36) and appear to play significant roles in enhancing heat tolerance by producing a decreased core temperature and reduced strain as acclimation occurs.

Similarly, endurance exercise training results in an increase in blood volume (4, 20, 26), which appears to be primarily the result of PV expansion (26). This hypervolemia is associated with decreased heart rate and increased stroke volume during rest and exercise, and increased maximal oxygen uptake ($\dot{V}O_{2\ max}$) and maximal cardiac output (20, 26). The thermoregulatory responses to exercise training are similar to those of acclimation, i.e., increased sweat rate, decreased heat storage, and decreased core temperature at a given absolute steady-state work load (25).

It appears that PV expansion observed during heat acclimation is primarily a thermoregulatory adaptation, although most acclimation studies have employed an exercise regimen with the heat exposure. It is not clear whether hypervolemia following only exercise training is primarily the result of similar thermal stresses or a function of increased metabolic demands.

The present study was undertaken to determine if the chronic increase in PV that accompanies exercise training is due only to elevated rectal temperature or if there may be additional exercise-metabolic factors involved.

PROCEDURE

Eight healthy, moderately trained male college students (18–26 yr) volunteered to participate in the study. Following preliminary anthropometric measurements and determination of $\dot{V}O_{2\ max}$ and body fat content, the subjects were divided into two groups (Table 1).

The experimental protocol consisted of a 4-day control period, 8 days of 2 h/day heat exposure or exercise training, and 7 days of recovery. The subjects in the heat exposure group sat in a chamber for 2 h/day for 8 consecutive days at 42°C dry bulb (T_{db}) and 93% relative humidity (rh); the subjects' rectal temperatures (T_{re}) were raised by 1.72 ± 0.04°C each day. The subjects in the exercise-training group rode a Collins bicycle ergometer 2 h/day for 8 consecutive days at 25°C T_{db} and 60% rh at a relative load (60–65% $\dot{V}O_{2\ max}$) that gave the same equilibrium T_{re} and about equal areas under their T_{re} response curve when compared with those in the heat exposure group (Fig. 1). The subjects sat for at least 30 min before each 2-h exposure commenced. No fluid was consumed during the 2-h exposures. The subjects were told to eat and drink normally during the study and to eat breakfast on each of the 8 exposure days. With this experimental design the effect on PV expansion from the exercise (metabolic) factors could be isolated from the effect of increased body temperature.

METHODS

Maximal oxygen uptake was measured on *day 3* of the control period and on the 2nd day of recovery. The test started with a load of 100 W for 6 min, then 175 W for 6 min, 225 W for 6 min, and additional increments of 25 W/3 min until exhaustion. Expired gas flowed through

an Otis-McKerrow respiratory valve and the volume was measured with a Parkinson-Cowan (model CD-4) high-velocity low-resistance meter. Aliquots of the gas were collected in oiled 200-ml syringes, and the composition was determined with a Beckman E2 oxygen analyzer and a Godart Capnograph CO_2 analyzer. The gas analyzers were calibrated with standard gas analyzed by the Scholander technique (35).

Rectal temperature (thermistor inserted 20 cm) and skin temperatures at six locations were measured every 5 min during the 2-h exposure periods with individually calibrated thermistors (Yellow Springs Instrument series 400), with a Digitek (United Systems) instrument. The thermistors were attached to the skin with holders that allowed essentially free air movement (10). The skin and rectal temperatures were used to calculate mean skin ($\bar{T}_{sk}$) and mean body ($\bar{T}_{mb}$) temperatures according to the weighting scheme of Hardy and DuBois (13)

TABLE 1. *Subjects' descriptive data and average rectal, mean skin, and mean body temperatures during eight 2-h adaptation periods*

Age, yr	Ht, cm	Wt, kg	Body Fat, %	$\dot{V}O_{2\,max}$, l/min	T_{re},* °C	$\bar{T}_{sk}$,* °C	$\bar{T}_{mb}$,* °C
			Heat-exposure group				
23 ±1	174 ±2	78.00 ±2.48	14.5 ±1.8	4.29 ±0.08	38.15 ±0.13	38.82† ±0.22	38.28† ±0.22
			Exercise-training group				
21 ±1	179 ±2	70.60 ±4.54	13.6 ±2.9	4.41 ±0.35	38.17 ±0.08	32.36 ±0.03	37.01 ±0.07

Values are means ± SE. $\dot{V}O_{2\,max}$, maximal O_2 uptake; T_{re}, rectal temperature, $\bar{T}_{sk}$, mean skin temperature; $\bar{T}_{mb}$, mean body temperature. * Mean of 25 values taken at 5-min intervals over the 2-h period. † $P < 0.05$ from the exercise-training group.

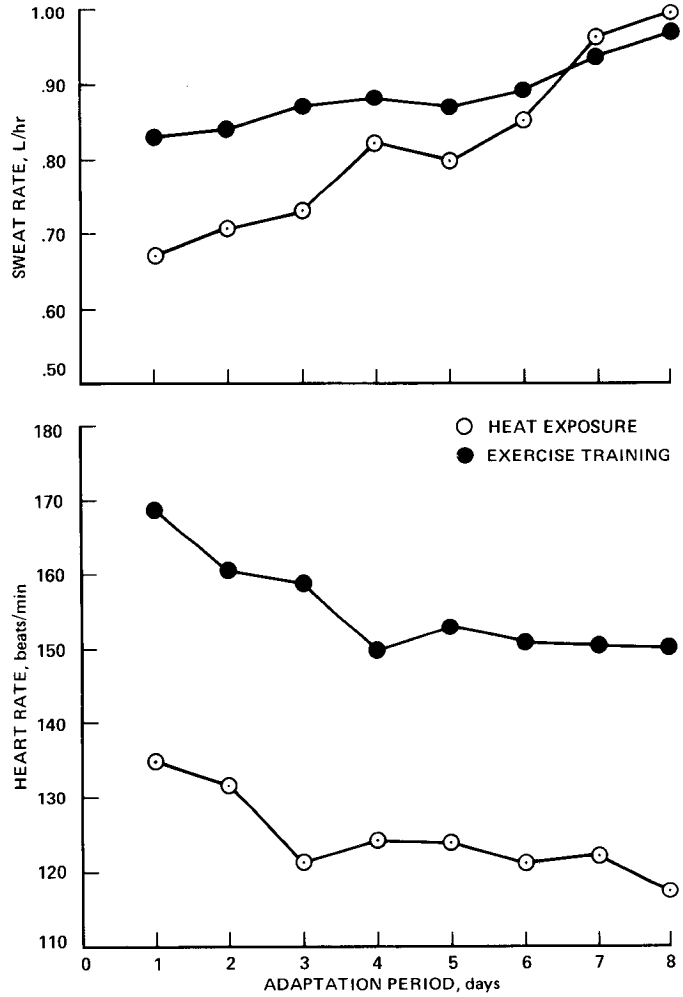

FIG. 2. Mean postexposure sweat rate and heart rate responses during heat-exposure and exercise-training regimens.

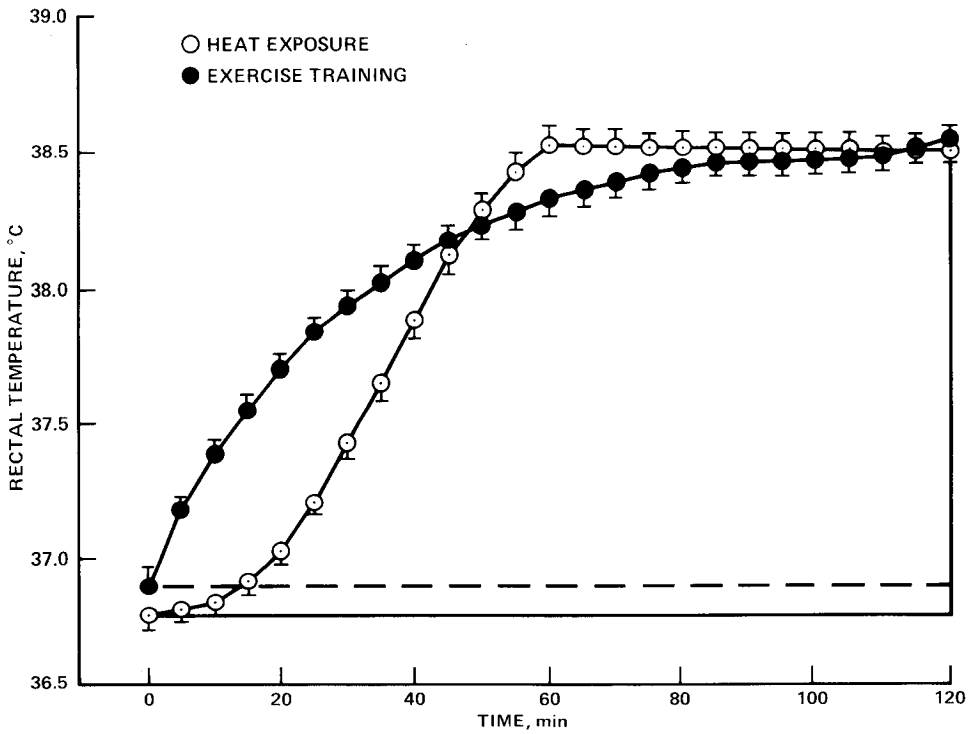

FIG. 1. Mean (±SE) rectal temperature response curves during 2-h heat exposure and exercise training regimens.

$$\bar{T}_{sk} = 0.06 \text{ arm} + 0.13 \text{ forearm} + 0.19 \text{ chest} + 0.20 \text{ back} + 0.21 \text{ thigh} + 0.21 \text{ leg}$$

$$\bar{T}_{mb} = 0.8\ T_{re} + 0.2\ \bar{T}_{sk}$$

Sweat loss was calculated from change in body weight during the 2-h exposures and corrected for blood withdrawal, respiratory water loss, and gas exchange. Heart rate was obtained every 5 min from an electrocardiogram.

Plasma volume was measured five times during each experiment with a modified Evan's blue dye (T-1824) dilution method (6): *1*) on *days 1* and *4* of the control periods with an error of ±1.0%, *2*) on *day 4* of the adaptation periods, *3*) on the 1st day of recovery, and *4*) after 7 days of recovery. Total blood volume (BV) and red cell volume (RCV) were calculated from PV and hematocrit

$$BV = PV \times \left[\frac{100}{100 - (0.874 \times Hct)}\right] \qquad (1)$$

$$RCV = BV - PV$$

Antecubital venous blood samples (25 ml) were collected without stasis 5 min before and immediately after the 2-h adaptation periods on *days 1*, *2*, *4*, and *8*. Plasma from all blood samples was analyzed for Na^+ and K^+ (Instrumentation Laboratory flame photometer, model 143), osmolality by freezing-point depression (Advanced Instruments, model 3R-AS), and for Mg^{2+} and total Ca^{2+} (Perkin-Elmer atomic absorption, model 403). Total plasma protein and albumin concentrations were determined by the colorimetric techniques of Lowry et al. (23) and Debro et al. (5), respectively. The plasma globulin fraction was total protein minus albumin.

Microhematocrit (Hct) values were determined in quadruplicate with an error of ±0.025%. Raw hematocrit values were corrected for trapped plasma and whole-body Hct by multiplication with the factors 0.96 and 0.91, respectively (2, 3). Hemoglobin (Hb) concentration was measured by the cyanomethemoglobin technique (Coulter hemoglobinometer, model ZBI).

Plasma arginine vasopressin (AVP) concentration was determined by radioimmunoassay (16). Plasma renin activity (PRA) was analyzed with the modified method of Haber et al. (11) utilizing a New England Nuclear kit.

Total plasma osmolar, protein, and electrolyte contents were calculated by multiplying their concentrations times PV. Percent change in PV (%ΔPV) during each 2-h adaptation period was calculated from the corrected Hct values and Hb concentrations (9). Changes in plasma osmolality, AVP, and PRA concentrations during the exposures were expressed as the difference between the pre (resting) and post (after exposure) values.

The data were analyzed by analysis of variance and the null hypothesis was rejected when $P < 0.05$. Nonsignificant differences were indicated by NS.

RESULTS

Responses to maximal exercise. Following the 8-day adaptation period the mean (±SE) $\dot{V}O_{2\ max}$ of the resting, heat-exposure group decreased slightly from 4.29 ± 0.08 to 4.20 ± 0.08 l/min (NS); however, all four subjects in the exercise-training group elevated their $\dot{V}O_{2\ max}$ following the 8-day exercise regimen from a mean of 4.41 ± 0.35 to 4.60 ± 0.33 l/min (+4.3%, $P < 0.05$) and exhibited an increase in maximal work load of 25 W (+10.0%, $P < 0.05$). The average (±SE) maximal heart rates decreased in both groups following their respective 8-day exposures: from 184 ± 5 to 175 ± 5 beats/min (−4.9%, $P < 0.05$) in the heat group, and from 193 ± 3 to 181 ± 3 beats/min

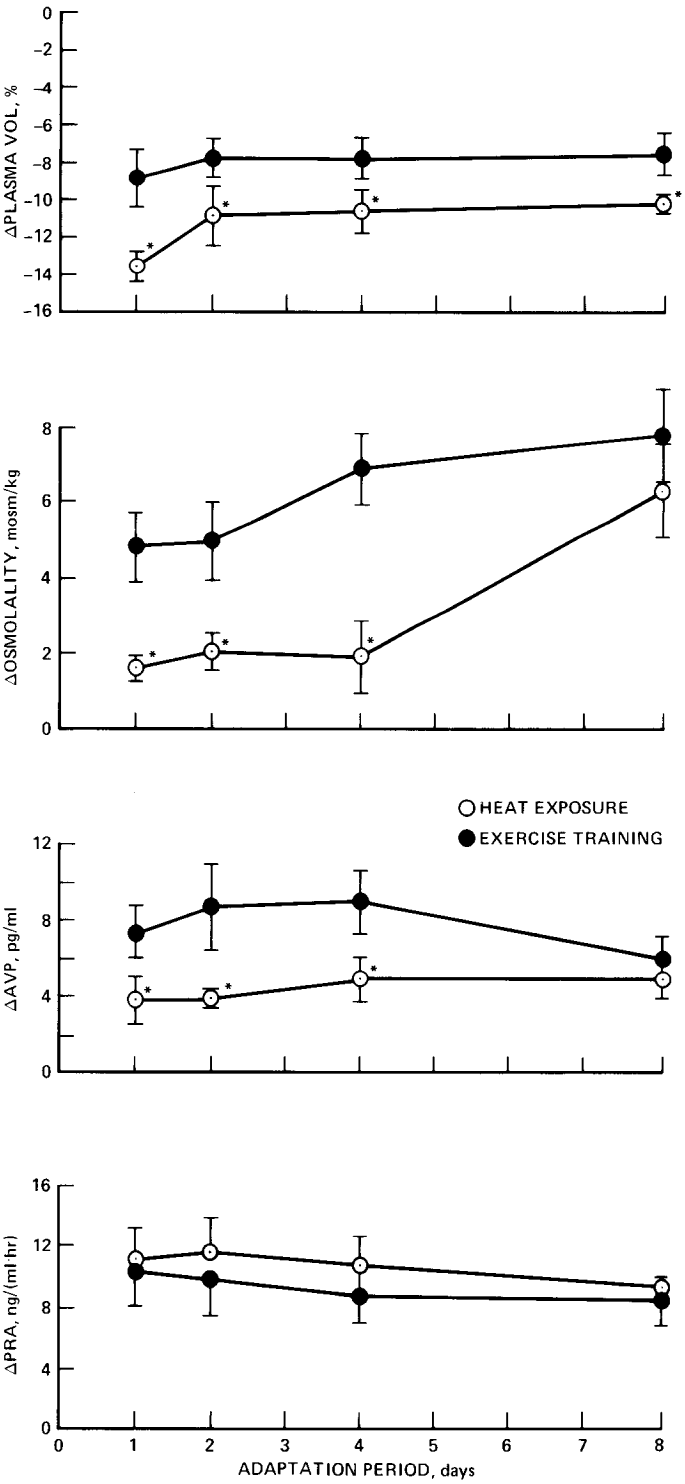

FIG. 3. Mean (±SE) changes in plasma volume, osmolality, arginine vasopressin (AVP), and renin activity (PRA) following 2-h heat-exposure and exercise-training regimens. * $P < 0.05$ from exercise-training response.

(−6.2%, $P < 0.05$) in the exercise group.

Responses during 2-h adaptation periods. Mean total body sweat rates during the adaptation periods increased in both groups from *day 1* to *8* (Fig. 2); the increase in the heat group, from 0.67 l/h on *day 1* to 0.99 l/h on *day 8* (+48%, $P < 0.05$), was greater than the increase in the exercise group (0.83 l/h on *day 1* to 0.97 l/h on *day 8*, Δ = +17%, NS). Both groups demonstrated exponentially decreasing responses in heart rate: from 135 ± 6 beats/min on *day 1* to 117 ± 6 beats/min on *day 8* (Δ = 18 beats/min, $P < 0.05$) in the heat group, and from 169 ± 5 beats/min on *day 1* to 148 ± 4 beats/min on *day 8* (Δ = 21 b/min, $P < 0.05$) in the exercise group (Fig. 2).

The mean values of rectal, mean skin, and mean body temperatures during the 2-h adaptation periods (mean of 25 values taken at 5-min intervals) are presented in Table 1. The mean T_{re} was the same for both groups, and this was confirmed by essentially equal areas under the T_{re} response curves: 30.53°C·min for the heat group and 30.88°C·min for the exercise group (Fig. 1). Thermal equilibrium was reached at 60 min in the heat-exposure group, and was essentially reached in the exercise group at about 110 min of exposure. $\bar{T}_{sk}$ and $\bar{T}_{mb}$ were higher ($P < 0.05$) in the heat group (Table 1). To maintain the T_{re} at 38.5°C during the 8 days of exercise in this study, it was necessary to increase the mean (±SE) absolute work loads from 920 ± 56 kpm/min on *day 1* to 1,027 ± 59 kpm/min on *day 8*. Since the $\dot{V}O_{2\ max}$ of the exercise group increased, the absolute work load required to maintain a given relative work load (i.e., 65% $\dot{V}O_{2\ max}$) also increased. Similarly, the heat-exposed subjects required progressively longer exposures on successive days of acclimation to produce a T_{re} of about 38.5°C. These responses indicated a progressive reduction in physiological strain.

On *days 1*, *2*, *4*, and *8* of the adaptation periods, the 2-h heat exposures produced a mean plasma volume loss (shift) of 12.0% (range 10.0–13.7%), which was larger ($P < 0.05$) than the %ΔPV of −8.7% (range 7.2–9.8%) produced by 2 h of exercise (Fig. 3, Table 2). The exercise group showed a consistently larger change in plasma osmolar concentration during the 2-h exposure periods than did the heat group; these differences were significant ($P < 0.05$) on *days 1*, *2*, and *4* (Fig. 3). The changes in osmolality correlated +0.96 ($P < 0.05$) with the changes in plasma [Na^+]. The change in plasma [K^+] in the exercise group was higher ($P < 0.05$) than that of the heat group; but the changes in Ca^{2+} and Mg^{2+} concentrations were similar during exercise and heat exposure (Table 2).

AVP and PRA were significantly elevated above resting levels as a result of both adaptive regimens (Fig. 3, Table 2). The exercise group AVP increased by 7.9 pg/ml ($P < 0.05$), nearly twice the change observed in the heat-exposed subjects (+4.3 pg/ml, $P < 0.05$). Exercise produced a slightly smaller elevation in PRA (+9.7 ng·ml^{-1}·h^{-1}, $P < 0.05$) than that induced by heat (+11.5 ng·ml^{-1}·h^{-1}, $P < 0.05$). AVP correlated +0.70 ($P < 0.05$) with the change in plasma osmolality and −0.41 (NS) with %ΔPV. The ΔPRA was negatively correlated with %ΔPV ($r = -0.64$, $P < 0.05$) but showed a low correlation with the change in plasma osmolality ($r = 0.03$, NS).

Plasma volume and plasma content. Body weight increased in each subject in the exercise group following 8 days of training from a mean level of 70.60 ± 4.54 to 71.30 ± 4.61 kg (+700 g, $P < 0.05$). A smaller increase, from 78.00 ± 2.48 to 78.35 ± 2.57 kg (+350 g, NS), was observed in the heat group.

Resting levels of blood and plasma volumes and plasma total protein, electrolyte, and osmolar contents before, during, and after the 8-day exposure periods are presented in Fig. 4. Compared to preadaptation levels, the PV of the exercise group increased by 270 ml ($P < 0.05$) on *day 4* and by 427 ml (+12.0%, $P < 0.05$) on *day 8*. In the heat group PV increased by only 33 ml (+0.9%, NS) by *day 4* but increased by 177 ml (+4.9%, $P < 0.05$) on *day 8*. These PV increases were associated with significant decreases in Hct in both the exercise group (37.5 ± 1.4 to 35.3 ± 0.8%, $P < 0.05$) and the heat-exposure group (from 38.0 ± 2.7 to 36.1 ± 3.5%, $P < 0.05$). As a result, blood volume increased by the same magnitude as PV because red cell volume remained essentially constant (Fig. 4).

Resting plasma electrolyte and osmolar contents increased during the 8-day adaptation periods in both groups in isotonic proportion to the increase in PV (Fig.

TABLE 2. *Sweating, plasma volume change, and plasma concentrations of electrolytes, proteins, osmolality, renin activity, and arginine vasopressin*

	Heat-Exposure Group			Exercise-Training Group		
	Rest	Post	%Δ	Rest	Post	%Δ
Sweat production, l/h		0.81 ± 0.04*			0.89 ± 0.02*	
Plasma volume, %Δ		−12.0 ± 0.8*†			−8.7 ± 0.7*	
Na^+, meq/l	140.9 ± 0.2	141.8 ± 0.4*†	+0.6	141.0 ± 0.3	143.7 ± 0.3*	+1.9
K^+, meq/l	4.20 ± 0.04	4.17 ± 0.04†	−0.7	4.16 ± 0.06	4.78 ± 0.08*	+14.9
Ca^{2+}, mg/100 ml	9.60 ± 0.08	10.37 ± 0.13*	+8.0	9.83 ± 0.12	10.35 ± 0.10*	+5.3
Mg^{2+}, mg/100 ml	1.99 ± 0.03	1.97 ± 0.02	−1.0	2.03 ± 0.03	1.95 ± 0.04	−3.9
Total protein, g/100 ml	7.22 ± 0.07	7.98 ± 0.07*	+10.5	7.11 ± 0.08	7.77 ± 0.09*	+9.3
Albumin, g/100 ml	4.90 ± 0.06	5.48 ± 0.11*	+11.8	4.89 ± 0.10	5.45 ± 0.10*	+11.5
Globulin, g/100 ml	2.32 ± 0.12	2.50 ± 0.13	+7.8	2.22 ± 0.11	2.32 ± 0.12	+4.5
Osmolality, mosmol/kg	290.9 ± 0.6†	293.3 ± 0.8*	+0.8	288.0 ± 0.7	294.3 ± 0.8*	+2.2
PRA, ng Ang I·ml^{-1}·h^{-1}	1.2 ± 0.3	12.7 ± 1.0*	+958.3	1.1 ± 0.2	10.8 ± 1.2*	+881.8
AVP, pg/ml	1.2 ± 0.2	5.5 ± 0.5*	+358.3	1.4 ± 0.2	9.3 ± 1.9*	+564.3

Values are means ± SE from *days 1*, *2*, *4*, and *8*. Post, after 2-h exposures; PRA, plasma renin activity; AVP, arginine vasopressin. * $P < 0.05$ from rest value. † $P < 0.05$ from comparable exercise-training group value.

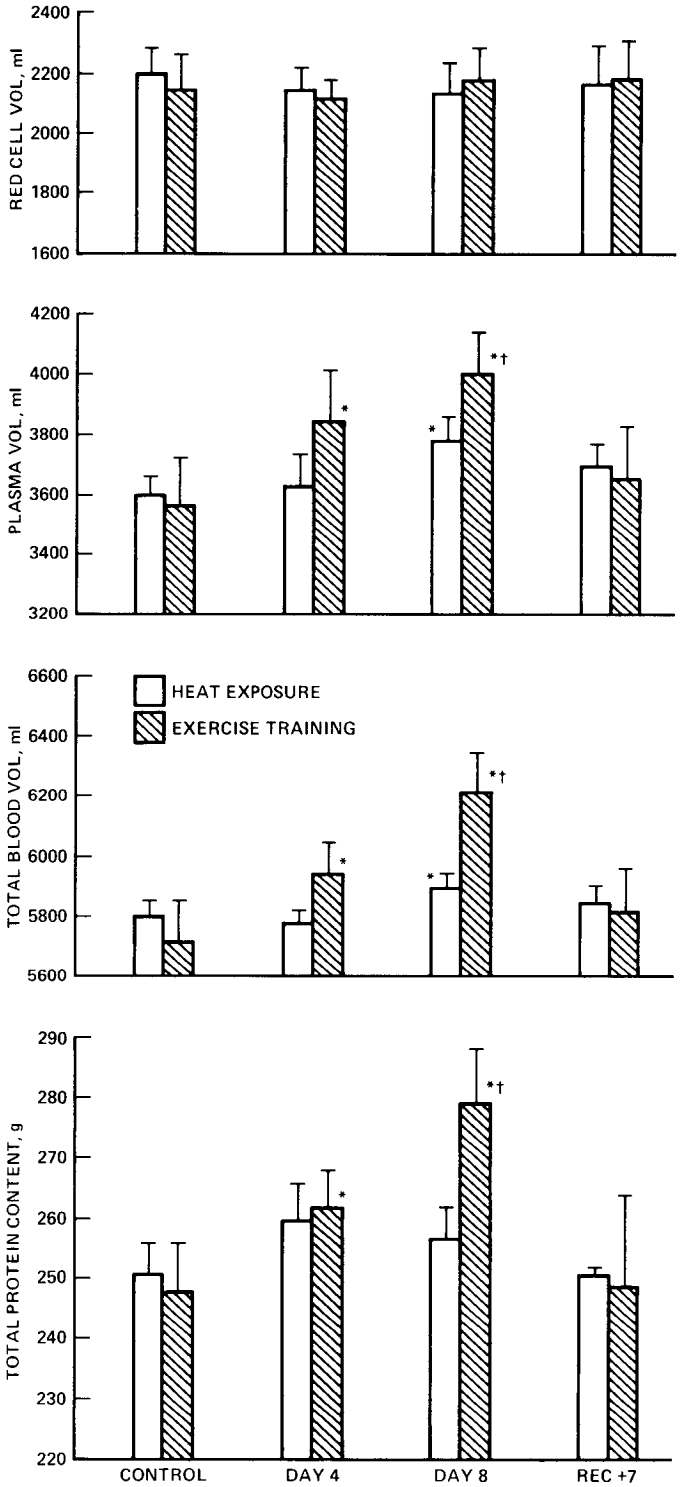

FIG. 4. Mean (±SE) resting plasma, red cell, and total blood volumes and total protein content during control, adaptation (*days 4* and *8*), and recovery periods for heat-exposure and exercise-training regimens. * $P < 0.05$ from control value (one-tailed test). † $P < 0.05$ from *day 4* value (one-tailed test).

5). The exercise group had greater increases ($P < 0.05$) in Na^+ (+1.4 g), K^+ (+74 mg), and osmolar contents (+140 mosmol) following adaptation than the heat group: Na^+ = +0.7 g, K^+ = +59 mg, and osmolar content = +62 mosmol. Plasma Ca^{2+} and Mg^{2+} contents were essentially constant during adaptation in both groups: Ca^{2+} varied between 346 and 370 mg, and Mg^{2+} between 71 and 77 mg. The increase in plasma total protein content in the heat group was only 6 g (NS), but in the exercise group it increased by 31 g ($P < 0.05$) due mainly to an increase in albumin (+28 g, $P < 0.05$) and a minor increase in globulin (+3 g, NS).

Plasma volume, electrolyte, and protein contents had essentially returned to control levels by 7 days after adaptation (Figs. 4 and 5).

DISCUSSION

Temperature vs. metabolic factors and hypervolemia. The present study was designed to isolate the temperature factor from the exercise factor(s), by comparing the changes in PV following exercise training and heat exposures of equal duration, when the rectal temperature responses of the two groups were the same (i.e., the areas under the rectal temperature curves with time of exposure were equal). The PV of the heat exposure group increased by 4.9% (177 ml, $P < 0.05$) after 8 days of heat treatment and that of the exercise group increased by 12.0% (427 ml, $P < 0.05$). These results suggest that about 40% of the hypervolemia induced by exercise training could be attributed to a thermal (body temperature) stimulus; the remaining 60% appears to be contributed by additional factors related to the exercise.

The hypervolemia observed during exercise-induced heat acclimation appears to be a response to increased thermoregulatory and metabolic demands. If the hypervolemic response were proportional to the total stress (thermal plus metabolic), then, with the same increase in body heat storage (core temperature) in the two conditions, a greater increase in plasma volume would be expected during exercise training in a cool environment than during rest in a hot environment. The results of the present study support that hypothesis. Furthermore, previous experiments from our laboratory (4) have demonstrated that 8 days (2 h/day) of exercise training at 50% $\dot{V}O_{2\ max}$ in the heat (42°C T_{db}, 50% rh) produced an even greater increase in PV of 552 ml (+17%, $P < 0.05$). Hypervolemia stabilized at 23% over control levels after 13 days of heat acclimation under even more severe conditions (36). That evidence lends support to the hypothesis that increased metabolism or other responses induced by exercise are necessary for maximal expansion of plasma volume; the exercise factor and the heat storage factor appear to be additive for induction of hypervolemia following chronic adaptive exposures.

The temperature and metabolic stimuli required to induce exercise hypervolemia must be applied periodically to maintain plasma expansion. Following the 8-day exercise and heat-exposure periods, the subjects maintained sedentary minimal activity for the next 7 days and PV returned to within 60–80 ml of control values. The plasma solute contents and concentrations and endocrine levels also approached control values. Thus, the control mechanism for PV expansion with chronic intermittent, exercise responds within 4 days [probably after the first exposure (36)] with increased fluid and electrolyte retention and diminishes within 1 wk when the stimuli are removed.

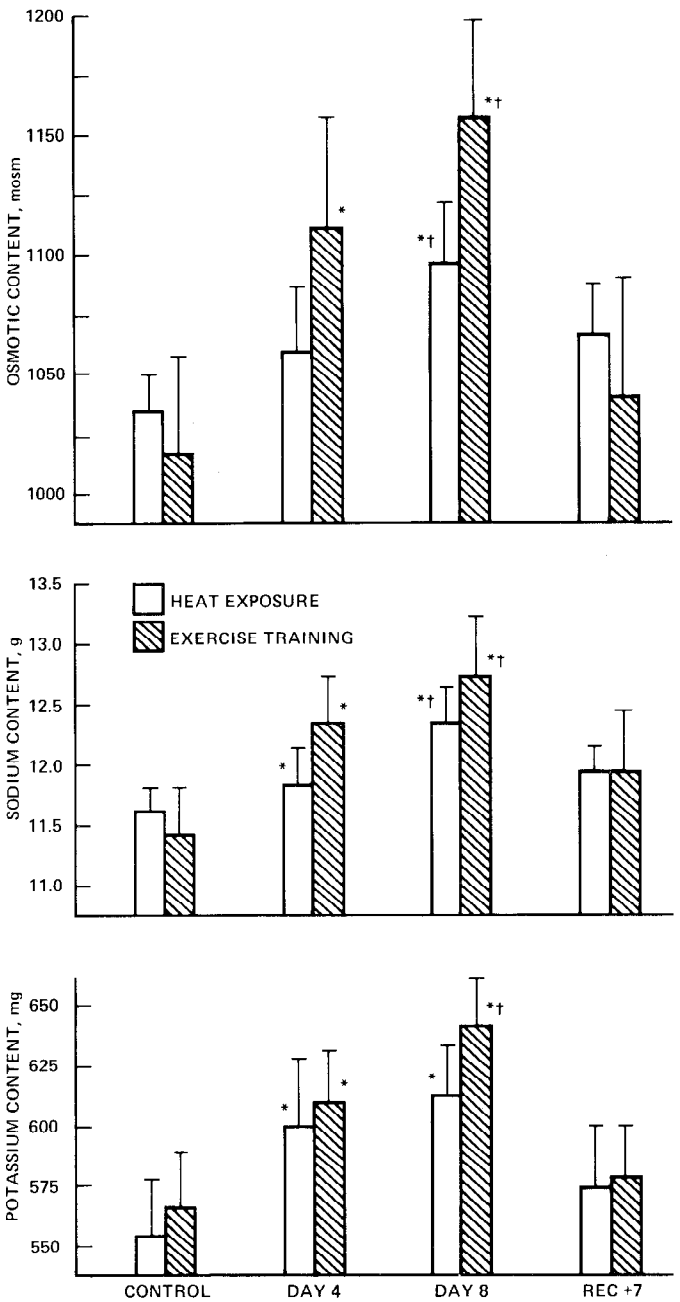

FIG. 5. Mean (±SE) resting osmotic, sodium, and potassium contents during control, adaptation (*days 4* and *8*), and recovery periods for heat-exposure and exercise-training regimens. * $P < 0.05$ from control value (one-tailed test). † $P < 0.05$ from *day 4* value (one-tailed test).

Plasma fluid shifts and hypervolemia. The average plasma shifts (losses) during the eight 2-h exposures were −8.7% during exercise training and −12.0% during heat exposure (Fig. 4), but resting plasma volume after adaptation increased by 12.0% (427 ml) after exercise and by only 4.9% (177 ml) after heat exposure. The greater net fluid shift with heat exposure was most probably due to greater filtration of vascular fluid from increased capillary hydrostatic pressure associated with increased cutaneous blood flow in response to the high skin temperatures (>38.8°C and 6.5°C higher than $\bar{T}_{sk}$ during exercise). There was probably no net gain in extracellular fluid volume in the exercise group from metabolic water (+175 ml) because it was nearly equal to that group's greater sweat rate of 160 ml over the eight adaptation periods (Table 2). The corresponding metabolic water production in the heat group was 22 ml. Clearly, the magnitude of the PV shifts per se during adaptation was not related to the ultimate levels of resting hypervolemia.

Plasma proteins and hypervolemia. After the 8-day adaptation period, the exercise group increased its plasma total protein content by 31 g, which agrees with the increase of 32 g observed by Senay et al. (36) after 10 days of exercise-heat acclimation. Protein content of the resting heat group increased by only 6 g; however, our high correlation of 0.96 between plasma volume and protein content supports previous findings that hypervolemia induced by exercise training accompanies hyperproteinemia (21, 32). Since 1 g of protein "binds" 14–15 ml of water (34, 36), the 31-g increase in protein content of the exercise group would increase the plasma water-binding capacity by 435–465 ml, which agrees with our mean hypervolemia of 427 ml. The 6-g increase of protein content in the heat group would increase plasma water-binding capacity by only 85–90 ml, about half the observed increase of 177 ml. The balance of this volume expansion could have been associated with increased osmotic (sodium) content (Fig. 5). It appears that most of the increase in plasma protein content with classical heat acclimation is due to the metabolic (exercise) stimulus, rather than to environmental and body heating, since the differential hyperproteinemia between the two conditions is independent of the change in core temperature.

The mechanism of the increase in plasma protein content with induction of hypervolemia is not clear. If there is an isotonic expansion of the total extracellular volume during heat-exercise acclimation, as measured by Bass et al. (1), there would be an isotonic expansion of both plasma and interstitial fluid volumes (ISV) with proportional increases in total protein content. In normal resting men the respective total protein concentrations (and volumes) of the thoracic lymphatic system, PV and ISV, are approximately 5.0 g/100 ml (1.5 liters), 7.2 g/100 ml (3.6 liters), and 4.3 g/100 ml (12.0 liters) (27–29, 33); so the respective total protein contents would be 75, 259, and 516 g (total 850 g). A similar calculation for albumin would give 30, 176, and 348 g (total 554 g). A 12% isotonic fluid expansion would increase total protein by 102 g and albumin by 66 g. It is difficult to envision this additional quantity of protein coming entirely from the cutaneous interstitial spaces via the lymphatic system by means of a flushing action (36), because the result would be a protein deficit in the ISV in opposition to the findings of Bass et al. (1). Since the rate of degradation and probably synthesis in resting subjects of human albumin is 8–12%/day, γ-globulin 4–6%/day, and fibrinogen 35%/day (24), an alternative source of additional protein could come from de novo synthesis. These values may not hold during exercise training inasmuch as both increased protein synthesis and degradation occur after exercise (12).

Plasma electrolyte, osmotic, and endocrine responses and hypervolemia. The interactions between fluid volume, electrolytes, and the renin-angiotensin-aldosterone

and vasopressin systems are complex because the levels of PRA and AVP are affected by each other (15, 17) as well as by changes in blood pressure (19), blood volume (18, 31, 37), plasma Na^+, K^+, and osmolality (18, 30, 31), and direct sympathetic input to juxtaglomerular cells (38). The average increases in PRA during the 2-h exposures were essentially similar for both groups, but average AVP levels were greater by a factor of two during exercise than during heat exposure at rest. Because the loss in PV during the 2-h exposures was 28% less in the exercise group, the elevated AVP was not proportional to PV loss. The mean losses in PV during exercise and heat exposure of −8.7 and −12.0%, respectively, resulted in total blood volume losses of about −5.6 and −7.6%, respectively (assuming no significant change in RCV). These acute decreases in blood volume were probably not sufficient to increase AVP at rest, because the release of vasopressin without osmolar changes requires more than a 10% reduction of effective blood volume (19); but this relationship may not hold during exercise. The greater AVP concentrations in the exercise group, however, accompanied the greater changes in plasma osmolality during the 2-h exposures. Those results agree with previous conclusions that hyperosmolality appears to be the dominant factor in the regulation of AVP release, with hypovolemia acting as a secondary stimulus (18, 30, 31).

The significantly elevated vasopressin concentrations during exercise adaptation did not stimulate commensurate increases in PRA (Fig. 4). This suggests that PRA was at its maximal level under these conditions to induce maximal sodium retention to protect against the stress-induced losses of PV. Thus, the magnitude of the loss in PV during the adaptation exposures, or the magnitude of the increase in PRA, was not a primary factor that could account for the final increased levels of PV. But the greater change in AVP, which was associated with the increases in plasma osmolality during exercise adaptation, was more closely related to the greater chronic hypervolemia. It would appear that during exposure periods the elevated PRA would enhance sodium conservation which, in turn, would elevate plasma osmolality and vasopressin to thus enhance fluid retention.

It is still an open question whether there are sufficient residual stimuli from fluid and electrolyte parameters to account for the progressive chronic hypervolemia after intermittent exposure to stress. After 10 min of maximal exercise, plasma volume, electrolyte, osmotic, and protein contents and concentrations returned to control levels within 1 h of recovery (7, 39). After 60 min of submaximal exercise it appears that more than 1 h is required for recovery of those parameters (7). In general, the time for restoration of fluid balance after stress is directly proportional to the time of exposure and to the level of dehydration incurred; recovery after exercise stress takes longer than after resting stress (8). Since exercise apparently depletes intracellular water to a greater extent than resting heat exposure (22), it is possible that depletion of intracellular fluid volume as well as depletion of the extracellular fluid volume are important parts of the chronic hypervolemic mechanism.

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