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EFFECTS OF BODY MASS AND MORPHOLOGY ON THERMAL
RESPONSES IN WATER(U) ARMY RESEARCH INST OF
ENVIRONMENTAL MEDICINE NATICK MA M M TONER ET AL.

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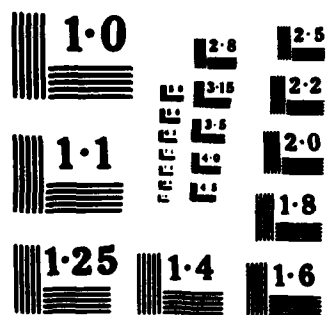
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EFFECTS OF BODY MASS AND MORPHOLOGY
ON THERMAL RESPONSES IN WATER

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Abstract

Ten male volunteers were divided into two groups based on body size and weight. The large body mass (LM) group (n=5) was 16.3 kg heavier and $0.24 \text{ m}^2 \cdot \text{kg}^{-1} \cdot 100$ smaller in surface area-to-weight ratio ($P < 0.05$) than the small body mass group (n=5). Both groups were similar in total body fat and skinfold thicknesses ($P > 0.05$). All individuals were immersed for 1 h in water at 26°C during both rest and one intensity of exercise (metabolic rate $\sim 550 \text{ W}$). During resting exposures, metabolic rate ($\dot{M}$), mean-heat flow ($\dot{H}_c$), and rectal temperature (T_{re}) were not different ($P > 0.05$) between the LM and SM groups at min 60. Esophageal temperature (T_{es}) was higher ($P < 0.05$) for the SM group at min 60, though the change in T_{es} during the 60 min between groups was similar (LM, -0.4°C ; SM, -0.2°C). Similarly during exercise $\dot{M}$, $\dot{H}_c$, T_{re} and T_{es} were not different ($P > 0.05$) between groups at min 60. These data illustrate that moderate differences in body size and weight between individuals from a given population do not effect thermal responses in water. Also, studies contrasting dissimilar populations such as men and women should consider alternative explanations for differing thermal responses when body size differences are of similar magnitude as presently reported.

Key words: Body size - Body mass - Thermoregulation - Metabolism - Water immersion.

The role of surface area to mass ratio ($A_D \cdot \text{wt}^{-1}$) in human thermoregulation has been described in both the high (Bar-Or et al. 1969; Epstein et al. 1983; Shapiro et al. 1980; Shapiro et al. 1981; Wyndham et al. 1964c) and low (Buskirk and Kollias 1969; Hayward et al. 1975; Kollias et al. 1974; McArdle et al. 1984a; Sloan and Keatinge, 1973; Smith and Hanna 1975; Strong and Goldman, In Press) ambient temperature literature. Recent work in the heat by Epstein et al. (1983) suggested that heat intolerance might be related to low $A_D \cdot \text{wt}^{-1}$ whereby a small surface area relative to body weight would reduce the potential for evaporative cooling and therefore increase core temperature responses compared with higher $A_D \cdot \text{wt}^{-1}$. Shapiro et al. (1980) also suggested that the higher $A_D \cdot \text{wt}^{-1}$ of females compared with males contributed to the lower rectal temperature (T_{re}) responses in hot-humid environments. In a similar fashion, $A_D \cdot \text{wt}^{-1}$ has also been implicated in the water immersion literature as a contributor to heat transfer. Sloan and Keatinge (1973) showed that the fall in T_{re} was related to $A_D \cdot \text{wt}^{-1}$ in young swimmers whereas Buskirk and Kollias (1969) reported that the smaller $A_D \cdot \text{wt}^{-1}$ in large individuals favored heat conservation in both cold air and cold water.

Morphological and body mass characteristics appear from these data (Buskirk and Kollias 1969; Epstein et al. 1983; Shapiro et al. 1980; Sloan and Keatinge 1973) to be significant factors that distinguish thermal responses between individuals. However, when establishing relationships through either statistical or theoretical means one must be cautious of the interpretation and the magnitude of the relationships. Indeed, though the $A_D \cdot \text{wt}^{-1}$ may be different between groups of men and women or between heat intolerants and normals, differences in T_{re} response

between groups might be due to factors other than morphology or body mass which have yet to be elucidated.

The purpose of the present study was to examine the role of morphology and body mass upon thermal and metabolic responses of individuals in water. Two groups of individuals from a similar population had matching subcutaneous and total body fat content but different body mass and morphology (i.e. total weight, lean body weight and $A_D \cdot \text{wt}^{-1}$). These subjects were immersed in water at 26°C and the thermal and metabolic responses of these groups were contrasted during rest and exercise exposures for 1 h.

METHODS

Subjects. Ten males were divided into two groups (n=5 each) so as to maximize differences in body weight and $A_D \cdot \text{wt}^{-1}$ between groups but match groups on both subcutaneous and total body fat. The physical and morphological characteristics of the subjects are shown in Table 1. The subjects had no prolonged exposure to cold within several months of the study. Each volunteered for all aspects of the study and gave their written consent. All were medically cleared for participation.

Protocol. Procedures for the experiment have been outlined in detail elsewhere (Toner et al. 1984) therefore only a brief description will be reported presently. Prior to experimental tests, height, hydrostatic and body weights, and skinfold thicknesses were obtained on all subjects and these results were used to establish the two experimental groups (i.e. large body mass (LM) and small body mass (SM), n=5 each). Prior to the water experiments, all subjects dressed in nylon swim suits and sat quietly in a room at approximately 22°C. Two water experiments were

performed; one with the subject resting on a chair and the other with the subject exercising. Leg exercise was performed on a modified water ergometer (Toner et al. 1984) at an intensity equivalent to approximately an oxygen uptake of $1.5 \text{ l} \cdot \text{min}^{-1}$. All water experiments were 1 h in duration with subjects immersed to the neck in water at 26°C . Experiments were performed in a random fashion. Oxygen uptake ($\dot{V}\text{O}_2$) was measured at 5, 15, 30, 45 and 60 min whereas internal temperatures and heat flow measures were continuously recorded. Within one week following experimental sessions, limb volumes were measured.

Measurements. Determination of body density was obtained from hydrostatic weighing (Goldman and Buskirk 1961) and percent body fat was estimated from density; total skinfold thickness was the sum of eleven skinfolds with locations at the chin, tricep, bicep, forearm, calf, knee, thigh, suprailiac, chest, subscapular, side. Limb volumes of both arms and both legs were determined (Katch et al. 1974). A_D was determined by use of the DuBois equation (DuBois and DuBois 1916).

Oxygen uptake was calculated by open-circuit spirometry. Expired air was collected in a Tissot spirometer and aliquot samples were obtained and analyzed for O_2 (Applied Electrochemistry S-3A) and CO_2 (Beckman LB-2) concentrations. Analyzers were calibrated frequently with gases previously verified.

During all water experiments body temperature value were continually monitored. Rectal temperature (T_{re}) was recorded from a thermistor (Yellow Springs Instrument, Yellow Springs, OH) inserted 10 cm into the rectum. Esophageal temperature (T_{es}) was obtained from a thermistor inserted in the naris and swallowed to the level of the heart. Mean weighted skin temperature ($\bar{T}_{sk}$) was obtained by area weighting a five point thermocouple harness

$T_{sk} = 0.22 T_{calf} + 0.28 T_{thigh} + 0.28 T_{chest} + 0.14 T_{forearm} + 0.08 T_{triceps}$. Mean heat flow ($\dot{H}_c$) was similarly calculated. Water temperature was determined by five thermocouples placed 10 cm from the body approximating the skin temperature sites. All temperature data were processed through a Hewlett-Packard micro-voltmeter and scanner, and recorded in a 9825 B computer.

Statistical Analysis. Metabolic and thermal values were analyzed by repeated measures design of analysis of variance with one grouping factor (body size) and two repeated factors (activity level, time). Significant differences for the analysis of variance were further tested with the Tukey multiple range and interaction post-hoc test to determine the difference between means. The 0.05 level of significance was chosen for these analyses.

RESULTS

A comparison of the physical characteristics of the LM and SM groups is illustrated in Table 1. There were no significant differences in height, X_{body} fat, total skinfolds and A_D between the two groups ($P > 0.05$). However, the LM group was on the average 16.3 kg heavier in body weight, 14.2 kg heavier in lean body weight, $0.24 \text{ m}^2 \cdot \text{kg}^{-1} \times 100$ smaller in $A_D \cdot \text{wt}^{-1}$ and larger in limb volumes ($P < 0.05$) than the SM group.

Tables 1 and 2 about here

Table 2 illustrates the metabolic and thermal responses of the two groups while resting in 26°C water over 60 min. M remained unchanged throughout the 60 min for both the LM and SM groups. Values for T_{es} at min 60 were significantly lower ($P < 0.05$) than at 5 and 30 min in the LM whereas T_{es} remained unchanged ($P > 0.05$) throughout the immersion period in the SM group. T_{re} values were on the average 0.5°C lower ($P < 0.05$) at min 60 compared with both the 5- and 30-min values for both groups. Values for

$\bar{T}_{sk}$ were significantly lower ($P < 0.05$) at 30 and 60 min compared with min 5. $\bar{H}_c$ was lower ($P < 0.05$) at min 30 and 60 compared with min 5 in both groups.

Table 3 about here

During exercise, metabolic and thermal responses were again contrasted over 1 h (Table 3). $\dot{M}$ which averaged between 2 and 5 times the resting values was significantly higher ($P < 0.05$) at min 5 compared with the average values at min 30 and 60 for both groups. In contrast to the drop in T_{es} and T_{re} observed during rest (c.f. Table 2), both T_{es} and T_{re} increased ($P < 0.05$) during the first 30 min and stabilized during the final 30 min of exposure for the LM group. T_{re} remained unchanged ($P > 0.05$) throughout the 60 min of immersion whereas T_{es} increased significantly ($P < 0.05$) during the initial 30 min and remained unchanged ($P > 0.05$) during the last 30 min for the SM group. $\bar{T}_{sk}$ was lower ($P < 0.05$) at min 30 and 60 compared with min 5, though there were no differences ($P > 0.05$) between rest or exercise in either group. Similar to rest $\bar{H}_c$ was significantly lower ($P < 0.05$) at min 30 and 60 compared with min 5 in both groups, though H_c was higher ($P < 0.05$) during rest compared with exercise.

Figures 1 and 2 about here

Figure 1 illustrates the comparison between the LM and SM groups for final T_{re} and T_{es} values. During rest, the average T_{es} was higher ($P < 0.05$) for the SM compared with the LM group, whereas there were no differences ($P > 0.05$) between groups for T_{re} . During exercise, there were no significant differences ($P > 0.05$) between groups for either T_{es} or T_{re} values.

Figure 2 examines $\dot{M}$ and $\bar{H}_c$ between the two groups. There were no significant differences ($P > 0.05$) in $\dot{M}$ between groups during rest or exercise.

In a similar fashion, $\bar{H}_c$ values were not significantly different ($P > 0.05$) between groups during either rest or exercise. $\bar{T}_{sk}$ were similar ($P > 0.05$) between groups during both rest and exercise.

DISCUSSION

Several studies have demonstrated that T_{re} responses were significantly different between males and females (McArdle et al. 1984a; Shapiro et al. 1980), lean and obese individuals (Miller Jr. and Blyth 1958), as well as heat intolerant and normal control subjects (Epstein et al. 1983) within various environments. The magnitude of the T_{re} difference between these groups ranged from 0.7 to 1.0°C. The conclusions drawn from these investigations suggested that the differing thermal responses can be attributed in part to the $A_D \cdot wt^{-1}$ differences between groups. The present study examined individuals with similar skinfolds and total body fat but different $A_D \cdot wt^{-1}$ and total body weight so as to describe the thermal differences based on body morphology and mass. Despite larger body weight and $A_D \cdot wt^{-1}$ in the LM group, similar T_{re} , T_{es} , $\bar{H}_c$ and M values were observed in both groups. It might be argued that the differences in $A_D \cdot wt^{-1}$ between the groups in the present study were not great enough to show differences in thermal responses. However, the differences between body sizes in the present study ($0.24 \text{ m}^2 \cdot \text{kg}^{-1} \times 100$) were of a similar magnitude as reported by Epstein et al. ($0.24 \text{ m}^2 \cdot \text{kg}^{-1} \times 100$) between heat intolerant and controls (1983), Shapiro, et al. (1980) between men and women ($0.25 \text{ m}^2 \cdot \text{kg}^{-1} \times 100$), and Hayward and Keatinge (1981) between men and women ($0.20 \text{ m}^2 \cdot \text{kg}^{-1} \times 100$).

It is also possible that the statistically non-significant results between groups in the present study may be attributed to the selected environmental conditions. Water immersion however, provides an ideal medium to observe surface heat transfer and therefore to examine the effects of $A_D \cdot \text{wt}^{-1}$ upon thermal responses. The convective heat transfer coefficient both theoretical (Rapp 1971) and measured (Boutelier et al. 1977; Nadel et al. 1974) is high in water, and the effective surface area in contact with the environment is greater in water than in air (Molnar 1946). Therefore, the skin temperature is uniform and approximates the water temperature. In addition, immersion in cool water at 26°C provides an adequate stress whereby total body insulation is near maximum and little additional peripheral vasoconstriction can be achieved in colder water (Hong et al. 1969). Maximal vasoconstriction is essential in both groups if one wants to observe a strict surface phenomenon because similar core temperatures could be achieved in LM and SM groups by differences in vasomotor regulation of circulatory heat transfer from the core to the skin surface. Therefore, core temperature responses in cool water are predominately a function of morphological and body mass factors and to some degree a relative distribution of heat stores within the different body compartments. Thus, immersion in water at 26°C appears to be a proper environment to examine thermal response differences between the LM and SM groups.

Both groups were exposed to a rest and exercise condition so as to examine possible interactions between body mass and physical activity level. During rest, vasoconstriction is near maximum in the limbs and the majority of heat loss is in the trunk (Veicsteinas et al. 1982). It is possible that resting in cool water provides a situation whereby the limbs that are

minimally perfused with blood are not potential major avenues for heat loss (Veicsteinas et al. 1982). Therefore although the $A_D \cdot wt^{-1}$ between groups were different during rest, the reduced A_D for effective heat transfer eliminates the morphological advantage of the LM group. Another potential problem during rest would be the expected differences in metabolic rate between groups. The large group with greater overall body weight and lean body weight would be expected to have a greater basal metabolism and a larger capacity for shivering because of the larger lean body weight. Therefore, the differences in body mass and $A_D \cdot wt^{-1}$ may be offset by the potential differences in metabolic rate. These potential problems were considered within the experimental design by including an exercise condition. During exercise, circulation to the contracting musculature would provide a heat source to the limbs such that the effective $A_D \cdot wt^{-1}$ for heat dissipation would be maximized in all subjects. In addition a given exercise intensity on a leg ergometer elicits similar metabolic rates regardless of body weight and therefore should yield similar rates in water at 26°C.

Though the LM group was expected to have a greater metabolic rate during rest compared with the SM group, the present results showed no differences between groups. The 26°C exposure did not appear a sufficient cold-water stress, because of the relatively high body fat of both groups, to permit the greater shivering potential of the LM group to be expressed. Similarly, there were in general no differences in thermal responses between the LM and SM groups, though at rest T_{es} was significantly higher for the SM compared with the LM group. This difference does not appear to be physiologically significant because the change in T_{es} across the immersion period was similar between the LM (-0.4°C) and SM (-0.2°C) groups. Also,

T_{re} values were the same for both groups (Fig. 1). These results should be considered important because in addition to a more advantageous $A_D \cdot wt^{-1}$ configuration, the LM group has a potentially greater internal insulation provided by their larger lean body weight. As demonstrated by Veicsteinas et al. (1982) during resting conditions in water, the muscle tissue of the limbs provides the predominate resistance to heat transfer from the core to the water. Although both groups have similar fixed resistances provided by subcutaneous tissue, the LM group would be expected to have a lower core-to-skin conductance because of their larger muscle mass. Despite the morphological ($A_D \cdot wt^{-1}$) and body mass (total and lean-body weight) advantages of the LM group, both groups had similar metabolic and thermal responses.

Studies which have suggested that $A_D \cdot wt^{-1}$ or body size may account for differences in thermal responses have established either statistical (Kollias et al. 1974; Sloan and Keatinge 1973) or theoretical (Wyndham et al. 1964c) relationships. Both of these types of relationships have limitations. First, although statistical relationships are established between $A_D \cdot wt^{-1}$ and T_{re} , it is clear that other factors correlate highly with $A_D \cdot wt^{-1}$. For example, Kollias et al. (1974) and McArdle et al. (1984a) both showed high correlation between $A_D \cdot wt^{-1}$ and body fat. When two independent variables ($A_D \cdot wt^{-1}$ and body fat) correlate highly, it is difficult to adequately interpret the relationships between each independent variable and the dependent variable (T_{re}) (Kerlinger and Pedhazur 1973).

Second, theoretical relationships or interpretations also have limitations. McArdle et al. (1984a) reasoned that the larger $A_D \cdot wt^{-1}$ might account for the observed lower T_{re} responses of women compared with men during rest in cold water. However, McArdle et al. (1984b) observed

these same subjects under identical environmental conditions but had the subjects exercise. In this situation the men and women had similar thermal responses despite the $A_D \cdot \text{wt}^{-1}$ differences. The theoretical possibility of $A_D \cdot \text{wt}^{-1}$ as an important factor in thermal physiology was therefore abandoned (McArdle et al. 1984b). Wyndham et al. (1964c) also reasoned that $A_D \cdot \text{wt}^{-1}$ was involved in thermoregulatory differences between Aborigines and Caucasians whereas subsequent cross-cultural studies on Arabs and Caucasians (Wyndham et al. 1964b) and on Bushmen and Bantu (Wyndham et al. 1964a) found no thermal advantage for the large compared to small $A_D \cdot \text{wt}^{-1}$ groups.

The results of the present study illustrates that within a given population and sex, differences in $A_D \cdot \text{wt}^{-1}$ do not account for differences in thermal responses. These data suggest that other explanations should be explored to account for thermal differences between the sexes or between populations. It must be emphasized that the role of body morphology and mass cannot be discounted in thermoregulation especially when large differences in $A_D \cdot \text{wt}^{-1}$ and mass are noted within an individual (arm vs. leg exercise) (Toner et al. 1984) or between individuals (younger individual compared with older) (Sloan and Keatinge 1973).

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Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on the Use of Volunteers in Research.

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TABLE 1. Physical characteristics of the large- and small-mass groups.

		Ht	Wt	LBW	%BF	Skin	A_D	$A_D \cdot wt^{-1}$	LV_A	LV_L
Small Group n=5	$\bar{X}$	170.3	66.4	54.9	17.0	108.6	1.84	2.69	2.26	9.24
	S.D.	9.0	10.6	8.8	3.0	32.7	0.21	0.18	0.31	1.79
Large Group n=5	$\bar{X}$	180.1	82.7	69.1	16.4	135.1	2.02	2.45	2.77	11.23
	S.D.	7.8	6.5	4.8	3.0	33.3	0.10	0.12	0.28	1.52
P		n.s.	<0.05	<0.01	n.s.	n.s.	n.s.	<0.05	<0.05	<0.05

Ht is height (cm); Wt is weight (kg); LBW is lean body weight (kg); %BF is percent body fat (%); Skin is total sum of 11 skinfolds (mm); A_D is surface area (m^2); $A_D \cdot wt^{-1}$ is surface area to weight ratio ($m^2 \cdot kg^{-1} \cdot 100$); LV_A is arm volumes (l); LV_L is leg volumes (l).
n.s. is non-significant.

TABLE 2. Resting metabolic and thermal responses overtime in large- and small-mass groups during immersion in water at 26°C ($\bar{X} \pm \text{SD}$).

	Group	Large			Small	
	Time (min)	5	30	60	5	30
Metabolic Rate (W)	124 (33)	120 (32)	152 (34)	211 (98)	180 (71)	198 (58)
Esophageal Temperature (°C)	36.7 (0.3)	36.7 (0.3)	36.3 (0.2)	36.9 (0.2)	36.9 (0.1)	36.7 (0.3)
Rectal Temperature (°C)	37.0 (0.2)	36.9 (0.3)	36.5 (0.4)	37.0 (0.2)	36.9 (0.1)	36.5 (0.2)
Mean Skin Temperature (°C)	26.6 (0.1)	26.3 (0.2)	26.2 (0.2)	26.8 (0.2)	26.5 (0.2)	26.4 (0.2)
Mean Heat Flow (W·m ⁻²)	79 (11)	49 (4)	41 (3)	77 (13)	56 (8)	51 (12)

TABLE 3. Exercising metabolic and thermal responses overtime in large- and small-mass groups during immersion in water at 26°C ($\bar{X} \pm \text{SD}$).

	Large			Small		
	5	30	60	5	30	60
Metabolic Rate (W)	550 (90)	530 (61)	550 (65)	581 (59)	525 (56)	527 (59)
Esophageal Temperature (°C)	36.5 (0.2)	37.3 (0.3)	37.2 (0.2)	36.8 (0.3)	37.4 (0.2)	37.3 (0.2)
Rectal Temperature (°C)	37.0 (0.2)	37.2 (0.2)	37.4 (0.3)	37.1 (0.3)	37.2 (0.4)	37.3 (0.4)
Mean Skin Temperature (°C)	26.4 (0.2)	26.2 (0.2)	26.2 (0.2)	26.6 (0.4)	26.3 (0.3)	26.3 (0.3)
Mean Heat Flow ($\text{W} \cdot \text{m}^{-2}$)	88 (11)	71 (8)	74 (25)	90 (16)	71 (11)	71 (11)

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FIGURE LEGEND

Figure 1. Comparison of esophageal (T_{es}) and rectal (T_{re}) temperatures between small-mass (SM) and large-mass (LM) groups during rest and exercise in water at 26°C ($\bar{X} \pm SD$).

Figure 2. Comparison of metabolic rate (left) and mean heat flow (right) between small-mass (SM) and large-mass (LM) groups during rest and exercise in water at 26°C ($\bar{X} \pm SD$).

Figure 1

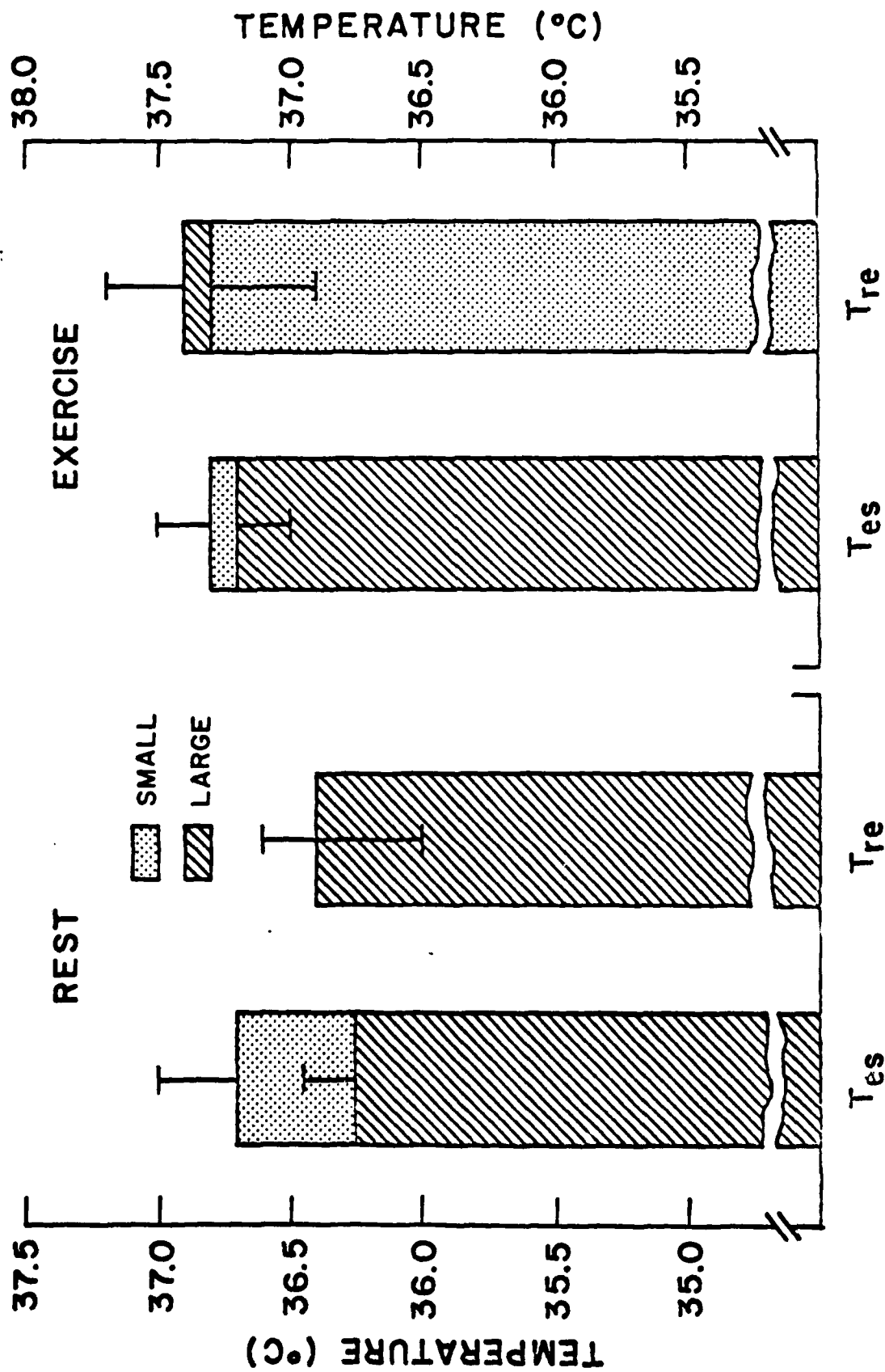
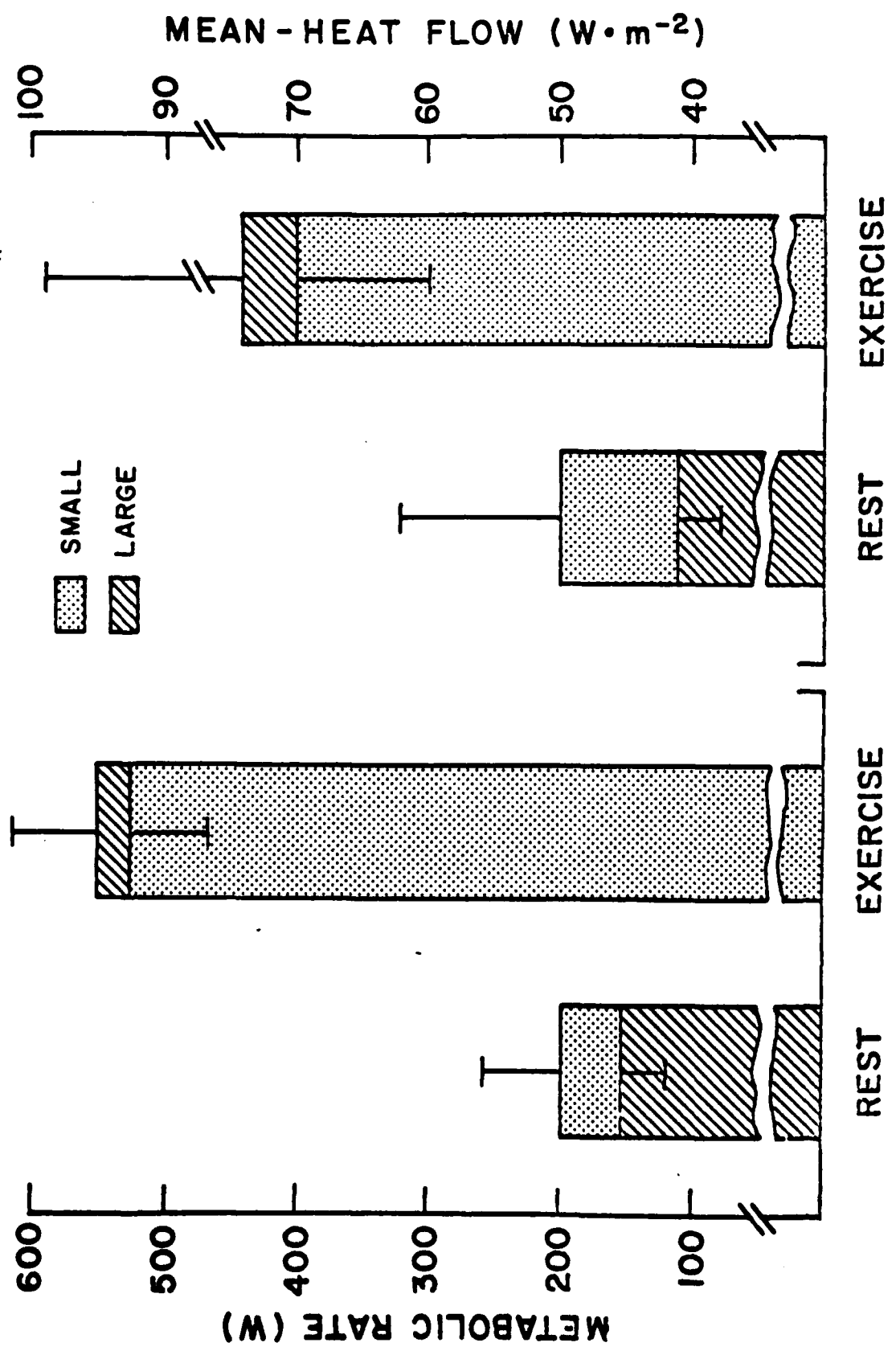


FIGURE 2



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