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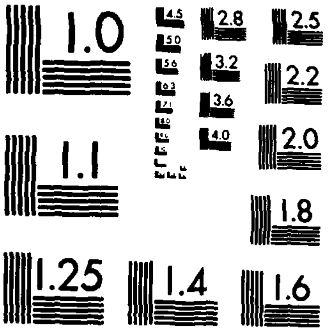

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The metabolic heat production of twenty male subjects undergoing total immersion in water between 36°C and 20°C was measured as functions of time and water temperature. These were converted to explicit linear functions of core (T_{re}) and mean skin ($\bar{T}_{sk}$) temperatures for each individual immersion. The functions were used to define planes of thermogenic activity which allowed comparison of the threshold and magnitude of shivering between individuals of any morphological group. The thermogenic planes showed a much steeper slope with respect to the T_{sk} axis for small, thin men than for

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large, fat men, while men of average weight and fat composition exhibited an immediate slope. Small, lean men also exhibited thermogenic planes having steeper slopes with respect to the T_{re} axis than did average men. Whole body insulation was evaluated for each individual immersion. Analysis showed that small, lean men maximally vasoconstrict at higher bath temperatures than did large, fat men and that small, lean men were unable to maintain their maximum whole body insulation before the latter attain their maximum insulation. The decline in insulation, seen above a certain critical metabolic level, reflects the increasing muscle blood flow necessary to support active shivering; this critical level appears to be 150 W in small to average size subjects.

HUMAN RESEARCH

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 Use of Volunteers in Research.

A

Metabolic and Vasomotor Insulative
Responses Occurring on Immersion in Cold Water

by

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Abstract

The metabolic heat production of twenty male subjects undergoing total immersion in water between 36°C and 20°C was measured as functions of time and water temperature. These were converted to explicit linear functions of core (T_{re}) and mean skin ($\bar{T}_{sk}$) temperatures for each individual immersion. The functions were used to define planes of thermogenic activity which allowed comparison of the threshold and magnitude of shivering between individuals of any morphological group. The thermogenic planes showed a much steeper slope with respect to the $\bar{T}_{sk}$ axis for small, thin men than for large, fat men, while men of average weight and fat composition exhibited an intermediate slope. Small, lean men also exhibited thermogenic planes having steeper slopes with respect to the T_{re} axis than did average men. Whole body insulation was evaluated for each individual immersion. Analysis showed that small, lean men maximally vasoconstrict at higher bath temperatures than did large, fat men and that small, lean men were unable to maintain their maximum whole body insulation before the latter attain their maximum insulation. The decline in insulation, seen above a certain critical metabolic level, reflects the increasing muscle blood flow necessary to support active shivering; this critical level appears to be 150 W in small to average size subjects.

INTRODUCTION

Scholander (20,21) has given evidence that certain individuals adjust to cold stress preferentially by raising their metabolic heat production (shivering thermogenesis) while others appear to adjust preferentially by cardiovascular compensation (peripheral vasoconstriction). Although most men respond to cold stress by a combination of cardiovascular and metabolic reactions, it is evident that all do not respond equally to a given thermal stimulus. Individual differences appear in the graded intensities of these two kinds of responses and in their integration.

The literature reports a wide variance in the metabolic heat resulting from shivering thermogenesis among subjects having very different body size and composition (5,7,14,16). The finding that thin men shiver more intensely than fat men under the same ambient temperatures has been attributed to a greater heat debt in thin men (7), and the corresponding greater depression of deep thermoreceptors in thin men.

A number of studies have investigated the role of body fat and body size in determining core conductance (5,7,8,13,14,16,22) during water immersion. A large part of this literature has been limited to the evaluation of body insulation under steady state conditions. Because of uncertainties in the usual methods of determining heat storage, the literature in general does not address the changes in core conductance which result as cardiovascular compensation occurs, or when metabolic heat production is time variable for a fixed stimulus.

Scholander _et al_ (19) have made use of the concept of a critical ambient temperature at which animals achieve maximum insulation and below which metabolism is increased in order to maintain core temperature. Cannon and Keatinge (7) have criticized the use of a critical ambient temperature because their data from water immersion studies for human subjects in heat balance showed that while the thinnest men exhibited nearly equivalent T_w for maximal insulation and metabolic threshold, fat men showed a wide difference between the water temperatures at which their metabolic rate was increased and at which they achieved maximal tissue insulation. Instead they recommended the use of a metabolic threshold temperature below which there is an increase in the metabolic rate. They inferred that the metabolic threshold temperature is approximately equal for thin and fat men (about 33°C) and is determined by cutaneous receptors. In thin men they found the metabolic response to be reinforced by the stimulation of deep receptors. The threshold temperature for vasoconstriction is reportedly governed by cutaneous receptors in both fat and thin men (7).

We raise the question of whether individual differences in shivering heat production can be correlated with morphological factors. We have sought to examine the relationship between heat production during shivering, the temperature of certain body compartments and the morphology of the individual (body fat and mass and surface area). Least squares linear regression formulae for metabolic rates as functions of core and skin temperatures are used to define planes of thermogenic activity; this permits a comparison of the onset temperatures and the magnitude of shivering between individuals of different morphology.

We have used a time dependent model of heat transfer also to represent the heat storage and energy exchanges between the body core, fat and epithelial compartments, and have followed the changes in core conductance from thermoneutrality, through vasoconstriction, and into cold induced vasodilation for subjects representing different morphological types. The subjects were expected to increase their body insulation (decrease core conductance) as the environmental temperature dropped from the thermoneutral value, with a maximum insulation that should be related to both body size and fat content.

The measurement of the change in insulation per decrement of ambient temperature should shed more light on the question of a threshold temperature for vasoconstriction. We quantify individual differences in vascular clamping with changes in skin, core and ambient temperatures. Correlated with the metabolic response, they show how body insulation degrades with shivering. Information relating to the threshold of vasoconstriction is augmented by measurement of the rate of change of thermal resistance and the threshold of shivering metabolism by measurement of the rate of change of metabolic heat production. The threshold and intensity of vasoconstriction and shivering metabolism in different morphological groups is compared to ascertain whether there are correlations between these responses and morphology. Altogether they demonstrate that thermoregulation exhibits a wide spectrum of metabolic and cardiovascular components.

METHODS

Water immersion is widely recognized as a useful technique for studying human responses to cold stress because of the rapid changes in body compartment temperatures and the large metabolic and cardiovascular compensation which can be accomplished as a result of the high thermal conductivity of the water medium (3,9,10,17,24). In this environment, greater metabolic and cardiovascular adjustments eventuate than in air for the same range of ambient temperatures, but the resultant core temperatures are lower. This results in a driving force for even greater metabolic and cardiovascular adjustments.

Experimental procedures reported earlier (23) were followed unless otherwise stated. Quantitation of the shivering response was determined by a single EMG electrode (Beckman) placed over the quadriceps of the thigh.

Shivering was recorded both by continous EMG tracing of this signal and by visual observation using a 5 point rating scale ranging from violent to quiescence. EKG and respiratory rates were continuously recorded on a GRASS polygraph.

Data Analysis Methods

For each experimental run, a regression equation was obtained relating the metabolic heat production to a linear function of skin and rectal temperatures and the time rate of change of skin temperature. If the correlation coefficient was better than $r = 0.80$, the heat input (Q) was set equal to the linear regression equation, minus 8% of its current value to account for respiratory heat loss; otherwise Q was set equal to the simple average metabolic rate determined by the 10 measurements taken over the course of the one hour immersion minus the 8%. This formulation permitted the separate evaluation of changes in internal and external conductances with water temperature. The details are described elsewhere (23).

RESULTS

Heat Loss vs Water Temperature

The mean weighted skin temperature falls exponentially for all nude subjects, approaching in the asymptotic limit a temperature which is only slightly higher than the bath temperature (Fig. 1). The mean steady state thermal gradient from skin to water bath for this subject population is 0.11 ± .05°C at 35°C; it is 0.4 ± 0.3°C at 32°C, 0.8 ± 0.5°C at 28°C, 1.0 ± 0.5°C at 24°C, and 1.49 ± 0.6°C at 20°C (Fig. 1). The surface heat flow is greatest at 20°C, with the steady state heat flux from the head (465 ± 116 W/m^2), and larger muscle masses of the chest (250 ± 70 W/m^2), abdomen (350 ± 116 W/m^2) and lateral thigh (350 ± 116 W/m^2) exceeding that from the smaller, more distal masses such as triceps (233 ± 58 W/m^2), calf (205 ± 12 W/m^2) and instep

(58 ± 23 W/m^2) (Fig. 2). The area weighted steady state mean heat flow averaged over the subject population was 23 ± 12 W/m^2 at 35°C, 105 ± 12 W/m^2 at 32°C, 186 ± 35 W/m^2 at 28°C, 244 ± 58 W/m^2 at 24°C and 337 ± 81 W/m^2 at 20°C; the relationship between area weighted mean heat flow and water temperature appears to be linear below the thermal neutral zone and averages 81 W/m^2 for every 4°C drop in bath temperature (Figure 3).

Heat Loss vs. Shivering Intensity

Individual skin temperatures show a small variability between subjects - about 1°C at the lowest bath temperature (Fig. 1). One of the reasons for this variability is different shivering responses; local surface film conductance varies with the magnitude of agitation of the adjacent water layers. Fig. 4 shows the variation of mean skin to water conductance with shivering intensity, for 10 Ss at the three lowest water temperatures. The surface conductance was calculated from the mean weighted heat flow and the measured skin to water temperature gradient. A graded response of 5 arbitrary units (a.u.) of EMG activity corresponds to light shivering, 10 a.u. to moderate shivering, and 15 a.u., or above to violent shivering. Despite the scatter in the data, it is clear that surface heat transfer increases monotonically with shivering intensity. Apparently, the range of the skin to water heat transfer coefficient is between 175 and 350 $W/m^{2\circ}C$ for $20 \leq TW \leq 28^\circ C$, depending to a large degree on body motion.

As expected, the surface heat transfer coefficient increases with metabolic rate (Figs. 4 + 5). This is not because the body heat storage is negligible; if this were true, heat loss would scale with heat produced and it does not. Fig. 5 shows the relationship between shivering intensity and the metabolic heat production. The range for light shivering corresponds to between 100-250 W; for moderate shivering between 200-450 W; and violent shivering is in excess of 450 W. In the light-moderate range, a 100% increase in metabolic heat production produces a 50% increase in EMG activity (on average) (Fig. 5), while this same increase yields only a 20% increase in surface heat transfer (Fig. 4).

Metabolic Responses

In water at 35 and 32°C, the oxygen consumption of all subjects is essentially the same as their pre-immersion values; about 12-15 l/h. In colder water (20°C), the $\dot{V}O_2$ showed an average increase to 55-60 l/h. (Figure 6), i.e., for the group as a whole the heat due to shivering amounted, on average, to between 4 and 5 times the resting metabolic rate. In general, metabolic rates increase as the water temperature decreases, until shivering exhaustion saturates the response. There is, however, marked individual variation at temperatures below 32°C (Fig. 7). The threshold onset of shivering thermogenesis occurs at higher water temperatures for lean (wt < 70 kg, BF < 12%) than for heavy subjects (wt > 90 kg, BF > 19%). While there are no clear statistical differences between the average metabolic heat output for the two groups during immersion at 28°C, the lean group of subjects show a marked increase in heat production at 20°C compared to the heavy subjects (Fig. 6); the average metabolic increase shown by the lean subjects was 209 W compared to 52 W shown by the heavy subjects.

A subject's skin and rectal temperatures are components of the sensory input which determines his metabolic response. In Fig. 7, the variation of metabolic heat production is plotted against skin and rectal temperatures for five typical subjects whose body types may be characterized as: a) heavy and fat (BF = 23%, wt = 96.24 kg), b) average (BF = 11%, wt = 84.72 kg; BF = 15%, wt = 72.25 kg), or c) small and lean (BF = 7%, wt = 69.33 kg; BF = 9%, wt = 61.14 kg). The data presented were obtained after the initial cold shock if any, following immersion, had passed; i.e., when the skin temperature and heat flow stabilized to a constant value. This restriction was made to simplify the analysis, as metabolic rates have been shown to depend also upon the rate of change of skin temperature (4). For any measured core and skin temperature combination, the metabolic heat production is larger for smaller, leaner subjects than for heavier, fatter ones. In the range of skin temperatures between 19-32°C and rectal temperatures between 35-38°C, the small man almost always shivered more intensely than the heavy man, thus raising his metabolic heat production much higher.

Linear regression equations relating the metabolic heat production to $\bar{T}_{sk}$ and T_{re} were obtained for each subject from data collected for all immersion temperatures; these are plotted as three dimensional planes (Fig. 7). The regression planes for groups of different morphology show great differences of slope with respect to the $\bar{T}_{sk}$ axis. The thermogenic response of the average lean subject to a 1°C change in mean skin temperature is four times the response of a heavy subject. A subject of average build has a thermogenic plane that exhibits an intermediate slope with respect to $\bar{T}_{sk}$.

Fig. 8 shows the cumulative regression planes calculated for the entire subject pool, after it had been split into three categories: small, lean, with $wt < 70$ kg and $BF < 12\%$; average, with $70 \text{ kg} \leq wt \leq 90$ kg and $12\% \leq BF \leq 19\%$; and heavy, fat, with $wt > 90$ kg and $BF > 19\%$. The three planes are defined by the following regression equations (in W):

$$1160.5 - 19.8\ \bar{T}_{sk} - 11.0\ T_{re};\ \text{(small, lean)}\ r = .66$$

$$629 - 15.1\ \bar{T}_{sk} - .41\ T_{re};\ \text{(average)}\ r = .75$$

$$543.0 - 4.65\ T_{sk} + 21.86\ T_{re}\ \text{(heavy, fat)}\ r = .44$$

Though there is considerable variability within each group, there are greater differences across the groups. The small and lean subjects show the greatest metabolic response to decrements in skin temperatures; the average subjects produce a thermogenic plane with smaller slopes with respect to the $\bar{T}_{sk}$ axis and an average elevation, with respect to total thermogenic activity level which was intermediate between the lean and heavy groups. The heavy subjects, as a group, showed the smallest metabolic activity and the smallest change per decrement in $\bar{T}_{sk}$.

The thermogenic planes generally have a negative slope with respect to the T_{re} axis; a positive slope may be found if shivering exhaustion occurs or if the depression of rectal temperature was not sufficient to drive shivering thermogenesis. The water temperature range was great enough that most lean and average subjects demonstrated a negative slope. The heavy subjects did not exhibit a rectal temperature depression greater than 0.5°C, while some lean subjects exhibited a rectal temperature depression of more than 2°C. Consequently, the range of validation of metabolic regressions upon T_{re} is not equivalent for the three groups of subjects. This explains the poorer correlation of metabolic rate and $\bar{T}_{sk}$ and T_{re} for the heavy subject pool. As a group, the heavy subjects showed a small average decrease in metabolic heat production with a drop in T_{re}.

Cardiovascular Responses

Fig. 9 shows the relationship between the average metabolic rate for each subject over the 60 minute immersion period and the change in HR averaged over the same immersion period compared to the out of water control. For the subgroup of subjects (1-10) from whom this data were obtained, the following correlations were observed: the HR of all but one subject dropped from the control rate (determined under thermoneutral conditions) upon immersion in water at temperatures ranging between 32-28°C. This reflex bradycardia is the normal response to the distributed baroreceptors sensing a rise in blood pressure following immersion (1). Coincident with the rise of metabolic rates above 150-

200 W, HR values exceeded the out of water control values. This occurred at water temperatures of 28°C and below. The subject pool for which these measurements were made included no subject whose morphology was classified as heavy, fat. They were classified as average to small. At 32°C; the average HR for the group was -1.8 bpm lower than the control average; at 28°C the average HR climbed to + 0.65 bpm higher than control; at 24°C to + 8.5 bpm higher than control and at 20°C to 17 bpm higher than control.

Insulative Responses

The total tissue conductivity from central core to skin surface contains a fixed component that depends on body composition and a variable component that depends on cutaneous circulation. Fig. 10 shows the variation of total tissue conductance for each subject as a function of T_w. The conductance data represent the overall conductance averaged over an experimental run at a fixed ambient temperature. Core conductance is uniformly highest (insulation smallest) at the highest water temperature (35°C). As the water temperature is lowered, total insulation rises, peaks at a maximal value and then gradually falls. The position of maximum insulation shifts towards the lower water temperature and the insulation increases as the weight of the subject increases. Heavy men attain their maximum core insulation in water of 20°C or less, while small and average men attain their maximum insulation in the temperature interval between 28-32°C.

Fig. 11 shows the variation of the normalized insulation curve versus the average metabolic rate for the interval of immersion. The data indicate two general phenomenona that are observed for small to average subjects (Fig. 11A). In the transition to maximum insulation, H increases by no more than 15-30 W. After maximal insulation is achieved, then shivering heat production increases. A comparison between their average metabolic rate and their total insulation shows that small to average size men cannot sustain an average metaoblic level higher than 150 W for 60 minutes of immersion and still maintain maximum insulation. These data indicate that small to average men achieve the peak insulation for metabolic rates under 150 W. Comparison with Fig. 5 indicates that, for this subject group, maximal insulation is consistent only with light shivering. The data on normalized body insulation versus metabolic activity for heavy and fat men (Fig. 11B) is incomplete in that maximal vasoconstriction was not necessarily realized in 20°C water for this group, although the average metabolic heat production increased 40% above test shown at $T_w = 28^oC$.

DISCUSSION

We have shown that individual differences exist in the onset of metabolic and insulative compensation in a sample population of adult males between 17-28 years of age. Since both vasoconstrictive and metabolic compensation begin at higher T_{sk} and T_{re} for small, lean men than for fat, heavy men, it is apparent that these differences can not be fully explained by postulating a greater heat debt at initiation of cold compensation in small men. Neither can they be explained by assuming a uniformly greater surface heat flow in small men. While metabolic heat production and core conductance exhibited greater variability from subject to subject, skin temperatures and surface heat loss showed a generally uniform dependence upon time and T_w, with small variations in the steady state limit that did not correlate with subject morphology. Surface heat loss in the steady state correlated with the muscular activity associated with shivering and with the mean surface temperature. To the extent that shivering increased the surface heat loss while vasoconstriction reduced it, the net heat loss of a small, lean man could be greater or less than that of a heavy, fat man depending on whether the heat loss to shivering convection outweighed the heat retained by vasoconstriction. Surface temperature and heat flow measurements established that differences in surface heat loss were not attributable to uniformly higher $\bar{T}_{sk}$ for any particular morphological group; surface heat transfer coefficients were not equivalent because greater shivering in small men increased the surface convection currents.

Surface averaged heat transfer coefficients from skin to water ranged from 175 to 350 W/m^2 ^{o}C in this study; the variation depended on body motion. This range includes the values found by Witherspoon *et al* (26) for copper manikin measurements in "still water" and in water flowing at 0.15 m/sec, and the values found by Nadel *et al* (15), for subjects at rest in still water (233 W/m^2 ^{o}C). It is, however, at least four times the value found by Boutelier *et al*. (3) who determined the convective heat exchange coefficient using the steady state metabolic heat production and the thermal gradient measured between the water bath and skin thermocouples covered by small copper plates and a permeable polystyrene tape.

Shivering Thermogenesis

It has been reported that the metabolic heat production rises faster in thin than in fat men when the bath temperature is lowered below 33^{o}C (7,13). Our results confirm this finding for large versus small men; we have related shivering thermogenic activity to core and skin temperatures on the basis of thermal mass rather than fat composition *per se*. Though the rectal and skin sites are but two of the many sites whose sensory inputs go into the determination of the total integrated thermoregulatory response (18), they appear to be a minimum necessary number for highlighting the individual differences in thermogenic activity, and are suggestive of a mechanism involving different thresholds for thermogenesis for the different morphological groups. The thermogenic planes which describe the variation of metabolic heat production as a linear function of $\bar{T}_{sk}$ and T_{re} have clearly distinguishable slopes with respect to the $\bar{T}_{sk}$ axis for both large and small subjects. It would appear that the cold stimulation of surface thermosensitive neurons produces a higher level of autonomic motor activity in small men than in heavy men, in the temperature range between 20-30°C. This has the effect of reducing the width of their thermoneutral zone on the low temperature side. Whether or not this is a learned adaptation, the early onset increase in metabolic heat production serves to lengthen their survival time in a cold environment. If lean men were not so responsive to surface heat loss, their core temperatures would fall much faster than is the case (23). Yet even with their sizable outputs of metabolic power the small mass subject cannot maintain nearly as high core temperatures as a large subject (23).

The shivering initiated at higher ambient temperatures among small men in the 17-28 years of age category is similar to the cold acclimation that Scholander _et_ _al_ (20) observed among Norwegian college students after undergoing six weeks of cold stress which was occasioned by the removal of some external insulation in a subarctic climate. The cold acclimated group showed greater metabolic heat output at higher ambient temperatures than did controls. They reported an increase in the basal metabolic rate by 50-55% over a group of control subjects. We hypothesize that small men, having less internal insulation and less thermal mass for heat storage, are naturally more cold acclimatized than heavy men in the sense that they have adjusted their metabolic threshold at higher surface temperatures than those used by large men and in addition have increased the sensitivity of both the deep thermoreceptors to depressions of core and of the surface thermoreceptors to depressions of $\bar{T}_{sk}$.

The thermogenic planes representing the statistical averages compiled for the three body types have relatively small slopes with respect to the T_{re} axis; this appears to be in contradiction with the dramatic thermogenesis some individuals show during rectal temperature drops. This is a statistical manifestation of the high variability among the subjects' T_{re} for a given value of H. Core temperatures are functions of the total heat stores which were created by previous shivering, which was peripherally as well as centrally elicited. The data suggest that the metabolic threshold temperature of large and small men is controlled by cutaneous receptors in agreement with the conclusion of Cannon and Keatinge (7). One difficulty in ascertaining the morphological connection between thermogenesis and core temperature in the case of heavy subjects is that they did not experience the severe depressions of core temperatures, which might have induced equivalently high metabolic activity, as the lean subjects did. Further work involving the immersion of heavy subjects at lower bath temperatures is needed to elucidate these differences.

Insulative Acclimation

Scholander et al (20) did not observe insulative acclimation in the group of Norwegian college students who spent six weeks minimally clothed in a subarctic climate. These workers did find evidence of insulative acclimation in a group of Australian aborigines (21) whose cultural habits required sleeping under mild cold stress induced by deprivation of external insulation. Their method of determining the changes of body insulation was simply to compare the $\bar{T}_{sk}$ of the test subjects to that of controls. Lower average skin temperatures were taken to be indicative of diminished core to skin conductance. They did not see significant metabolic acclimation in this group.

Our testing revealed significant insulative compensation to cold stress in all subjects; the same individuals who exhibited the highest threshold metabolic compensation also exhibited the highest threshold insulative compensation as well. Though the intensity of these responses parallel each other, it appears that the response of most small to average subjects to a moderate cold stress can be divided into two separate phases (Fig. 11). The first is predominately a vasoconstriction phase which occurs in the range of light shivering (100-250 W) and is characterized by only small increases in metabolic heat production (15-30 W). The second phase shows substantial increases in heat generation with progressive decreases in body insulation. An increase in metabolic rate above 150 W was accompanied by a decrease in total body insulation from the maximal insulation. Presumably a small cutaneous circulation is necessary to sustain shivering.

For any morphological group, the intensity of the cold compensation increased with the subject's heat debt. However, compared to large men, small men exhibited a greater increase in both metabolic heat production and in percent change of body insulation per decrement of surface temperature and, also, a greater increase in metabolic heat production per decrement of core temperature. This finding implies that the intensity of metabolic or insulative compensation does not scale with the magnitude of the heat debt when comparing different morphological groups.

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Table 1. ANTHROPOMETRIC RECORD OF SUBJECTS PARTICIPATING IN THIS STUDY

Subject	Body Weight (kg)	Height (m)	Mean Skinfold (mm)	Body Fat (%)	Surface Area (m^2)
1.	61.14	1.72	5.28	8.6	1.72
2.	68.09	1.68	8.42	14.1	1.78
3.	61.26	1.70	6.32	10.7	1.71
4.	84.72	1.82	6.48	11.0	2.06
5.	69.33	1.75	4.73	7.3	1.84
6.	64.35	1.74	5.33	8.7	1.77
7.	70.07	1.69	5.75	9.6	1.80
8.	73.99	1.77	8.85	14.7	1.90
9.	66.89	1.78	4.89	7.7	1.83
10.	64.43	1.74	6.11	10.3	1.78
11.	96.24	1.86	16.93	16.9	2.21
12.	70.22	1.77	10.63	16.9	1.86
13.	72.12	1.83	8.70	14.5	1.94
14.	95.55	1.78	17.63	23.1	2.10
15.	63.40	1.76	6.88	11.7	1.78
16.	66.35	1.76	6.54	11.1	1.82
17.	69.13	1.70	9.15	15.1	1.80
18.	72.25	1.75	9.94	16.1	1.87
19.	63.51	1.69	7.17	12.2	1.73
20.	73.34	1.71	12.63	19.0	1.85

Figure Legends

Fig. 1. The time course of the average area weighted mean skin temperatures, for a group of nude subjects undergoing whole body water immersion at 20°, 24°, 28°, 32°, and 36°C. Skin temperatures achieve quasi-steady state values within 15 minutes of immersion.

Fig. 2. The anisotropy of surface heat flow determine at the following sits: lateral neck or forehead, chest, abdomen, lateral thigh, triceps, calf and instep for subjects in water at 20°C.

Fig. 3. The time course of area weighted mean surface heat flow determine for subjects in water at 20°, 24°, 28°, 32°, and 36°.

Fig. 4. Skin conductance as determine from the quotient of surface heat flow and the thermal gradient from skin to water. Shivering intensity was measure at 20°,24°, and 28°C with and EMG electrode affixed to the quadriceps of the thigh. Numbers indicate the subjects for whom the surface conductance and shivering intensity were determined.

Fig. 5. The average of shivering intensity (in EMG units) versus the metabolic heat production averaged over the immersion period. The data were obtained from subjects (1-10) at the three lowest bath temperature (28°, 24°, 20°C).

Fig. 6 A. Average oxygen uptake for the group of twenty subjects evaluated twelve minutes apart at each bath temperature. No reduction of $\dot{V}O_2$ with time was noted for the group as a whole, indicating that shivering exhaustion did not usually limit heat production even at 20°C.

B. The mean rate of heat production determined during the last 50 min of immersion at 28°C (——) and 20°C (----) for each subject, plotted as a function of his body weight and body fat.

Fig. 7. The rate of metabolic heat production, plotted as a function of both skin and rectal temperatures for subjects representing small, lean; average; and heavy, fat body types. The thermogenic planes, which are defined by the regression equations shown for each subject, indicate the individual variability. Dashed lines upon the plane indicate the slopes with respect to the T_{re} and T_{sk} axes; adjacent vertical lines represent a 50 W incremental rise. Extension of the planes was limited by the range of data collected.

Fig. 8 The three planes which represent the best statistical prediction of metabolic rates (H, in W) as linear functions of skin and rectal temperatures for the three body types. They are defined by the following regression equations:

H =: $1160.5 - 19.8\ T_{sk} - 11.0\ T_{re}$; (small, lean) $r = 0.66$
$629 - 15.1\ T_{sk} - .41\ T_{re}$; (average) $r = 0.75$
$543.0 - 4.65\ T_{sk} + 21.86\ T_{re}$; (fat, heavy) $r = 0.44$

Fig. 9 The change in time averaged heart rate (HC) from the thermoneutral control value (measured in bpm) with the time averaged metabolic heat production. Data were obtained only for subjects 1-10. HR usually exceeded the out of water control values for rates of shivering heat production in excess of 150 W.

Fig. 10. The variation of total body insulation with water temperature. Only subjects completing the 60 min immersion at the lowest bath temperatures are included. Note that subjects 4,11,14 (heavy, fat-heavy, average phenotypes) demonstrated the greatest insulation at the lowest water temperature. All other subjects showed their greatest insulation at the higher water temperatures.

Fig. 11. The variation of the normalized whole body insulation with time averaged metabolic heat production which is evaluated for each bath temperature. (A. Only small to average phenotypes included; B. Only heavy, fat phenotypes included).

Fig. 1

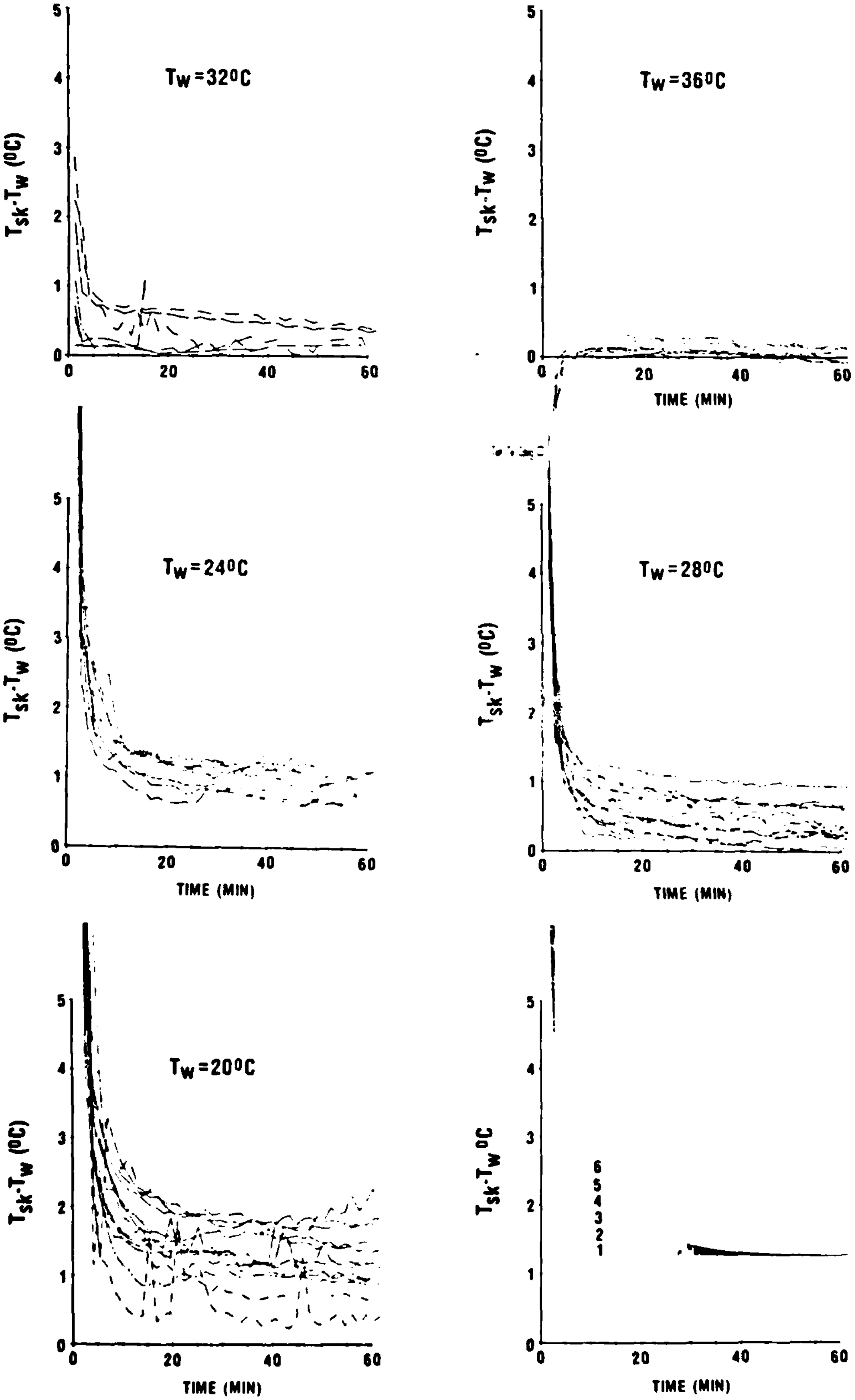

$T_W = 32^0C$
$T_W = 36^0C$
$T_W = 24^0C$
$T_W = 28^0C$
$T_W = 20^0C$
$T_{sk} \cdot T_W$ (^0C)
$T_{sk} \cdot T_W$ ^0C
0
1
2
3
4
5
20
40
60
TIME (MIN)
6
5
4
3
2
1

Fig. 2

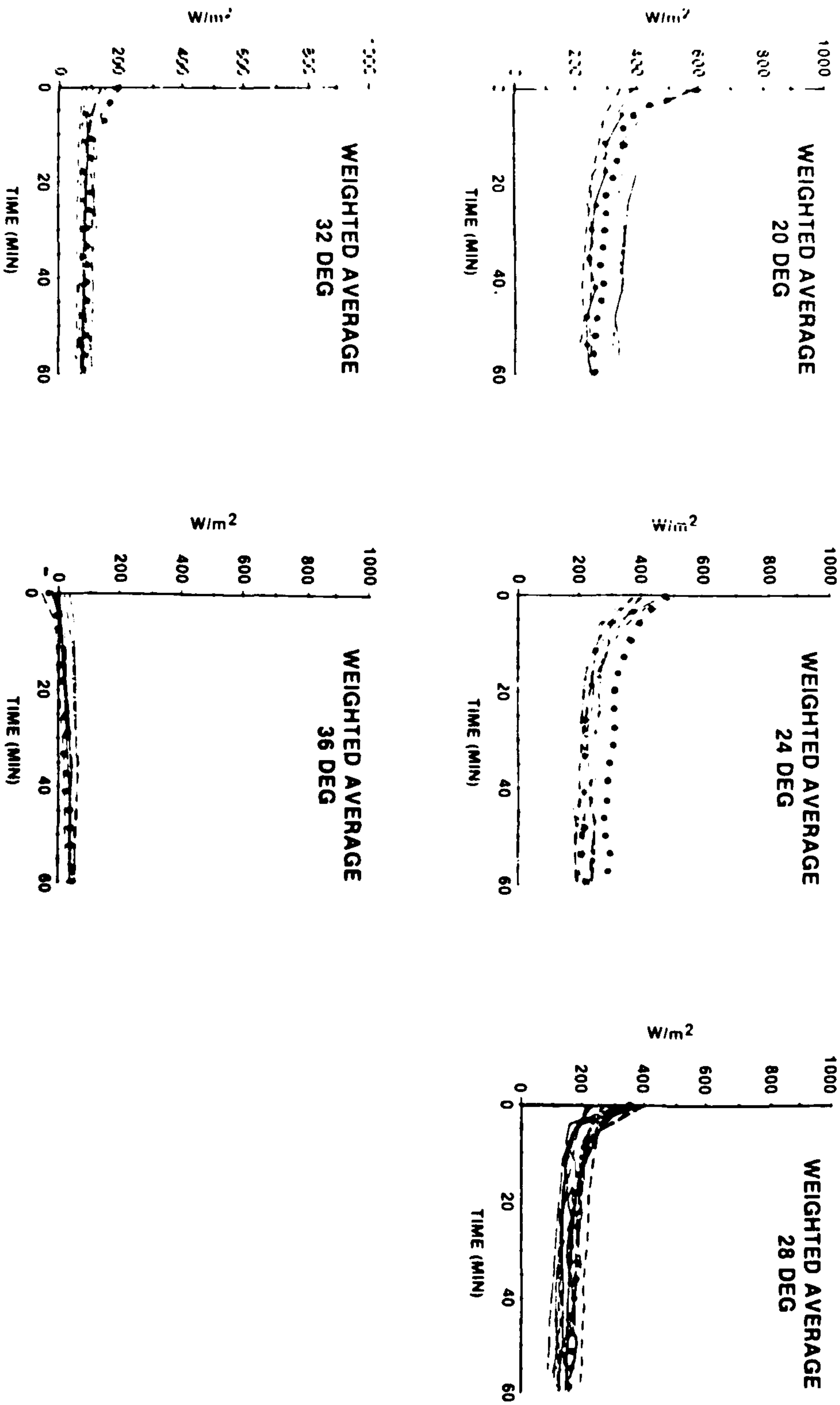

WEIGHTED AVERAGE 20 DEG
WEIGHTED AVERAGE 24 DEG
WEIGHTED AVERAGE 28 DEG
WEIGHTED AVERAGE 32 DEG
WEIGHTED AVERAGE 36 DEG
W/m2
1000
800
600
400
200
0
TIME (MIN)
0
20
40
60

Fig. 3

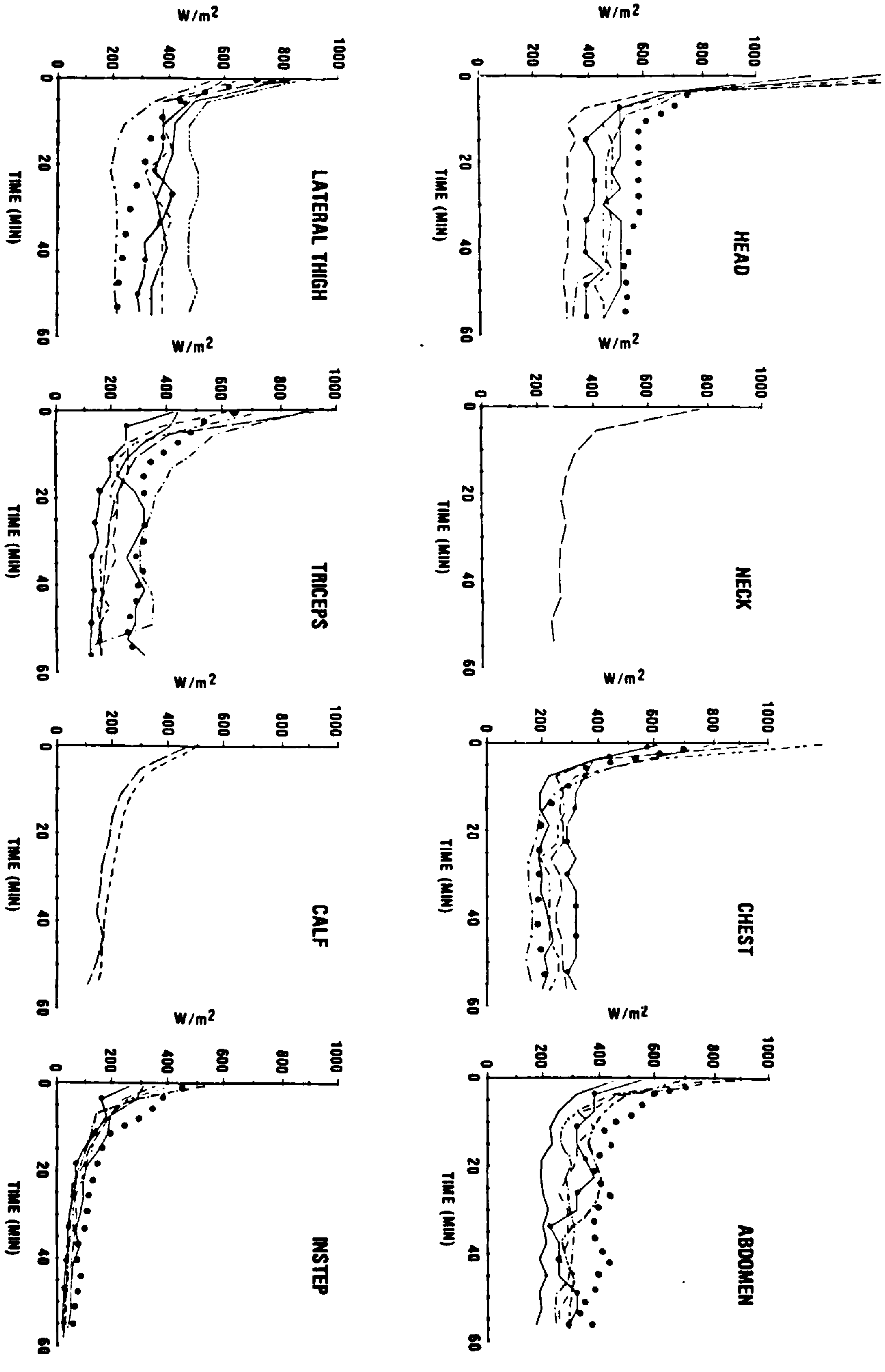

HEAD
NECK
CHEST
ABDOMEN
LATERAL THIGH
TRICEPS
CALF
INSTEP
W/m2
TIME (MIN)
0
200
400
600
800
1000
0
20
40
60

Fig. 4

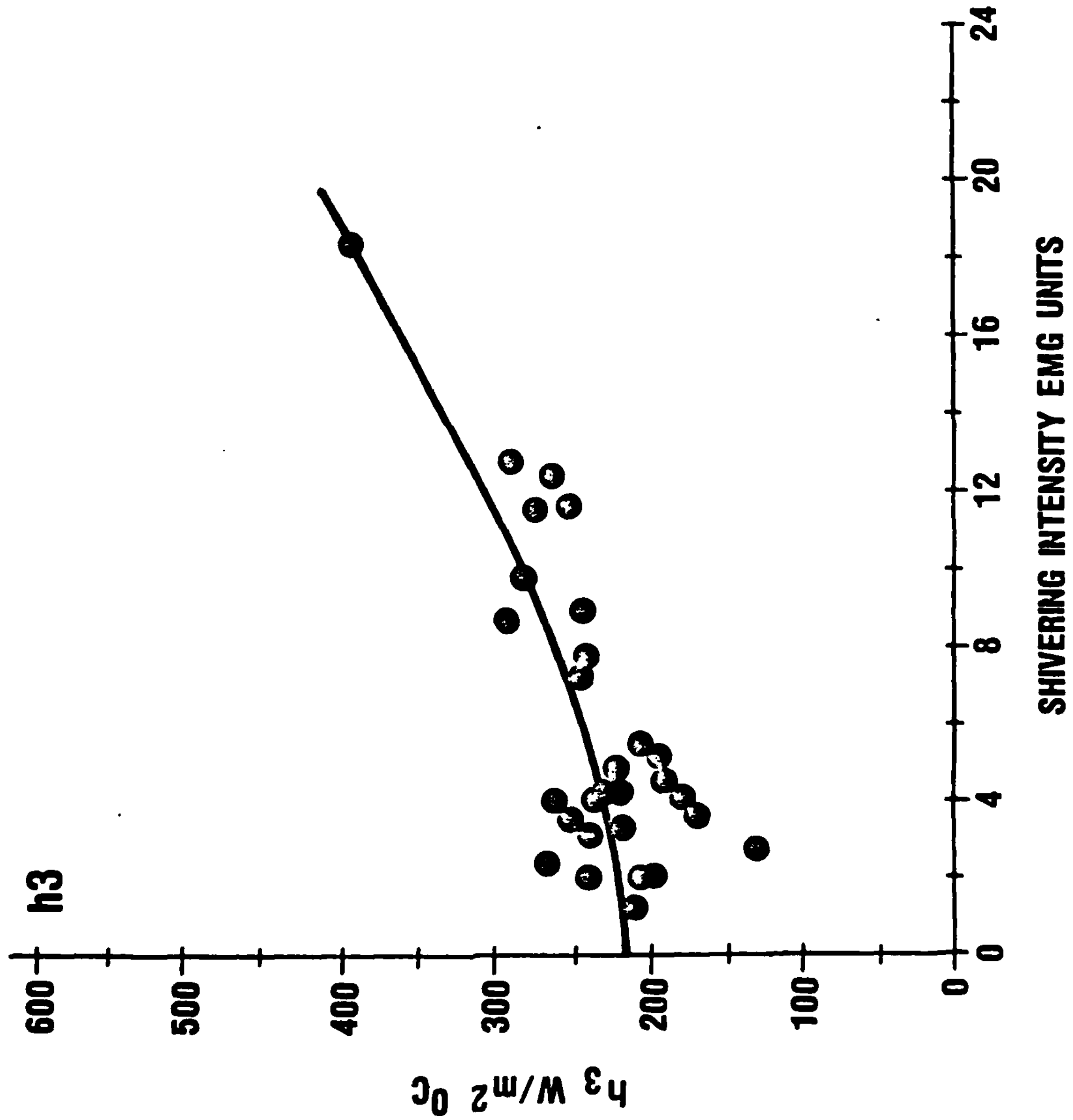

h3
600
500
400
300
200
100
0
h_3 W/m^2 °C
0
4
8
12
16
20
24
SHIVERING INTENSITY EMG UNITS

Fig. 5

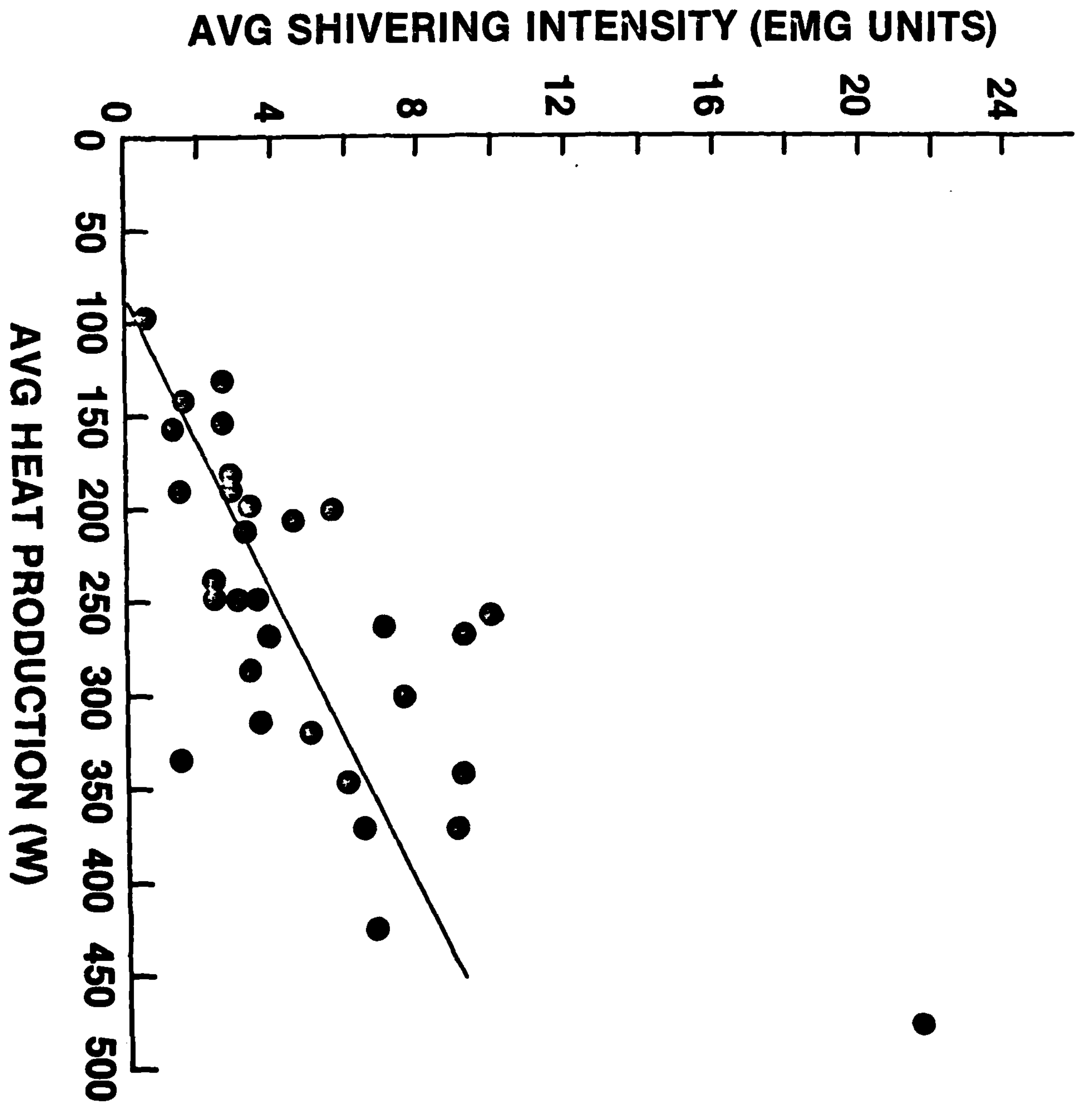

AVG SHIVERING INTENSITY (EMG UNITS)
0
4
8
12
16
20
24
AVG HEAT PRODUCTION (W)
0
50
100
150
200
250
300
350
400
450
500

Fig. 6 A

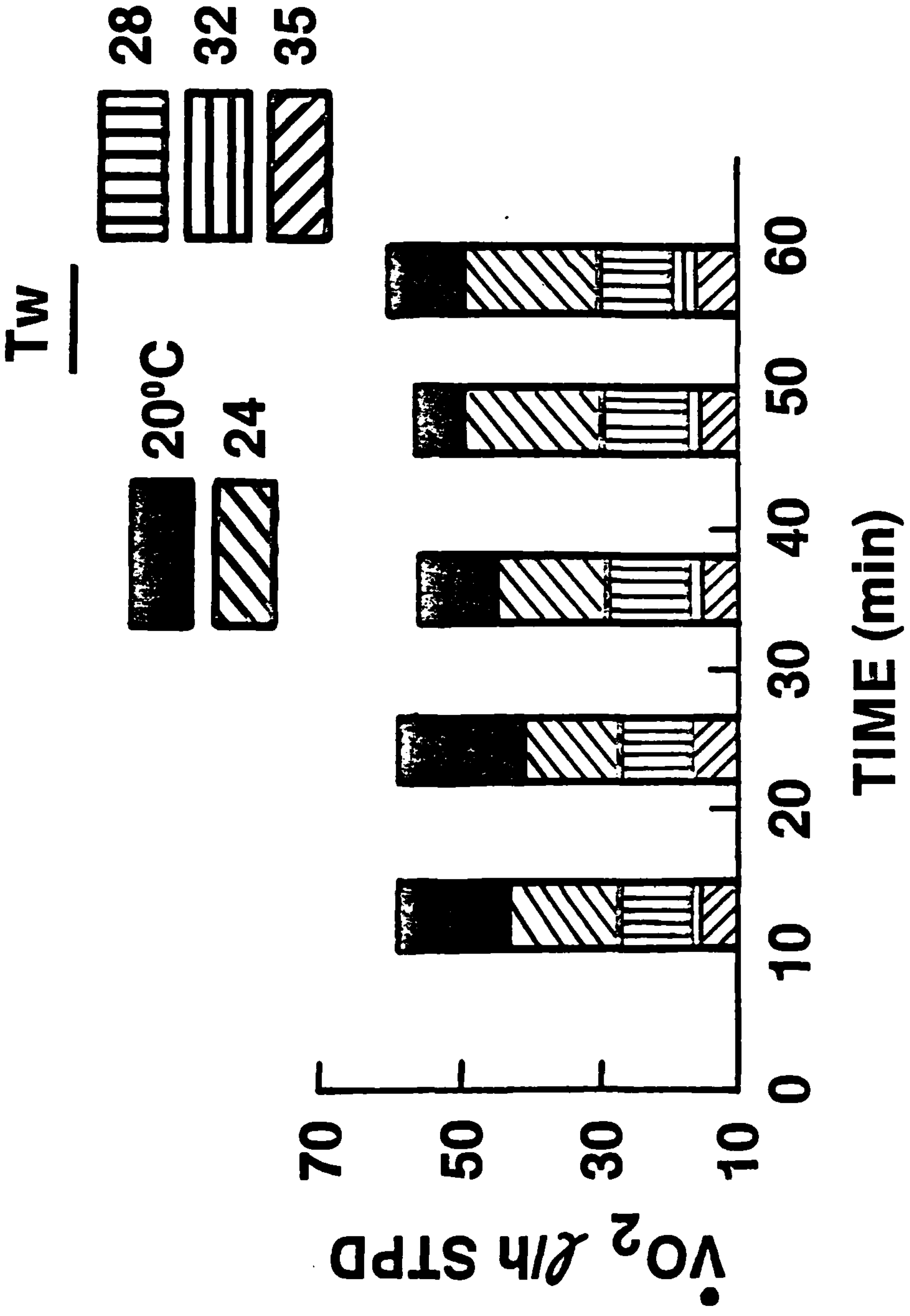

Tw
20°C
24
28
32
35
$\dot{V}O_2$ ℓ/h STPD
70
50
30
10
0
10
20
30
40
50
60
TIME (min)

Fig. 6B

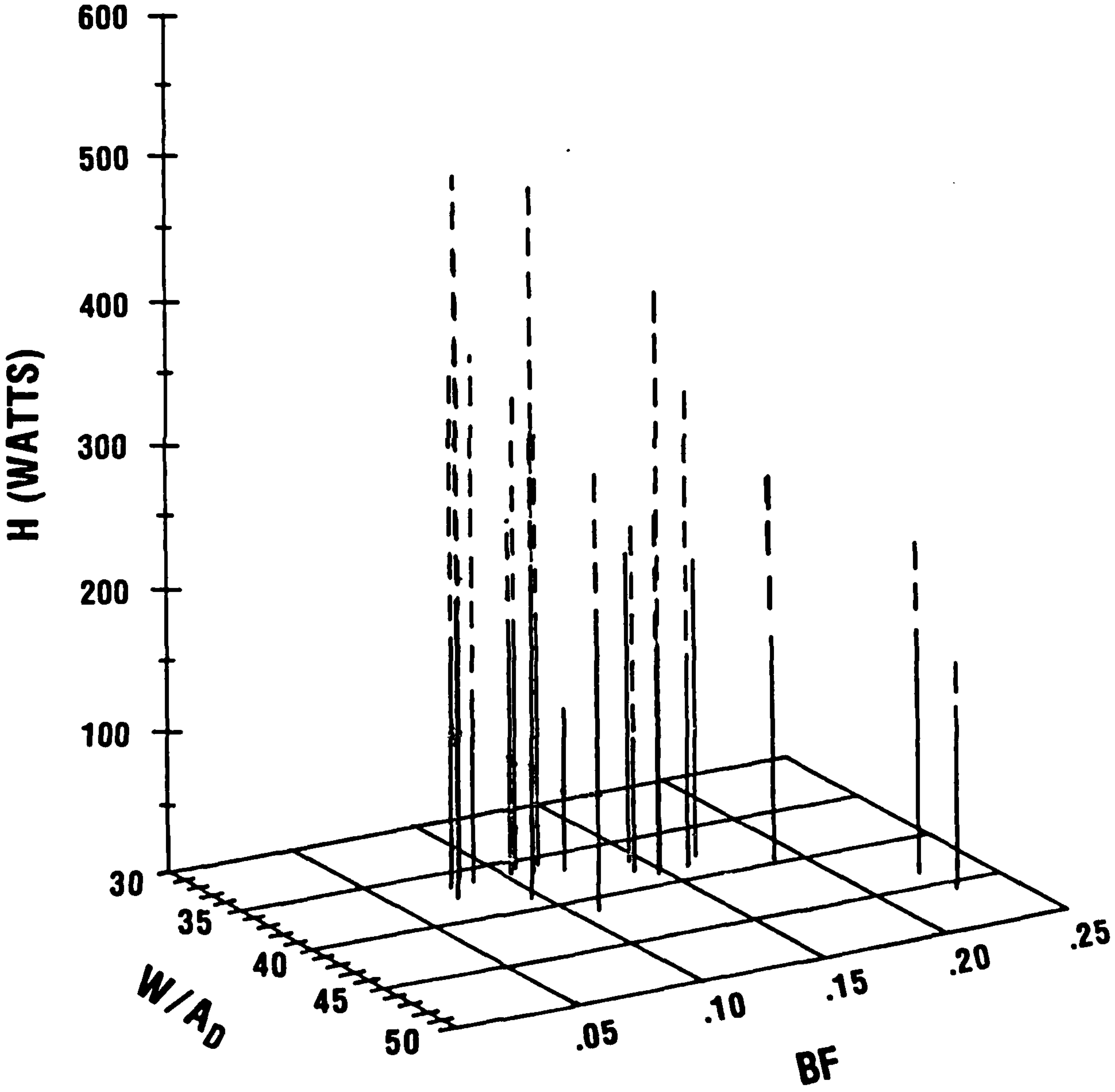
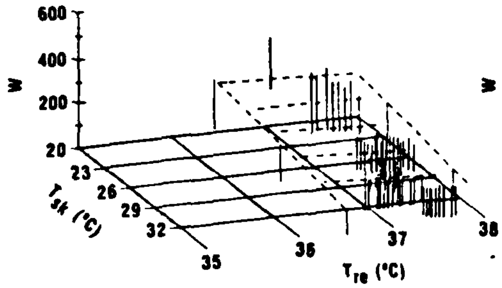


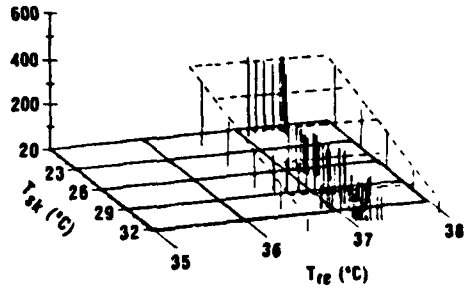
Fig. 7

$M = 1083.27 - 19.31(T_{re}) - 7.43(\bar{T}_{sk})$ (W) $r = .51$



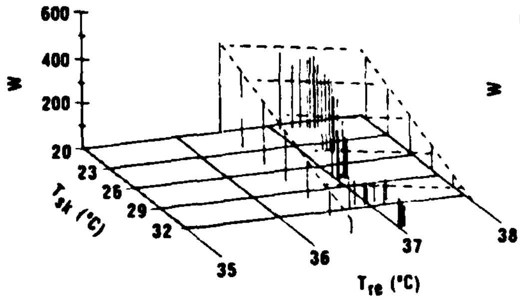
W = 96.24 kg BF = 23%

$M = 936.40 - 6.87(T_{re}) - 18.37(\bar{T}_{sk})$ (W) $r = .86$



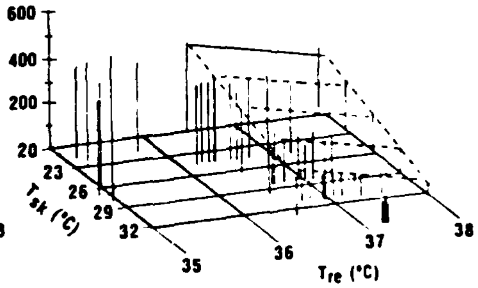
W = 72.25 kg BF = 15%

$M = 3224.30 - 64.90(T_{re}) - 22.72(\bar{T}_{sk})$ (W) $r = .82$



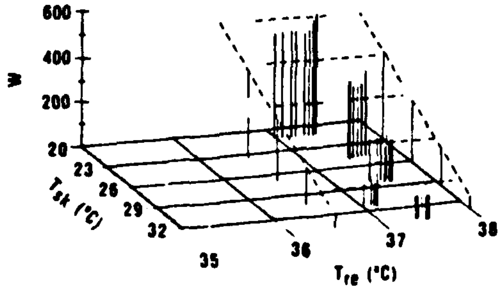
W = 84.72 kg BF = 11%

$M = 3867.89 - 85.20(T_{re}) - 17.77(\bar{T}_{sk})$ (W) $r = .91$



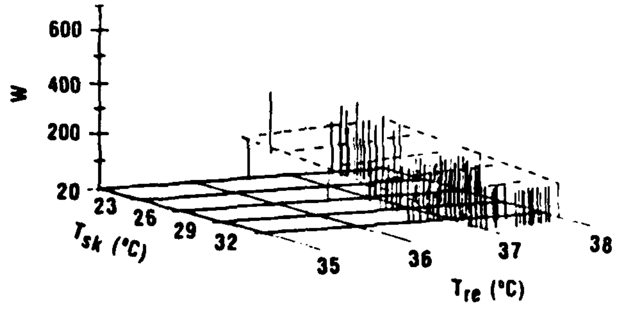
W = 61.14 kg BF = 8.6%

$M = 1721.76 - 14.41(T_{re}) - 33.69(\bar{T}_{sk})$ (W) $r = .93$

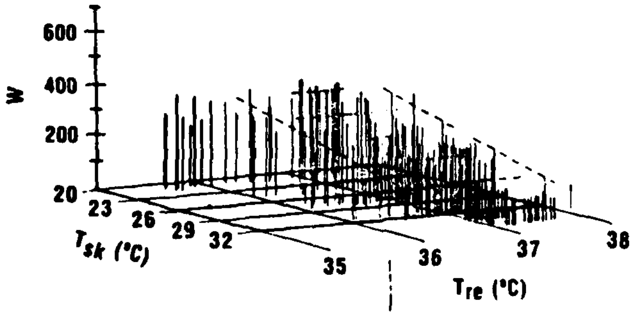


W = 69.33 kg BF = 7.3%

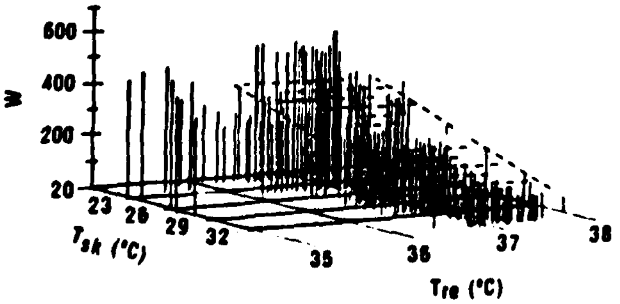
Fig. 4



HEAVY FAT SUBJECT GROUP (W>90kg; BF>20%)



AVERAGE SUBJECT GROUP (70kg< W<90kg; 12%<BF<20%)



SMALL, LEAN SUBJECT GROUP (W<70kg; BF<12%)

Fig. 9

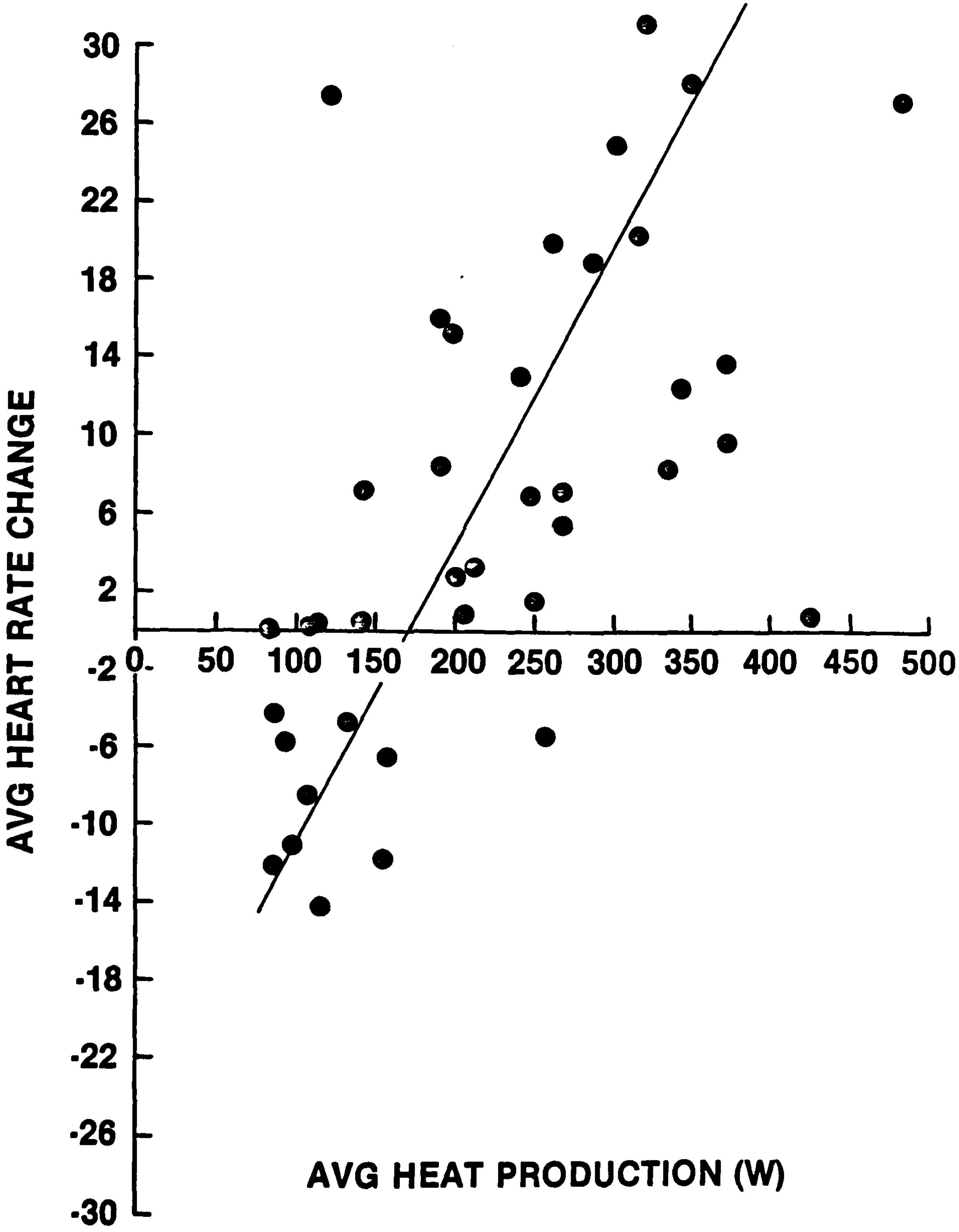

30
26
22
18
14
10
6
2
-2
-6
-10
-14
-18
-22
-26
-30
AVG HEART RATE CHANGE
0.
50
100
150
200
250
300
350
400
450
500
AVG HEAT PRODUCTION (W)

Fig. 10

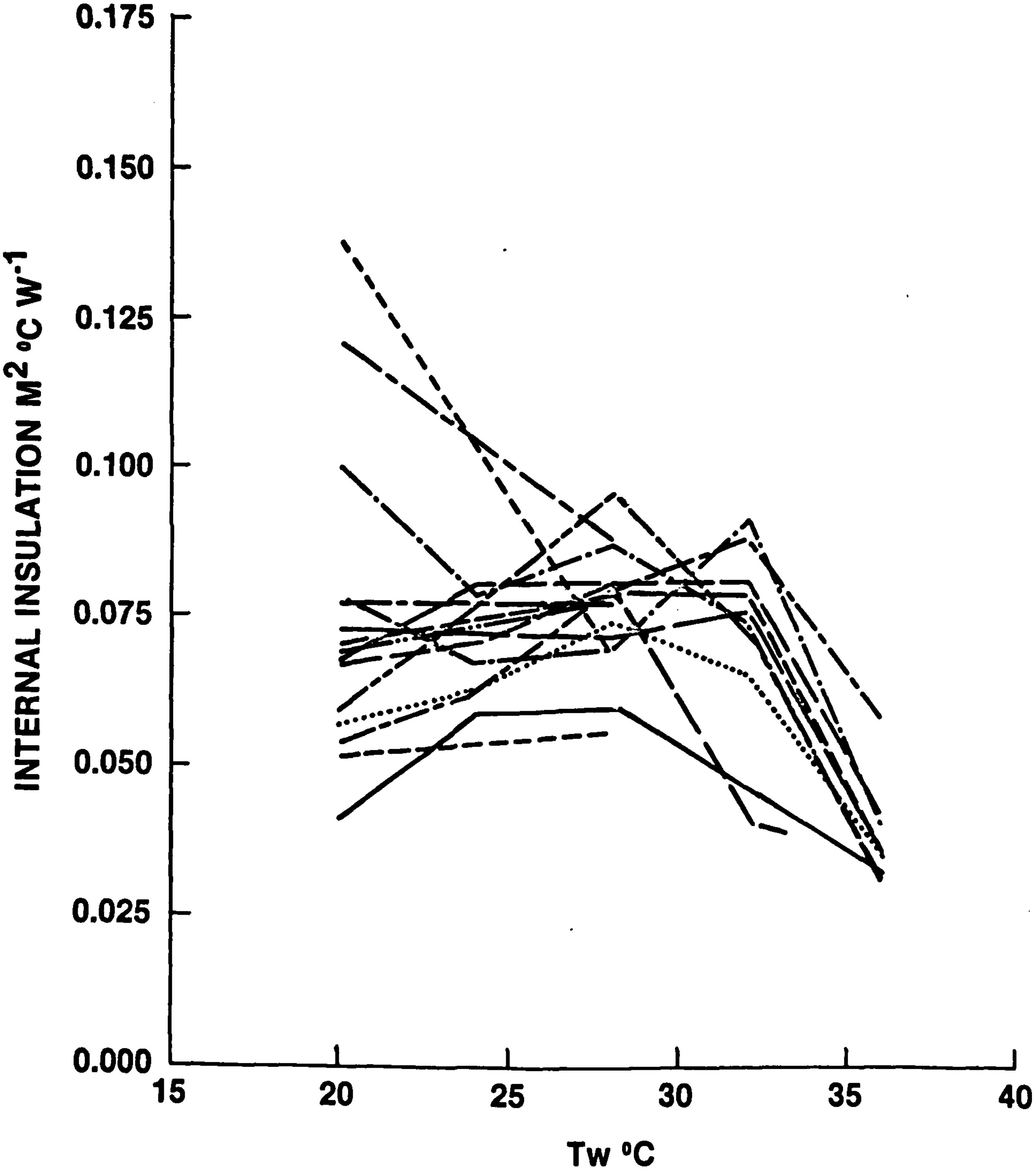

0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.000
INTERNAL INSULATION M^2 °C W^{-1}
15
20
25
30
35
40
Tw °C

Fig. 11A

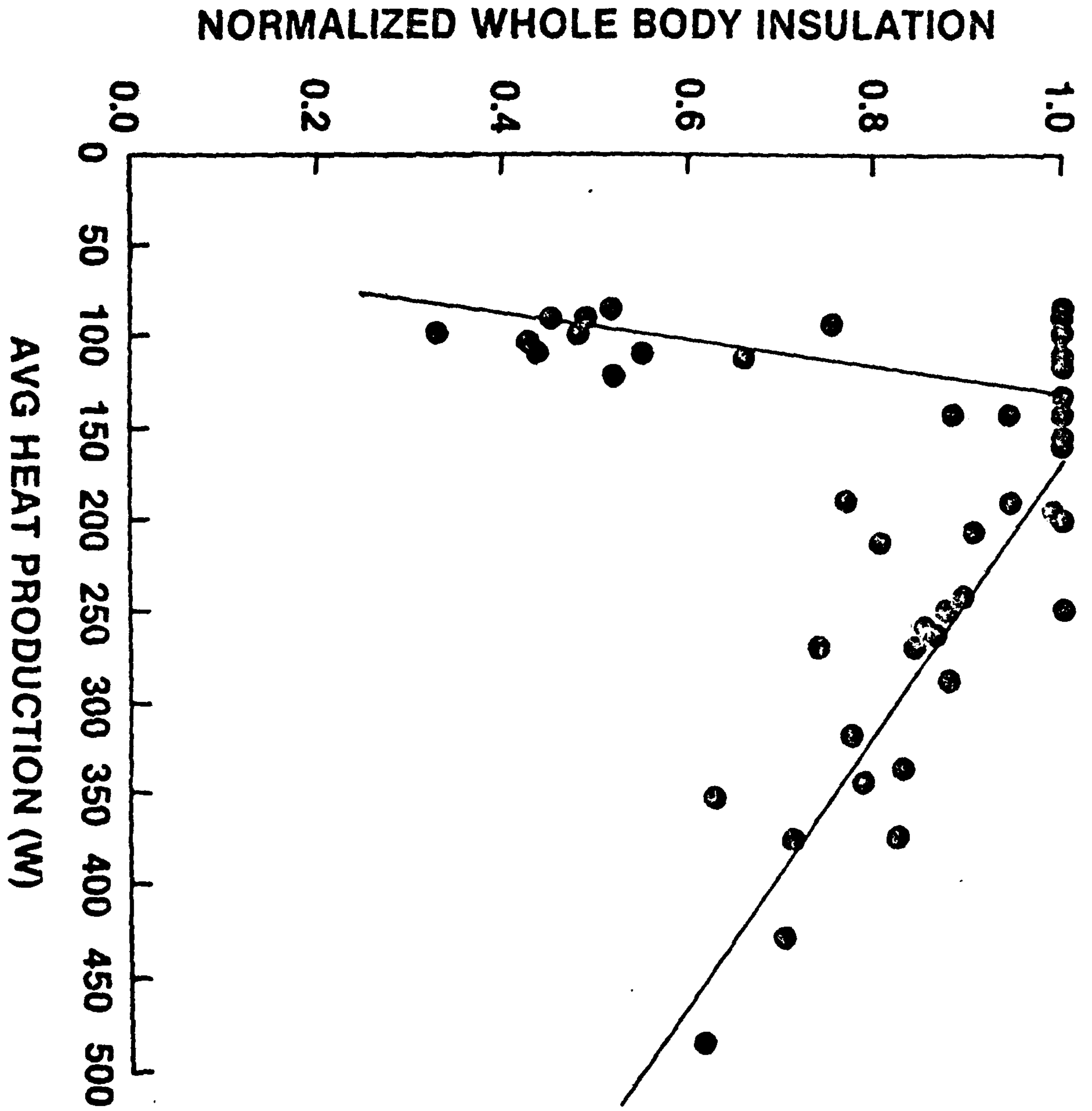
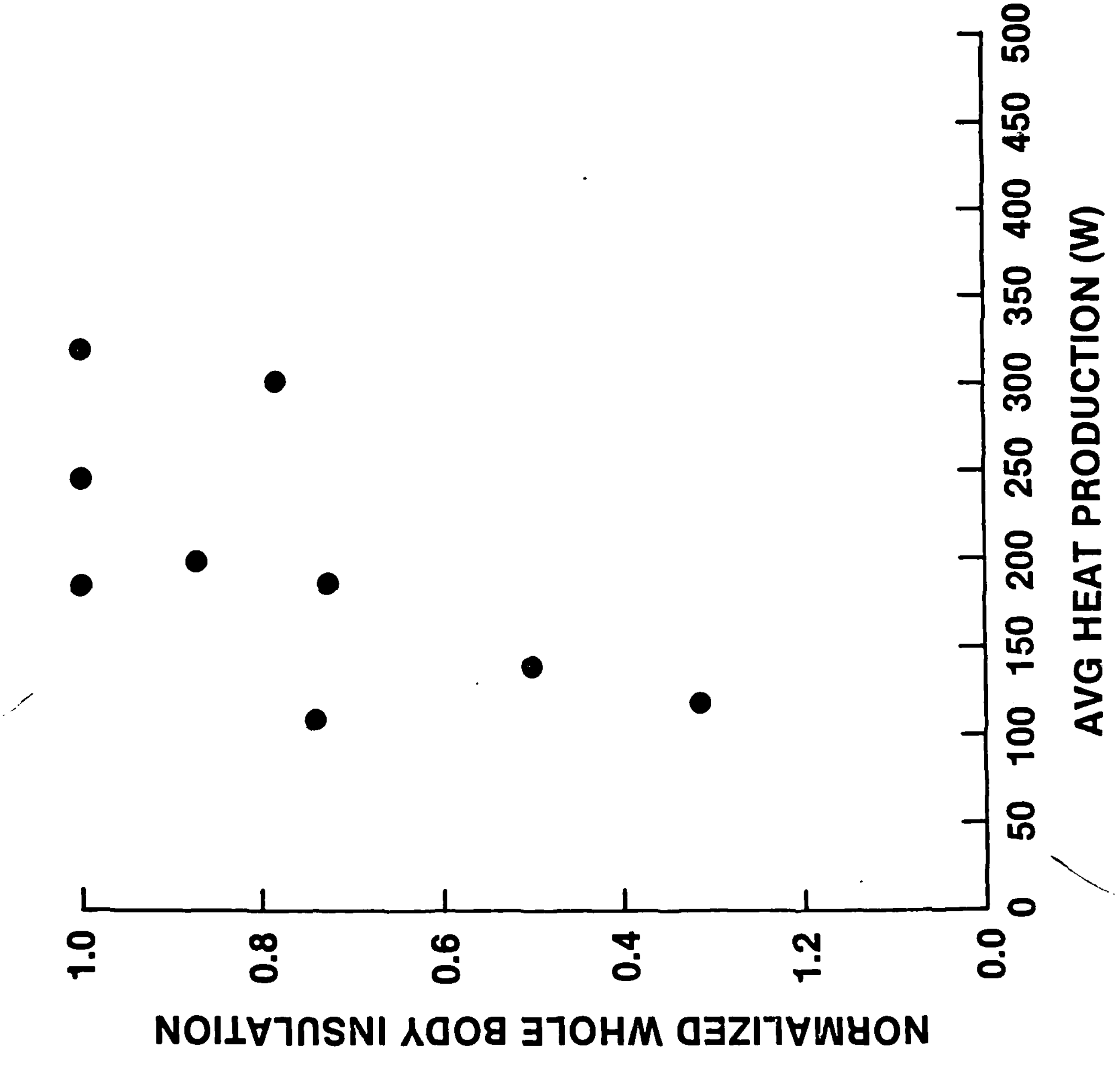

NORMALIZED WHOLE BODY INSULATION
0.0
0.2
0.4
0.6
0.8
1.0
0
50
100
150
200
250
300
350
400
450
500
AVG HEAT PRODUCTION (W)

Fig. 1 1B


NORMALIZED WHOLE BODY INSULATION
1.0
0.8
0.6
0.4
1.2
0.0
AVG HEAT PRODUCTION (W)
0
50
100
150
200
250
300
350
400
450
500