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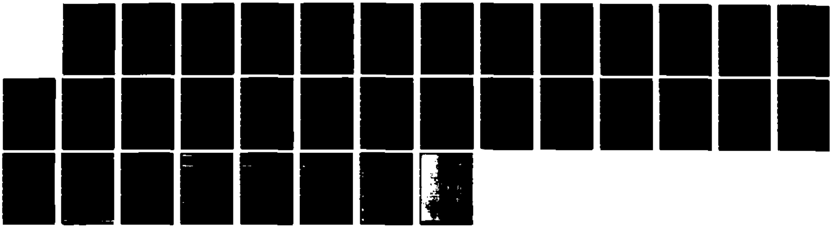

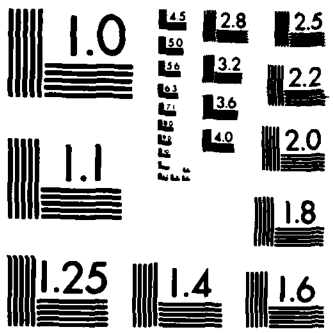

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Twenty male subjects (17 to 28 yrs of age) exhibiting a range of body weights (60 kg $\leq$ Wt $\leq$ 95 kg) and body fat (7%<BF<23%) underwent total immersion while at rest in water between 36°C and 20°C. The time course of mean skin ($\bar{T}_{sk}$) and rectal (T_{re}) temperatures as well as surface heat flow was simulated for each individual immersion with the aid of a time dependent system of differential, heat balance equations coupling different body compartments and the epithelium to the water bath. Metabolic heat production for each immersion (supplied as functions of T_{re} and $\bar{T}_{sk}$ minus 8% of the instantaneous value to

account for respiratory losses) were used as heat source terms. This formulation permitted the evaluation of internal and external conductances as a function of water temperature. Analysis showed that cardiovascular compensation occurs at higher bath temperatures for small, lean men compared to large, fatter men. It also showed that body size (expressed as the ratio of mass to surface area) in addition to fat content controls the maximal internal insulation as well as the rate of decline of T_{re}.

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.

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A Model of Heat Loss and Thermoregulation for Immersion in Cold Water

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Abstract

Twenty male subjects (17 to 28 yrs of age) exhibiting a range of body weights ($60\ kg \leq Wt \leq 95\ kg$) and body fat ($7\% \leq BF \leq 23\%$) underwent total immersion while at rest in water between 36°C and 20°C. The time course of mean skin ($\bar{T}_{sk}$) and rectal (T_{re}) temperatures as well as surface heat flow was simulated for each individual immersion with the aid of a time dependent system of differential, heat balance equations coupling different body compartments and the epithelium to the water bath. Metabolic heat production for each immersion (supplied as functions of T_{re} and $\bar{T}_{sk}$ minus 8% of the instantaneous value to account for respiratory losses) were used as heat source terms. This formulation permitted the evaluation of internal and external conductances as a function of water temperature. Analysis showed that cardiovascular compensation occurs at higher bath temperatures for small, lean men compared to large, fatter men. It also showed that body size (expressed as the ratio of mass to surface area) in addition to fat content controls the maximal internal insulation as well as the rate of decline of T_{re}.

INTRODUCTION

Partitional calorimetry has been applied to human immersion in cold water to determine core-skin conductance and surface heat transfer in the steady state (2,6,11,13,14). Few studies have used the transient behavior of core and skin temperatures to determine internal conductance values. Such an analysis is complicated by the difficulties in directly measuring instantaneous body heat stores. It is nevertheless useful, because it allows determination of the internal conductance values for a much greater range of physiological stresses than can be obtained under steady state limitations. Knowledge of the time rate of change of heat stores within the body compartments also allows one to predict the time course of temperature changes within the body compartments for exposure times, ambient temperatures and stress levels which are not easy to study experimentally.

A number of water immersion studies have investigated the role of body fat in retarding rectal temperature decline (3,5,6,10,11,14,15). Carlson et al. (6) reported that body insulation varied directly with specific gravity, yet the fraction of body volume calculated to be involved in insulation was always greater than the estimated fat content. In a study of male subjects having widely varying body size (50 to 150 kg) and body composition (4 to 40% body fat), Buskirk and Kollias (3) obtained a regression equation for the total body insulation (R) in water at 15°C as a function of the mean thickness of subcutaneous fat (SCF in mm) ($R = 0.101 + .028$ SCF, in $°C\ m^2\ W^{-1}$). Rennie et al. (14) obtained a different maximal tissue insulation in men and women exposed to 30°C water ($R = .043 + 0.021$ SCF). Kollias et al. (11) obtained still another expression for the total body insulation of a sample of American women in water at 20°C ($R = .074 + .018$ SCF). These workers compared their data with that of men exposed to the same conditions and concluded that women conduct heat faster than men with similar body fat content. The greater conductance of women was postulated to depend upon surface area and mass differences. Though the insulation component attributed to subcutaneous fat is similar in each study, the insulation component ascribed to body size is assumed to be constant for each population even though body size differed greatly between studies. Differences in body size and surface area were not considered in these regression analyses; the total insulation simply was considered one dimensional, as subcutaneous fat.

While subcutaneous fat provides significant insulation, body size itself can alter the maintenance of core temperature. The effect of varying thermal mass is most apparent in the transient state of core temperature decline. Keatinge (10) reported that the rate of fall of rectal temperature in water at 15^{o}C increased in proportion to the inverse of mean skinfold thickness. Sloan and Keatinge (15) found that a similar relationship in 20^{o}C water, was improved by making allowance for the size of their subjects (as expressed by their body weight to surface area ratio wt/A_D). These studies, unfortunately, did not allow for individual differences in metabolic heat production which influenced the rate of decline.

The present study applies a time dependent model of heat transfer to the problem of total body immersion in water at temperatures ranging from 35 to 20^{o}C while evaluating the internal and external conductances required to produce the time variable core and skin temperatures observed in a resting population having varying body mass (60-95 kg) and body composition (7-23% body fat). To accomplish this, we solved a system of time dependent, coupled linear differential equations which represent the heat storage and heat flow between major body compartments. The thermal masses of the body core, subcutaneous fat and skin compartments were evaluated for each individual from his anthropometric data. The metabolic rates, which were measured as a function of time, were converted to explicit linear functions of core and skin temperatures for each individual immersion and were incorporated as heat source terms. This analysis permitted us to compare the effects of changing the total body insulation and heat storage (via changes in vasoconstriction, body fat, body mass) against the effects of changing metabolic heat production on stabilizing core temperature.

METHODS

Data were available from a series of studies (4,8) conducted with 20 healthy male subjects totally immersed in water at 28 and 20°C; ten of these were also immersed at 36, 32, and 24°C. The anthropometric data of these subjects appear in Table 1. Skinfold measurements were obtained at the biceps, triceps, subscapular and suprailiac sites and body fat was calculated according to the method of Durnin and Womersley (7). Each subject was tested at a selected water temperature, once a week, over a period of ten weeks with two subjects studied each day (one in the morning and one in the afternoon). The morning subject had no breakfast and the afternoon subject no lunch and neither had exercised for at least an hour prior to the test. The immersion tank was 3 meters long, 3 meters wide and 4.6 meters deep with a volume capacity of 37.8 thousand liters. The water temperature was checked each morning and afternoon and monitored continuously during the test; it was found to vary no more than ± 0.3°C on any given day. The water was thoroughly mixed prior to the test to attain a uniform temperature in the tank. However, during the test the subject was in essentially "still" water. The ambient air temperature ranged from 23-24°C for the entire test. The subject was placed supine on a nylon mesh cot, attached to a platform that could be lowered with a hoist into the water to a depth at which the water completely covered his head. The subject was asked to refrain from voluntary motion. To keep him from floating, a lead strip was placed over his chest and one over his feet. Compressed air was bubbled through a water filled bottle and then to a Douglas bag from which the subject breathed using a J-valve with a mouthpiece. The subject usually kept his eyes closed during the entire immersion period.

Core temperature was measured with a thermistor probe inserted 10 cm into the rectum. The temperatures from 10 skin surface loci were measured from thermocouples fixed under a strip of thin surgical tape; this thin tape approximated the insulation derived from the outer layers of skin and simulated the measurement of sub-surface skin temperature rather than the temperature at the skin-water interface (2). The mean skin temperature ($\bar{T}_{sk}$) was calculated according to the following weights (1): instep (0.05), calf (0.15), medial thigh (0.125), lateral thigh (0.125), back (0.125), chest (0.125), upper arm (0.07), lower arm (0.07), hand (0.06), and forehead (0.10). The rate of free convection from the skin surface was measured with heat flow sensors (RdF Corporation Microfoil P/N 20460) attached at five body surface sites, with the same surgical tape at the edges of the plate; the sensor area of the plate was left uncovered. Heat flow measurements were corrected for the insulating effects of the skin sensors. The mean area weighted heat flow was determined with the following weights: lateral neck (0.1), chest (0.3), triceps (0.2), lateral thigh (0.2), and calf (0.2). Oxygen consumption and CO_2 production were measured every six minutes by collecting the expired air in a Tissot spirometer and analyzing for O_2 and CO_2 with a Beckman E-2 oxygen and a Beckman LB-2 CO_2 analyzer. Metabolic rates were calculated by the Weir formula (20).

Data were also available from a study (4) in which ten of the subjects also donned three different types of wet suits and repeated the water trials at 20 and 28°C, while fully instrumented to collect skin and rectal temperatures and surface heat flows. The insulation values (I_{cl}) of the wet suits in water were measured on an immersed copper manikin:

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polyurethane cell I_{cl} = .0946 $^{o}C\ m^2/W$ = 0.61 clo

vinyl polymer I_{cl} = .058 $^{o}C\ m^2/W$ = 0.37 clo

neoprene foam I_{cl} = .114 $^{o}C\ m^2/W$ = 0.74 clo

These are the effective combined thermal resistances of the wet suits plus the trapped water layer. The resistance of each suit alone was assumed to be the difference between the effective value and the insulation of the layer of still water surrounding an unclad manikin (I_w = 0.008 $^{o}C\ m^2/W$ = 0.05 clo). The mass of water which was trapped between the subject and the suit was estimated from the volume capacity of the suit and the water displacement of the subject when immersed.

Data Analysis Methods

The core and skin temperatures from all subject exposures were simulated with the aid of a time-dependent, multi-compartment model for one dimensional heat transfer, using input data consisting of skin and rectal temperatures, radial heat flow from the surface and the metabolic heat production. The model has similar features to the lumped parameter, one-dimensional versions developed by Stolwijk (16,17), Timball et al. (19) and Montgomery (12), but it divides the heat storage of each compartment of a nude man undergoing whole body water immersion into three components: (1) core, (2) subcutaneous fat and (3) skin. This formulation permits the separate evaluation of changes in internal and external conductances with water temperature. It is also easily expandable to treat the heat transfer between the additional component layers required when protective clothing is worn.

In this multi-compartment model as illustrated in Figure 1, heat transfer occurs through N, not necessarily contiguous, compartments (N arbitrarily large) which includes a body core, a fat compartment, a skin compartment, and any external thermal prot ·tive (c' ,ing, air and/or water) layers present. The heat transport equation balances the time rate of change of thermal energy stored within each compartment, with the net energy flux through each compartment plus the energy added or subtracted due to sources or sinks operative within the compartment. If one ignores the energy flux through the thermal gradient within each compartment (i.e. requires each compartment to be isothermal), the time rate of change of energy stored per unit area in the i-th compartment is:

$$(m_i/A_i)\, c_i\, \dot{T}_i = \sum_{k,j\neq i} h_{ij}\,(T_j - T_i) + Q_i\,(T_i, T_k, \dot{T}_i, t) = \text{system}*$$

where m_i/A_i is the mass of compartment i (m_i) divided by its surface area (A_i), c_i is the specific heat capacity, and h_{ij} is the heat transfer coefficient from compartment i to compartment j. The Q_i represent active sources of thermal energy which may be linear functions of the temperatures T_i, T_k, $\dot{T}_i$, or time t. We have specified Q_i to comprise the metabolic heat production which is operative only in the core compartment. The defined system, (*), is presented as a linear system of coupled, first order differential equations, the solution to which has already been given (18) in a complete analytical form.

The mass to area ratios for each compartment were determined from the anthropometric measurements on each subject, with the approximation that the geometry for radial heat flow would be represented as a series of concentric right circular cylinders, each of length equal to the height of the test subject. The details have been reported elsewhere (18).

For each subject exposure 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 (r) was better than 0.80, the heat input (Q_1) in (*) was set equal to the current value of the linear regression equation, minus 8% to account for respiratory heat loss; otherwise Q_1 was set equal to the simple average rate of metabolic heat production (H) determined by the 10 measurements taken over the course of the one hour immersion minus the 8%.

RESULTS

Time Course of Skin and Rectal Temperatures

To determine how the magnitude of the mismatch between the heat produced and the heat lost by the body may be used to evaluate internal conductances, a computer program was used to simulate the time course of the mean weighted skin and rectal temperatures of the twenty subjects for all exposures. Use of the program requires experimentally determined metabolic heat production and heat transfer coefficients from core to fat (h_1), from fat to skin (h_2), and from the skin to the infinite heat sink (h_3) presented by the water.

Evaluation of h_3

A computer fit to the $\bar{T}_{sk}$ for each experiment was obtained by varying h_3 until the experimentally observed steady-state temperature resulted. The steady-state temperatures are determined by h_3, as well as by the amount of heat added by conductive and convective transfer from other compartments. The characteristic time for the skin temperature decline depends upon both h_3 and the heat capacity of the skin layer. The h_3 values, which were determined from the area weighted heat flow measurements divided by the thermal gradient from skin to ambient, were used as input to the computer program; small corrections (10-20 $W/m^2\,^oC$) were usually necessary in order to reproduce the actual experimental steady state average skin temperatures.

Evaluation of h_2

The layer of subcutaneous fat serves not only as additional resistance to heat flow, but also as a locus for heat storage. While it protracts the time development of the fall of T_{re}, it may accelerate the fall of skin temperature by effectively insulating the epithelial layer from its heat source. The simplifying assumption that is made is that the subcutaneous layer provides the fixed resistance to heat flow; i.e. the fat layer conductance is independent of blood flow variations. It is difficult to separate the insulation afforded by body fat from that afforded by the combined mass of fat and body core since the average gradient across the fat layer is not measured. We have taken the view that h_2 across the subcutaneous layer is inversely proportional to the thickness of that layer. Hatfield and Pugh (9) give the thermal conductivity per mm of subcutaneous fat as 204.28 $W/m^2 \cdot {}^oC$. If an average thickness of the subcutaneous fat layer is determined from a number of skinfold thickness measurements at various sites (4 to 10), the conductivity of an individual's subcutaneous fat layer (h_2) may be calculated from the formula:

$$h_2 = \frac{204.28}{(\text{average skinfold}-3)/2} \qquad (\text{in } W/m^2 \cdot {}^oC)$$

where the skinfold is measured in mm (the double epithelial thickness is 3 mm) and assumed fixed for each subject; h_2 is used directly as input into the computer program.

Evaluation of h_1

We have collected the variable peripheral and fixed core resistances into a single variable core resistance. A single value of h_1 was determined for each subject exposure by a trial and error procedure which yielded the best overall representation of the time evolution of T_{re}. Rectal temperature is a sensitive function of both (a) the metabolic thermogenesis (H) and (b) the sum of the internal and external thermal resistances ($1/h_1 + 1/h_2 + 1/h_3$). Our method of calculating the total tissue conductance requires no assumption that a steady-state temperature distribution is achieved. The core temperature continues to drop long after the skin temperature has stabilized (Figures 2 & 3). This usually proves to be a vexing problem in calculating the tissue conductance, as it is difficult to determine instantaneous heat stores. The success of this formulation in accounting for body heat storage can be judged by the agreement between the calculated and the experimental temperatures (Figures 2 &3).

Modeling the Time Dependence of Core and Skin Temperatures

Figures 2 and 3 present some representative skin and rectal temperatures as a function of time following immersion at 28°C and 20°C for six of the subjects having lean (wt < 70 kg; BF < 12%), average ($70 \leq wt \leq 90$ kg; $12 \leq BF \leq 19\%$), or heavy (wt > 90 kg; BF > 19%) body composition. The skin to water temperature gradients differ between subjects by as much as ± 0.5°C. This may be explained principally by differences in shivering intensity (which control h_3) although core to skin conductances (i.e., $1/h_1 + 1/h_2$) play a minor role (18). Core temperature differences between subjects may be explained by differences in both thermogenic activity and intrinsic insulation ($1/h_1 + 1/h_2$). Although lean subjects demonstrate a much higher metabolic heat production than heavy subjects for an equivalent water temperature, the extra heat produced by lean subjects does not sustain as high a T_{re} as maintained by heavy subjects. By the end of a one hour immersion at 20°C, the T_{re} difference between subjects in the three morphological groups is in excess of 1°C.

After one-hour immersion, heavy men exhibited a higher T_{re} at 20°C than at 28°C. This occurred, in part, because shivering thermogenesis is somewhat greater at the colder temperature, but primarily because peripheral tissue conductance is much smaller (by 0.48 to 0.70). The heavy subject does not maximally vasoconstrict at 28°C, as judged from the fact that his core to skin resistance is greater at 20°C. The lean subjects, on the other hand, generally demonstrated a lower T_{re} in the colder water (see Figures 2 and 3). Computer fits to the T_{re} suggest that tissue conductances for lean subjects are fractionally greater at 20°C than at 28°C. The extra metabolic heat production at the colder temperature does not fully compensate for the heat loss due to the larger thermal gradient; thus, T_{re} drops faster. One subject (Figure 3, middle) did not maintain a safe T_{re} even for an hour at 20°C, although his shivering heat production was high (465 W), because a moderate cutaneous circulation is required to support shivering. Rectal temperature profiles are more variable among subjects having average body fat ($12\% \leq BF \leq 19\%$) and body weight ($70 \leq wt \leq 90$ kg). Core temperatures do not uniformly drop faster in the colder water, because increases in metabolic heat production can compensate for the larger thermal gradient (Figure 2, middle).

The Dependence of Core to Skin Conductivity on T_w

The total tissue conductivity from central core to skin surface depends upon body composition and cutaneous circulation. Figure 4 shows the variation of total tissue conductance with wt/A_D and T_w for the population of 20 Ss. The size of the subject population and its limited range of body types did not permit us to differentiate between the roles of lean versus fat body masses in controlling the total internal conductance. Conductance is uniformly highest for all subjects at 36°C. At lower water temperatures, the conductance data appear to divide into two general categories; subjects whose wt/A_D quotients are less than about 40 kg/m^2 in this study generally exhibit minimal conductance values at T_w between 28-32°C. Below a T_w of about 28°C, their circulatory heat losses increase because a greater perfusion of the muscle mass is necessary to support active shivering. The group of subjects whose wt/A_D quotients are greater than 40 kg/m^2 on the whole demonstrate their minimal conductance at considerably lower T_w (20°C or less). In 20°C water, the heavy men show a 50-75% increase in whole body thermal resistance above that attained at 28°C, while the lean subjects show, on average, 30% less than at 28°C. Such differences can result in greatly varying survival times from subject to subject. The combination of different shivering thresholds (18), different thresholds for vasoconstriction, and different lean and fat body masses, results in core to skin conductances which vary by a factor of three from lean to heavy subjects at 20°C (Figure 4).

Modification of Skin and Rectal Temperatures by Insulative Clothing

Figures 5 a and b illustrate two examples of experimental and computer simulated rectal and skin temperatures as a function of time when external insulation is worn. These two subjects represent the lean and heavy body types undergoing immersion at 20°C while nude and wearing three different types of wetsuits. The major effect of the additional insulation upon $\bar{T}_{sk}$ is to raise the $\bar{T}_{sk}$ above the unclothed value, as if the effective T_w were elevated. Similar surface temperatures as those obtained at 20°C with 0.37 clo insulation, would occur at 26°C without the extra insulation. Similarly, skin temperatures obtained while wearing 0.61 clo of insulation would result if nude in water at 27.5°C, and those obtained while wearing 0.74 clo of insulation would result if nude in water at 29°C. Independent heat flow measurements indicate that the quasi-steady state mean body surface heat flow drops from 350 W/m^2 for the nude lean subject to 134 W/m^2 in the 0.74 clo wet suit (Figure 6b). On the other hand, mean weighted heat loss for the heavy subject only drops from 244 W/m^2 with no protective clothing to 186 W/m^2 in the 0.74 clo wet suit (Figure 6a). Modeling estimates of the quasi steady state surface heat loss from these nude subjects fall close to the measured values (Figure 6).

The T_{re} of a heavy subject is lower (0.3°C) after 60 min immersion while wearing a wet suit than when nude in water while the opposite is true of a lean subject; his T_{re} is 0.2°C higher when wearing a wet suit (Figure 5). While the metabolic rates for each subject drop with increasing amounts of insulation, modeling calculations suggest that the core to skin conductance exhibits two, quite different patterns as the external insulation is increased. The core to skin conductance of the lean subject in all wet suits is virtually identical to his conductance while nude in water at 28°C; this is the temperature at which his core to skin conductance is minimal. The heavy subject showed a higher conductance when clothed than when nude in the water. This behavior is in agreement with the finding that heavy subjects exhibit minimal conductance at skin temperatures less than 28°C. At T_w = 20°C, all of the heavy subjects in the study ($wt/A_D > 40$ kg/m^2) showed a higher core temperature when immersed nude than when wearing wetsuits. They maintain their minimum core to skin conductance without protective clothing and, indeed, the extra insulation appears to increase skin conductance in 20°C water; in contrast, lean subjects require additional insulation to achieve minimal conductance in 20°C water.

DISCUSSION

Mean Weighted Skin Temperature Responses

Regardless of T_w, the $\bar{T}_{sk}$ showed a generally uniform dependence upon time for all subjects, with small variations (up to $\pm$.5°C) in the steady state limit depending on body motion, body fat, and peripheral circulation. Modeling calculations showed that the time course of decline follows the rate at which heat stored in the cutaneous layer is lost (2 min) and also the rate at which heat added to the skin from underlying layers is lost to the bath (8 min).

Rectal Temperature Responses

The fall of T_{re} showed a highly variable time course because of measured differences in metabolic heat production and inferred differences in tissue conductances. The latter, in turn, result from differences in conductive and convective pathways. Both fat and lean tissue mass differences alter conductive pathways. Convective pathways depend upon the extent of tissue vascularization, on the shunting of blood flow, and possibly on variations in countercurrent heat exchange. Shutdown of these convective pathways, which accompanies general vasoconstriction, is triggered at different T_w in different subjects (18). Nevertheless, satisfactory fits to the overall time course of T_{re} could be achieved by utilizing only three constant heat transfer coefficients; one from the body core, another from the fat component and a third from the surface. Our approach suggests that even though core temperatures are changing, the long term conductivities are operationally constant for a given T_w.

Errors in the measurement of core conductances from the transient state model

The three coefficients which yielded the best representative curves of skin and rectal temperatures were reduced indices of internal and external conductances. The usual methods for evaluating total internal conductance (the parallel sum of fat and core conductances) involve either (a) taking the ratio of a measured surface heat flow and the core to T_{sk} gradient or (b) using the measured metabolic rate plus the assumed heat storage and the core to T_{sk} gradient. The difficulties with the first approach are that perturbations of the surface heat flow are introduced by the presence of the sensors and an accurate surface weighted mean value heat flow is hard to obtain from a few spatially separated data points. In the second approach, errors can arise because of inaccurate assessments of instantaneous heat stores. Our evaluation of the instantaneous heat storage within the body core is also an estimate; any errors in that quantity would tend to be higher than the actual value since the entire body core is not uniformly at temperature T_{re}. This would cause our values of core conductances to be somewhat higher than the actual conductances. These errors diminish as the time rate of change of core temperature decreases. For the typical rates of fall in these experiments, errors in the estimated heat storage are small compared to the fluctuations of the instantaneous heat production.

More significant errors result when one makes the assumption of constant metabolic heat production. During the phase of quasi-constant surface flux, the metabolic rates (determined six min apart) could differ by 15% for successive

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intervals. Our formulation allows one to take account of the time varying metabolic rates which are often not considered in the evaluation of internal conductances, and to integrate the total heat inputs over time to obtain a more accurate determination of the current heat stores.

Fat Versus Lean Body Insulation

In view of the relatively small insulation values measured directly for isolated slabs of subcutaneous fat (9), it is difficult to see the physical justification for attributing far greater insulation to the total in situ fat mass than to an equivalent thickness of isolated fat as is suggested by many of the statistical regression formulae found in the literature (3,6,11,14). The probable explanation for the success of regression equations which provide that 1 mm of subcutaneous fat can have five to ten times the insulative value of a slab of non-vascularized tissue of equivalent thickness ($0.005\ m^2\ {}^{\circ}C/W$) is that first, a limited range of body sizes are represented in the frequency distribution used to determine the regression equation and, second, these distributions were considered to be only one dimensional in subcutaneous fat (SCF) rather than two dimensional in SCF and lean body mass per unit area (LBM/A_D). Further, most of these studies considered only a single bath temperature where the full range of an individual's circulatory compensation was not in evidence. At bath temperatures necessary to allow establishment of steady state core temperatures, it is not likely that maximal core insulation was ever achieved. The determination of whole body resistance through the solution of transient state behavior demonstrates that the threshold temperature of peripheral vasoconstriction is variable in the population and that maximal insulation may not be reached until T_w is lowered below $20^{\circ}C$.

Circulatory Losses

Although circulatory heat losses were not measured in this study, their changes with T_w could be inferred from changes in the total internal insulation. Figure 4 shows that the threshold for vasoconstriction depends on subject morphology. In agreement with the results of Cannon and Keatinge (5), we find that maximal tissue insulation was achieved at a significantly higher bath temperature for small, lean subjects ($wt/A_D < 40\ kg/m^2$) than for fat, heavy subjects. The variation of a man's total internal insulation (defined by $1/h_1 + 1/h_2$) is ascribed entirely to circulatory compensation rather than to modification of the intrinsic resistance of the fat layer which is completely passive. This compensation amounts to an average 100% increase in the small man's total internal insulation when the bath temperature drops from 36°C to 28°C (Figure 4); it amounts to an average 40% increase in the heavy man's total internal insulation when the bath temperature drops from 28°C to 20°C. Considering the swing of possible conductances, we see that convective pathways are more effective than conductive pathways in the removal of heat; and further, under vasoconstriction the core mass can account for greater insulation than the fat mass.

Finally, we have shown that the extra insulation afforded by wearing thermally protective garments has a calculatable effect on the time course of T_{sk} (Figure 5) and surface heat flows (Figure 6). Its effect upon metabolic heat production and the changes in body conductance are subtle and lead to some interesting alterations of T_{re} (18). For example, the simulation of T_{re} of fat, heavy subjects clearly show a degradation in whole body insulation if they are outfitted in protective garments. Paradoxically, the T_{re} drops faster, even though the total insulation (body plus garment) may be as great or greater than the maximum nude insulation. This paradox is resolved by the realization that metabolic heat production is also reduced. The use of protective garments may afford, as in this case, an insidious sense of security; a heavy subject's T_{sk} is elevated, yet his T_{re} drops faster than it otherwise would. Presumably, at a sufficiently low T_{re}, the signal to increase autonomic motor activity, and to decrease convective (circulatory) pathways, will be sent down the neural axis to the appropriate effectors. More work is needed to examine the role of deep body receptors in eliciting the action of autonomic effectors.

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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

Figure 1. Diagram of linearized model for radial heat transfer through N compartments which interact via an NxN array of heat transfer coefficients $h_{i,j}$. A mass m_i, surface area A_i, specific heat c_i, and a source of heat production or extraction Q_i, is allocated to each compartment i. Heat is exchanged bidirectionally between compartments whether adjacent or not.

Figure 2. Experimental versus computed time course of mean skin ($\bar{T}_{sk}$) and rectal (T_{re}) temperatures for representative subjects undergoing immersion at 20°C and 28°C; o = measured $\bar{T}_{sk}$ and T_{re} for 28°C immersion and Δ = measured $\bar{T}_{sk}$ and T_{re} for 20°C immersion. Solid lines are computed temperatures. Left to right: subject 14, subject 18, subject 16. The data were simulated using constant heat transfer coefficients for the entire exposure.

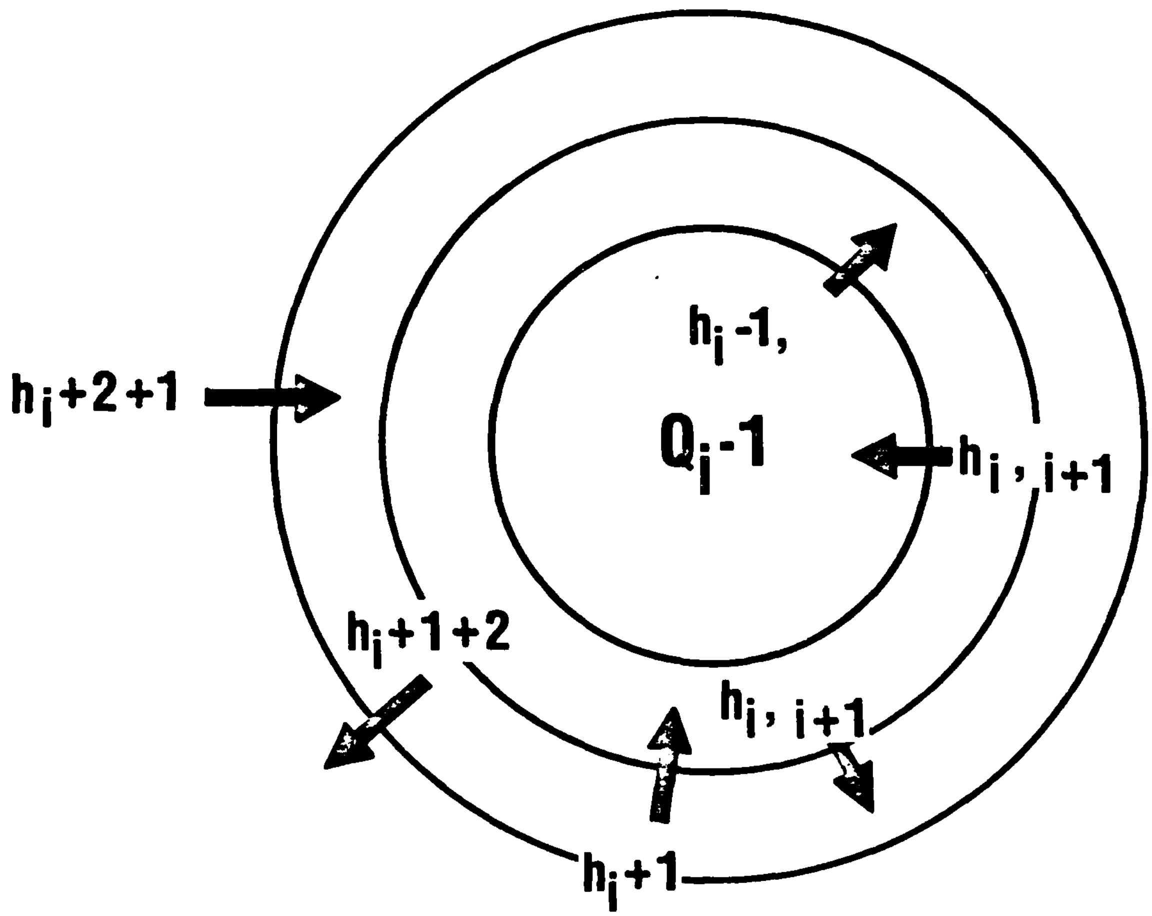
Figure 3. The time course of experimental and computed mean skin ($\bar{T}_{sk}$) and rectal (T_{re}) temperatures for representative subjects undergoing immersion at 20°C and 28°C; o = measured $\bar{T}_{sk}$ and T_{re} for 28°C immersion; Δ = measured $\bar{T}_{sk}$ and T_{re} for 20°C immersion. Solid lines are computed temperatures. Left to right: subject 4, subject 8, subject 10.

Figure 4. The variation of internal insulation versus body weight/surface area and water temperature for all subjects participating in a given immersion. The thermal resistances ($1/h_1+1/h_2$) were determined by trial variations of h_1 which yielded the best computed fit to the time course of rectal temperatures for each subject using the best representation of metabolic heat production (see Methods). These results show that the maximum whole body insulation depends critically on body mass as well as on water temperature.

Figure 5. Experimental versus computed mean skin (T_{sk}) and rectal (T_{re}) temperatures of a heavy, fat (a) and small, lean (b) subject as functions of time and external insulation worn. Solid, continuous, line = computed temperatures. Vertical lines rising from the bottom grid terminate at points whose temperature component is the measured T_{sk}; vertical lines descending from the top scale limit (40°C) terminate at points whose temperature component is the measured T_{re}.

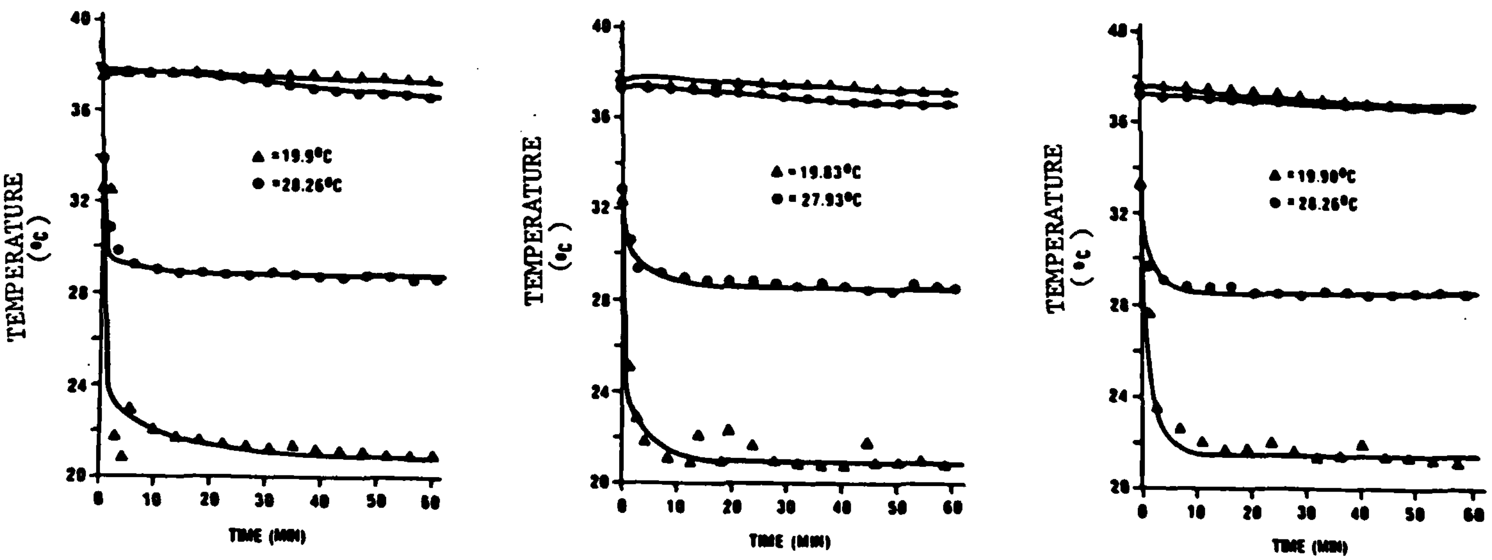
Figure 6. A comparison of the computed and measured mean heat flow for: (a) heavy and (b) lean subjects of Figure 5, immersed at 20°C. Circled points = measured surface heat flow for subjects both nude in water and clad in the 0.74 clo wetsuit. Solid line =computed surface heat flow for subjects nude in water. Speckled line =computed surface heat flow for subjects clad in the 0.74 clo wet suits.

Fig. 1



$$c_i m_i / A_i \dot{T}_i = \sum_{j,k \neq i} h_{i,j} (T_j - T_i) + Q_i (T_k, T_i, \dot{T}_i, t)$$

Fig. 2



A_D = 2.1 m^2
Wt = 95.55 kg
BF = 23.09%

h1 = 8.27 kcal/m^2 °C hr	h1 = 25.00 kcal/m^2 °C hr
h2 = 24.02 kcal/m^2 °C hr	h2 = 24.02 kcal/m^2 °C hr
h3 = 200.00 kcal/m^2 °C hr	h3 = 250.00 kcal/m^2 °C hr

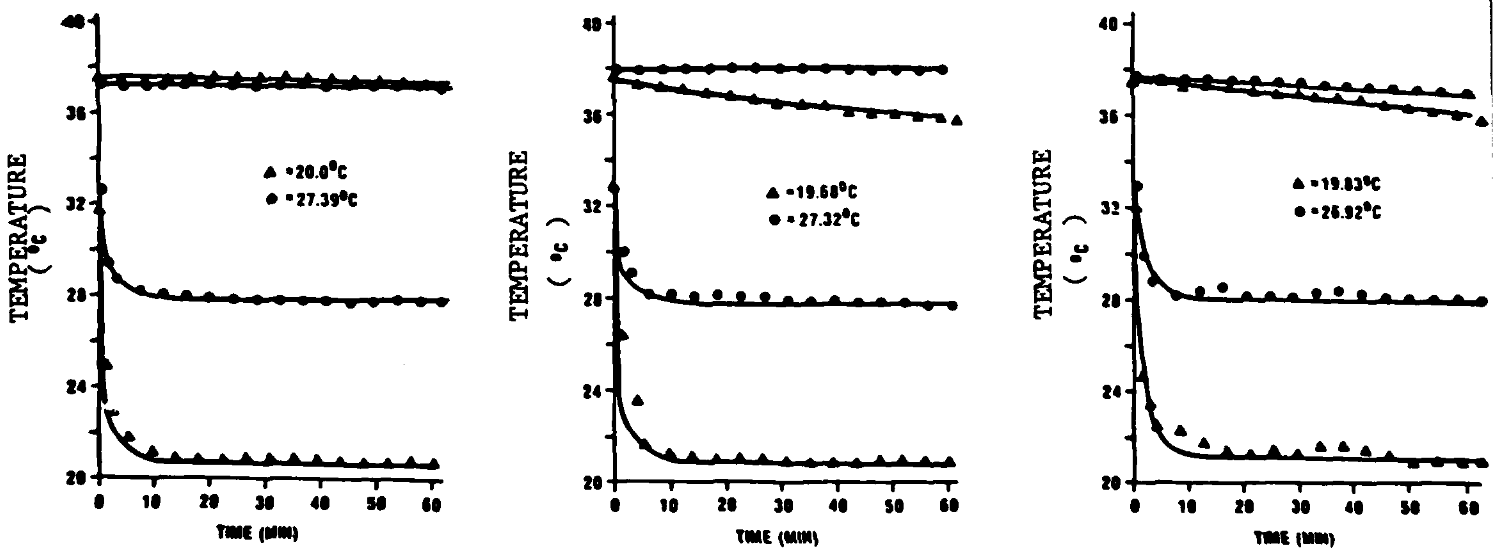
A_D = 1.87 m^2
Wt = 72.25 kg
BF = 16.1%

h1 = 15.87 kcal/m^2 °C hr	h1 = 12.47 kcal/m^2 °C hr
h2 = 50.63 kcal/m^2 °C hr	h2 = 50.63 kcal/m^2 °C hr
h3 = 250.00 kcal/m^2 °C hr	h3 = 200.00 kcal/m^2 °C hr

A_D = 1.82 m^2
Wt = 66.35 kg
BF = 11.1%

h1 = 15.15 kcal/m^2 °C hr	h1 = 14.00 kcal/m^2 °C
h2 = 99.25 kcal/m^2 °C hr	h2 = 99.25 kcal/m^2 °C
h3 = 222.22 kcal/m^2 °C hr	h3 = 200.00 kcal/m^2 °C

Fig. 3

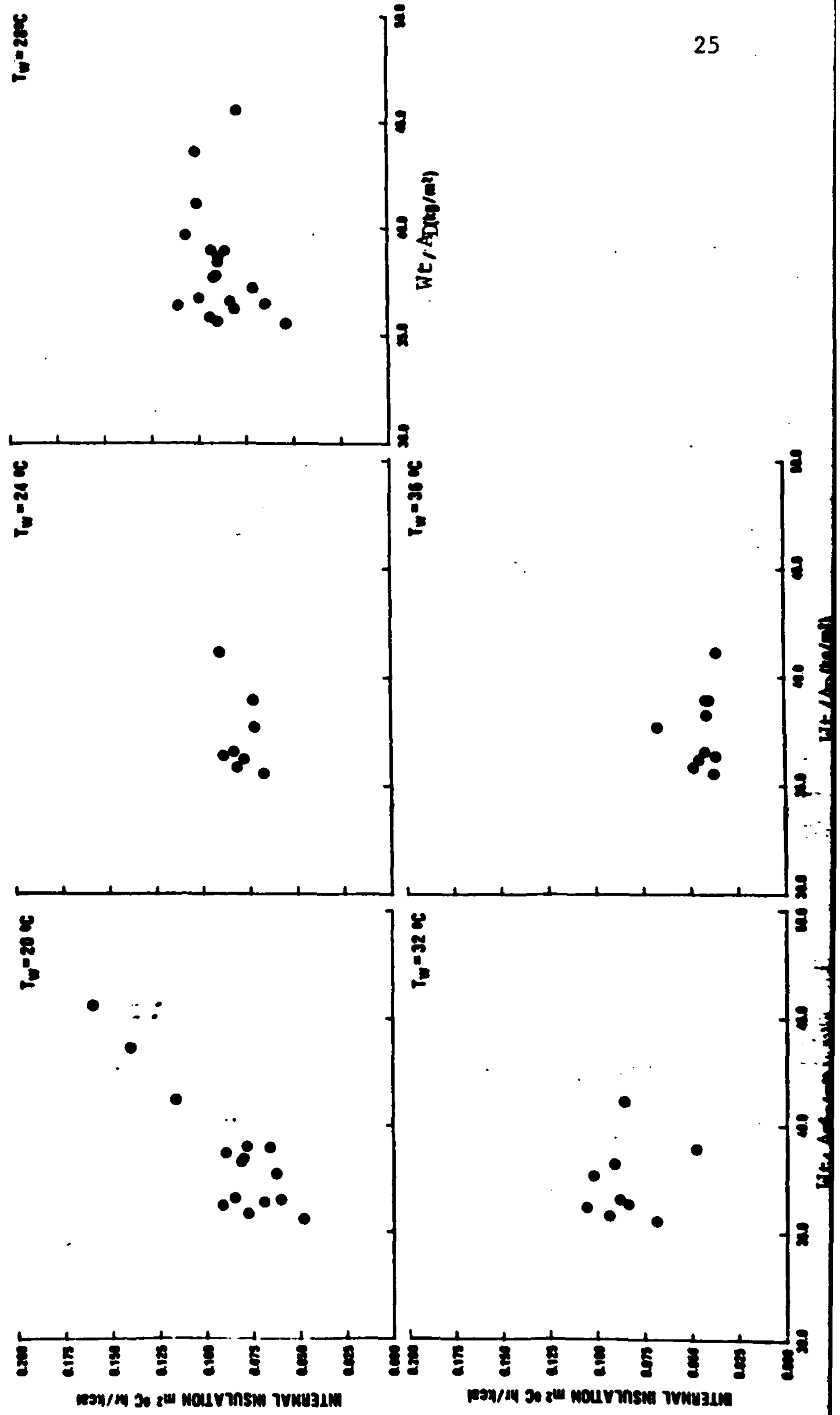


A_D = 2.06m²
Wt = 84.72kg
BF = 11.8%
h1 = 9.52 kcal/m² °C hr   h1 = 8.33 kcal/m² °C hr
h2 = 100.97 kcal/m² °C hr   h2 = 100.97 kcal/m² °C hr
h3 = 227.27 kcal/m² °C hr   h3 = 158.73 kcal/m² °C hr

A_D = 1.9m²
Wt = 73.99kg
BF = 14.7%
h1 = 20.00 kcal/m² °C hr   h1 = 10.00 kcal/m² °C hr
h2 = 60.06 kcal/m² °C hr   h2 = 60.06 kcal/m² °C hr
h3 = 222.22 kcal/m² °C hr   h3 = 200.00 kcal/m² °C hr

A_D = 1.78m²
Wt = 64.43kg
BF = 10.3%
h1 = 11.76 kcal/m² °C hr   h1 = 13.33 kcal/m² °
h2 = 112.98 kcal/m² °C hr   h2 = 112.98 kcal/m²
h3 = 220.20 kcal/m² °C hr   h3 = 111.11 kcal/m²

Fig. 4



Tw = 20 °C
Tw = 24 °C
Tw = 28°C
Tw = 32 °C
Tw = 36 °C
INTERNAL INSULATION m2 °C hr/kcal

Fig. 5a

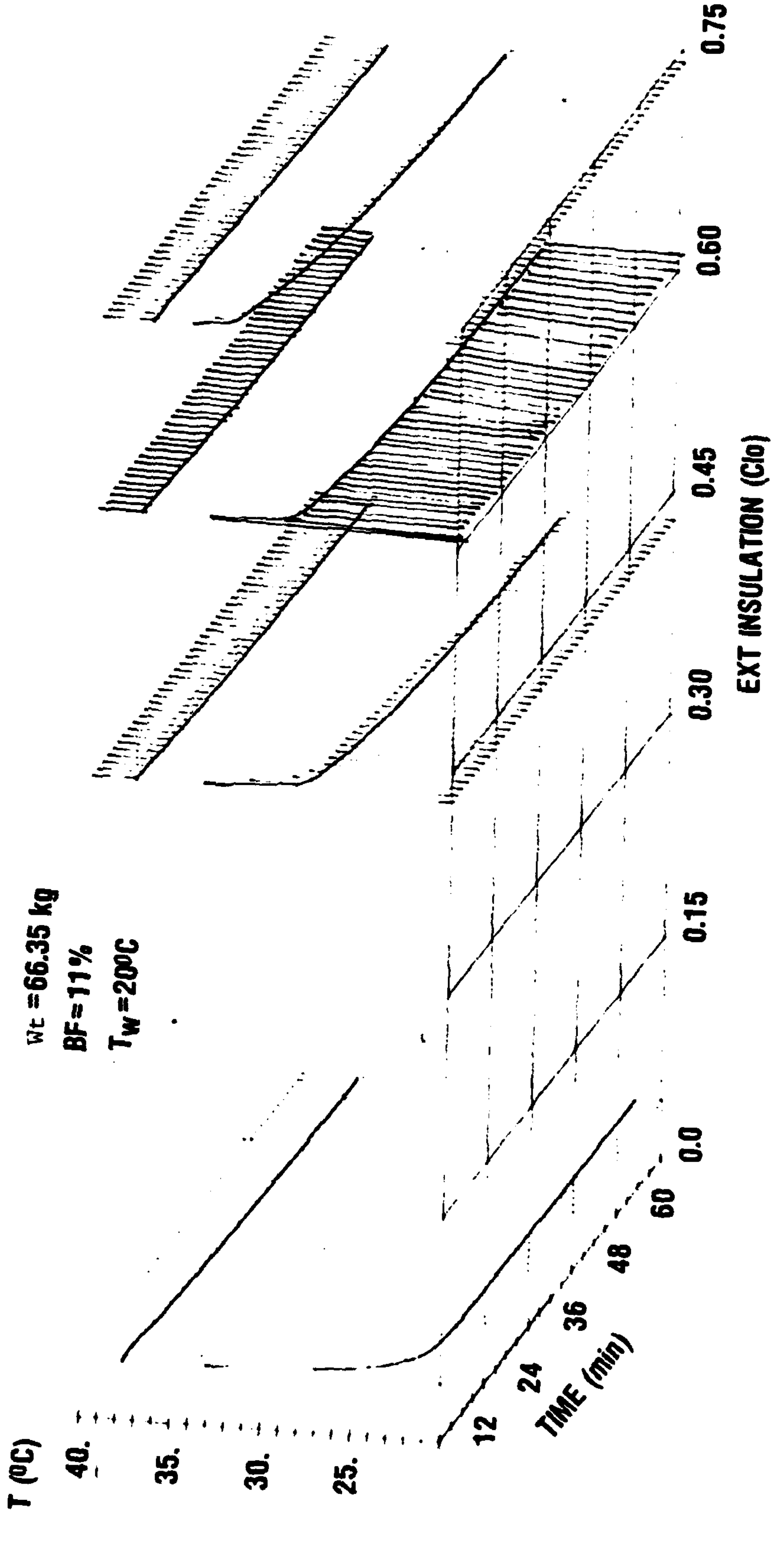

Wt = 66.35 kg
BF = 11%
T_W = 20°C
T (°C)
40.
35.
30.
25.
12
24
36
48
60
TIME (min)
0.0
0.15
0.30
0.45
0.60
0.75
EXT INSULATION (Clo)

Fig. 5b

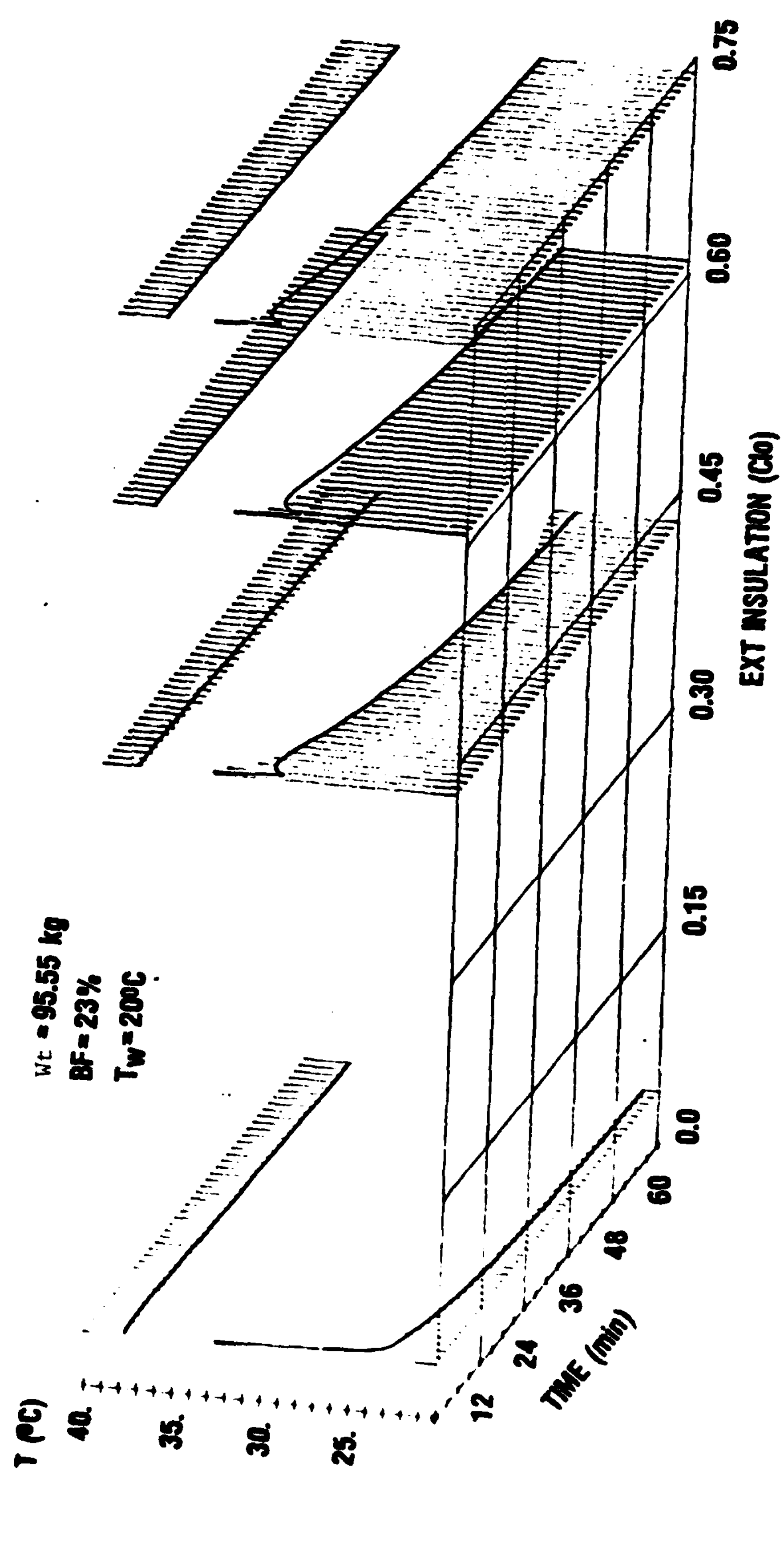
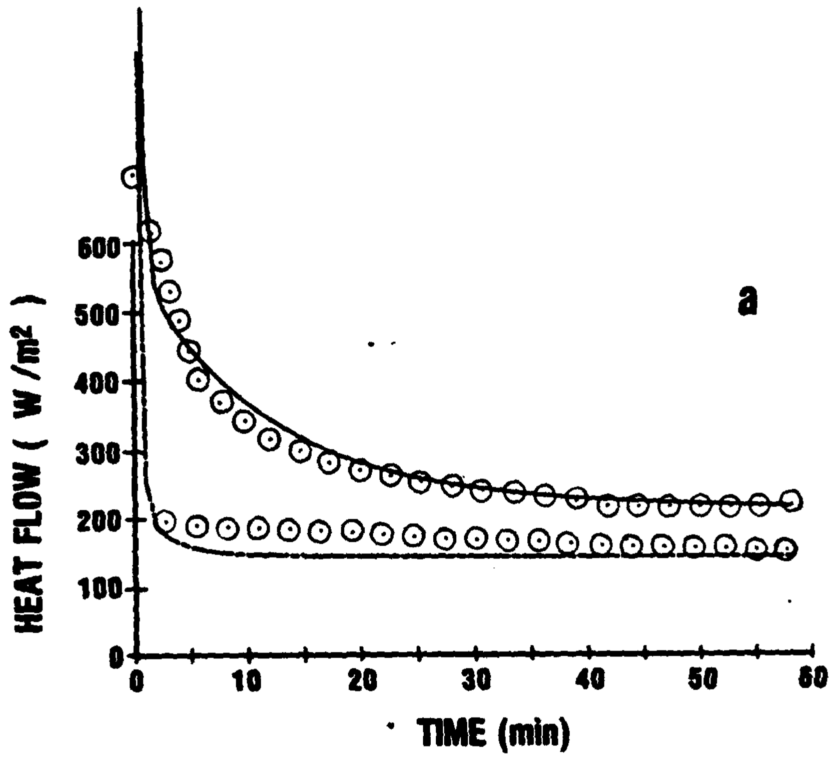
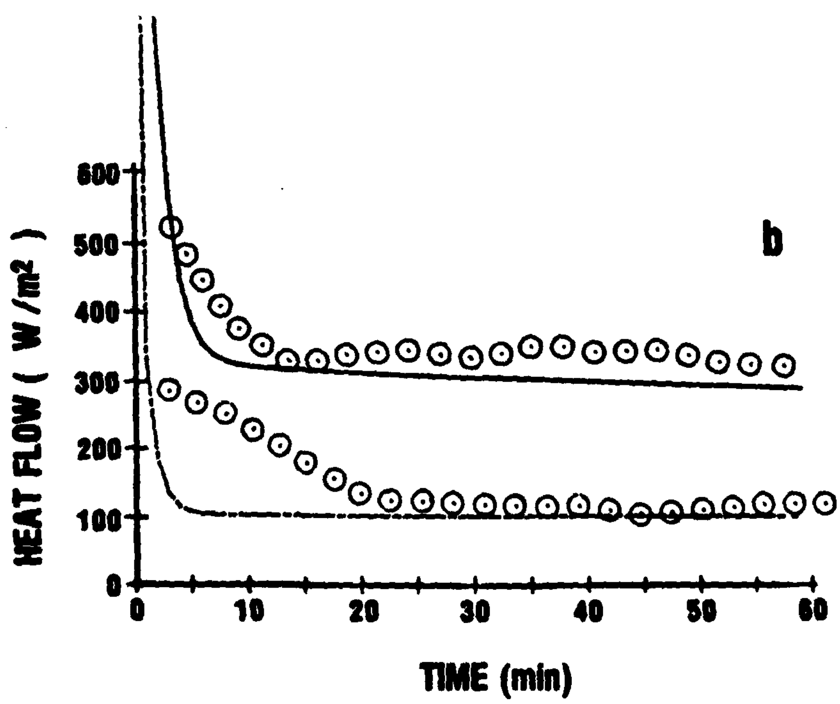

Wt = 95.55 kg
BF = 23%
T_W = 20°C
T (°C)
40.
35.
30.
25.
12
24
36
48
60
TIME (min)
0.0
0.15
0.30
0.45
0.60
0.75
EXT INSULATION (Clo)

Fig. 6


a
HEAT FLOW (W/m²)
0
100
200
300
400
500
600
0
10
20
30
40
50
60
TIME (min)


b
HEAT FLOW (W/m²)
0
100
200
300
400
500
600
0
10
20
30
40
50
60
TIME (min)

END

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