Heat loss from humans measured with a direct calorimeter and heat-flow meters

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1. Heat loss from three men and three women was measured in a direct calorimeter over 2 or 3 h periods and compared with that determined simultaneously from heat-flow meters attached to the skin surface at the waist. The comparisons were made at each of four ambient temperatures, 15, 20, 25 and 30°. Each subject wore a cotton boiler-suit and minimal underwear.

2. Oral temperatures and skin and clothing temperatures on both trunk and forearm were determined, thus enabling the subjects' internal and external insulation to be calculated.

3. Heat loss determined by the meters was lower than that determined by the calorimeter. The difference increased with increase in ambient temperature. 'Meter' heat loss decreased linearly as ambient temperature was raised.

4. It was concluded that heat-flow meters could provide a useful estimate of total heat loss when the evaporative component is low. The estimate might be improved if the subject is calibrated while wearing the meters in a calorimeter over several short periods. Heat-flow meters could therefore be of particular value in sedentary individuals, when the heart-rate method for estimating energy expenditure can be inappropriate.

Investigations into the energy expenditure of man and other animals have depended mainly on the use of whole-body calorimeters, or on the collection and analysis of samples of expired air. The use of calorimeters is not only expensive, but may also restrict activity; the collection of expired-air samples involves apparatus which is not socially acceptable over long periods for human subjects and not always practicable for animals. Moreover, the sporadic nature of sampling could lead to errors which do not appear to have been systematically investigated. An alternative method of estimating energy expenditure which could be used continuously during normal activities would therefore be a useful tool.

A number of possible alternative methods have been reviewed by Brockway (1978). The use of isotope dilution methods for water or carbon dioxide both have some potential, but they still require samples to be collected. Heart-rate has been used in animals by Webster (1967), Brockway & McEwan (1969) and Holmes *et al.* (1976) among others. Individual calibration is essential, and in some animals a relation between heart-rate and oxygen consumption is found while in others there is non discernible. These differences may be due to emotional factors. In humans, Dauncey & James (1979) also found that the heart-rate method could lead to large errors in the estimation of energy expenditure. These errors could be reduced only by an appropriate calibration of each subject. Since this calibration is best carried out in a whole-body calorimeter over a 24 h period, its use is somewhat limited.

Another method for estimating energy expenditure could involve the use of heat-flow meters (Hatfield, 1950; McGinnis & Ingram, 1974). These meters have been used on both man (Wever & Aschoff, 1957) and other animals (Ingram *et al.* 1975) and the information about heat loss which they produce has also been collected by radiotelemetry from pigs kept outdoors. The meters monitor heat flow from specific areas, however, and the extent to which this corresponds to heat flow from the whole body has not been determined. In the present study heat loss has been measured simultaneously from heat-flow meters attached to the trunk and from a whole-body calorimeter using human subjects at several environmental temperatures. Total energy expenditure and thermal insulation values have been calculated and the results from both sources compared. A preliminary report of this work has been published (Close *et al.* 1976).

EXPERIMENTAL

Subjects

The subjects, three men and three women, were volunteers in apparently good health who understood the nature of the investigation. Their main physical characteristics are given in Table 1. During the course of the experiments the subjects wore a cotton boiler-suit in addition to minimal underwear and footwear.

Plan of experiments

Each subject was exposed to each of the ambient temperatures (T_A) 15, 20, 25 and 30°. At 15, 20 and 25° measurements were made for two periods, each of 2 h duration, in the morning and afternoon of the same day. At these temperatures there were, therefore, six separate measurement periods for each sex. Each subject entered the calorimeter at approximately 09.30 hours and following a 0·5 h habituation period recordings were made for the succeeding 2 h period. During the period of observation the subject was seated. Between 12.00 and 14.00 hours the subject was allowed out of the calorimeter to eat a light lunch. The subject re-entered the calorimeter at approximately 14.00 hours and, following habituation, was subjected to a further 2 h period of observation.

At 30° it was found that a 0·5 h habituation period was insufficient to allow stability of measurements, particularly of evaporative heat loss. Each subject was therefore subjected to a 2 h habituation period in a room adjacent to the calorimeter. After a further 0·5 h habituation period within the calorimeter, measurements were then made over the 3 h period, 12.30–15.30 hours. There was, therefore, only one period of measurement for each subject at 30°.

Measurements

Calorimetry and heat loss. The calorimeters used to measure heat loss were based on the heat-sink design previously described by Mount *et al.* (1967) and Close & Mount (1975). Sensible heat loss was recorded from an automatically-operated heat-sink in the calorimeter while evaporative heat loss was recorded from the wet-and-dry bulb temperatures of the inlet and exhaust air and the ventilation rate through the calorimeter, which was maintained constant at 12000 m^3/h. Total heat loss and its sensible and evaporative components were recorded continuously at 5 min intervals throughout the 2 or 3 h period of measurement and calculated as the mean hourly rate at each period. Air movement within the calorimeters was below 0·1 m/s.

Heat flow. The heat-flow meters were of the type described by Hatfield & Wilkins (1950). Four heat-flow meters spaced equally in a belt were fastened in contact with the skin around the subject's waist. Each meter consisted of a tellurium disc covered on each side by a thin layer of copper; thus the passage of heat from the trunk resulted in a temperature difference between the two sides of the disc which in turn generated a potential difference corresponding to the heat flow. Although the meters were supplied previously calibrated, these calibrations were checked at the beginning and end of each period of observation. Heat flow from each subject was therefore continuously recorded simultaneously by both the meters and the calorimeter and was calculated as the mean hourly rate throughout each period at T_A 15, 20, 25 and 30°.

Table 1. *Physical characteristics of subjects*

Subject no.	Sex	Age (years)	Weight (kg)	Height (m)	Surface area* (m^2)	Trunk skinfold thickness (mm)
1	♂	31	73	1·78	1·90	6
2	♂	37	89	1·84	2·12	32
3	♂	46	58	1·73	1·69	8
4	♀	22	62	1·63	1·67	12
5	♀	25	54	1·61	1·55	8
6	♀	56	56	1·59	1·57	10

* Surface area was calculated from Dubois & Dubois (1916).

Recordings of body temperatures. Throughout each period of observation oral temperature was recorded by the subject at 15 min intervals with a mercury-in-glass clinical thermometer. From this, deep body temperature (T_c) was estimated by applying a +0·5° correction factor (Tanner, 1951). In addition, skin (T_s) and external clothing (T_{cl}) temperatures on both trunk and forearm were recorded at 15 min intervals with 36 s.w.g. Cu – constantan thermocouples fixed to each site with surgical tape.

Estimation of insulation. From the combination of T_c, T_s, T_{cl} and T_A (°) and that of heat loss (kJ/m^2 per h), estimates of tissue (I_t), clothing (I_{cl}) and air-ambient (I_a) insulation (°/m^2 per h per kJ) were calculated according to the formulas given by Burton & Edholm (1955):

$$I_t = \frac{(T_c - T_s)}{H_1}, \tag{1}$$

$$I_{cl} = \frac{(T_s - T_{cl})}{H_2}, \tag{2}$$

$$I_a = \frac{(T_{cl} - T_A)}{H_2}. \tag{3}$$

For calculations based on heat losses from the calorimeter, H_1 was the total heat loss and H_2 the sensible heat loss. The skin (T_s) and clothing (T_{cl}) temperatures were the averages from the trunk and forearm. When calculations were based on the heat-flow meter, no partition into sensible and evaporative heat loss was possible. Thus both H_1 and H_2 were the heat loss from the meter. T_s was the skin temperature on the trunk alone and T_{cl} its adjacent external clothing temperature.

RESULTS

Heat losses measured by the calorimeter

The results showing the influence of ambient temperature on sensible and evaporative heat losses measured by the calorimeter are presented in Fig. 1. Since there was no statistically-significant difference ($P > 0·05$) between values for the morning and afternoon sessions, mean values are given for each T_A. The total heat losses were expressed per unit surface area and the mean values are given in Table 2.

Between 15 and 25° the rate at which total heat loss decreased with an increase in T_A was 4·8 kJ/m^2 per h per deg. Sensible heat loss decreased at the rate of 8·2 kJ/m^2 per h per deg. The evaporative component of heat loss increased at the rate of 3·4 kJ/m^2 per h per deg.

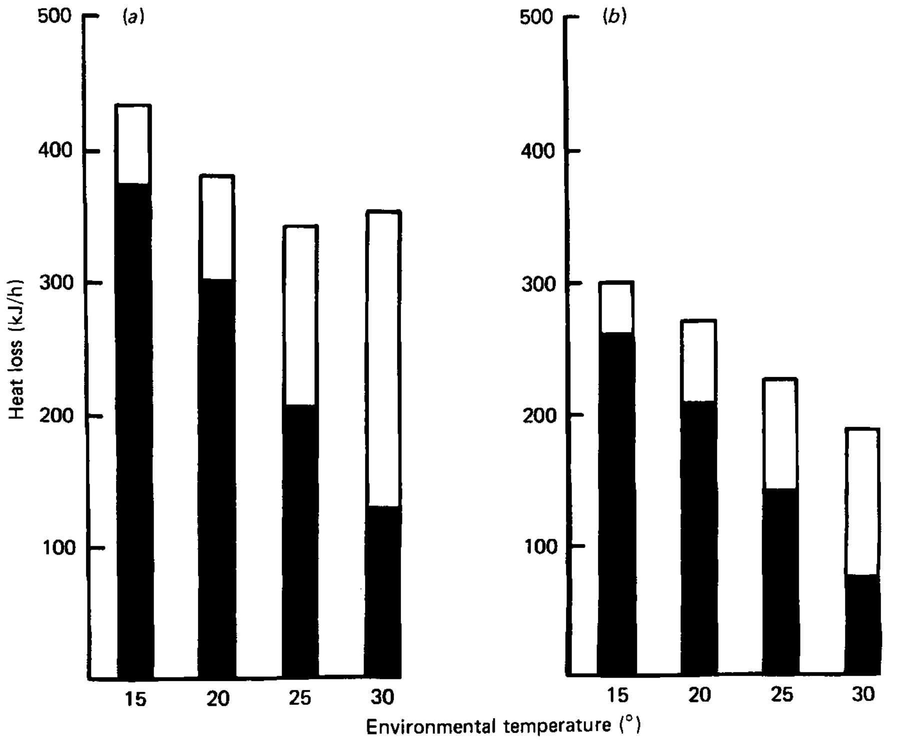

Fig. 1. Heat loss (kJ/h) of (*a*) men and (*b*) women in relation to environmental temperature (°). (■), sensible heat loss; (□), evaporative heat loss. For details of procedures, see p. 88.

Table 2. *Heat loss (kJ/m² per h), measured by the calorimeter, partitioned into evaporative and sensible components, and by the heat-flow meters in relation to environmental temperature* (T_A, °) *and values for 'meter' heat flow: total heat loss, and 'meter' heat flow: sensible heat loss*

(Mean values with their standard errors)

	'Meter' heat flow		Calorimeter heat loss: Total		Calorimeter heat loss: Sensible		Calorimeter heat loss: Evaporative		'Meter' heat flow: Total heat loss	'Meter' heat flow: Sensible heat loss
T_A	Mean	SE	Mean	SE	Mean	SE	Mean	SE		
15	223	16	208	10	180	8	28	2	1·07	1·24
20	176	10	185	10	145	8	40	3	0·95	1·21
25	126	9	160	14	98	7	62	8	0·79	1·29
30	81	3	152	17	57	5	95	12	0·53	1·42

Heat loss measured by the heat-flow meters

The mean heat loss from the trunk determined by the meters for morning and afternoon sessions are given in Table 2. The estimates of heat loss decreased linearly as T_A increased at the rate of 9·5 kJ/m² per h per deg. The values recorded by the meters on the trunk were always greater than the value for sensible heat loss from the whole body as measured by the calorimeter, and at 15° were greater than the calorimeter estimate for total heat loss.

Table 3. *Insulation (°/m² per h per kJ) of tissue* (I_t), *clothing* (I_{cl}) *and air-ambient* (I_a) *calculated from estimates of heat loss made by the calorimeter and the heat-flow meters in relation to environmental temperature* (T_A, °)

(Mean values with their standard errors)

Method of estimation	T_A	I_t Mean	I_t SE	I_{cl} Mean	I_{cl} SE	I_a Mean	I_a SE
Calorimeter	15	0·029	0·002	0·033	0·003	0·052	0·006
	20	0·020	0·002	0·035	0·002	0·055	0·005
	25	0·016	0·001	0·045	0·003	0·055	0·007
	30	0·013	0·001	0·042	0·007	0·060	0·007
Meter	15	0·025	0·003	0·028	0·003	0·048	0·006
	20	0·020	0·003	0·028	0·004	0·053	0·009
	25	0·019	0·003	0·034	0·004	0·044	0·005
	30	0·026	0·004	0·026	0·004	0·041	0·006

Insulation values based on measurements from the whole-body calorimeter

Since the calorimetric measurements of heat loss related to the total body surface, the estimates of insulation were calculated from the mean values of skin and clothing temperatures of the trunk and forearm. The values obtained are given in Table 3. I_t decreased with an increase in T_A ($P < 0·05$). Between 15 and 30°, I_a remained independent of environmental temperature. The estimates of I_{cl} were rather variable probably because of differences in posture adopted by the subjects.

Insulation values based on the heat-flow meters

The values for heat loss measured by the meters refer to the trunk only and the corresponding temperatures for skin and clothing have therefore been used to calculate estimates of insulation (Table 3). As with the estimates based on the results from the calorimeter the values for I_t decreased as T_A increased between 15 and 25°.

DISCUSSION

Total heat loss as measured by the calorimeter, which includes both evaporative and sensible components, was greater than that estimated by the meter at most ambient temperatures. The heat losses indicated by the meter, however, tended to exceed the sensible heat loss indicated by the calorimeter with the result that the meter gave the appearance of measuring some of the evaporative heat loss. The probable explanation is that some of the heat which would normally have been lost from the skin by vaporization of moisture was conducted through the meter and lost as sensible heat. Any moisture which accumulated under the meter may then have moved to the edges and evaporated on the exposed skin. In this way the meter would over-estimate sensible heat loss. Another factor which would contribute to the difference in the two estimates of heat loss is that the meters monitored heat loss from a restricted area on the trunk whereas the calorimeter measured heat loss from the whole body. When the heat loss as determined by the calorimeter was expressed per unit surface area it was assumed that the loss occurred evenly over the whole body. In fact when the limbs were vasoconstricted the losses would have been greater on the trunk than on the limbs. For these reasons precise agreement between the absolute values of the two estimates was not to be expected. Nevertheless, the meter might prove useful if it measured a predictable proportion of the total heat loss, and hence reflected the true rate of change of heat loss with change of ambient temperature.

As can be seen from Table 2 the difference between the total heat loss estimated by the

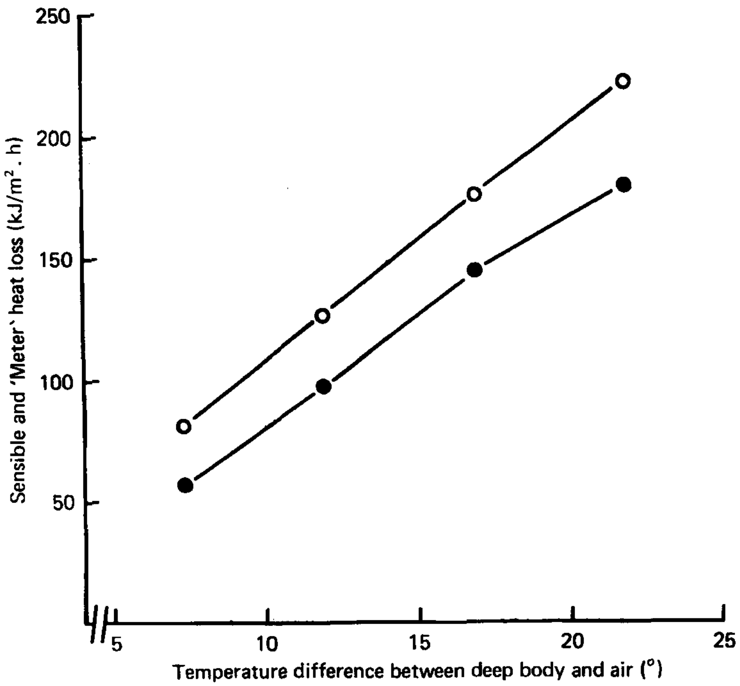

Fig. 2. The comparison of sensible (●—●) and 'meter' (○—○) heat loss (kJ/m^2 per h) in relation to the temperature difference (°) between deep body and air in human subjects. For details of procedures, see p. 88.

calorimeter and the heat loss estimated by the meter varied with the ambient temperature. The lower the ambient temperature the greater the proportion of the total heat loss was indicated by the meter. This trend was probably due to progressive vasoconstriction of the limbs resulting in less heat being lost from them. When the total heat loss measured by the calorimeter was divided by the total surface area of the subject, the heat loss from the trunk would then be underestimated. At high temperatures, when the limbs were vasodilated, a disproportionately higher amount of heat would be lost from them because of their smaller radius of curvature and greater surface area:volume. At high ambient temperatures the differences in estimates of total heat loss between calorimeter and meter were to be expected because evaporation accounts for a greater proportion of the total. From these considerations it appears that the estimates from the meters are nearest to the true value when the subject is 5 or 10° below the critical temperature, when the sensible heat loss accounts for the greater proportion of the total.

Another approach to the comparison of the two methods of estimating heat loss is to consider the rate of change in sensible and meter heat loss per ° change in T_A or per ° change in the deep body to air temperature gradient. The rates of sensible heat loss, as estimated by the calorimeter, decreased by 8·2 kJ/m^2 per h per ° increase in T_A, while meter heat loss decreased by 9·5 kJ/m^2 per h per ° When the results were expressed per ° change in the deep body to air temperature gradient, the rates of sensible heat loss decreased by 8·6 kJ/m^2 per h per °, compared with 9·8 kJ/m^2 per h per ° for the meter (Fig. 2).

Below the temperatures corresponding to minimal metabolism estimates of insulation based on either calorimetric or 'meter' heat loss were similar. At higher environmental temperatures the differences were greater and these discrepancies were again probably due to the greater proportion of heat being lost by evaporation.

The results of the present investigation indicate that the determination of heat flow from meters can provide information on heat loss and thermal insulation which relates to the whole body, only when the ambient conditions are specified and the evaporative component of heat loss is low. The calibration of meters on individuals in a calorimeter over several short periods would involve no more time than is involved in the best calibration using the heart-rate method; and could involve less time. Although the heart-rate method may give a useful indication of energy expenditure in an exercising subject, Dauncey & James (1979) found that errors could be large in sedentary subjects and those not involved in long periods of physical activity. Heat-flow meters might therefore be of particular use in estimating energy expenditure in just those conditions where the heart-rate method is of least value.

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