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THE TOTAL THERMAL INSULATION OF THE NEW-BORN BABY

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SUMMARY

1. One hundred and seventeen healthy new-born babies weighing between 0·9 and 4·8 kg at delivery have been studied during the first ten days of life, and sixteen of these babies have been studied serially for 6 weeks after birth. The babies lay supine in a draught-free environment (air speed 4–5 cm/sec) of moderate humidity. The operative temperature was between 26 and 38° C for the babies who were studied naked.

2. Total non-evaporative heat loss was calculated from simultaneous measurements of oxygen consumption, evaporative water loss and the concomitant change in mean body temperature.

3. Approximately 10 % of the total body surface area was in contact with the mattress or floor. Conductive heat loss accounted for only about 5 % of all non-evaporative heat loss when the naked baby was lying on a thick foam mattress, but for as much as 25 % when the baby was lying in a water-jacketed chamber with a floor of clear plastic ~ 5 mm thick.

4. Insulation to heat loss by convection and radiation varied with environmental temperature. Total specific insulation was low in a warm environment when the naked baby vasodilated, and rose by between 16 and 25 % to a maximum in an environment of 31° C. It decreased significantly when the baby became physically active in environments with a temperature less than this.

5. Total specific insulation in an environment of 31° C varied with body size: it averaged 0·156° C.m^2.hr/kcal in seven naked babies weighing 0·9–1·2 kg, rose to 0·190° C.m^2.hr/kcal in twelve babies weighing 1·8–2·2 kg, and averaged 0·201° C.m^2.hr/kcal in the thirty-four babies who weighed over 3 kg. Tissue insulation accounted for 23 % of this total specific insulation in the smaller babies, and about 28 % of the total in babies weighing over 3 kg.

6. Clothing ten babies in a vest, napkin and long cotton nightdress increased the total specific insulation by an average of 0·23° C.m^2.hr/kcal.

INTRODUCTION

The studies of Brück (1961), Adamsons, Gandy & James (1965), Hill & Rahimtulla (1965) and Hey (1969) have served to define in some detail the relation between oxygen consumption and environmental temperature in the naked new-born human infant. Unfortunately their results are not in themselves adequate to define thermal insulation with any precision because body temperature fluctuates significantly during even brief exposure to environmental temperatures outside the thermoneutral range.

We have now attempted to measure the total thermal insulation of babies in a draught-free environment by simultaneously measuring the oxygen consumption, evaporative water loss and change in mean body temperature that occurs under a variety of accurately defined environmental conditions. Estimates of total non-evaporative heat loss have been made on naked babies weighing between 0·9 and 4·8 kg at delivery, and serial observations have been obtained on a number of babies for up to 6 weeks after birth in order to study the influence of gestational age, post-natal age and body weight. By also making sample measurements of the conductive element of this total non-evaporative loss, estimates of the combined net loss from convection and radiation have been obtained by subtraction.

The insulation against convective and radiant heat loss in the naked baby is the sum of the insulation provided by the body tissues themselves (I_T) and the insulation provided by the ambient environment (I_A). (This latter component is often referred to as the 'air insulation', but such a terminology tends to obscure the fact that external insulation depends on the radiant as well as the convective property of the environment.) It has now been possible to calculate absolute values for these two components of the body's heat loss by utilizing some of the data on I_A/I_T contained in a previous paper (Hey & Katz, 1970).

METHODS

Theoretical analysis

Evaporative heat loss from the body is governed by a complex of physical and physiological factors. Non-evaporative heat loss is, in contrast, effectively proportional to the temperature difference between the body and its surroundings (Newton's Law) since it is permissible to ignore the fourth power terms involved in the relation for radiant exchange where the temperature difference is not large. It is therefore relatively easy to quantify the body's resistance to non-evaporative heat loss, and many measurements of this nature have been made on animals and on adult men and women. Heat loss due to contact with other solid objects has almost always been small enough to be neglected in these studies, and non-evaporative heat loss by convection and radiation from the skin have usually been considered jointly using the relation $(T_r - T_e)/H_{CR}$ to provide a measure of the body's *over-all thermal insulation*, where T_r is rectal or body core temperature, $\mathrm{T_e}$ is the operative environmental temperature (both in °C), and H_{CR} the total heat loss from the body by convection and radiation in kcal/hr.

It is convenient to relate this average insulation for the whole body to surface area in order to compare bodies of varying size, and conventional to measure the *specific insulation* per unit surface area (I) by

$$I = A(T_r - T_e)/H_{CR}, \tag{1}$$

where A is the *total* surface area of the body in m², but it must be realized that, in fact, only a fraction of this total area actually takes part in convective and radiant heat loss, the exact proportion depending on posture. This limitation is, luckily, relatively unimportant for the present purposes as posture varies little in the newborn human baby and does not seem to be significantly influenced by environmental temperature.

However, this specific insulation is necessarily only the sum of the separate and variable insulations afforded by the body tissues (I_T), the clothes (I_C) and the air and radiant surfaces involved (I_A)

$$I = I_A + I_C + I_T, \tag{2}$$

where

$$I_A = A(T_{\bar{c}} - T_e)/H_{CR}, \tag{3}$$

$$I_C = A(T_{\bar{s}} - T_{\bar{c}})/H_{CR}, \tag{4}$$

and

$$I_T = A(T_r - T_{\bar{s}})/(H_{CR} + H_{Es}), \tag{5}$$

where $T_{\bar{s}}$ and $T_{\bar{c}}$ are the mean temperature of the skin and the outer surface of the clothing respectively in °C, and H_{Es} is the evaporative heat loss from the skin in kcal/hr. Combining eqns. (3), (4) and (5) to obtain a total specific insulation against convective and radiant heat loss, as defined by eqn. (2), we obtain

$$I = [A(T_r - T_e) - H_{Es}.I_T]/H_{CR}. \tag{6}$$

This formulation is seen to differ slightly from the conventional definition given by eqn. (1). The discrepancy arises from failure to allow (in eqn. (1)) for the fact that evaporation of water from the skin accounts for a proportion of the heat conducted to the skin from the body core. The difference between eqns. (1) and (6) is only important when the difference between environmental temperature and rectal temperature is small, and does not appear to have been commented on before. (It should be noted in passing that if water does not evaporate from the skin surface but passes through the clothing by capillary action to evaporate on the surface of the clothing a modified version of eqn. (4) becomes appropriate and the eqn.

$$I = [A(T_r - T_e) - H_{Es}(I_T + I_C)]/H_{CR} \tag{7}$$

holds in place of eqn. (6).)

The difference between eqns. (1) and (6) becomes particularly noticeable in the special case where T_e equals $T_{\bar{s}}$ and H_{CR} is consequently zero. In these circumstances eqn. (1) predicts that $T_{\bar{s}}$ will then equal T_r, but in fact there will still be a gradient between rectal temperature and skin temperature (unless I_T is negligible) because of the heat loss caused by evaporation from the skin surface. Equation (6) predicts that H_{CR} is zero when T_e is slightly less than T_r, the exact difference between T_e and T_r being given by $H_{Es}.I_T/A$. The results presented in, for example, Fig. 3 are in reasonable accord with the prediction of eqn. (6) in this respect.

When $T_r - T_e$ is small, reasonably exact solutions to eqn. (6) are only possible if

H_{Es} and I_T are known, and it may be more appropriate to determine the total specific insulation I independently from the slope of the relation (Fig. 3) between H_{CR}/A and $T_r - T_e$, i.e. from

$$I = A\delta(T_r - T_e)/\delta H_{CR}, \tag{8}$$

although the relation is strictly only a straight line when H_{Es} and I_T are both constant.

Since the new-born baby is unable to stand, the above analysis is nevertheless incomplete, in that conductive heat loss (H_K) in kcal/hr is often too large to ignore. In the present studies the babies lay either on a thick foam mattress at the ambient operative temperature, or directly on the Perspex floor of the water-jacketed metabolism chamber. In the former case heat loss was small and lateral volumetric conduction complicates the analysis, but in the latter case (in which conductive loss was considerable) a reasonable estimate of the total resistance to the conductive loss (I_K) could be obtained by

$$I_K = A(T_r - T_b)/H_K, \tag{9}$$

where T_b is the temperature of the bath of water round the chamber in °C. In the naked baby this resistance to conductive heat loss has a tissue element, and a further important component in series due to the thickness and conductivity of the Perspex. This specific insulation (I_K) per square metre of total body surface area is in parallel with the insulation to convective and radiant heat loss of eqn. (6), and it follows that the over-all specific resistance (R) to all sensible or non-evaporative heat loss is given, to a reasonably close approximation, by

$$R = 1/(1/I + 1/I_K), \tag{10}$$

when T_e is approximately the same as T_b and the difference between T_e and T_r is not too small.

In the present study total heat loss was calculated from heat production less heat storage, evaporative heat loss was calculated from the measured water loss and conductive loss estimated from sample measurements of heat-flow multiplied by the measured area of direct contact. Heat loss by convection and radiation was then obtained by difference (eqn. 13). Values for the specific insulation to convective and radiant heat loss have been obtained from eqn. (6), supplemented by estimates derived from the use of eqn. (8); the partition of this insulation into an internal (I_T) and external (I_A) insulation has then been established from the data on I_A/I_T given by Hey & Katz (1970). Finally, the additional insulating effect of clothing has been obtained indirectly by difference using eqn. (2) after measuring the total specific insulation of a baby lying on a mattress both clothed and naked. No data were rejected merely because the baby became restless or cried.

Experimental technique

Subjects. A total of 117 healthy babies have been studied after delivery in the maternity wards of The London Hospital. The consent of the parents for the experiments was freely given. The weight of each infant (W) was measured in g immediately before study, and surface area in m^2 estimated (Boyd, 1935) from the formula

$$A = 4{\cdot}688\,W^{(0{\cdot}8168 - 0{\cdot}0154 \log W)} \times 10^{-4}. \tag{11}$$

Measurements of oxygen consumption, body temperature, evaporative water loss and conductive heat flow were made while the babies lay supine in a temperature-controlled metabolic chamber. Most of the babies were naked except for a urine bag and a thin stockingette napkin that measured 25 cm square and weighed under 6 g, but ten babies were studied for comparative purposes when they were dressed in a short woollen vest, a large towelling napkin that measured 55 cm square and weighed about 90 g, and a long cotton nightdress that came down over the feet and was provided with long sleeves. The studies were conducted at various times of day and estimates of heat production and heat loss were obtained at three to six different environmental temperatures in the 3–4 hr available between feeds. Thermal balance was assessed at each temperature for a minimum of 20 min, and often for 30–40 min, particularly in the clothed babies. Rectal temperature was not allowed to exceed 37·8 or fall below 36·0° C. Skin temperature was usually recorded in four places and these measurements used in the subsequent calculation of heat storage by the body; the babies were not, however, usually studied for long enough at any one environmental temperature for skin temperature to stabilize, and for this reason no attempt was made to use these approximate estimates of mean skin temperature to assess tissue insulation directly.

Environmental conditions. The small cylindrical water-jacketed Perspex metabolic chamber used for the majority of the studies was described by Hey (1969). Perspex has the property of being transparent to light but almost totally opaque to radiation with a wave-length (λ) of more than 5 μ. The radiant characteristics of the chamber were similar to those provided by most non-metallic surfaces (total hemispherical emittance $> 0{\cdot}9$ when $\lambda > 5\ \mu$). Mean air speed in the chamber with a baby present was 4–5 cm/sec. The operative temperature of the environment (Gagge, 1940) was calculated using an average of mean wall temperature ($T_{\bar{w}}$) and mean air temperature ($T_{\bar{a}}$)

$$T_e = 0{\cdot}6T_{\bar{w}} + 0{\cdot}4T_{\bar{a}} \tag{12}$$

in the knowledge that radiation was slightly more important than convection as a channel for thermal exchange under the prevailing conditions (E. N. Hey, in preparation). The difference between $T_{\bar{a}}$ and $T_{\bar{w}}$ seldom exceeded 1·3° C, but under certain circumstances T_e differed from the temperature of the water in the surrounding jacket by as much as 2° C. The babies lay on the floor of the small chamber either in direct contact with the Perspex, or only separated from it by the fine-mesh nylon net used to lift the baby into place. In the remaining studies the babies lay on a flat foam mattress in a larger version of the same chamber. Mean vapour pressure was maintained at between 17 and 19 mm Hg in the small chamber and at 10 mm Hg in the large chamber; there were no other significant differences between the environments provided by the two chambers (Hey & O'Connell, 1970).

Heat production. Oxygen consumption was measured by recording the change in the circulating gas volume in the apparatus under conditions of constant temperature and humidity (Hill & Rahimtulla, 1965). Heat production in kcal/hr was calculated from the measured oxygen consumption on the assumption that 4·83 kcal of heat are produced for every litre of oxygen utilized (when measured dry at s.t.p.). The error inherent in this assumption of a fixed respiratory quotient is small (Karlberg, 1952).

Heat storage. Rectal temperature was measured with a thermocouple inserted 7–12 cm into the rectum. Three or four representative skin temperatures were also measured continuously whenever possible with 36 S.W.G. thermocouples held in place with plaster tape and an approximate average skin temperature calculated using weighting factors derived from the data of Klein & Scammon (1930) on the surface area of the various parts of the body at birth. Mean body temperature was calculated from 0·7 T_r plus 0·3 $T_{\bar{s}}$ and any change in the heat content was estimated from the change in mean body temperature taking 0·83 to be the specific heat of the body tissues (Burton & Edholm, 1955). No attempt was made to open the chamber and reposition any skin thermocouples that came loose in the middle of a period of measurement; where more than one skin thermocouple came loose no attempt was subsequently made to estimate mean skin temperature and heat storage was calculated directly from the change in rectal temperature. A sudden change in environmental temperature was only reflected in the direction and rate of change of T_r after 5–8 min. Measurement of heat storage and thermal balance was never begun, therefore, until 10 min after any change in environmental temperature was effectively complete.

Evaporative heat loss. Total evaporative water loss was measured using the technique developed by Hey & Katz (1969). The same precautions were taken to ensure that there was no leak of urine or faeces during the study. Evaporative heat loss was then calculated from the measured water loss on the assumption that the evaporation of 1 g of water from the skin and respiratory tract results in the loss of 0·6 kcal of heat from the body (Hardy, 1949).

Conductive heat loss. Heat loss from the baby to the bottom of the small water-jacketed Perspex chamber was sampled using one to three calibrated Hatfield–Turner heat flow disks (Hatfield & Wilkins, 1950). These disks were placed under the baby in such a way that contact was maintained both with the baby and with the surface on which it lay. Plaster tape was used to hold the disk in place on the baby's back. No difficulty was encountered in recognizing when the baby had moved in such a way that the disk was no longer in contact with the surface on which the baby lay, because of the sudden change and irregularity in the heat flow record. Similar measurements were made in the large metabolism chamber; these babies lay on a firm plastic foam mattress 1 cm thick enclosed within a thin sheet of polyethylene suspended on a thin sheet of Perspex within the chamber.

The area of contact involved in direct conductive heat transfer was subsequently measured by placing the baby on a transparent surface of the same shape as the bottom of the metabolic chamber, tracing the area of skin contact from below and then measuring it with a planimeter. Similar measurements were made for the babies lying on a firm flat surface. Independent measurements of the area of actual contact were made on each occasion by two observers, and all planimeter measurements were checked in triplicate. The replicate estimates seldom differed by more than 8 %.

Convective and radiant heat loss. Heat loss by convection and radiation was then calculated by difference from the calculated heat of metabolism (M), heat storage (S), total evaporative heat loss (H_E) and conductive loss (H_K), where the units in each case are kcal/hr, since

$$H_{CR} = M - S - H_E - H_K. \qquad (13)$$

This loss includes the loss that occurs when the inspired air is warmed in the respiratory tract, as well as the convective and radiant heat loss that occurs from the surface of the body. However, in an environment of 16° C, which represented the coldest conditions studied, the heat lost by warming the inspired air accounted for less than 5 % of the total convective and radiant heat loss.

Statistics. Where the mean of a series of observations is reported, the estimated S.D. of the observations has been given. Linear relations between variables subject to measuremental error have been calculated by minimizing the squares of the perpendicular distances of the points from the line using the technique described by Kendall & Stuart (1961).

RESULTS

Non-evaporative heat loss in the naked baby

Conductive loss. The area of skin in contact with other surfaces was measured in forty-two naked babies weighing between 1·0 and 4·5 kg when 0–14 days old. When these babies lay supine on a firm flat surface, a constant 8–11 % of the total estimated body surface area was found to be in contact with the Perspex. When the babies lay supine on a curved surface similar to that experienced within the small cylindrical metabolism chamber, the area of contact was very similar, but the exact percentage varied slightly with body size (Fig. 1). Skin over the back of the trunk accounted for more than three quarters of the total area involved in surface contact.

Heat flow per °C temperature gradient between the body core and the water in the jacket surrounding the Perspex wall of the small metabolism chamber was effectively constant at 17·5 kcal/hr. °C. m^2 surface

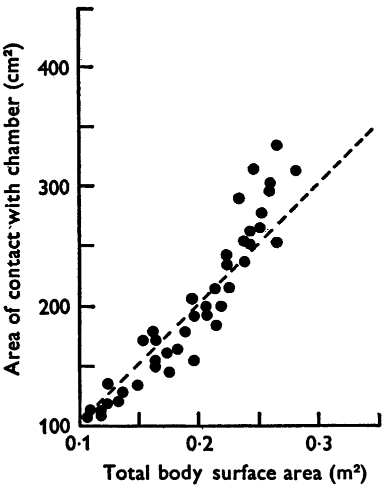

Fig. 1.

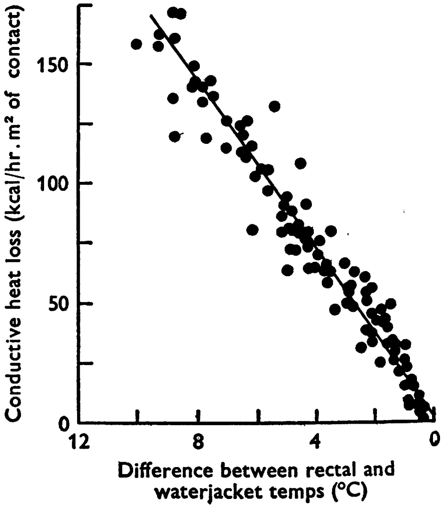

Fig. 2.

Fig. 1. The relation between the area of skin involved in conductive heat loss and estimated body surface area (eqn. (11)) in a series of forty-two babies studied in a small cylindrical metabolic chamber (diameter 16 cm) during the first 2 weeks of life. The percentage of the total surface area in contact with the wall of the chamber varies slightly with body size: the interrupted line shows the result that would be expected were a constant 10 % of the skin involved in conductive heat loss.

Fig. 2. Conductive heat loss to the Perspex floor of the water-jacketed metabolism chamber in twenty naked babies weighing between 2 and 4 kg and less than 2 weeks old. The estimates were obtained by measuring heat loss with two to three heat flow disks secured to the back of the trunk in babies lying supine on the surface of the cylindrical chamber. The relation between heat loss and temperature gradient was approximately linear over the range of environmental temperature examined, yielding a mean conductance of 17·5 kcal/hr. °C. m^2 of surface contact; thermal conductance usually exceeded this average figure, however, when the temperature gradient was less than 3° C.

contact (Fig. 2) irrespective of body size. The interposition of a thin nylon net reduced heat flow very little provided the baby still rested on the Perspex and was not suspended above it. Since the Perspex of the chamber wall was three sixteenths of an inch thick, and given a value of 0·062° C.m^2.hr/kcal for the insulation of Perspex sheeting 1 cm thick, it is possible to calculate that the mean insulation to heat loss provided by the tissues of the back of the trunk was 0·028° C.m^2.hr/kcal.

Similar studies were undertaken in a series of babies lying on a flat foam mattress 1 cm thick suspended on a sheet of Perspex within the large metabolism chamber. About 10–14 % of the total body surface area appeared to be in contact with the mattress, but accurate assessment was difficult: the increased percentage contact was clearly due to the compressibility of the foam surface. Conductive heat loss from the body while lying on this mattress was approximately 3 kcal/hr.°C.m^2 of surface contact.

Convective and radiant loss. The relation between environmental temperature and heat loss by convection and radiation is not linear, but it is possible to express the results obtained over certain ranges of environmental temperature by a meaningful linear relation (Fig. 3). Specific thermal insulation was at a maximum when the environmental temperature was between 30 and 33° C; it decreased about 20 % when the environmental temperature exceeded about 34° C, and also decreased to a lesser extent when the environmental temperature fell below 29·5° C. The magnitude of the fall in total insulation in a warm environment when rectal temperature was high ($T_r \geqslant 37{\cdot}2°$ C) can be accounted for by the known threefold decrease in tissue insulation in these circumstances (Hey &

Legend to Fig. 3.

Fig. 3. The relation between the net temperature gradient and total heat loss by convection and radiation in twelve babies 0–14 days old and weighing between 1·8 and 2·2 kg. Results obtained when rectal temperature (T_r) was 37·2° C or more are indicated by open symbols. The lower line is the best-fit relation for all the data obtained when T_r was less than 37·2° C (mean 36·9° C) and the operative environmental temperature (T_e) was between 29·5 and 33° C: the relation has a slope that is equivalent to an insulation of 0·190° C.m^2.hr/kcal (eqn. (8)) and an intercept on the x axis of 0·26° C. The results obtained when T_e was below 29·5° C nearly all lie above the dotted extension of this line; most of the babies were physically active in an environment as cool as this. The upper line is the best-fit relation for all the data obtained when T_r was 37·2° C or more (mean 37·4° C) and T_e was between 34 and 37·5° C: this relation has a slope that is equivalent to an insulation of 0·151° C.m^2.hr/kcal and an intercept of 0·22° C on the x axis. This intercept differs significantly from zero ($P < 0{\cdot}05$). The air speed was 4–5 cm/sec.

Katz, 1970). No consistent changes in behaviour or posture were detected at high environmental temperature as long as rectal temperature was not allowed to exceed 37·8° C. Most of the babies did, however, become restless at low environmental temperature, and this probably accounts for the tendency for total insulation to fall in these circumstances (cf. Fig. 4). Heat loss tended to zero when the environmental temperature was between 0·2 and 0·5° C below that of the body core.

Further data on the relation between environmental temperature and total insulation in a group of thirteen babies weighing between 2·8 and

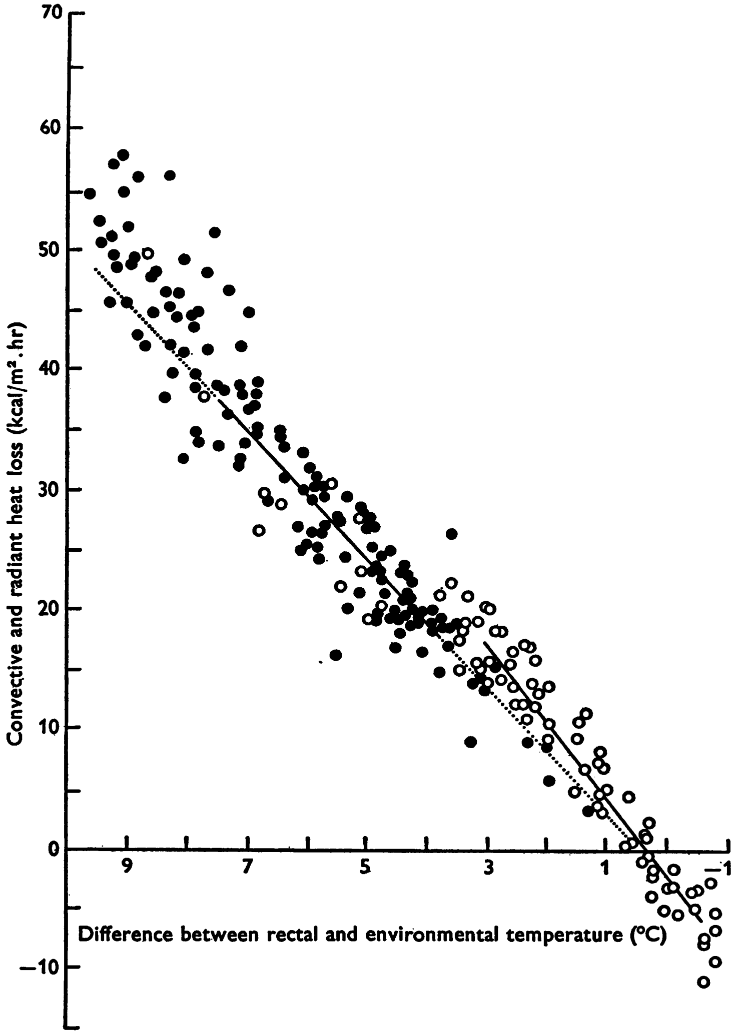

Fig. 3. For legend see opposite page.

3·2 kg are summarized in Fig. 4. Mean specific insulation was 0·198 ± 0·008° C.m^2.hr/kcal in an environment of 31° C (range 30·5–31·5° C) and 0·160 ± 0·021° C.m^2.hr/kcal in an environment of 35° C (range 34·5–35·5° C). These insulations have been calculated from eqn. (6) using the data of Hey & Katz (1969, 1970) to calculate the approximate magnitude of the small term $H_{\mathrm{Es}} . I_{\mathrm{T}}$. While the use of eqn. (6) instead of eqn. (1) made little difference to most of the estimates of total insulation, it did make a substantial difference to the estimates obtained when environmental temperature exceeded 34° C.

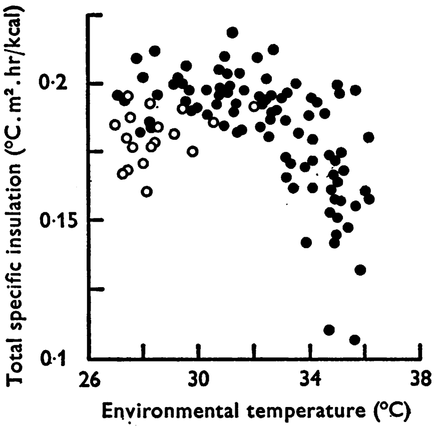

Fig. 4.

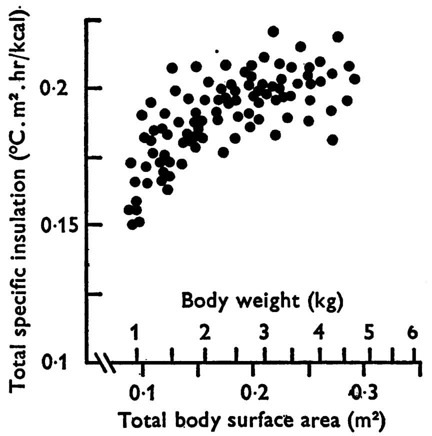

Fig. 5.

Fig. 4. The relation between environmental temperature and total specific insulation to convective and radiant heat loss in thirteen naked babies 0–14 days old who weighed between 2·8 and 3·2 kg at birth. Open symbols have been used to indicate results obtained at a time when the infant was physically active. Insulation was low at high environmental temperature because of vasodilatation and low tissue insulation; total insulation reached a maximum in an environment of about 31° C, but decreased in an environment colder than this with the onset of restlessness and increased physical activity.

Fig. 5. The relation between body size and total specific insulation to convective and radiant heat loss in ninety-seven naked babies who were studied when less than 14 days old in an environment of between 30 and 32° C. Mean total insulation per unit surface area (eqn. (6)) was significantly reduced in babies weighing 2 kg or less at birth.

Mean total insulation per unit surface area calculated using eqn. (6) varied significantly with body size, particularly in babies weighing under about 2 kg (Fig. 5 and Table 1). Fifteen of the babies had an abnormally low birth weight for their period of gestation (below the 10th percentile on the criteria of Thomson, Billewicz & Hytten, 1968) while a further seven babies had an abnormally high birth-weight (above the 90th percentile); there was no correlation between gestational age and insulation in babies of the same weight at birth. Eleven babies of low birth-weight were studied at regular intervals for at least 6 weeks after birth; insulation increased with body size but there was no significant independent correlation with post-natal age.

TABLE 1. Estimates of mean total specific thermal insulation to convective and radiant heat loss (± S.D. of the observations) in fifty-one babies

Weight group (kg)		No. of subjects (n)	Total specific thermal insulation (°C.m^2.hr/kcal)
Range	Mean wt.		
0·9–1·2	1·04	7	0·156 ± 0·008
1·4–1·6	1·52	10	0·176 ± 0·009
1·8–2·2	1·98	12	0·190 ± 0·008
2·8–3·2	3·00	13	0·198 ± 0·008
3·8–4·2	4·01	9	0·204 ± 0·009

The babies were studied lying supine in an operative environment of between 30 and 32° C during the first 3 weeks of life. The air speed was 4–5 cm/sec.

Non-evaporative heat loss in the clothed baby

The effect of clothing on heat loss was also studied. Figure 6 shows the total non-evaporative loss observed in ten clothed babies who were examined while lying on a foam mattress 1 cm thick in the large metabolism chamber. These babies weighed between 2 and 3 kg (mean 2·53 kg) and were each dressed in a short woollen vest, a large towelling napkin and a full length cotton nightdress. From the slope of the relation in Fig. 6 it appears that the mean specific resistance to heat loss by convection, radiation and conduction in these babies was 0·419° C.m^2.hr/kcal. If it can be assumed that the relation is effectively linear in these clothed babies, we can predict that non-evaporative loss should dwindle to nothing when environmental temperature rises to 36·4° C. This temperature is 0·4° C below the mean rectal temperature of these babies at the time of study and the difference, although not significant, is approximately what would be predicted on the basis of eqn. (6). More precise and adequate data will, however, be necessary before it is possible to judge whether eqn. (6) or eqn. (7) is a better approximation to the truth.

A comparable group of babies (mean weight 2·49 kg) were examined while lying naked on the same mattress; the resistance to all non-evaporative heat loss in these ten babies was 0·183° C.m^2.hr/kcal. Conventional clothing is seen to increase the resistance to non-evaporative heat loss by a factor of more than two (Fig. 6). When the babies were exposed naked to an environment cool enough to produce a 50 % increase in heat production rectal temperature nearly always fell; clothed babies, in marked contrast, nearly always maintained their deep body temperature when exposed to an environment cool enough to provoke a comparable metabolic response.

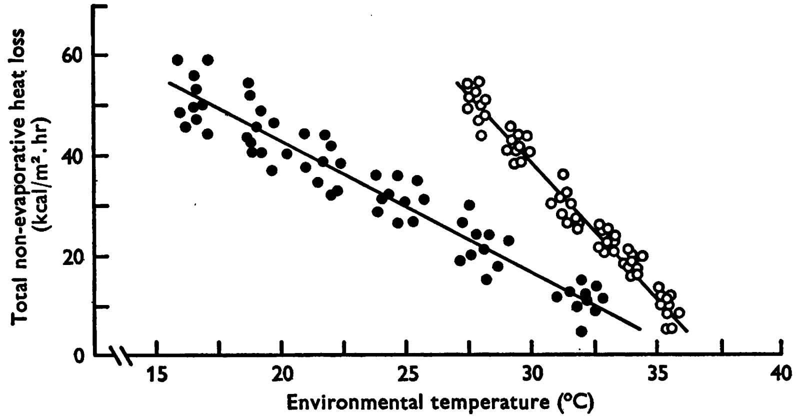

Fig. 6. The relation between environmental temperature and total non-evaporative heat loss in babies lying on a foam mattress 1 cm thick in a draught-free environment. The babies were 0–14 days old and weighed between 2 and 3 kg at birth. Open symbols show the results obtained in ten babies who were naked; filled symbols show the results obtained in ten babies who were dressed in a short woollen vest, a large towelling napkin and a long cotton nightdress. The addition of this clothing increased the total specific insulation of the babies by an average of 0·23° C.cm^2.hr/kcal.

DISCUSSION

Conductive heat loss accounted for up to a quarter of all the observed non-evaporative heat loss in those babies who were studied lying naked on the floor of the metabolism chamber. It was more difficult to measure conductive heat loss accurately in those babies who were studied naked while lying on a thick foam mattress because of uncertainty about the exact area of contact, but it was estimated that only about 5 % of all the non-evaporative heat loss in these babies was dissipated by direct conduction. This latter assessment is certainly in keeping with the estimate of 0·195 °C.m^2.hr/kcal for the mean resistance to heat loss by convection and radiation in babies weighing between 2 and 3 kg lying naked on the floor of the metabolic chamber (Fig. 5) and the estimate of 0·183° C.m^2.hr/kcal for the mean resistance to *all* non-evaporative heat loss in the ten babies studied lying on a thick foam mattress (Fig. 6).

This large variation in conductive heat loss makes it impossible to equate the environmental conditions employed during the present study directly with those employed for the concurrent study of the I_A/I_T ratio (Hey & Katz, 1970). The use of an operative temperature scale makes due allowance for any possible difference in the convective and radiant environments (Gagge, 1940) but makes no allowance for any conductive difference. Since direct measurements of conductive heat loss were made in the two environments it is, however, possible to equate the two temperature scales in terms of their effect on a baby's total non-evaporative heat loss. On this basis it can be shown that an operative temperature of 28° C has the same effect on the over-all thermal balance of a baby lying directly on the floor of the metabolism chamber as an operative temperature of about 25·5° C has on a baby lying on a foam mattress. No such adjustments are necessary before comparing the present data with those on oxygen consumption and evaporative water loss reported previously (Hey, 1969; Hey & Katz, 1969), since the environmental conditions were the same in each case.

All the data on convective and radiant heat loss obtained during the present study were consistent with the theoretical prediction that this heat loss should tend towards zero at an environmental temperature that is a little $(H_{Es}.I_T/A)$ below deep body temperature. The results of Day (1943) on twenty-five babies weighing between 1·5 and 3 kg, and the data on adult man obtained by Gagge, Winslow & Herrington (1938) also match the predictions of eqn. (6) very closely. Although the difference was only large when environmental temperature was high, we have, for consistency, used either eqn. (6) or eqn. (8) rather than eqn. (1) to derive all the estimates of total specific insulation reported in this paper.

By combining the present data on total insulation (Table 1) with the information on the I_A/I_T ratio contained in the paper of Hey & Katz (1970) it is possible to calculate values for the insulation of the ambient environment and the insulation of the body tissues (Table 2). In making these calculations it has been assumed that ambient insulation does not vary with environmental temperature as long as posture and physical activity do not change. The values for ambient and tissue insulation in a 1 kg baby have been estimated by extrapolation from the data on I_A/I_T in four babies who weighed between 1·1 and 1·3 kg, as it was not considered justifiable to try and measure *equilibrium* skin temperature in the smallest babies during subjection to cold.

Resistance to heat loss from the skin (i.e. ambient insulation) is about 0·175° C.m^2.hr/kcal in adult man under environmental conditions comparable to those used for the present study according to the data of Winslow, Gagge & Herrington (1939). This insulation is considerably greater than the value we found in any of the babies at birth, and a difference in posture seems unlikely to be the cause: the supine posture of the babies and their proximity to a mattress would almost certainly reduce heat loss more than the semi-recumbent sitting posture adopted for the studies on adult man. It seems more likely that the difference is due to the influence of body shape, for it is a well established physical principle that convective heat loss per unit surface area is increased in surfaces with a small radius of curvature. The same principle probably accounts for the observed difference between the ambient insulation of the 1 kg and the 4 kg babies (Table 2). The comparable way in which tissue insulation varies with body size has been commented upon in a previous paper (Hey & Katz, 1970).

TABLE 2. Predicted values for the tissue and ambient components of the total specific resistance to convective and radiant heat loss in °C.m².hr/kcal for naked babies weighing 1, 2, and 4 kg when lying on a flat surface in draught-free surroundings with an air speed of 4–5 cm/sec and a total emittance > 0·9 for radiation with a wave-length in excess of 5 μ

Body wt. (kg)	Ambient environmental insulation	I_A/I_T ratio	Tissue insulation	Total insulation
1	0·120	8·6	0·014	0·134
		3·3	0·036	0·156
2	0·140	8·7	0·016	0·156
		2·8	0·050	0·190
4	0·146	8·2	0·017	0·163
		2·5	0·058	0·204

The calculations are based on measurements of the ratio of ambient insulation to tissue insulation (I_A/I_T) obtained by Hey & Katz (1970) under cool conditions when maximally vasoconstricted, and under warm conditions when vasodilated, while the values for maximum total insulation derive from the data in Fig. 5 and Table 1.

The estimates for resistance to heat loss from the skin by convection and radiation in new-born babies (Table 2) are in apparent conflict with the only other estimate available (Day, 1943). Day was himself surprised to note that the total specific insulation of the babies he studied was similar to that of the two adults who were studied under comparable environmental conditions by Hardy & Soderstrom (1938) even though skin temperature and tissue conductivity were higher in the babies. Calculations based on Day's data give a value slightly in excess of 0·2°C.m².hr/kcal for the insulation of the ambient environment. Day's babies were secured by the ankles, 'fastened snugly' to a wide-meshed hammock 'by a cotton belt which covered the lower half of the abdomen and hips' and studied in a copper calorimeter whereas the present data were obtained from babies who were lying unrestrained and almost totally naked on a flat surface in surroundings that reflected little of the baby's radiation. These differences are almost certainly sufficient to explain the observed difference in ambient insulation.

Units of specific thermal insulation have been used throughout in presenting the results of this study. These units relate the mean resistance of a body to heat loss to the *total* surface area of that body and this practice has serious limitations because a significant and variable fraction of the total skin surface is prevented by body posture from partaking effectively in thermal exchange with the surroundings. It is thus possible for the specific insulation of the body to alter following a change in posture while the insulating properties of the body tissues and of the external environment themselves remain unaltered. The very important role that postural change can play in modifying heat loss from the body has been clearly demonstrated by Mount (1966, 1968) in his studies of thermoregulation in the new-born piglet. We have, however, been unable to detect any instinctive postural reactions in the human infant to changes in the thermal environment, and this impression is borne out by the near linearity of, for example, Fig. 3. The observed decrease in total specific insulation in a warm environment (Figs. 3 and 4) is fully accounted for by the fall in tissue insulation that is known to occur in these circumstances (Table 2). The change that occurs in a cold environment is the opposite of the change that would be produced by huddling; it seems likely that the observed decrease (Fig. 4) is in fact due to increased convective heat loss when the baby cries and becomes physically active (cf. Winslow & Gagge, 1941), and it seems reasonable to interpret the naked baby's increased activity as a method of attracting maternal attention. It is noteworthy that this response is not normally seen when a clothed or swaddled baby is subjected to a comparable degree of cold stress (Hey & O'Connell, 1970).

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