Metabolic rate of sleeping infants

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Abstract

Aim—To measure the sleeping metabolic rate (SMR) of healthy infants in the first year of life.

Methods—The SMR was measured on 73 infants aged 1 to 12 months in a special nursery using indirect calorimetry. One hundred satisfactory observations were made. The room air and radiative temperatures, humidity, and amount of insulation were measured. Parents chose the clothing and bedding that they judged their infant needed.

Results—The mean (SD) SMR was 2.4 (0.4) watts (W)/kg or 45 (10) W/m². The mean SMR of infants aged 1–2 months was 38 compared with 44 W/m² in infants of 8–12 months; the difference was not significant. There were no obvious differences in SMR between boys and girls. But there were wide differences in SMR between apparently similar infants, range 1.4 to 3.5 W/kg. Most parents selected insulation between 1 and 3 togs, and this was weakly negatively correlated with air temperature.

Conclusion—These wide variations in SMR mean that it is impossible to give specific guidelines on the amount of clothing and bedding a particular infant will need for thermal comfort in a given room temperature.

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The incidence of the sudden infant death syndrome (SIDS) in the UK has fallen in the recent years, but it is still the commonest mode of death in infancy beyond the neonatal period.¹ Evidence continues to suggest that a fever and overheating are implicated.^{2–4} Yet, little is known about the heat exchanges of infants aged between 1 and 12 months in different environments. In particular, there are few measurements of the rates at which sleeping infants produce heat by metabolism in known thermal conditions. Such information on the heat balance of infants is essential if recommendations are to be made on both the room temperature, clothing, and bedding insulation that they require for thermal comfort and the adjustment which should be made when an infant has a fever.

Theoretical models have been used to predict the effect of sleeping position on the thermal balance of infants aged up to 1 year,⁵ but these predictions are based on measurements of the metabolic rates of only 14 infants,

aged 6 to 10 days.⁶ Even less is known about the ranges of environmental (room) temperature and thermal insulation within which infants can maintain their thermal control and beyond which hypothermia or hyperthermia occur. For obvious reasons, it is impossible to test experimentally the effects of extreme environments (hot or cold) on the heat balance of young infants. Nevertheless, it is important to try and predict those combinations of the environmental variables (room temperature, clothing, and bedding insulation) which might overpower an infant's thermoregulatory capacity. Such estimations should be possible by inserting reliable information on rates of heat production in known thermal conditions into mathematical models of heat exchange.

In 1985, Schofield reviewed all the published measurements of the metabolic rates of infants over the previous 60 years.⁷ From these data, he formulated equations to predict the basal metabolic rate (BMR in watts, W) from body mass (m_b in kilograms, kg) and height (h in meters, m) for all age groups. For infants aged under 3 years, BMR for males was best predicted according to:

$$\text{BMR} = 0.0081 m_b + 73.48h - 29.91 \quad (1)$$

and for females, from

$$\text{BMR} = 0.79 m_b + 49.55h - 20.02 \quad (2)$$

These equations are based on 162 and 137 measurements for males and females, respectively. The data for infants under 1 year of age come from five studies in which indirect calorimetry was used to measure sleeping or resting metabolic rate rather than 'basal metabolic rate'.^{8–12} Nevertheless, the abbreviation BMR will be used in this paper to distinguish the values predicted by Schofield's equations from those measured in our study. Almost 100 of the 299 measurements used to formulate equations (1) and (2) were made on infants during their first week of life. Furthermore, 60 of the infants aged between 8 days and 1 year were sedated during measurement, although this was not thought to affect their metabolic rate.¹²

More recently, the doubly labelled water technique has been used to measure total energy expenditure (TEE in joules, J).^{13, 14} Energy expenditure measured by indirect calorimetry and the doubly labelled water technique have been compared in preterm infants,^{13, 15} and in term infants after abdominal surgery.¹⁴ In these studies on newborn and sick infants the difference in energy expenditure determined by the two methods was not significant. In lively infants, it is anticipated that the average rate of energy expenditure (TEE divided by time period) will exceed the BMR or resting rate.

The present work aims to measure the rates of metabolic heat production during daytime

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sleep of infants aged between 1 week and 1 year in known thermal environments. These metabolic rates will then be compared with previous measurements obtained by either indirect calorimetry or the doubly labelled water technique. Our purpose is to provide data for a theoretical model of the relationship between the heat balance of a sleeping infant and the thermal environment.

Methods

SUBJECTS

Healthy infants aged between birth and 1 year were recruited from the local community. Posters asking for volunteers were displayed at 30 general practitioners' surgeries throughout the Nottingham area and on the maternity wards at the Queen's Medical Centre (Nottingham). In addition, several baby clinics were visited on a regular basis to enrol the mothers. More than 180 infants were recruited between October 1991 and May 1993.

Many of the infants did not sleep in the nursery for the required duration. Nevertheless, 100 satisfactory measurements of sleeping metabolic rate (SMR) were made on 73 infants, of which 48 were male. Thirty eight of the infants were firstborn, 22 second, 11 third, one fourth, and one fifth. All were singletons. A single measurement of SMR was made on 55 infants, and two, three, and four measurements were made on 11, five, and two infants, respectively. The interval between measurements was always greater than four weeks. The values of SMR reported throughout are mean (SD).

The values of body mass at birth were 3.53 (0.51) and 3.35 (0.40) kg for boys and girls, respectively. The period of gestation was 37 weeks or more in 68 of the infants, and the remaining five were between 35 and 37 weeks.

The values of axilla temperature were between 36.0 and 37.0°C for 99 out of the 100 measurements, and within the 'normal' range defined by Morley *et al.*,¹⁶ to be 35.6 to 37.2°C. One infant had an axilla temperature of 37.4°C, but no obvious sign of illness.

It was impossible to impose a minimum fast on the infants in the age range studied, particularly as they had to sleep in a strange environment. Consequently, the time interval between the infants having been fed and the onset of the measurements varied between 10 and 240 minutes, with 32 of the 100 measurements having been started within 60 minutes of the last feed.

EXPERIMENTAL PROCEDURE

The metabolic rates were measured in a small nursery (3 m long, 2 m wide, 3 m high) in the Department of Child Health. The temperature in the nursery was not controlled, but remained steady throughout each period of measurement. The one external window in the room was triple glazed, two of the panes having darkened glass to minimise transmission of solar radiation. The door was draught proofed to minimise the rate of air movement in the nursery, and had a double glazed observation window. During measurements the infants

were asleep in their normal sleeping position and dressed in their usual daytime clothing, modified as the mother felt necessary for the temperature within the room. A cellular blanket was available to cover the infant if the mother required. The tog values of the clothing and bedding (combined) covering each infant were calculated from the 'tog table' published by Bacon *et al.*¹⁷

SMR was measured by indirect calorimetry using the Datex Deltatrac Metabolic Monitor.¹⁸ A Perspex hood placed over the head of the sleeping infant was ventilated at a constant rate of about 10 l/minute. This flow rate was checked at regular intervals and did not change by more than $\pm 5\%$. The oxygen and carbon dioxide concentrations of the air entering and leaving the hood were measured continuously. The rates of oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) were calculated from the differences in concentration and the flow rate. The Deltatrac calculates the metabolic rate at one minute intervals and automatically calculates the mean (SD) of these readings over a given time interval.¹⁸ The respiratory quotient (RQ) was calculated as the ratio of $\dot{V}CO_2$ to the corresponding $\dot{V}O_2$.

The hood was placed over the infant's head about 10 minutes after he or she had fallen asleep. The hood was kept in place for a minimum of 20 minutes. Observations made during the first five minutes of each measurement period were discarded to allow equilibration of the expired air within the mixing chamber of the metabolic monitor. Subsequent recordings of the gas concentrations were examined and any artefacts discarded (these usually occurred when the infant moved and disturbed the hood). Sleeping metabolic rates were then calculated as the mean (SD) rate during the 15 minute period which followed the 'discarded' five minute equilibration period. Values of SMR are expressed in W, W per unit body mass (W/kg¹), which is the relevant unit for energy expenditure, and in W per unit body surface area (W/m²), which is the relevant unit for heat exchange. The body surface area A (m²) was calculated in accordance with Gehan and George,¹⁹ from

$$A = 0.0235h^{0.42246}m_b^{0.51456} \quad (3)$$

The infant's body temperature was measured immediately after the hood was removed by placing a clinical mercury-in-glass thermometer in the axilla for five minutes. The infants were then weighed naked to the nearest ± 0.01 kg and their height measured to the nearest ± 0.01 m. In addition, their parents completed a questionnaire that sought information on birth weight, prematurity, medication, feeding method, parity, and night time clothing and bedding. The time of the last feed was also recorded.

Shortly after the measurement period, the dry and wet bulb temperatures in the nursery were measured with a whirling psychrometer. The mean radiant temperature of the walls and other surrounding surfaces in the room was measured with a portable infrared thermometer. The rate of air movement in the nursery was measured periodically with a hot wire

Figure 1 Distribution of air temperature in the nursery. The mean radiative temperatures were within $\pm 1^\circ\text{C}$ of the air temperatures.

anemometer and was always below 0.05 m/s. The infants lay on a mattress 10 cm thick covered by a cotton sheet so that the conductive losses through the mattress would be negligible.

The study protocol had been approved by the hospital ethics committee and informed consent was obtained from all parents, most of whom were present during the measurements.

Results

Figures 1 and 2 show the frequency distributions of the air temperature T_a ($^\circ\text{C}$) and vapour pressure (kPa), respectively, in the nursery at the end of the measurement periods. For 76% of the measurements T_a was between 20 and 24°C . The lowest and highest air temperatures were 16 and 27°C respectively. The range and mean values of T_a are almost identical to those in a large investigation of the thermal environment for babies at home in Nottingham.²⁰ The vapour pressure in the nursery had a normal distribution around a mean value of 1.13 kPa (range 0.59–1.73 kPa). The mean radiative temperature of the walls in the nursery was always within $\pm 1^\circ\text{C}$ of the air temperature.

Figure 3 shows the distribution of the amount of insulation (clothing and bedding) which covered each infant during measurement. The insulation selected was between 1 and 3 togs for nearly 80% of the infants. There was a weak negative correlation between insulation and air temperature ($r = -0.29$) but no significant correlation between insulation and age ($r = 0.07$).

In fig 4 SMR (W/kg) is plotted against age in years. Values of SMR range from about 1.4 to 3.5 W/kg , although most values are between 1.5 and 3.0 W/kg . The average value for all the measurements is about 2.4 W/kg . At each age there are large differences in the SMR between individuals, typically by a factor of about two. The vertical bars on the graph indicate one SD from each mean value. The SDs range from ± 1 to 25% of the SMR values, with 91 of the 100 measurements having a SD of less than $\pm 10\%$. The corresponding number of measurements with SDs in the ranges ± 10 to 20% and ± 20 to 30% were six and three respectively. The SD was not related to the age of the infant.

Figure 5 presents values of SMR, expressed as per unit surface area (W/m^2), plotted against age. These values are based on the same data as in fig 4. The large difference in metabolic rate

Figure 2 Distribution of vapour pressure in the nursery.

Figure 3 The tog value of insulation selected by parents when their infants (1–12 months of age) were laid down to sleep in the nursery.

per unit area between individuals of the same age is apparent. For example, values of SMR range from 30 to 57 W/m^2 for infants aged 0.8 years. The mean values of SMR for infants aged 0.1 to 0.2, 0.2 to 0.3, 0.3 to 0.4, 0.4 to 0.6, 0.6 to 0.8, and 0.8 to 1.0 years are 38, 37, 45, 49, 50, and 44 W/m^2 respectively. The mean (SD) SMR for all our measurements is $45 (9.8) \text{ W/m}^2$. For comparison, fig 5 also shows the mean (and range) SMR value of 26 W/m^2 reported by Wheldon for infants under 2 weeks of age.²¹ Metabolic rate per unit area appears to increase over the first few weeks of life, but the timing of this rise in SMR is not clear from the data and may differ between infants.

In our study, SMR did not appear to be affected by the duration of fast or the time of day when the measurement was made. There was no correlation between insulation (fig 3) and SMR ($r = 1.6$). There was a weak positive correlation between SMR and T_a ($r = 0.32$).

The value of RQ usually remained steady during the measurement period and the mean values ranged from 0.81 to 0.98. The SD in RQ was less than 5% for 85 of the 100 measurements, and greater than 10% for only one measurement. There was no relationship between RQ and age.

Figure 6 compares the SMR (W) with the 'basal metabolic rate' BMR predicted by equations 1 and 2. The thick line is the 1:1 line. The thin line shows the 'best fit' straight line ($r^2 = 0.61$) through the data, and is described by

$$\text{SMR} = 0.84 \text{ BMR} + 1.7 \quad (4)$$

The gradient of 0.84 is significantly different from unity (t value = -2.37 , $p < 0.05$). The intercept of 1.7 W does not differ significantly from zero (t value = 0.56). The best straight

Figure 4 Sleeping metabolic rate (W/kg) of infants in the nursery plotted against age (1–12 months). The vertical bar shows the SD of each mean SMR measurement.

Figure 5 SMR (W/m²) of infants in the nursery plotted against age (1–12 months). On the left of the figure the open circle represents the mean (SD) value (thick bar) and range (fine bar) of the SMR for term infants studied during the first two weeks of life.²¹

line relationship, forced through the origin, is described by

$$\text{SMR} = 0.92 \text{ BMR} \quad (5)$$

with $r^2 = 0.60$. This gradient of 0.92 is also significantly different from unity (t value = 5.14, $p < 0.05$) indicating that the Schofield equations overestimate SMR by 8%, on average. More significantly, there is considerable scatter in the measured values of SMR about these lines. Typically, the rate of heat production by a sleeping infant can be 25% above, or below, the value predicted by Schofield's equations and by equation (5).

In the present study, there were no obvious differences between the metabolic rates of the male and female infants. Therefore, BMR was calculated from both equations (1) and (2) for all the infants in our study, to determine if one of Schofield's equations provided a better fit to our data than the calculation of BMR for males and females separately. Table 1 shows the intercepts, gradients and r^2 values for the three

Figure 6 SMR (W) plotted against the values predicted by Schofield's equations. The heavy line represents the 1:1 line; the thin line is the 'best fit' straight line through points (see text for details).

linear regressions of SMR compared with BMR. The data indicate that the use of separate equations for male and female infants does not improve significantly the prediction of SMR.

Table 2 gives the values of TEE (expressed as a rate per unit mass) for infants, measured in five recent studies using the doubly labelled water technique. The average of these eight values of TEE is 3.5 W/kg, nearly 50% above the average value of SMR (W/kg) for the data in fig 4.

Discussion

We report large differences between infants (aged from 1 month to 1 year) in the rate of metabolic heat production during sleep. This finding is consistent with the marked differences in the rate of $\dot{V}O_2$ between individuals that have been reported in studies on smaller groups of infants (aged 1–5 months) when asleep.²² Neither the duration of fast nor the sex of the child appeared to affect SMR, which is in agreement with the findings of others.^{6–23} Some investigators have found that metabolic heat production varies with sleep state^{22–24–25} while others have not.^{23–26} Brain activity was not assessed in the current study but the infants were judged to be in a 'quiet' sleep, with little or no body movement. We cannot exclude the possibility that differences in sleep state may account for some of the interindividual differences in SMR we observed.

Our measurements of SMR correspond reasonably well with the values of BMR predicted by Schofield's equations. However, our study does not reveal a metabolic difference between boys and girls up to 1 year of age and does not support the use of separate equations to estimate their metabolic rates during sleep. Either equation can be used for both sexes. Moreover, the differences in SMR between individuals mean that equations such as those formulated by Schofield, and based on body dimensions or age, are of limited value when the metabolic rate of an individual has to be predicted. Schofield estimated that the standard error was about $\pm 16\%$ when equations (1) and (2) are used to estimate the metabolic rate of an individual. This standard error fell to

Table 1 The intercept, gradient and r^2 values for the 'best fit' straight lines between the measured values of SMR (present study) and the values of BMR predicted by equations (1) and (2) from Schofield⁷

Equation	Intercept (SE) (W)	Gradient (SE)	r^2
1 or 2 (according to sex)	1.7 (3)	0.84 (0.07)	0.61
1	1.8 (3)	0.83 (0.08)	0.60
2	0.8 (3)	0.89 (0.07)	0.61

Table 2 Reported values of TEE (W/kg) in infancy

Study	No of infants	Age (years)	Mean (SD) TEE (W/kg)
Butte <i>et al</i> (1988) ³³	16	0.33	3.68 (1.07)
Roberts <i>et al</i> (1988) ²⁷	18	0.25	3.54 (0.39)
Lucas <i>et al</i> (1987) ³⁴	49	0.13	3.40 (0.92)
Lucas unpublished, reported in Prentice <i>et al</i> (1988) ³⁵	49	0.25	3.54 (0.82)
Davies <i>et al</i> (1989) ³⁶	37	0.50	3.83 (0.63)
	39	0.10	3.13 (0.81)
	34	0.21	3.24 (0.69)
	37	0.50	3.82 (0.59)

about $\pm 3\%$ when the same equations were used to predict the mean metabolic rate of 100 infants.

The values of SMR reported here are similar in magnitude to corresponding figures quoted by other workers. For example, Roberts *et al* measured the metabolic rate of a group of infants, soon after birth and at an average age of 0.26 years.²⁷ The newborn infants, studied while asleep, had a mean SMR of 2.0 W/kg. The older infants, studied while awake, had a mean metabolic rate of 3.0 W/kg. In our study, the mean SMR of eight sleeping infants between the ages of 0.23 and 0.27 years was 2.0 (0.42) W/kg, a value which is closer to that of the newborn infants. Wigfield *et al* used barometric plethysmography to measure the metabolic rate of 11 infants in the first week of life, and six infants aged 0.25 years.²⁸ The mean metabolic rate for the newborn infants was 31 (3.2) W/m², and for the older infants 41 (2.7) W/m². These values are within the range of SMR values reported in this study (fig 5). Fleming *et al* measured the metabolic rates of 12 infants during sleep at home by means of open circuit calorimetry.² The mean values (expressed in ml oxygen/m²/min) at around 1, 3, and 5 months were 122, 138, and 141 in quiet sleep and 131, 154, and 151 in rapid eye movement sleep, with standard errors around ± 15 . Our data, from 32 observations on infants aged between 0.1 and 0.4 years and calculated in the same units, give a mean of 145 with a SD of 13.

Table 2 shows that measurements of TEE using the doubly labelled water technique gives values of metabolic heat production for infants that are much higher than those we observed during sleep. This is not unexpected, because healthy infants spend more of their day awake and active, during which time their metabolic heat production will be higher than when they sleep.

In relation to an infant's heat balance, our most significant finding is the large difference in SMR between infants of the same age. In the

study situation the effective environmental temperature also varied, so it is possible that some of the variation is due to some infants reacting to a relatively cool environment with an increase in SMR. However, the infants were comfortably asleep, at the end of the study period their hands and feet did not feel cool, and in a subsequent study we have found that even a small deliberate drop in environmental temperature causes arousal. It is probable therefore that the infants were in, or close to, thermoneutral conditions. Similar variations in resting or basal metabolic rate have been reported in newborn infants or adults.

One consequence of these variations is that the conditions for thermal comfort will also differ widely between infants. Consider, for example, two infants aged 1 month, one (infant A) with a SMR of 25 W/m² and the other (infant B) with a SMR of 35 W/m². Suppose that they are dressed identically in a vest, Babygro, and disposable nappy and that their evaporative heat losses (minimum) account for 25% of the total heat loss.²⁹⁻³⁰ Assume that they both have a tissue (vasoconstricted) thermal resistance of 80 s/m (equivalent to a thermal insulation of 0.6 togs).²⁵ To maintain a constant body core temperature of 37°C at an air temperature of 20°C, without having either to sweat or to increase their rate of heat production, heat transfer theory³¹ indicates that infant A would require 320 s/m (about 2.5 togs) more insulation than infant B. This is equivalent to about two layers of blanket.

When infant B is wrapped in the amount of bedding which infant A requires for thermal comfort at an air temperature of 20°C, he will need to vasodilate and increase his evaporative heat loss to about 45% of his metabolic rate to maintain a body temperature of 37°C. An increase in SMR, caused for example by fever, would have to be balanced almost entirely by a rise in the rate of evaporative heat loss in order to prevent an uncontrolled increase in body temperature. In contrast, if infant A is wrapped in the same amount of bedding as infant B (healthy) requires for thermal comfort when $T_a = 20^\circ\text{C}$, he would have to increase his metabolic heat production by about 35% to maintain his body temperature at 37°C. These differences in thermal requirement, resulting from the different rates of metabolic heat production, make it impossible to give specific guidelines on the amount of clothing and bedding that an individual infant of a given age will require for thermal comfort at a particular room temperature.

A range of clothing and bedding insulations based on the lowest and highest rates of metabolic heat production could be calculated from our data for infants up to the age of 1 year. However, the width of this range at each air temperature would limit the value of such calculations as a guide to parents on the individual care of their infant. Indeed, parents are unlikely to know whether their infant has a high or low SMR. In our view it is wiser to reinforce the parents' awareness of when their infant is too warm or cool, so that they can, with confidence, adjust the amount of clothing

and bedding insulation and/or the room temperature. The weak negative correlation we report between the insulation and air temperature indicates that parents take some account of room temperature and appear to be aware of their child's requirements. This observation is in agreement with Wigfield *et al* who concluded that parents in Avon generally provide the correct amount of insulation to maintain their infants in thermal comfort,²⁸ and with the general guidance given in the report of the expert group *Back to Sleep*.³² Conversely, our study indicates that some parents took no account of the room temperature when selecting the level of insulation, and thermal problems could occur when a high level of insulation coincides with a high rate of metabolism.

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