Estimation of the energy cost of physical activity in infancy

Jonathan C K Wells, Peter S W Davies

Abstract

***Objective*—To estimate physical activity energy expenditure (AEE) in groups of free living infants in the first year of life.**

***Design*—Mixed longitudinal study of 124 healthy infants, using 232 estimations of AEE made between 1.5 and 12 months. Infants studied at more than one time point were treated as new cross sectional data points. Total energy expenditure and body composition were estimated using doubly labelled water. Sleeping metabolic rate was predicted from weight.**

***Results*—AEE increased from 5% of energy intake at 1.5 months to 34% at 12 months. Growth costs declined by 90%, but metabolisable intake by only 20%, over the same period.**

***Conclusions*—Energy is increasingly diverted from growth to activity during infancy. Values for AEE may aid in estimating energy requirements of groups factorially. Further work is required, however, on individual variability in AEE, and on the effects of disease, hospitalisation, surgery, and malnutrition.**

(*Arch Dis Child* 1998;**78**:131–136)

Keywords: energy requirements; energy expenditure; doubly labelled water

The most recent international report on dietary energy recommended that requirements be based on measurements of energy expenditure.[1] This approach has been applied extensively to adults because of the large quantity of data relating to basal metabolic rate (BMR) and physical activity in many different populations and environments. Energy requirements are therefore estimated as the sum of BMR, which is a function of body size and composition, and a multiple of BMR, which represents physical activity level (PAL).[1] These components can also be measured simultaneously as total energy expenditure (TEE) using the doubly labelled water method.[2]

In infants basal metabolism has been investigated in a number of studies,[3–5] but there is still a dearth of data on the energy cost of physical activity. Furthermore, growth costs (tissue synthesis and energy stored in new tissue) must also be taken into account. Growth costs can be estimated from the rate of weight gain,[1] and energy stored in new tissue can be combined with TEE to calculate energy requirements.[6–8] The relation between activity level and energy requirements in infancy remains poorly understood, however, and energy requirements remain based on weight[9] or age,[1] which acts as a proxy for weight. Hospitalisation, surgery, malnutrition, and disease may all influence physical activity which may in turn influence nutritional status. There is therefore a need for quantitative information on activity energy expenditure (AEE) in health and disease in the first year of life.

In the present study we describe estimation of mean AEE in healthy infants using a variant of the method described previously.[8] Our laboratory has collected data on TEE in infants throughout the first year of life, reported previously.[6 8 10 11] In this paper we have combined these data sets and calculated average AEE at five time points. The data permit an insight into the way AEE develops in the free living population over time.

Subjects and methods

A total of 138 infants was recruited from the Rosie Maternity Hospital in Cambridge into three separate studies of energy metabolism in the first year of life; two were cross sectional and the other was longitudinal. The hospital oversees approximately 4000 births per year. All infants were healthy, born at term, and had no known condition adversely influencing health or development. The majority of the infants were exclusively breast fed or formula fed in the first few months of life. Ethical permission for the studies was granted by the ethical committees of Cambridge Health Authority and the MRC Dunn Nutrition Unit.

The longitudinal study comprised 52 infants with measurements being made at 6 weeks and 12 weeks, and reduced numbers being followed up at 6 months and 9 months. Two further cross sectional studies investigated 50 infants at 12 weeks, 19 at 9 months, and 19 at 12 months. Infants measured more than once were treated as new cross sectional data points, as the aim was to describe average AEE in each age group.

Social class was assessed by paternal occupation.[12] Fathers were classified as 1 (professional occupation), 2 (managerial or technical occupation), 3 (skilled occupation, whether manual or non-manual), 4 (partly skilled occupation), or 5 (unskilled occupation). Infants were classified as either breast fed or formula fed according to feeding mode during the first 12 weeks after birth, rather than at the time of the measurement.

Each infant was studied over an eight day period. Nude body weight was measured on days 1 and 8 using Seca 724 electronic scales (CMS Weighing Ltd, London) and was accurate to within 20 g. Supine length and skinfold thickness at the triceps and subscapular sites were also measured on day 1. The data

Dunn Nutrition Unit, Cambridge
J C K Wells

Childhood Nutrition Research Centre, Institute of Child Health, London
J C K Wells

Queensland University of Technology Red Hill, Australia
P S W Davies

Correspondence to:
Dr J C K Wells,
Dunn Nutrition Unit,
Downham's Lane, Milton
Road, Cambridge CB4 1XJ.

Accepted 21 July 1997

Table 1 Age, anthropometry, energy expenditure, and growth costs of each age group; values are mean (SD) unless otherwise stated

	6 weeks	*12 weeks*	*6 months*	*9 months*	*12 months*
Number	49	92	37	36	18
% Boys	41	44	35	34	55
% Breast fed	41	42	51	58	83
Age (days)	36 (3)	81 (6)	181 (5)	276 (4)	368 (5)
Weight (kg)	4.54 (0.48)	5.89 (0.60)	7.70 (0.77)	8.91 (1.14)	10.27 (1.36)
Length (cm)	54.7 (1.8)	59.9 (2.1)	66.7 (2.1)	71.6 (2.9)	76.8 (3.7)
Triceps (mm)	6.6 (0.9)	7.7 (1.3)	7.6 (1.3)	8.3 (2.2)	9.0 (2.1)
Subscapular (mm)	6.8 (1.0)	7.6 (1.4)	7.3 (1.3)	6.6 (1.3)	6.6 (1.7)
BMI (kg/m^2)	15.2 (1.1)	16.4 (1.2)	17.3 (1.3)	17.5 (1.6)	17.3 (1.3)
Weight gain (kg/week)	0.24 (0.08)	0.20 (0.10)	0.12 (0.10)	0.11 (0.11)	0.09 (0.09)
Predicted SMR (kJ/kg/day)	237 (3)	230 (3)	223 (5)	219 (5)	218 (5)
TEE (kJ/day)	1270 (380)	1800 (420)	2530 (420)	3020 (670)	3290 (540)
TEE (kJ/kg/day)	281 (80)	297 (75)	329 (52)	337 (76)	323 (58)
FFM (kg)	3.66 (0.33)	4.49 (0.47)	5.55 (0.47)	6.54 (0.86)	7.69 (0.99)
Fat mass (kg)	0.87 (0.31)	1.39 (0.45)	2.15 (0.53)	2.44 (0.65)	2.58 (0.90)
Fat gain (g/day)	14.4 (3.2)	12.8 (3.7)	3.7 (4.0)	3.1 (5.2)	1.7 (3.3)
Protein gain (g/day)	3.3 (1.4)	2.8 (1.7)	2.5 (1.7)	2.4 (1.9)	2.1 (1.6)

on weight were used to calculate weight gain over the study period. Body mass index (BMI) was calculated as weight divided by height squared.

TOTAL ENERGY EXPENDITURE

TEE was measured using the doubly labelled water method. This technique has been described in detail elsewhere,[2 10] and the results of the studies have been described previously.[6 8 10 11] Briefly, carbon dioxide production is estimated over a seven day period from the difference between the turnover rates of two tracer isotopes, ^{2}H and ^{18}O in the body water pool. The ^{2}H tracer is lost from the body as water, while the ^{18}O tracer is lost as water and as carbon dioxide. Thus, the difference between the elimination rates of the two isotopes is an estimate of carbon dioxide production rate. Using an assumed respiratory quotient based on food quotient,[13] carbon dioxide production can be used to predict oxygen consumption and hence, using Weir's equation, energy expenditure. The technique has been successfully validated in studies of infants and has a mean precision in this age group of approximately 5%.[14–16]

GROWTH COSTS

Growth costs were calculated from experimental data on body composition and literature data on the reference child.[17] The approach involved firstly estimating fat free mass (FFM) on day 1 from total body water (TBW) obtained from the doubly labelled water method and secondly, taking into account that percentage body water of the reference child changes through the first year of life. This approach allowed calculation of FFM on day 8 taking into account the relative gains in protein and fat at different ages. Differences in FFM between days 1 and 8 were used to calculate daily protein gain. A similar approach was used for fat mass, calculated on days 1 and 8 as the difference between body weight and FFM, allowing daily fat gain to be calculated. Values for the gain per day of protein and fat were then combined with published estimates of the energy cost of tissue synthesis and the energy stored in new tissue. The details are given below.

TBW on day 1 was calculated as the ^{18}O dilution space divided by 1.01.[18] FFM on day one of the study period was calculated as TBW divided by a value for the proportion of FFM that is water.[17] Fat mass of the body was calculated as body weight minus FFM. Protein mass was calculated as FFM multiplied by a value for the proportion of FFM that is protein.[17] The proportion of the body that is water, and the proportions of FFM that are water and protein, all differ between the sexes and decline with increasing age of the infant.[17] The data on the reference child were therefore used to derive age related equations for the changes using separate curves for each sex.

The expected decline in the proportion of body weight that is water was calculated for each infant over the study week, taking into account sex and age. This percentage decline

Table 2 Components of metabolisable energy intake for each age group expressed as absolute values and per kg body weight; values are mean (SE)

	6 weeks	*12 weeks*	*6 months*	*9 months*	*12 months*
(kJ/day)					
Energy intake	1912 (61)	2362 (52)	2730 (85)	3216 (130)	3410 (131)
Stored	636 (20)	562 (18)	195 (32)	179 (38)	117 (38)
BMR*	867 (12)	1116 (11)	1439 (21)	1659 (35)	1892 (62)
Thermogenesis	95 (3)	118 (3)	136 (4)	161 (6)	170 (7)
Synthesis	202 (8)	175 (8)	105 (13)	98 (15)	79 (17)
AEE	109 (47)	391 (37)	846 (59)	1134 (95)	1151 (123)
(kJ/kg/day)					
Energy intake	421 (12)	402 (8)	356 (10)	358 (14)	334 (13)
Stored	140 (4)	96 (3)	26 (4)	20 (4)	11 (3)
BMR*	191 (1)	190 (1)	187 (1)	184 (1)	184 (1)
Thermogenesis	21 (1)	20 (1)	18 (1)	18 (1)	17 (1)
Synthesis	45 (2)	30 (1)	14 (2)	11 (2)	7 (2)
AEE	24 (10)	67 (6)	111 (7)	128 (11)	115 (13)
AEE/SMR†	0.10 (0.04)	0.29 (0.03)	0.50 (0.03)	0.58 (0.05)	0.53 (0.06)

* BMR is abstract calculated value for basal metabolic rate. † Expressed as fraction of predicted SMR.

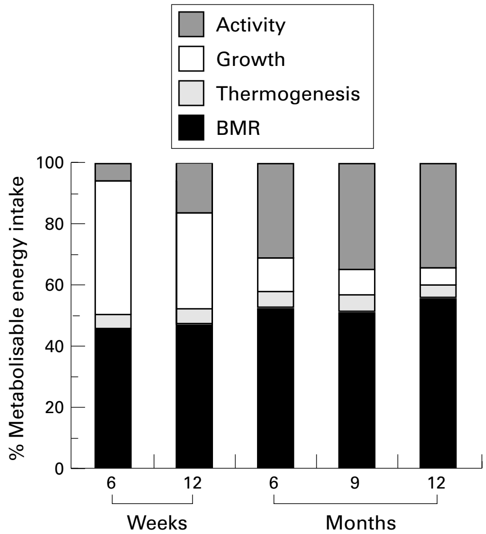

Figure 1 Components of energy expenditure as percentage of metabolisable energy intake in each age group.

was then multiplied by the value for TBW that would be predicted from body weight on day 8 if body composition remained constant during the study week. The decline in the proportion of FFM that is water and protein was also calculated for each infant taking sex and age into account. In this manner FFM on the last day of the study period was calculated and from it fat mass and protein mass. Thus:

$$\text{FFM start} = \frac{\text{TBW}}{\text{\% FFM as water on day 1}}$$

$$\text{\%TBW start} = \frac{\text{TBW start}}{\text{Weight start)}}$$

$$\text{FFM end} = \frac{\text{\%TBW start.}[1-\text{\% decline in \%TBW}]\text{. weight end}}{\text{\% FFM as water on day 8}}$$

From these values, the predicted gains per day in fat and protein were calculated. The energy cost of tissue synthesis was taken as 6.6 kJ/g fat and 32.6 kJ/g protein.[19] The energy stored in new tissue was derived using values of 38.7 kJ/g fat gained and 23.6 kJ/g protein gained.[19] The values for energy stored were added to TEE to calculate metabolisable energy intake.

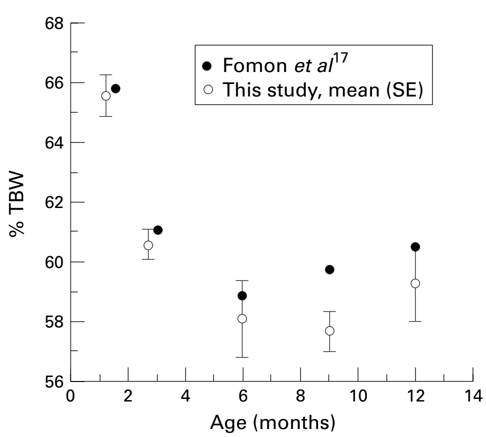

Figure 2 Percentage body water and age in the reference child and this study.

MINIMAL METABOLISM

Minimal metabolic rate was estimated as sleeping metabolic rate (SMR) from anthropometry using equations derived from infants of the same age range and population.[5] Separate equations were used for boys and girls. Weight alone was used to predict SMR. However, our methodology for the calculation of the components of energy metabolism in infants described previously[8] used not the average but the minimal level of SMR, termed minimal observed energy expenditure, or MOEE.[4] Predicted SMR was therefore multiplied by 0.89 to obtain estimated MOEE.[20] MOEE was further adjusted for thermogenesis, as described below, to give BMR. BMR thus represents an abstract quantity as in reality thermogenesis is continually present in minimal metabolism due to frequent feeding.

THERMOGENESIS

Thermogenesis was assumed to be 5% of metabolisable intake.[21] This aspect of energy metabolism has received inadequate experimental attention in infants, but there is little evidence that it shows marked variation among individuals.[22] A study in premature infants found values of 6.0% and 7.5% in breast fed and formula fed infants respectively,[23] but the energy content of the milk fed to these infants was high in comparison with contemporary milks.[24] Furthermore, these infants were fed every two to three hours, which is more frequent on average than in normal term infants.[25] Thus the 5% value was assumed to be suitable.

Metabolisable energy intake was calculated as the sum of TEE and energy stored in new tissue. Since infants are fed frequently even MOEE will include the effects of thermogenesis. Thermogenesis was therefore assumed to be distributed proportionally between MOEE and AEE, and proportional values were subtracted from each of these two components as described previously.[8]

PHYSICAL ACTIVITY

The difference between TEE and energy expended on tissue synthesis, BMR, and thermogenesis was assumed to be the cost of physical activity, AEE. Values for AEE were expressed as absolute values, per kg body weight, and also as a mean PAL in relation with predicted minimal metabolism, that is, AEE/SMR. The values for minimal metabolism were SMR as described above and represent the average level of minimal metabolism over a 24 hour period.[5] This approach differs slightly to that used in adults where PAL is calculated as TEE/BMR.[1] Such an approach in infants, however, would result in PAL including the costs of growth, and AEE/SMR is a more appropriate index.

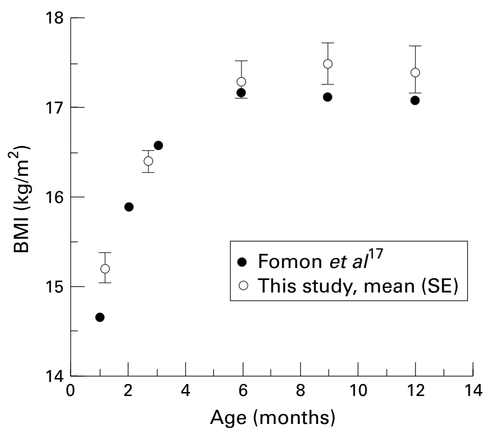

Figure 3 BMI and age in the reference child and this study.

Results

Tables 1 and 2 refer only to infants in whom measurements were successful (n = 124). Unsuccessful measurements (n = 21) occurred when the infant vomited or regurgitated an unknown portion of the isotopic dose within four hours of dosing or from poor parental compliance in the collection of urine samples. On these 124 infants, 232 successful doubly labelled water measurements were made, the numbers being 49, 92, 37, 36, and 18 at 6 weeks, 12 weeks, 6 months, 9 months, and 12 months of age respectively. The longitudinal study, between 6 weeks and 9 months of age, comprised 20 infants measured four times, 15 infants measured three times, 16 infants measured twice, and one infant measured once. The remaining 75 infants were each measured once.

All infants were of white ethnic status. Mean (SD) birth weight of the sample was 3490 (410) g, and gestational age was 39.3 (1.3) weeks. Birth rank distribution was 51, 45, 21, seven, and one in ranks 1, 2, 3, 4, and 6 respectively. Social class distribution was 37, 36, 36, 10, and five in classes 1 to 5 respectively. Table 1 gives age and anthropometry of the age groups, together with minimal metabolism predicted from body weight. Mean weight and length were very close to the 50th centile for the British population at each age.[26]

Table 1 also gives results of the doubly labelled water method and estimated growth costs, and table 2 gives the components of the energy balance equation. Table 2 also shows the mean AEE/SMR values. Figure 1 shows AEE as a percentage of metabolisable energy intake over the first year of life.

Figure 2 compares percentage body water between the reference child[17] and the infants in this study, and fig 3 shows a similar comparison for BMI.

There were no differences in AEE or AEE/kg between the sexes at any time point, nor between the diet groups during the first 6 months (data not shown).

Discussion

Physical activity has long remained the most difficult component of infant energy expenditure to study. Until recently, research was restricted to the investigation of behaviour rather than energy expenditure. Consequently, growth costs and minimal metabolism have been studied in detail, but AEE, although an increasing proportion of energy expenditure as the infant develops and potentially the component most responsive to environmental effects, has received little attention. Understanding the development of AEE in healthy free living infants may help in estimating energy requirements of infants in health and disease, and data on AEE may in some cases enable energy requirements of groups to be estimated factorially.

Conditions such as surgery, disease, and malnutrition affect the various components of energy metabolism in different ways. For example, minimal metabolism may increase with fever although this is not always the case,[27] while growth is reduced in malnutrition but accelerated during recovery. Physical activity might be reduced during long term illness and hospitalisation, but the significance of this for energy requirements is not known. Alternatively, activity might be unaffected by illness, while appetite might decrease thus leading to weight loss. Furthermore, anecdotal evidence suggests that some conditions may actually increase activity levels. For example, high levels of distress, which are associated with increased energy expenditure in early life,[28] are observed in infants suffering from chronic lung disease. Thus the relation between AEE and energy requirements merits detailed investigation.

AEE is calculated by subtraction after taking other TEE components into account, and is thus influenced by any inaccuracy in measuring those components. In our study minimal metabolism and thermogenesis were predicted rather than measured, and a proportion of individual variation in these components has not been taken into account. However, the assumptions used in estimating these components should not cause significant bias when applied to large groups of infants. The approach for estimating body composition assumes that the compositional data of the reference child are appropriate. Few data exist to allow consideration of this issue, but recent experimental evidence provides support for the values for the water content of FFM in early infancy.[29]

Growth costs were also estimated and these could be inaccurate if contemporary infants in Cambridge do not deposit fat and protein in the same way as the reference child. Total growth rates, however, were very similar in the Cambridge infants and the reference child. Furthermore, comparison of percentage body water shows little difference until 9 months of age (fig 2). At 9 and 12 months of age, our infants had lower percentage body water, indicating that they were fatter, and these differences are reflected in greater BMI at the same time points (fig 3). The Cambridge infants therefore appear to have shown slightly greater fat deposition between 6 months and 9 months, but the significance of this for AEE at 6 months is minimal because weight gain, and hence growth costs, are already much reduced by this time. Values for AEE at 9 and 12 months should not be influenced because the change in percentage body water between these ages is similar for the compared groups.

Thus it is unlikely that the use of several assumptions to predict AEE has severely compromised accuracy of the mean values. Our study does not allow interindividual variation in AEE to be considered, however, because the prediction of SMR results in extreme values for AEE being rounded towards the mean. More indirect evidence suggests that AEE is the most variable component of energy expenditure. Actual measurements in 12 week old infants show a coefficient of variation of 10.5% for SMR and 19% for TEE,[8] indicating that interindividual variability in TEE is due more to growth and physical activity than to minimal metabolism. Behavioural studies of 12 week old infants indicate wide interindividual variability in the proportion of time spent in low cost compared with high cost activities,[25] and this variability persists through infancy.[30] Physical activity represents one dimension of temperament, which is stable within individuals over time,[31] and gives rise to persistent infant behaviour and consistent parental response. Growth costs (of which only tissue synthesis is included in TEE) also vary widely among infants but decline markedly during the first year of life and contribute increasingly less to the variability in TEE.

It is important to note that physical activity is always partly determined by the environment, such that measurements represent a description of activity levels in a given population rather than a prescription of optimum levels for health. For example, our families were characterised by high levels of parental motivation as evidenced by participation in the study, and the possibility of an effect of the social environment on AEE should not be discounted. However, as all infants in the present study were healthy and as the sample size was relatively large, we have assumed that these activity levels are representative of healthy infants in general. The slight reduction in AEE/SMR value at 12 months of age compared with 9 months may be due to environmental rather than developmental factors. Nevertheless, another study suggests that AEE (calculated as TEE − BMR) in preschool children is closer to 0.4 BMR or even lower if thermogenesis is taken into account.[32] Thus the reduction of AEE/SMR at 12 months of age compared with 9 months could be a natural aspect of the development of physical activity.

Our study found that AEE increased markedly over the first year of life, from 5% of metabolisable energy intake at 6 weeks to 34% at 12 months. At each age group AEE was found to be greater then previously estimated despite the fact that energy intake was lower than previous estimations.[21] The increase with age, shown most clearly by the AEE/SMR ratio, may be assumed to reflect the increase in mobility and decrease in time spent sleeping over the infant period. Behavioural studies suggest that infants spend on average 15.4 hours asleep at 6 weeks, almost two thirds of the 24 hour period.[33 34] At 12 months, the average value remains high at 13 hours, but most of the sleep time is in the night and motor movement has become a major determinant of energy expenditure.[34] Thus the relative requirements of growth and physical activity are to a large extent reversed over the first year of life, such that between 6 weeks and 12 months energy intake per kg body weight declines only by 20%, although growth costs decline by 90%.

Mean energy intake at each age is substantially below that recommended by the current international guidelines.[1] This discrepancy has been reported previously in a number of previous studies most notably that of Whitehead *et al* which focused on measured food intakes,[35] and that of Prentice *et al* which considered TEE.[6] Some of the infants described in the study by Prentice *et al* have been included in the present sample. Although AEE is higher than previously assumed, minimal metabolism adjusted for thermogenesis is lower. We suggest that the lower energy intakes reported in recent studies need not necessarily indicate reductions in infant physical activity. Rather, in addition to a secular trend of decline in recent decades,[35] energy intakes may have been erroneously estimated in earlier studies through the use of methodologies that exaggerate the quantity and energy quality of milk intake.[36] The possibility remains, however, that care practices have changed over time and secular changes in family size and structure may also have influenced AEE even at this early age.

Although the prediction of SMR reduced the accuracy of individual AEE values, we did consider whether there was a broad effect either of sex or of feeding mode during the six month period when breast milk or formula milk was the main component of dietary intake. No such effects were observed in keeping with measurements of behavioural activity in a subsample of the same infants.[25] However, the effect of behaviour on AEE has been shown in early and late infancy. At 12 weeks of age AEE was increased by irritability and reduced by greater time spent asleep.[28] AEE was also affected by family size and decreased with increasing number of siblings.[28] In late infancy the time spent upset and the time spent feeding were negatively associated with time spent being active and with TEE.[30] Other factors reported to influence infant activity level include blood concentrations of certain hormones.[37]

In common with current international recommendations,[1] we have expressed energy metabolism variables on an absolute and per kg basis. It should be borne in mind, however, that energy expenditure per kg body weight is not mass independent,[38] and its use may be the source of bias when comparing groups or individuals of different sizes. As only some aspects of infant activity involve motor movement, the relation between AEE and size is likely to be indirect and dependent on age. Furthermore, changes in body size over the first year of life correspond to marked changes in body composition,[39] and FFM is a more suitable index than weight in terms of which to express

AEE for comparative purposes. Thus adjusting AEE for body size requires multiple regression analysis using FFM as the index of body size, but when comparing groups of similar body size and body composition it may be more appropriate to make no adjustment for size.

If minimal metabolism is normal the expression of AEE in terms of SMR may be a useful way in which to compare groups and individuals particularly where body size differences are due to differences in age. A similar approach is used in adults because the energy expenditure of most adult activities is related to body size.[1] Minimal metabolism in infants, however, may be altered by disease or severe malnutrition in which case such an approach would not be suitable.

In summary, our study quantifies AEE over the first year of life and indicates that energy is increasingly diverted away from growth to physical activity. Owing to a lack of data on the energetics of different infant activities, energy requirements are still estimated from body weight or age,[1 9] even though the relation between body size and TEE is weak in infants due to the strong effect of behaviour.[30] Until recently it was not possible to take physical activity into account and our data may be of assistance by showing how AEE becomes increasingly important as a component of energy expenditure with increasing infant age. There is now a need to investigate variation in AEE—for example, among healthy individuals, and to consider the effects of malnutrition, disease, hospitalisation, and surgery. Recent reports suggest that malnutrition remains a problem for infants in hospital,[40 41] and understanding the energy requirement for physical activity in particular diseases may aid in resolving this.

We acknowledge financial support from Ross Laboratories (Columbus, OH, USA) and the Nestlé Foundation (Lausanne, Switzerland) for the doubly labelled water studies, and thank Dr Gill Price for her valuable comments on the manuscript.

1 FAO/WHO/UNU. Energy and protein requirements. *WHO technical report series 724*. Geneva: WHO, 1985
2 Coward WA. The doubly-labelled water ($^2H_2{}^{18}O$) method: principles and practice. *Proc Nutr Soc* 1988;**47**:209–18.
3 Karlberg P. Determination of standard energy metabolism (basal metabolism) in normal infants. *Acta Paediatr Scand* 1952;suppl 89.
4 Butte NF, O'Brien Smith E, Garza C. Energy utilisation of breast-fed and formula-fed infants. *Am J Clin Nutr* 1990;**51**:350–8.
5 Wells JCK, Joughin C, Crisp JA, *et al*. Comparison of measured sleeping metabolic rate and predicted basal metabolic rate in the first year of life. *Acta Paediatr* 1996;**85**:1013–8.
6 Prentice AM, Lucas A, Vasquez-Velasquez L, *et al*. Are current guidelines for young children a prescription for overfeeding? *Lancet* 1988;**ii**:1066–9.
7 Lucas A. Energy requirements in normal infants and children. In: Schürch B, Scrimshaw NS, eds. *Activity, energy expenditure and energy requirements of infants and children*. Lausanne: IDECG, 1990;117–36.
8 Wells JCK, Davies PSW. The energy cost of physical activity in twelve-week old infants. *Am J Hum Biol* 1995;7:85–92.
9 Department of Health. *Report on health and social subjects 41: dietary reference values for food energy and nutrients for the United Kingdom*. London: HMSO, 1991.
10 Davies PSW, Ewing G, Lucas A. Energy expenditure in early infancy. *Br J Nutr* 1989;**62**:621–9.
11 Davies PSW, Wells JCK, Hinds A, *et al*. Total energy expenditure in 9 month and 12 month infants. *Eur J Clin Nutr* 1997;51:249–52.
12 Office of Population Censuses and Surveys. *Standard occupational classification*. London: HMSO, 1991.
13 Black AK, Prentice AM, Coward WA. Use of food quotients to predict respiratory quotients for the doubly-labelled water method of measuring energy expenditure. *Hum Nutr: Clin Nutr* 1986;**40C**:381–91.
14 Roberts SB, Coward WA, Schingenseipen KH, *et al*. Comparison of the doubly labeled water ($^2H_2{}^{18}O$) method with indirect calorimetry and a nutrient balance study for simultaneous determination of energy expenditure, water intake, and metabolisable energy intake in pre-term infants. *Am J Clin Nutr* 1986;**44**:315–22.
15 Jones PJH, Winthrop AL, Schoeller DA, *et al*. Validation of doubly labeled water for assessing energy expenditure in infants. *Pediatr Res* 1987;21:242–6.
16 Jensen CL, Butte NF, Wong WW, *et al*. Determining energy expenditure in preterm infants: comparison of $^2H_2{}^{18}O$ method and indirect calorimetry. *Am J Physiol* 1992;**263**: R685–92.
17 Fomon SJ, Haschke F, Ziegler EE, *et al*. Body composition of reference children from birth to age 10 years. *Am J Clin Nutr* 1982;**35**:1169–75.
18 Whyte RK, Baylet RS, Schwarz HP. The measurement of whole body water by $H_2{}^{18}O$ dilution in newborn pigs. *Am J Clin Nutr* 1985;**41**:801–9.
19 Roberts SB, Young VR. Energy costs of fat and protein deposition in the human infant. *Am J Clin Nutr* 1988:**48**:951–5.
20 Butte NF, Wong WW, Ferlic L, *et al*. Energy expenditure and deposition of breast-fed and formula-fed infants during early infancy. *Pediatr Res* 1990;**28**:631–40.
21 Waterlow JC. Basic concepts in the determination of nutritional requirements of normal infants. In: Tsang RC, Nichols BL, eds. *Nutrition during infancy*. Philadelphia: Hanley and Belfus, 1988:1–19.
22 Roberts SB, Lucas A. Energetic efficiency and nutrient accretion in preterm infants fed extremes of dietary intake. *Hum Nutr: Clin Nutr* 1987;**41C**:105–13.
23 Mestyan J, Jarai I, Fekete M. The total energy expenditure and its components in premature infants maintained under different nursing and environmental conditions. *Pediatr Res* 1968;**2**:161–71.
24 Lucas A, Davies PSW. Physiologic energy content of human milk. In: Atkinson SA, Hanson LA, Chandra RK, eds. *Breastfeeding, nutrition, infection and infant growth in developed and emerging countries*. St John's, Newfoundland: Arts Biomedical, 1990:337–57.
25 Wells JCK, Davies PSW. Diet and behavioural activity in 12-week-old infants. *Ann Hum Biol* 1995;**22**:207–15.
26 Freeman JV, Cole TJ, Chinn S, *et al*. Cross-sectional stature and weight reference curves for the UK, 1990. *Arch Dis Child* 1995;**73**:17–24
27 McIntyre J. Hull D. Metabolic rate in febrile infants. *Arch Dis Child* 1996;**74**:206–9.
28 Wells JCK, Davies PSW. The relationship between behaviour and energy expenditure in 12 week infants. *Am J Hum Biol* 1996;**8**:465–72.
29 Butte NF, Wong WW, Fiorotto M, *et al*. Influence of early feeding mode on body composition of infants. *Biol Neonate* 1995;**67**:414–24.
30 Wells JCK, Hinds A, Davies PSW. Free-living energy expenditure and behaviour in late infancy. *Arch Dis Child* 1997;**76**:490–4.
31 Rothbart MK. Longitudinal observation of infant temperament. *Dev Psychol* 1986;**22**:356–65.
32 Davies PSW, Gregory J, White A. Physical activity and body fatness in pre-school children. *Int J Obe* 1995;**19**:6–10.
33 Parmalee AH, Wenner WH, Schulz HR. Infant sleep patterns from birth to 16 weeks of age. *J Pediatr* 1964;**65**:576–82.
34 Wooding AR, Boyd J, Geddis DC. Sleep patterns of New Zealand infants during the first 12 months of life. *J Pediatr Child Health* 1990;**26**:85–8.
35 Whitehead RG, Paul AA, Cole TJ. A critical analysis of measured food intakes during infancy and early childhood in comparison with current international recommendations. *J Hum Nutr* 1981;**35**:339–48.
36 Lucas A, Ewing G, Roberts SB, *et al*. How much energy does the breast-fed infant consume and expend? *BMJ* 1987;**295**:75–7.
37 Marcus J, Maccoby EE, Jacklin CN, *et al*. Individual differences in mood in early childhood: their relation to gender and neonatal sex steroids. *Dev Psychobiol* 1985;**18**:327–40.
38 Heusner M. Body size and energy metabolism. *Ann Rev Nutr* 1985;**5**:267–93.
39 Davies PSW. Estimates of total body fatness in infancy and childhood. *Am J Hum Biol* 1992;**4**:621–4.
40 Moy RJD, Smallman S, Booth IW. Malnutrition in a UK children's hospital. *J Hum Nutr Dietet* 1990;**3**:93–100.
41 Hendrikse WH, Reilly JJ, Weaver LT. Malnutrition in a children's hospital. *Clin Nutr* 1997;**16**:13–18.