Public Health Nutrition: 8(7A), 1010–1027 DOI: 10.1079/PHN2005793

Energy requirements during pregnancy and lactation

Nancy F Butte[1],* and Janet C King[2]
[1]USDA/ARS Children's Nutrition Research Center, Children's Nutrition Research Center, Department of Pediatrics, Baylor College of Medicine, 1100 Bates Street, Houston, TX 77030, USA: [2]Children's Hospital Oakland Research Institute, 5700 Martin Luther King Jr Way, Oakland, CA 94609, USA

Abstract

Objective: To estimate the energy requirements of pregnant and lactating women consistent with optimal pregnancy outcome and adequate milk production.
Design: Total energy cost of pregnancy was estimated using the factorial approach from pregnancy-induced increments in basal metabolic rate measured by respiratory calorimetry or from increments in total energy expenditure measured by the doubly labelled water method, plus energy deposition attributed to protein and fat accretion during pregnancy.
Setting: Database on changes in basal metabolic rate and total energy expenditure during pregnancy, and increments in protein based on measurements of total body potassium, and fat derived from multi-compartment body composition models was compiled. Energy requirements during lactation were derived from rates of milk production, energy density of human milk, and energy mobilisation from tissues.
Subjects: Healthy pregnant and lactating women.
Results: The estimated total cost of pregnancy for women with a mean gestational weight gain of 12.0 kg, was 321 or 325 MJ, distributed as 375, 1200, 1950 kJ day^{-1}, for the first, second and third trimesters, respectively. For exclusive breastfeeding, the energy cost of lactation was 2.62 MJ day^{-1} based on a mean milk production of 749 g day^{-1}, energy density of milk of 2.8 kJ g^{-1}, and energetic efficiency of 0.80. In well-nourished women, this may be subsidised by energy mobilisation from tissues on the order of 0.72 MJ day^{-1}, resulting in a net increment of 1.9 MJ day^{-1} over non-pregnant, non-lactating energy requirements.
Conclusions: Recommendations for energy intake of pregnant and lactating women should be updated based on recently available data.

Keywords
Lactation
Exclusive breastfeeding
Energy intake
Basal metabolic rate
Total energy expenditure

Energy requirements of pregnant women

Introduction

The definition of energy requirements during pregnancy from the 1985 FAO/WHO/UNU report on Energy and Protein Requirements[1] may be paraphrased:

> *'The energy requirement of a pregnant woman is the level of energy intake from food that will balance her energy expenditure when the woman has a body size and composition and level of physical activity consistent with good health, and that will allow for the maintenance of economically necessary and socially desirable physical activity. In pregnant women the energy requirement includes the energy needs associated with the deposition of tissues consistent with optimal pregnancy outcome.'*

These basic principles underpin recommendations for energy requirements during pregnancy. Women ideally should enter pregnancy with a body size and composition consistent with long-term good health. Appropriate ranges of body mass index (BMI) consistent with long-term good health and optimal pregnancy outcome are definable. Women should gain weight at a rate and with a composition consistent with good health for herself and her child. Energy intake should allow women to maintain economically necessary and socially desirable levels of physical activity during pregnancy.

Recommendations for energy intake of pregnant women should be population-specific, because of differences in body size and lifestyles. The extent to which women change habitual activity patterns during pregnancy will be determined by socioeconomic and cultural factors specific to the population. FAO/WHO/UNU energy recommendations[1] refer to groups, not to individuals. Pregnant women throughout the world cannot be considered as belonging to a single group. Well-nourished women from developed societies may have different energy needs in pregnancy than shorter women from developing societies. Undernourished pregnant women may have different energy needs than

---

*Corresponding author: Email nbutte@bcm.tmc.edu overweight and obese pregnant women. Even within a specific population group, high variability is seen in the rates of gestational weight gain and energy expenditure, and hence in the energy requirements among women.

Gestational weight gain for optimal pregnancy outcome

To define the energy cost of pregnancy, desirable gestational weight gains must be stipulated. Desirable gestational weight gains are those associated with optimal outcome for the mother in terms of maternal mortality, complications of pregnancy, labour and delivery, postpartum weight retention and lactational performance, and for the infant in terms of foetal growth, gestational duration, mortality and morbidity. The WHO Collaborative Study on Maternal Anthropometry and Pregnancy Outcomes[2] reviewed information on 110 000 births from 20 different countries to define those anthropometric indicators which are most predictive of foetal outcome (low birth weight (LBW), intrauterine growth retardation (IUGR) and preterm birth) and maternal outcome (preeclampsia, postpartum haemorrhage and assisted delivery). Mean maternal heights ranged from 148 to 163 cm, prepregnancy weights from 42.1 to 65.6 kg, and birth weights from 2.633 to 3.355 kg. In terms of foetal outcome, attained weight (prepregnancy + weight gain) during pregnancy was the most significant anthropometric predictor of LBW (odds ratio, OR = 2.5) and IUGR (OR = 3.1), but not preterm birth. For predicting LBW, maternal prepregnancy weight and achieved weights at 20, 28 and 36 weeks of gestation performed similarly (OR = 2.4–2.6). For predicting preterm delivery, prepregnancy weight, prepregnancy BMI, and attained weight gain between 20 and 28 weeks of gestation had OR in the moderate range (1.3–1.4). For assisted delivery, maternal height had the highest positive OR (1.6), while the OR for predicting preeclampsia and postpartum haemorrhage were less than one[3,4].

Women with short stature, especially in developing countries with inadequate health care systems, are at risk of LBW, small for gestational age (SGA) and preterm delivery, as well as obstetric complications during labour and delivery[3]. Short stature, which may be accompanied by pelvic restriction, has been associated with increased risk of intrapartum caesarean section, prematurity, SGA and perinatal death[5]. Short stature often reflects poor childhood growth and suboptimal development of the anatomical and physiological systems that are needed to sustain optimal foetal growth. The risk:benefit ratio of improving maternal nutrition during pregnancy has been evaluated in Guatemalan women[6]. Increases in foetal growth (+100 g) comparable to those attributable to improved diet during pregnancy are associated with an increase in risk of caesarean delivery (8/1000 cases), but a decrease in risk of perinatal distress (34/1000 cases)[6]. Also, the relationship between maternal stature and birth weight was investigated in 8870 US women with uncomplicated pregnancies[7]. Increasing maternal height was positively associated with birth weight in white, black and Asian, but not Hispanic women. The relationship between maternal weight gain and birth weight was not modified by maternal height.

The WHO Collaborative Study on Maternal Anthropometry and Pregnancy Outcomes[2] was used to define desirable birth weights and maternal weight gains associated with lower risk of foetal and maternal complications, i.e. LBW, IUGR, preterm birth, preeclampsia, postpartum haemorrhage and assisted delivery. Birth weights between 3.1 and 3.6 kg (mean, 3.3 kg) were associated with the optimal ratio of maternal and foetal outcomes. The range of gestational weight gains associated with birth weights greater than 3 kg was 10–14 kg (mean, 12 kg).

In 1990, the Institute of Medicine[8] recommended ranges of weight gain for women with low (BMI < 19.8), normal (19.8–26.0), and high (>26.0–29.0) prepregnancy BMI. The recommended ranges were derived from the 1980 US National Natality Survey and based on the observed weight gains of women delivering full term (39–41 weeks), normally grown (3–4 kg) infants without complications[9]. Abrams *et al.*[10] systematically reviewed studies that examined weight gain in relation to foetal and maternal outcomes. The review showed that weight gain within the Institute of Medicine's recommended ranges was associated with the best outcome for both mothers and infants. The recommended ranges of weight gain for women with low (12.5–18.0 kg) and normal (11.5–16.0 kg) prepregnancy BMI are slightly higher than the range observed in the WHO Collaborative Study[2].

Energy cost of pregnancy

Energy cost of pregnancy includes energy deposited in maternal and foetal tissues, and the increase in energy expenditure attributed to maintenance and physical activity. Weight gain during pregnancy comprises the products of conception (foetus, placenta, amniotic fluid), the increases of various maternal tissues (uterus, breasts, blood, extracellular extravascular fluid), and the increases in maternal fat stores. As a result of the increased tissue mass, the energy cost of maintenance, as well as physical activity, rises during pregnancy.

Hytten and Chamberlain[11] developed a theoretical model to estimate the energy requirements during pregnancy for well-nourished women (Table 1). Assumptions underlying this model were: a prepregnant body weight between 60 and 65 kg, an average gestational weight gain of 12.5 kg, and an average infant birth weight of 3.4 kg. This model was the basis of the 1985 FAO/WHO/UNU recommendations for energy intake of pregnant women. To calculate the energy cost of protein and fat deposition, Hytten and Chamberlain used the heat of combustion values of 5.6 kcal g^{-1} protein and 9.5 kcal g^{-1}

Table 1 Hytten and Chamberlain's theoretical model of cumulative energy cost of pregnancy[11]

Rates of tissue deposition	0–10 weeks*	10–20 weeks	20–30 weeks	30–40 weeks	Cumulative total (g)
Weight gain (g day^{-1})**	12	48	64	57	12 500
Protein deposition (g day^{-1})**	0.64	1.84	4.76	6.10	925
Fat deposition (g day^{-1})**	5.85	24.80	21.85	3.30	3825
Factorial estimation of energy cost of pregnancy	0–10 weeks*	10–20 weeks	20–30 weeks	30–40 weeks	Cumulative total (kJ)
Protein deposition (kJ day^{-1})	15	43	112	143	21 698
Fat deposition (kJ day^{-1})	233	986	869	131	152 001
Increment in basal metabolic rate (kJ day^{-1})	187	414	620	951	149 440
Efficiency of energy utilisation (kJ day^{-1})***	44	144	160	122	32 314
Total energy cost of pregnancy (kJ day^{-1})	477	1586	1761	1347	355 460

* Interval (56 d) computed from last menstrual period.
** Total weight gain of 12.5 kg, protein deposition of 925 g, fat deposition 3.825 kg taken as 23.42 kJ g^{-1} for protein and 39.75 kJ g^{-1} for fat.
*** Efficiency of energy utilisation taken as 0.90.

fat, and assumed the efficiency of energy utilisation was the same as that for maintenance (0.90). In fact, animal data suggest the efficiency of energy utilisation for protein and fat deposition may be lower (0.70)[12]. In Hytten and Chamberlain's model fat accretion (43%) and basal metabolism (42%) account for most of the energy cost of pregnancy. Since the time Hytten and Chamberlain published this model, there have been several longitudinal studies on energy balance during pregnancy from developing and developed countries. In the following sections, these empirical data will be reviewed.

Protein and fat accretion

There are several methodological considerations regarding the determination of protein and fat accretion during pregnancy. Protein is deposited predominantly in the foetus (42%), but also in the uterus (17%), blood (14%), placenta (10%), and breasts (8%)[11,13]. Protein is deposited unequally across pregnancy, predominantly in late pregnancy. Hytten and Chamberlain[11] estimated that 925 g protein are deposited in association with a 12.5 kg gestational weight gain.

Protein deposition has been estimated indirectly from measurements of total body potassium accretion, measured by whole body counting in a number of studies of pregnant women (Table 2). The study design (cross-sectional or longitudinal), stage of pregnancy and type of whole body counter differed across studies[14–19]. MacGillivray[14] studied eight women in early pregnancy and another 16 in late pregnancy; since the same women were not studied repeatedly, the increase in TBK is questionable. The results of Emerson[16] based on a sample size of five women are questionable; the potassium per kilogram gained was high, and TBK did not decline in the postpartum period in three of the subjects. King[15] observed a rate of 24 milli equivalents of K per week between 26 and 40 weeks of gestation. Pipe[17] found a 312 meq K increase. Lower increments of 110 and 187 meq of K at 36 weeks were found over prepregnancy values[18,19]. Based on a K:N in foetal tissues of 2.15 meq K/g N, total protein deposition estimated from the longitudinal studies of King, Pipe, Forsum and Butte was 686 g.

Cumulative fat accretion in foetal and maternal compartments contributes substantially to the overall energy cost of pregnancy; therefore, methodological errors in the estimation of fat accretion can significantly affect energy requirements. In a number of studies, fat accretion during pregnancy was estimated from skinfold measurements. The average gain in maternal fat stores was

Table 2 Increment in total body protein estimated from changes in total body potassium of well-nourished women during pregnancy

Reference	*n*	Study interval (weeks of pregnancy)	TBK measurement	Increase in TBK (meq)	TBK (meq day^{-1})	TBK (meq kg^{-1} gained)	Increment in protein (g)
MacGillivray, 1959[14]	8 16	11.2–37.3 cross-sectional	1952 meq 2541 meq	589	3.22	42.1	1712
King, 1973[15]	10	26–40 longitudinal	24 meq per week	336	3.41	44.3	977
Emerson, 1975[16]	5	20, 24, 28, 32, 35 longitudinal	2712 meq 3192 meq	480	3.43	86.5	1395
Pipe, 1979[17]	27	10–14, 24–28, 36–38 longitudinal	2442 meq 2754 meq	312	1.78	30.0	907
Forsum, 1988[18]	22	0–36 longitudinal	2397 meq 2507 meq	110	0.44	9.4	320
Butte, 2002[19]	34	0–36 longitudinal	2604 meq 2770 meq	187	0.79	12.8	544

1.2 kg in women from developed countries as estimated from skinfold measurements[17,20–22]; this value is substantially lower than that measured by body composition methods in similar population groups. The average gain in maternal fat stores of 1.1 kg in women from developing countries[23–25] was questionably similar, despite significantly lower gestational weight gains (9.8 vs. 12.8 kg). Skinfold measurements lack the precision necessary to estimate accurately changes in fat mass, particularly during pregnancy when fat accretion is not equally distributed across all adipose sites.

Measurements of fat accretion using body composition methods are scarce in women from developing countries. Lawrence[26] estimated fat accretion in pregnant Gambian women using total body water. Women supplemented with energy-dense groundnut biscuits gained 9.2 kg of which 2.0 kg was fat, and unsupplemented women lost an estimated 0.3 kg fat (total weight gain = 7.2 kg). These estimates of fat accretion were not corrected for the increased hydration of FFM.

Two-component body composition methods based on total body water, body density, and total body potassium are invalid during pregnancy because of the increased hydration of FFM[27]. The constants for hydration, density and potassium content of FFM used in two-compartment models are not applicable to pregnant women and would lead to erroneous estimations of FFM and FM. For example, applying the usual constant of 0.73 for the hydration of FFM in the TBW method results in an overestimation of maternal FM in late pregnancy, whereas use of 1.1 kg cm^{-3} for the density of FFM in the hydrodensitometry method results in an underestimation of maternal FM. Corrected constants for the hydration, density and potassium content of FFM in pregnancy have been published[27,28]. Two-component models that use corrected constants are acceptable, or three- and four-component models[17,29,30] in which the hydration or density of FFM is measured are appropriate for use in pregnant women.

Fat accretion estimated using corrected two-component models, or three- and four-component body composition models in well-nourished pregnant women are summarised in Table 3. Mean fat accretion measured up to a mean of 36 weeks of gestation was 3.7 kg, and was associated with a mean weight gain of 11.9 kg. Extrapolated to 40 weeks of gestation, mean fat accretion would be 4.3 kg, associated with a total weight gain of 13.8 kg. The fat gain associated with the mean weight gain of 12 kg (range 10–14 kg) observed in the WHO Collaborative Study[2] would be 3.7 kg (range 3.1–4.4 kg).

Rates of fat accretion during the first, second and third trimesters of pregnancy were available in a subset of the studies presented in Table 3. In these longitudinal studies conducted in well-nourished women[17,18,31–34], rates of fat accretion averaged 8 g day^{-1} in the first trimester, 26 g day^{-1} in the second trimester, but were quite variable in the third trimester from −7 to 23 g day^{-1}.

Table 3 Changes in total body fat mass in well-nourished women during pregnancy

Reference	Multicomponent body composition model	Country	*n*	Initial measurement (week of gest)	Final measurement (week of gest)	Gestational wt gain (kg)	Gest wt gain extrapolated (kg)*	Fat mass gain (kg)	Fat mass gain extrapolated (kg)**	Daily increment in body fat mass: First trimester (g day^{-1})	Second trimester (g day^{-1})	Third trimester (g day^{-1})
Pipe, 1979[17]	TBW, TBK	UK	27	12	37	10.4	13.2	2.4	3.1		24.6	−7.01
Forsum, 1988[18]	TBW, TBK	Sweden	22	0	36	11.7	13.0	5.4	6.0		27.8	22.6
Goldberg, 1993[32]	TBW, TBK	UK	12	0	36	11.9	13.2	2.8	3.1	13	25.4	4.8
de Groot, 1994[31]	UWW	USA	12	0	34	11.7	13.8	3.4	4.0	13.1	19.5	10.4
Spaaij, 1993[20]	UWW	Netherlands	26	0	35	11.7	13.4	2.4	2.7			
van Raaij, 1988[28]	UWW	Netherlands	42	11	35	9.15	12.7	2.5	3.5			
Lindsay, 1997[61]	UWW	USA	27	0	34.5	12.6	14.6	5.9	6.8			
Lederman, 1997[96]	TBW, UWW, BMC	USA	46	14	37	12.1	15.3	3.8	4.8			
Kopp-Hoolihan, 1999[33]	TBW, UWW, BMC	USA	9	0	35	11.2	12.8	4.1	4.7	1.4	36.6	−1.43
Sohlstrom, 1997[97]	MRI	Sweden	16	0	5–10 pp	15.8	15.8	3.6	3.6			
Butte, 2002[19]	TBW, UWW, BMC	USA	34	0	36	12.8	14.2	4.6	5.1	5.8	20.0	20.6
Mean			24.8	3.4	35.6	11.9	13.8	3.7	4.3	8.3	25.7	8.3

Abbreviations: TBW – total body water; TBK – total body potassium; UWW – underwater weighing; BMC – bone mineral content; MRI – magnetic resonance imaging.
*GWG: assumed linear rate of weight gain in second and third trimester, plus 1.6 kg gain in first trimester[8].
**Fat gain: assumed fat gain proportional to total weight gain.

Basal metabolism

As a result of increased tissue mass, the energy cost for maintenance rises during pregnancy. This increase in basal metabolic rate (BMR) is one of the major components of the energy cost of pregnancy. Several longitudinal studies have been published which measured changes in BMR (or RMR: resting metabolic rate) throughout pregnancy.

In Table 4 changes in BMR during pregnancy relative to either a prepregnancy or an early pregnancy (10–18 weeks) baseline measurement are presented. Since BMR was frequently measured throughout pregnancy the cumulative change in BMR throughout pregnancy could be calculated. The most striking feature in Table 4 is the wide variability in cumulative maintenance costs among populations: from +210 MJ in Swedish women to −45 MJ in unsupplemented Gambian women. Also, the cumulative maintenance costs across the entire pregnancy showed wide variation between individuals within populations[20,32,35,36]. Cumulative increases in BMR are significantly correlated with total weight gain ($r = 0.79$; $P < 0.001$) and prepregnancy percent fat mass ($r = 0.72$; $P < 0.001$)[37]. For a gestational weight gain of 12.5 kg, the cumulative increase was 160 MJ, which is remarkably close to the original estimate of 150 MJ based on literature values of changes in oxygen consumption of individual organs and processes[13].

Energy requirements should be derived based on healthy populations with favourable pregnancy outcomes. Women with inadequate gestational weight gains and lesser increases in basal metabolism probably reflect suboptimal nutritional conditions. In healthy, well-nourished women, the cumulative increases in BMR ranged from 124 to 210 MJ, with an average increase of 157 MJ for the entire pregnancy. The average increases in BMR over prepregnancy values were 4.5, 10.8 and 24.0% for the first, second and third trimesters, respectively.

Total energy expenditure by respiratory calorimetry or doubly labelled water method

Whole room respiration calorimetry has been performed in well-nourished women[31,34,38,39] and marginally-nourished women[40] during pregnancy (Table 5). These short-term 24-hour studies can demonstrate changes in energy expenditure under standardised protocols, but make no allowance for free-living physical activity. The 24-hour EE increased similarly in all studies averaging 1, 4, and 20% above prepregnancy values in the first, second and third trimesters, respectively. BMR increased by 5, 10, and 25% across trimesters. The increment in 24-hour EE was largely due to the increase in BMR. Another calorimetric study in Gambian women found much more modest increments in BMR and 24-hour EE, indicating energy sparing during pregnancy[36]; the different results may be attributed to the study design (longitudinal vs. cross-sectional), subjects' nutritional status and season.

Table 4 Cumulative increase in basal metabolic rate (BMR) in pregnant women from developed and developing countries

				BMR (MJ day^{-1})					% Change in BMR from prepregnancy values		
Reference	Country	n	Weight gain (kg)*	Prepregnancy	1st trimester	2nd trimester	3rd trimester	Cumulative increase in BMR (MJ)**	1st trimester	2nd trimester	3rd trimester
Developed countries											
Durnin, 1987[98]	Scotland	88	12.4	6	6.3	6.5	7.3	126	5	8	22
van Raaij, 1987[22]	Netherlands	57	11.6					144			
Forsum, 1988[42]	Sweden	22	13.4	5.6		6	7.1	210		7	27
Goldberg, 1993[32]	England	12	13.7	6	6.3	6.4	7.2	124	5	7	20
Spaaij, 1993[48]	Netherlands	26	13.7	5.4	5.7	6.2	6.6	189	6	15	22
de Groot, 1994[99]	Netherlands	12	11.6	5.8	6.3	6.5	7.2		9	12	24
Kopp-Hoolihan, 1999[35]	USA	10	13.2	5.5	5.4	6.4	7.1	151	−2	16	29
Mean		32	12.8	5.7	6.0	6.3	7.1	157	5	11	24
Developing countries											
Lawrence, 1987[26]	Gambia	21	7.2					−45			
Lawrence, 1987[26]	Gambia	29	9.2					4			
Thongprasert, 1987[23]	Thailand	25	9.6					100			
Tuazon, 1987[24]	Philippines	40	10.3		5	5.3	5.8	89			
Poppitt, 1993[36]	Gambia	21	8.7	5.2	5.1	5.3	5.6	27	−2	2	8
Mean		27	9.0	5.2	5.1	5.3	5.7	35	−2	2	8

*Weight gain was extrapolated to 40 weeks of gestation, assuming that the average weight gain during the first 10 weeks of pregnancy is 0.65, and that weight increases by 0.40 kg per week towards term[11].
**Calculated as cumulative increase in BMR over pregnancy using prepregnancy or early pregnancy values as baseline.

Table 5 24-hour energy expenditure measured by room calorimetry in well-nourished women during pregnancy

Reference	Country	*n*	Measurement period (week of gest)	Wt (kg)	Height (m)	BMI	TEE ($MJ\,day^{-1}$)	BMR ($MJ\,day^{-1}$)	AEE ($MJ\,day^{-1}$)	PAL	Wt/NPWt	TEE/NPTEE	BMR/NPBMR	AEE/NPAEE	TEE ($MJ\,kg^{-1}$ per day)	BMR ($MJ\,kg^{-1}$ per day)	AEE ($MJ\,kg^{-1}$ per day)
Heini, 1992[40]	Gambia	41	NP	51.3	1.59	20.3	6.97								0.136		
			12	53.5	1.60	20.9	7.09				1.04	1.02			0.133		
			24	54.5	1.60	21.3	7.19				1.06	1.03			0.132		
			36	63.1	1.62	24.0	8.44				1.23	1.21			0.134		
de Groot, 1994[99]*	Netherlands	12	NP	61.4	1.70	21.2	8.63	5.82	2.81	1.48					0.141	0.095	0.046
			12	62.1	1.70	21.5	8.73	6.27	2.46	1.39	1.01	1.01	1.08	0.88	0.141	0.101	0.040
			23	66.4	1.70	23.0	9.08	6.52	2.56	1.39	1.08	1.05	1.12	0.91	0.137	0.098	0.039
			34	72.3	1.70	25.0	9.94	7.23	2.71	1.37	1.18	1.15	1.24	0.96	0.137	0.100	0.037
Butte, 1999[39]	USA	67	37	75.2	1.64	28.0	9.48	7.29	2.19	1.30					0.126	0.097	0.029
Butte, 2002[34]	USA	34	NP	59.3	1.64	22.0	7.36	5.54	1.83	1.33					0.124	0.093	0.031
			9	60.2	1.64	22.4	7.41	5.65	1.76	1.31	1.02	1.01	1.02	0.96	0.123	0.094	0.029
			22	65.1	1.64	24.2	7.76	5.91	1.85	1.31	1.10	1.05	1.07	1.01	0.119	0.091	0.028
			36	72.2	1.64	26.8	9.05	7.00	2.05	1.29	1.22	1.23	1.26	1.12	0.125	0.097	0.028

Abbreviations: BMI – body mass index; TEE – total energy expenditure; BMR – basal metabolic rate; AEE – activity energy expenditure; PAL – physical activity level; NP – non-pregnant.

Free-living total energy expenditure of pregnant women has been measured longitudinally by doubly labelled water in well-nourished women[32,34,35,41,42] (Table 6). TEE increased throughout pregnancy in proportion to the increase in body weight. TEE increased by 1, 6, and 19%, and weight increased by 2, 8, and 18% over baseline in the first, second and third trimesters, respectively. The increments in TEE (0.1, 0.4 and 1.5 $MJ\,day^{-1}$ in the first, second and third trimesters, respectively) were similar to the increments observed by 24-hour calorimetry. BMR increased by 2, 9 and 24% over baseline. Activity energy expenditure (TEE−BMR) averaged −2, 3 and 6% relative to baseline. Because of the larger increment in BMR, PAL declined by 0.13 PAL units from 1.73 prior to pregnancy to 1.60 in late gestation in these well-nourished women.

Free-living total energy expenditure has been measured cross-sectionally in pregnant women relative to non-pregnant, non-lactating (NPNL) controls from developing countries using doubly labelled water, activity diaries and heart rate monitoring (Table 7)[43–46]. With the exception of the Gambian study by Singh[44], TEE and AEE declined throughout pregnancy relative to controls. The PAL in the NPNL controls was 1.88 and declined to 1.68 at term, consistent with observations that women perform less arduous tasks as they approach term in these countries.

Total energy cost of pregnancy

Total energy cost of pregnancy in well-nourished women was estimated factorially from the increment in BMR (Table 4) or from the increment in TEE (Table 6), plus the energy deposition associated with a mean gestational weight gain of 13.8 kg (Table 8). Energy deposition was derived from the estimated increase in protein (Table 2), and the mean increase in fat mass in well-nourished women (Table 3). The two approaches gave similar results for the total energy cost of pregnancy (374 vs. 369 MJ).

The energy cost of pregnancy is not equally distributed over pregnancy. Energy deposition as protein occurs primarily in the second (20%) and third trimesters (80%). The distribution of energy deposition as fat was based on rates of weight gain in Scottish primigravid women estimated by the IOM subcommittee[8]. Rates of weight gain of 1.6 kg in the first trimester, 0.45 kg per week in the second trimester and 0.40 kg per week in the third trimester indicate a distribution of 11, 47 and 42% in the first, second and third trimesters, respectively. The increases in basal metabolism and TEE are most pronounced in the second half of pregnancy. The two approaches provided slightly different distributions, but average approximately 430, 1375, and 2245 $kJ\,day^{-1}$, for the first, second and third trimesters, respectively.

The total cost of pregnancy was also calculated for women with a mean gestational weight gain of 12.0 kg, as found in the WHO Collaborative Study on Maternal Anthropometry and Pregnancy Outcomes[2] (Table 9).

Table 6 Total energy expenditure measured by doubly labelled water method in well-nourished women during pregnancy

Reference	Country	*n*	Measurement period (week of gest)	Wt (kg)	Ht (m)	BMI	TEE (MJ day^{-1})	BMR (MJ day^{-1})	AEE (MJ day^{-1})	PAL	Wt/NPWt	TEE/NPTEE	BMR/NPBMR	AEE/NPAEE	TEE (MJ kg^{-1} per day)	BMR (MJ kg^{-1} per day)	AEE (MJ kg^{-1} per day)
Goldberg, 1991[41]	UK	10	NP			21.2	9.78	5.86	3.92	1.67							
		10	36				10.33	7.29	3.04	1.42			1.24	0.78			
Forsum, 1992[42]	Sweden	19	NP	60.7	1.66	22.0	10.10	5.60	4.50	1.80					0.166	0.092	0.074
		19	36	72.7	1.66	26.4	12.20	7.30	4.90	1.67	1.20	1.21	1.30	1.09	0.168	0.100	0.067
		22	NP	61.0	1.65	22.4	10.40	5.60	4.80	1.86					0.170	0.092	0.079
		22	17	63.7	1.65	23.4	9.60	6.00	3.60	1.60	1.04	0.92	1.07	0.75	0.151	0.094	0.057
		22	30	70.2	1.65	25.8	12.50	6.90	5.60	1.81	1.15	1.20	1.23	1.17	0.178	0.098	0.080
Goldberg, 1993[32]	UK	12	NP	61.7	1.64	22.9	9.52	6.05	3.47	1.57					0.154	0.098	0.056
		12	6	62.2	1.64	23.1	9.72	6.29	3.43	1.55	1.01	1.02	1.04	0.99	0.156	0.101	0.055
		12	12	63.3	1.64	23.5	10.16	6.23	3.93	1.63	1.03	1.07	1.03	1.13	0.160	0.098	0.062
		12	18	65.4	1.64	24.3	10.28	6.25	4.03	1.64	1.06	1.08	1.03	1.16	0.157	0.096	0.062
		12	24	68.7	1.64	25.5	10.97	6.61	4.36	1.66	1.11	1.15	1.09	1.26	0.160	0.096	0.063
		12	30	71.7	1.64	26.7	11.20	6.90	4.30	1.62	1.16	1.18	1.14	1.24	0.156	0.096	0.060
		12	36	73.6	1.64	27.4	11.25	7.55	3.70	1.49	1.19	1.18	1.25	1.07	0.153	0.103	0.050
Kopp-Hoolihan, 1999[35]	USA	10	NP			23.1	9.23	5.50	3.73	1.68							
		10	8–10				8.57	5.46	3.11	1.57		0.93	0.99	0.83			
		10	24–26				10.09	6.46	3.63	1.56		1.09	1.18	0.97			
		10	34–36				11.42	7.08	4.35	1.61		1.24	1.29	1.16			
Butte, 2002[34]	USA	34	NP	59.3	1.64	22.0	10.18	5.54	4.65	1.84					0.172	0.093	0.078
		34	9	60.2	1.64	22.4		5.65			1.02		1.02			0.094	
		34	22	65.1	1.64	24.2	10.54	5.91	4.63	1.78	1.10	1.04	1.07	1.00	0.162	0.091	0.071
		34	36	72.2	1.64	26.8	11.27	7.00	4.27	1.61	1.22	1.11	1.26	0.92	0.156	0.097	0.059

Abbreviations: BMI – body mass index; BMR – basal metabolic rate; AEE – activity energy expenditure; PAL – physical activity level; NP – non-pregnant.

Table 7 Total energy expenditure measured during pregnancy in women from developing countries

Reference	Country	*n*	Measurement period (week of gest)	Wt (kg)	Ht (m)	BMI	TEE (MJ day^{-1})	BMR (MJ day^{-1})	AEE (MJ day^{-1})	PAL	Wt/ NPWt	TEE/ NPTEE	BMR/ NPBMR	AEE/ NPAEE	TEE (MJ kg^{-1} per day)	BMR (MJ kg^{-1} per day)	AEE (MJ kg^{-1} per day)
Doubly labelled water method																	
Singh, 1989[44]	Gambia	6	NP	50.0	1.58	20.0	8.67	5.01	3.66	1.73					0.173	0.100	0.073
		6	20	59.5	1.66	21.6	10.80	5.97	4.83	1.81	1.19	1.25	1.19	1.32	0.182	0.100	0.081
Heini, 1991[43]	Gambia	7	NP	50.3	1.59	20.0	9.66	5.28	4.38	1.83					0.192	0.105	0.087
		8	12	53.5	1.60	20.9	10.55	5.63	4.92	1.87	1.06	1.09	1.07	1.12	0.197	0.105	0.092
		8	24	54.7	1.60	21.4	9.04	5.49	3.55	1.65	1.09	0.94	1.04	0.81	0.165	0.100	0.065
		9	36	65.0	1.63	24.4	9.53	6.83	2.70	1.40	1.29	0.99	1.29	0.62	0.147	0.105	0.042
Activity diaries/heart rate method																	
Lawrence, 1988[100]	Gambia	32	<9			20.0	10.00										
			28–40				9.30										
Panter-Brick, 1993[45]	Nepal	19	a-NP	45.9	1.50	20.4	9.11	5.15	3.96	1.77					0.198	0.112	0.086
			b-NP	47.0	1.50	20.9	9.86	5.22	4.64	1.89					0.210	0.111	0.099
			c-NP	46.8	1.50	20.8	10.42	5.21	5.21	2.00					0.223	0.111	0.111
			d-NP	46.7	1.50	20.8	10.48	5.21	5.27	2.01					0.224	0.112	0.113
		24	a-3rd trimester	53.6	1.50	23.8	8.22	5.34	2.88	1.54	1.17	0.90	1.04	0.73	0.153	0.100	0.054
			b-3rd trimester	53.6	1.50	23.8	9.34	5.43	3.91	1.72	1.14	0.95	1.04	0.84	0.174	0.101	0.073
			c-3rd trimester	53.3	1.50	23.7	9.77	5.31	4.46	1.84	1.14	0.94	1.02	0.86	0.183	0.100	0.084
			d-3rd trimester	51.5	1.50	22.9	10.00	5.26	4.74	1.90	1.10	0.95	1.01	0.90	0.194	0.102	0.092
Dufour, 1999[46]	Columbia	114	NP	55.4	1.56	22.7	10.19	5.22	4.97	1.95					0.184	0.094	0.090
		40	14	56.0	1.57	22.7	10.10	5.33	4.77	1.89	1.01	0.99	1.02	0.96	0.180	0.095	0.085
		54	25	59.9	1.57	24.4	9.30	5.55	3.75	1.68	1.08	0.91	1.06	0.75	0.155	0.093	0.063
		43	35	63.1	1.57	25.6	10.04	5.92	4.12	1.70	1.14	0.99	1.13	0.83	0.159	0.094	0.065

Abbreviations: BMI – body mass index; TEE – total energy expenditure; BMR – basal metabolic rate; AEE – activity energy expenditure; PAL – physical activity level; NP – non-pregnant.

Table 8 Total energy cost of pregnancy in well-nourished women with gestational weight gain of 13.8 kg

	1st Trimester*	2nd Trimester	3rd Trimester	Total deposition (g)
Rates of tissue deposition				
Weight gain (g day^{-1})**	20	70	62	13 800
Protein deposition (g day^{-1})**	0	1.5	5.9	686
Fat deposition (g day^{-1})**	6.0	21.7	19.4	4300
Total energy cost of pregnancy estimated from the increment in basal metabolic rate and energy deposition				
				Total energy cost (kJ)
Protein deposition (kJ day^{-1})	0	35	140	16 217
Fat deposition (kJ day^{-1})	232	841	752	166 419
Increment in basal metabolic rate (kJ day^{-1})	249	465	1015	157 000
Efficiency of energy utilisation (kJ day^{-1})***	48	134	191	33 964
Total energy cost of pregnancy (kJ day^{-1})	529	1475	2097	373 599
Total energy cost of pregnancy estimated from the increment in total energy expenditure and energy deposition				
				Total energy cost (kJ)
Protein deposition (kJ day^{-1})	0	35	140	16 217
Fat deposition (kJ day^{-1})	232	841	752	166 419
Increment in total energy expenditure (kJ day^{-1})	100	400	1500	186 000
Total energy cost of pregnancy (kJ day^{-1})	332	1276	2391	368 635

*Interval (79 d) computed from last menstrual period; total pregnancy (266 d).
**Total weight gain of 13.8 kg, protein deposition of 686 g, fat deposition 4.3 kg taken as 23.64 kJ g^{-1} for protein and 38.70 kJ g^{-1} for fat.
***Efficiency of energy utilisation taken as 0.90.

It was assumed that the increments in BMR and TEE were proportional to the weight gain. The total energy cost of pregnancy would be 321 or 325 MJ, distributed as 375, 1200, 1950 kJ day^{-1}, for the first, second and third trimesters, respectively.

Metabolic adjustments to meet energy requirements during pregnancy

Metabolic adjustments in basal metabolism, thermic effect of feeding and energetic efficiency may occur to meet the increased energy needs of pregnancy under certain physiological circumstances such as undernutrition and overnutrition. The rise in BMR during pregnancy observed in women from developed and developing countries varies dramatically. The different patterns are discussed extensively by Prentice *et al.*[37] In well-nourished women BMR usually begins to rise soon after conception and continues to rise until delivery. Even in well-nourished women considerable variation in the cumulative increase in BMR is seen. In 10 American women the rise in BMR ranged from −10 to 346 MJ; women with the largest cumulative increase in BMR deposited the least amount of fat[35]. In women from developing countries with weight gains around 9 kg, BMR usually begins to rise in the later half of pregnancy. However, in undernourished Gambian women a pronounced suppression of basal metabolism has been demonstrated that persisted well into the third trimester of pregnancy[26]. As a result, the cumulative area

Table 9 Total energy cost of pregnancy in women with gestational weight gain of 12 kg

	1st Trimester*	2nd Trimester	3rd Trimester	Total deposition (g)
Rates of tissue deposition				
Weight gain (g day^{-1})**	18	60	54	12 000
Protein deposition (g day^{-1})**	0	1.3	5.1	597
Fat deposition (g day^{-1})**	5.2	18.9	16.9	3741
Total energy cost of pregnancy estimated from the increment in basal metabolic rate and energy deposition				
				Total energy cost (kJ)
Protein deposition (kJ day^{-1})	0	30	121	14 109
Fat deposition (kJ day^{-1})	202	732	654	144 784
Basal metabolic rate (kJ day^{-1})	217	405	883	136 590
Efficiency of energy utilisation (kJ day^{-1})***	42	117	166	29 548
Total energy cost of pregnancy (kJ day^{-1})	460	1283	1824	325 031
Total energy cost of pregnancy estimated from the increment in total energy expenditure and energy deposition				
				Total energy cost (kJ)
Protein deposition (kJ day^{-1})	0	30	121	14 109
Fat deposition (kJ day^{-1})	202	732	654	144 784
Total energy expenditure (kJ day^{-1})	87	348	1305	161 820
Total energy cost of pregnancy (kJ day^{-1})	289	1110	2080	320 713

*Interval (79 d) computed from last menstrual period; total pregnancy (266 d).
**Total weight gain of 12 kg, protein deposition of 597 g, fat deposition 3.74 kg taken as 23.64 kJ g^{-1} for protein and 38.70 kJ g^{-1} for fat.
***Efficiency of energy utilisation taken as 0.90.

under the curve had become negative, indicating that the average BMR in pregnancy was even lower than before pregnancy. This is remarkable in light of gestational weight gain. This finding of increased energetic efficiency in the basal state in Gambian women was reproduced in British[38] and Dutch[20] pregnant women; the thinner British women showed a depression in BMR, adjusted for FFM, up to 24 weeks of gestation[38]. In contrast, no correlation was found between initial body fatness and changes in BMR in Scottish[47] or Gambian women[36].

Thermic effect of feeding (TEF) refers to the increase in energy expenditure above basal metabolism following the ingestion of food. It is mainly due to the energy cost of digestion, absorption, transport and storage of food, and averages approximately 10% of the daily energy intake. It has been hypothesised that the TEF during pregnancy might be lowered through changes in metabolic substrate routing. However, well-controlled human trials revealed no[38,48,49] or only minor changes in TEF of little nutritional importance[50–52].

It has been hypothesised that the energetic efficiency of performing physical activities might be increased in pregnancy. Prentice[37] reviewed studies in which changes in the energy cost of non-weight-bearing (cyclo-ergometer exercise) and weight-bearing (treadmill exercise and step-test) activities were measured at a standard pace and/or intensity[31,36,38,40,53–59]. The net cost of non-weight-bearing activities (actual metabolic rate minus basal metabolic rate) did not change throughout pregnancy, except in late pregnancy when it increased by about 10%. The net cost of weight-bearing activity remained fairly constant during the first two trimesters of pregnancy, and then increased progressively up to term by about 15%. The fact that the net cost remained stable up to the third trimester is remarkable, since body weight at the end of the second trimester is already substantially increased by 5–8 kg, which implies an improvement in energetic efficiency to perform weight-bearing work.

Meeting energy requirements during pregnancy

Increase in food intake during pregnancy

Most dietary studies in well-nourished women revealed no or only minor increases in energy intake that only partially covered the energy cost of pregnancy. An analysis of available data from longitudinal studies in populations with average birth weights >3 kg revealed a cumulative intake of only 85 MJ over the whole of pregnancy or only 0.3 MJ day^{-1} or 25% of the estimated needs[37]. Underestimation of dietary intake in longitudinal studies due to subject fatigue or alterations in normal eating habits during record keeping is likely. The expected increment in energy intake ($<20\%$ above prepregnant level) might be too small to be detected by the commonly used food consumption methods. The most compelling evidence of under-reporting comes from simultaneous measurements of total energy expenditure by the doubly labelled water method and food intake[60]; there is no reason to believe pregnant women differ in the inclination to under-report.

Reduction in physical activity

The energy cost of someone's daily physical activity depends on the time-activity pattern, the pace or intensity of performing the various activities, and body weight. Since body weight increases over pregnancy, an increase in energy cost occurs, at least for weight-bearing activities. However, women may compensate for this by reducing the pace or intensity with which the activity is performed. Pregnant women may also change their activity patterns, and thereby reduce the amount of time spent on weight-bearing activities. Both options assume that mothers are able to change their daily activities or to change the pace or intensity of the work performed. This might be the case for many women, but it certainly does not hold for all. For instance, low-income women from developing countries often have to continue their strenuous activity patterns until delivery. In contrast, women who are sedentary prior to pregnancy have little flexibility to reduce their level of physical activity.

Time-motion studies provide valuable information on the time spent in various physical activities. Time-motion studies from various countries including Scotland, the Netherlands, Thailand, the Philippines, Gambia and Nepal found no conclusive evidence that women reduce the energy cost of pregnancy by engaging in less activity[61]. A review of 122 studies found that in most societies, women were expected to continue with partial or full duties throughout most of pregnancy[62]. Although time-motion studies provide insight into activity patterns, they do not give quantitative estimates on how much energy is expended on activity. The doubly labelled water method provides a quantitative estimate of the amount of energy expended in physical activity. Unfortunately, the limited number of doubly labelled water studies on pregnant women is not representative of pregnant women globally.

Special considerations of underweight, overweight, short stature and adolescence

Being either underweight or overweight during pregnancy increases the risk of poor maternal and foetal outcomes. Prepregnancy weights below 50 kg and heights below 150 cm are associated with increased risk of maternal complications; prepregnancy weights below 45 kg and heights below 148 cm were associated with poor foetal outcomes[3].

Maternal obesity is also associated with a higher risk for maternal and foetal complications. Relative risk of neural tube defects, spina bifida, congenital malformations and preterm delivery are higher in overweight and obese women. The incidence of hypertension, gestational diabetes and caesarean section were higher in overweight and obese women when compared to women with BMI between 18.5 and 24.9[63]. The linear relationship between gestational weight gain and birth weight is modified by maternal prepregnancy BMI, such that women with lower BMI must gain more to produce birth weights comparable to women with normal BMI. Women with high BMI not only produce infants with higher birth weights, but can do so with lower gestational weight gains[8]. These relationships were developed from US National Natality data and are the basis for the IOM recommendations for gestational weight gain by maternal prepregnancy BMI. International guidelines for weight gain by prepregnancy BMI are not available, however, the general principle probably holds. Women with low prepregnancy BMI would benefit, in terms of birth weight, from being at the upper end of the range of gestational weight gains (10–14 kg) observed in the WHO Collaborative Study[2]. However, the risk of assisted delivery in women with short stature would have to be considered, especially in areas with inadequate obstetric care.

Dramatic changes in growth and development occur during adolescence, when up to 20% of total growth in stature can occur[3]. Special recognition of adolescent pregnancy is important not only because of the nutritional needs of the growing adolescent and foetus, but also because of increased pregnancy complications associated with an immature body. The risk of certain adverse foetal and maternal outcomes is greater for adolescents. Women under 18 years of age were at greater risk of preterm delivery[64] low birth weight[64–67] and small for gestational age infants than older women[65]. Higher risk is associated with being at the younger end of the 13–19 year age range[67]. Risk of maternal complications, particularly assisted delivery, was the same or lower for adolescents[65,66,68,69].

Energy requirements of lactating women

Introduction

From the 1985 FAO/WHO/UNU report on Energy and Protein Requirements[1] the following definition of energy requirements of lactation can be reconstructed:

> *'The energy requirement of a lactating woman is the level of energy intake from food that will balance her energy expenditure when the woman has a body size and composition and a breast milk production which is consistent with good health for herself and her child; and that will allow her for the maintenance of economically necessary and socially desirable physical activity.'*

To operationalise this definition, the energy cost of milk production must be added to women's energy requirements, assuming that they resume their usual level of physical activity. Human milk production is remarkably similar across populations. Prentice *et al.*[70] reviewed data on the volume of milk produced at peak lactation from 26 studies from different nutritional and cultural settings. Although milk composition varies, the mean amount of milk produced by mothers from developed countries was quite similar to women from developing countries. Although milk production is remarkably robust, the extent of exclusive breastfeeding and the duration of breastfeeding, which of course impact energy turnover in the postpartum period, vary significantly among women. Exclusive breastfeeding is recommended for the first 6 months postpartum with introduction of complementary foods and continued breastfeeding thereafter[71].

Energy cost of lactation

The amount of milk produced, the energy content of the milk, and the energetic efficiency of milk synthesis will determine the energy cost of lactation. Any alterations in maternal basal metabolism, thermogenesis or physical activity during lactation would impact the total energy requirements of lactating women.

Milk production

Milk production rates in women from developed and developing countries are presented from 0 to 24 months postpartum in Table 10, based on a WHO comprehensive review[72]. Mean milk production rates through 5 months postpartum are almost identical ($749\,\mathrm{g\,day^{-1}}$) for exclusively-breastfeeding women in developed and developing countries. From 6 months onwards, partial breastfeeding is recommended. The variation in milk production is larger, as infant intake is reduced by the amount and nature of complementary feedings. Mean milk production rates were 492 and $608\,\mathrm{g\,day^{-1}}$ in partially breastfeeding women from developed and developing countries, respectively.

Energy content of human milk

The energy content of human milk depends primarily on milk fat concentration which shows complex diurnal, within-feed and between-breast fluctuations. 24-hour milk sampling schemes have been developed which minimally interfere with the secretion of milk flow and capture the diurnal and within-feed variation[73]. Gross energy content

Table 10 Milk production rates of exclusively and partially breastfeeding women from developed and developing countries[72]

Postpartum period (months)	0–2	3–5	6–8	9–11	12–23
	Milk production ($\mathrm{g\,day^{-1}}$)				
Exclusive breastfeeding					
Industrialised countries	710	787	803	900	
Developing countries	714	784	776		
Partial breastfeeding					
Industrialised countries	640	687	592	436	448
Developing countries	617	663	660	616	549

of milk was measured on representative 24-hour milk samples using adiabatic bomb calorimetry or proximate analysis in a number of studies of well-nourished women (Table 11). The mean gross energy of milk from these studies was 2.80 kJ g^{-1} or 0.67 kcal g^{-1}.

Efficiency of converting dietary energy to milk energy

In order to appropriately apply the factorial method to determine the energy cost of lactation, the efficiency of converting dietary energy into human milk is required. Energetic efficiency has been estimated from theoretical biochemical efficiencies of synthesising the constituents in milk and from metabolic balance studies[74].

Biochemical efficiency can be calculated from the stoichiometric equations and the obligatory heat losses associated with the synthesis of lactose (95%), protein (88%), *de novo* fat synthesis (73%), and transfer of performed fat (98%). Depending on the amount of performed fat, the biochemical efficiency would be about 91–94%. This estimate would represent the maximal efficiency since digestive, absorptive, inter-conversion and transport costs have been ignored. Because of such omissions, calorimetric efficiencies are usually 10–15% lower than biochemical efficiencies[12]. Applying this correction to the estimate of biochemical efficiency derived above (91–94%) would yield a figure of 80–85%.

Crude estimates of the energetic efficiency of milk synthesis have been made in humans. Thompson[75] derived a figure of 80% efficiency from the lower 95% confidence level based on differences in food intake between lactating and non-lactating women; no measurements of milk energy transfer or changes in maternal fat stores were made. Calorimetry data on lactating women also have been used to estimate the energetic efficiency[41,76]. Based on the assumption that BMR encompasses the extra cost of milk synthesis, and that milk synthesis is a continual process, efficiencies of 94% in Gambian women and 99, 97 and 111% in British lactating women were calculated. Apparent efficiency in excess of 100% can only be explained by down-regulation of other metabolic processes or by measurement errors. Given the imprecision of these estimates, the biochemical derivation of 80% seems reasonable.

Total energy expenditure by respiratory calorimetry or doubly labelled water method

Room respiration calorimetry has been performed on lactating and non-lactating postpartum women[39]. 24-hour TEE and sleeping metabolic rate were higher in lactating than in non-lactating women, most likely because of the energy cost of milk synthesis and possibly because of heightened sympathetic nervous system and adrenal activity. During the course of the 24-hour calorimetric study, women expressed all their milk, which was analysed by bomb calorimetry. Milk energy output averaged 2167 and 1920 kJ day^{-1} at 3 and 6 months, respectively. Mean PAL within the confines of the calorimeter was 1.34. Based on these findings the minimum energy requirement of exclusively breastfeeding women would be 1.4 times BMR, plus 2000 kJ day^{-1} to support milk production.

Table 11 Gross energy content of human milk measured by bomb calorimetry or proximate analysis of 24-hour representative milk samples

Reference	Method	Month of lactation	Gross energy content (kJ g^{-1})	Gross energy content (kcal g^{-1})
Wood, 1982[101]	Bomb calorimetry	1	2.75	0.66
		2	2.72	0.65
		3	2.55	0.61
		4	2.53	0.61
		5	2.36	0.57
Butte, 1984[102]	Bomb calorimetry	1	2.85	0.68
		2	2.68	0.64
		3	2.59	0.62
		4	2.68	0.64
Garza, 1986[73]	Bomb calorimetry	1	3.01	0.72
		4	3.05	0.73
Sadurskis, 1988[81]	Bomb calorimetry	2	2.68	0.64
Butte, 1990[103]	Bomb calorimetry	1	2.76	0.66
		4	2.59	0.62
Dewey, 1991[104]	Protein, fat, lactose	3	2.93	0.70
	23.6, 38.7, 16.5 kJ g^{-1}	6	3.01	0.72
	5.65, 9.25, 3.95 kcal g^{-1}	9	3.10	0.74
		12	3.10	0.74
Motil, 1997[105]	Bomb calorimetry	6	2.80	0.67
		12	2.80	0.67
		18	3.00	0.72
		24	2.80	0.67
Butte, 2001[77]	Bomb calorimetry	3	2.68	0.64
Mean			2.78	0.67

Free-living TEE has been measured in lactating women using the doubly labelled water method and activity diaries. Doubly labelled water studies in well-nourished women are summarised in Table 12. TEE and AEE during lactation were not significantly different from NPNL state in American and Swedish women[35,42,77]. In the British study[41], there was a reduction in TEE caused mainly by a reduction in physical activity, since BMR was unchanged. Socioeconomic and cultural factors, no doubt, influence postpartum changes in AEE within and across societies, but lactating women are capable physiologically of resuming their usual level of physical activity shortly after delivery.

Doubly labelled water method has been used in lactating Mesoamerindians in Mexico[78] (Table 13). Mean TEE were 8912 and 9253 kJ day^{-1} for women with lower and higher BMI, respectively. TEE estimated by minute-to-minute observations of pregnant and lactating Nepali women was significantly influenced by season[45]. Lactating women had lower TEE during winter, but not the spring or monsoon season when all women sustained long hours of physical activity. Marked seasonal changes in physical activity and energy requirements have been shown to affect the reproductive and lactation performance of rural Gambian women[79].

Total energy requirements during lactation

Total energy requirements during lactation can be estimated by the factorial approach whereby the cost of milk production is added to the energy requirements of non-pregnant women, with an allowance made for energy mobilisation from tissue stores if replete. Energy cost of milk production requires knowledge of the amount of milk production, energy density of milk, and the energetic efficiency of milk synthesis (Table 14).

$$\begin{aligned}\text{Total energy requirements} &= (\text{NPNL BMR} \times \text{PAL})\\ &+ (\text{Milk production} \times \text{energy density}\\ &\times \text{conversion efficiency})\\ &- (\text{Energy mobilisation from tissue stores})\end{aligned}$$

For exclusive breastfeeding through 5 months postpartum, the energy cost of lactation would be 2.62 MJ day^{-1} based on a mean milk production of 749 g day^{-1}, energy density of milk of 2.8 kJ g^{-1}, and energetic efficiency of 0.80. In well-nourished women, this may be subsidised by energy mobilisation from tissues on the order of 0.72 MJ day^{-1}, resulting in a net increment of 1.9 MJ day^{-1} over NPNL energy requirements.

For partial breastfeeding from 6 to 24 months postpartum, the energy cost of lactation would be 1.93 MJ day^{-1} based on a mean milk production of 550 g day^{-1}, energy density of milk of 2.8 kJ g^{-1}, and energetic efficiency of 0.80. Weight loss is usually minor beyond 6 months postpartum; therefore, total energy cost

Table 12 Total energy expenditure measured by doubly labelled water method in well-nourished women during lactation

Reference	Country	*n*	Measurement period (weeks postpartum)	Wt (kg)	Ht (m)	BMI	TEE (MJ day^{-1})	BMR (MJ day^{-1})	AEE (MJ day^{-1})	PAL	Wt/NPWt	TEE/NPTEE	BMR/NPBMR	AEE/NPAEE	TEE (MJ kg^{-1} per day)	BMR (MJ kg^{-1} per day)	AEE (MJ kg^{-1} per day)
Lovelady, 1993[80]	USA	9	12–24	64.8	1.68	23.0	10.10	5.76	4.34	1.75					0.156	0.089	0.067
Goldberg, 1991[41]	UK	10	NP	57.1	1.64	21.2	9.78	5.86	3.92	1.67					0.171	0.103	0.069
			4	58.9	1.64	21.9	8.83	5.89	2.94	1.50	1.03	0.90	1.01	0.75	0.150	0.100	0.050
			8	58.9	1.64	21.9	9.09	5.85	3.24	1.55	1.03	0.93	1.00	0.83	0.154	0.099	0.055
			12	58.6	1.64	21.8	8.95	5.63	3.32	1.59	1.03	0.92	0.96	0.85	0.153	0.096	0.057
Forsum, 1992[42]	Sweden	32	NP	61.5	1.67	22.1	10.80	5.60	5.20	1.93					0.176	0.091	0.085
		32	8	64.4	1.67	23.1	10.60	5.90	4.70	1.80	1.05	0.98	1.05	1.20	0.165	0.092	0.073
		32	24	63.0	1.67	22.6	10.80	6.00	4.80	1.80	1.02	1.00	1.07	1.22	0.171	0.095	0.076
Kopp-Hoolihan, 1999[35]	USA	10	NP			23.1	9.23	5.50	3.73	1.68							
		10	4–6				8.98	5.56	3.42	1.61		0.97	1.01	0.92			
Butte, 2001[77]	USA	24	NPNL	61.6	1.63	23.1	10.58	5.65	4.93	1.87					0.172	0.092	0.080
		24	12	62.8	1.63	23.5	10.01	5.57	4.44	1.80	1.02	0.95	0.99	0.90	0.159	0.089	0.071

Abbreviations: BMI – body mass index; TEE – total energy expenditure; BMR – basal metabolic rate; AEE – activity energy expenditure; PAL – physical activity level; NP – non-pregnant.

Table 13 Total energy expenditure during lactation in women from developing countries

Reference	Country	*n*	Measurement period (weeks postpartum)	Wt (kg)	Ht (m)	BMI	TEE (MJ day^{-1})	BMR (MJ day^{-1})	AEE (MJ day^{-1})	PAL	Wt/NPWt	TEE/NPTEE	BMR/NPBMR	AEE/NPAEE	TEE (MJ kg^{-1} per day)	BMR (MJ kg^{-1} per day)	AEE (MJ kg^{-1} per day)
Activity diaries method																	
Panter-Brick, 1993[45]	Nepal	19	NPNL	45.9	1.50	20.4	9.11	5.15	3.96	1.77					0.198	0.112	0.086
				47.0	1.50	20.9	9.86	5.22	4.64	1.89					0.210	0.111	0.099
				46.8	1.50	20.8	10.42	5.21	5.21	2.00					0.223	0.111	0.111
				46.7	1.50	20.8	10.48	5.21	5.27	2.01					0.224	0.112	0.113
		11	L	51.8	1.49	23.3	9.56	5.31	4.25	1.80	1.13	1.05	1.03	1.07	0.185	0.103	0.082
				49.3	1.49	22.2	8.06	5.10	2.96	1.58	1.05	0.82	0.98	0.64	0.163	0.103	0.060
				48.9	1.49	22.0	9.49	5.10	4.39	1.86	1.04	0.91	0.98	0.84	0.194	0.104	0.090
				46.8	1.49	21.1	9.66	4.98	4.68	1.94	1.00	0.92	0.96	0.89	0.206	0.106	0.100
Doubly labelled water method																	
Butte, 1997[78]	Mexico	21	12	47.2	1.49	21.3	9.13	5.31	2.90	1.72					0.193	0.113	0.061
			24	46.3	1.49	20.9	8.68	5.39	2.37	1.61	0.98	0.95	1.02	0.82	0.187	0.116	0.051
		19	12	56.7	1.49	25.5	9.28	5.84	2.32	1.59					0.164	0.103	0.041
			24	56.3	1.49	25.4	9.22	5.94	2.37	1.55	0.99	0.99	1.02	1.02	0.164	0.106	0.042

Abbreviations: BMI – body mass index; TEE – total energy expenditure; BMR – basal metabolic rate; AEE – activity energy expenditure; PAL – physical activity level; NP – non-pregnant.

Table 14 Energy cost of milk production for exclusive and partial breastfeeding 0–24 months postpartum

Postpartum period (months)	0–2	3–5	6–8	9–11	12–23
	Energy cost of milk production (MJ day^{-1})				
Exclusive breastfeeding					
Industrialised countries	2.49	2.75	2.81	3.15	
Developing countries	2.50	2.74	2.72		
Partial breastfeeding					
Industrialised countries	2.24	2.40	2.07	1.53	1.57
Developing countries	2.16	2.32	2.31	2.16	1.92

Energy cost of lactation based on milk production rates[72], milk energy density of 2.8 kJ g^{-1} and energetic efficiency of milk synthesis of 0.80.

of milk production must be derived from diet. Total energy requirements of partially lactating women beyond 6 months postpartum would be 1.93 MJ day^{-1} over NPNL energy requirements. In reality, milk production rate, and therefore the associated energy cost, is extremely variable in partially breastfeeding women, and depends upon complementary feeding practices.

Alternatively, total energy requirements may be estimated from the sum of TEE plus milk energy output, minus the energy mobilised from tissues.

$$\text{Total energy requirements} =$$
$$\text{TEE} + (\text{Milk production} \times \text{energy density}) -$$
$$(\text{Energy mobilisation from tissue stores})$$

Knowledge of TEE circumvents any assumptions regarding the energetic efficiency of milk synthesis or activity energy expenditure, since they are included in TEE. This approach was taken in four studies of well-nourished women between 1 and 6 months postpartum[41,42,77,80] (Table 15). Milk energy output averaged 2.15 MJ day^{-1}. TEE plus milk energy output averaged 11.74 MJ day^{-1}. Total energy requirements were 11.38 MJ day^{-1}, since 0.72 MJ day^{-1} was mobilised from tissue stores.

Metabolic adjustments to meet the energy cost of lactation

Basal metabolism

The BMR of lactating women would be expected to be slightly elevated if milk synthesis is a continuous process. At energetic efficiencies of 80 and 95%, milk synthesis would increase BMR by 11 or 2%, respectively. An increase less than this would be indicative of energy-sparing.

Comparisons of BMR in lactating and NPNL women have yielded equivocal results. Some studies have shown a slight increase in BMR[42,81,82] or a decrease[57], but the majority have shown similar BMR in the lactating and non-lactating state[41,77,83–85]. Since BMR is unchanged or

Table 15 Total energy requirements during lactation estimated from total energy expenditure, milk energy output and energy mobilisation in well-nourished women

Reference	Country	*n*	Measurement period (weeks postpartum)	TEE (MJ day^{-1})	Milk energy output (MJ day^{-1})	Total energy requirements (MJ day^{-1})	Energy mobilisation (MJ day^{-1})	Net energy requirement (MJ day^{-1})
Lovelady, 1993[80]	USA	9	12–24	10.10	2.20	12.30	1.20	11.10
Goldberg, 1991[41]	UK	10	NP	9.78				
			4	8.83	2.24	11.07		11.07
			8	9.09	2.23	11.32		11.32
			12	8.95	2.22	11.17		11.17
Forsum, 1992[42]	Sweden	23	NP	10.80				
		23	8	10.60	1.97	12.57	0.30	12.27
		23	24	10.80				
Kopp-Hoolihan, 1999[35]	USA	10	NP	9.23				
		10	4–6	8.98				
Butte, 2001[77]	USA	24	NPNL	10.58				
		24	12	10.01	2.02	12.03	0.65	11.38
Mean					2.15	11.74	0.72	11.38

Abbreviations: TEE – total energy expenditure; NPNL – non-pregnant, non-lactating.

slightly elevated during lactation, there is little evidence for energy conservation.

Thermic effect of feeding

Two longitudinal studies have been published on changes in TEF in response to a standardised liquid meal during lactation. Illingworth *et al.*[85] observed a significant reduction in TEF of 30% during lactation, whereas Spaaij *et al.*[82] did not observe a difference compared with the prepregnancy baseline measurement. TEF in lactating and non-lactating women also has been evaluated in two cross-sectional studies[86,87]. In both studies the energy content of the test meals was not similar for lactating and non-lactating women, and therefore the findings are difficult to interpret. Although equivocal, available evidence does not support significant changes in TEF during lactation.

Metabolic efficiency of performing physical activities

Several investigators have measured the energy cost of cycle ergometer or treadmill exercise in postpartum women[57,82,88]. The available results indicate that the gross and net energy cost of these standardised activities in lactation is not different from the values in the non-pregnant non-lactating state.

Meeting energy requirements during lactation

Reduction in maternal energy stores

Fat stores accumulated during pregnancy may cover part of the energy cost of lactation. Utilisation of tissue stores to support lactation is not obligatory and the extent to which energy is mobilised to support lactation depends on the nutritional status of the mother and amount of weight gained during pregnancy.

Changes in weight and body composition during lactation are variable, and depend on gestational weight gain, lactation pattern and duration, physical activity level and seasonal food availability[37]. Weight changes are usually highest in the first 3 months of lactation and are generally greater in women who breastfeed exclusively. A review of 17 studies found that mean rates of weight change in the first 6 months postpartum are generally greater in well-nourished women (−0.8 kg per month) than undernourished women (−0.1 kg per month)[89]. Based on an energetic factor of 27.2 MJ kg^{-1}, these rates of weight loss would be equivalent to 21.8 MJ per month or 0.72 MJ day^{-1} in well-nourished women, and 2.7 MJ per month or 90 kJ day^{-1} in undernourished women.

In well-nourished women it is reasonable to estimate that 0.72 MJ day^{-1} of tissue stores may be utilised to support lactation during the first 6 months postpartum. For women who are underweight, or did not gain sufficient weight during pregnancy, it is recommended that the full energy cost of lactation should be provided.

Reduction in physical activity

The ability of mothers to change their daily activities or to change pace or intensity of the work performed will depend on their culture and socioeconomic situations. Time-motion studies have been conducted longitudinally[24,41,59,81] and cross-sectionally[45,90] in lactating women. Although study designs and research methodology varied, some patterns emerged from these studies. In developed countries women tend to decrease total physical activity in the first month postpartum, and to resume their usual levels of physical activity thereafter. In developing countries, physical activity levels are generally higher and therefore the potential for savings by reducing expenditure is greater. However, in everyday practice these women cannot or may not reduce their activities during lactation, except for certain temporary cultural practices. There does not appear to be any sustained change in activity patterns between lactating and non-lactating women after the initial months of breastfeeding.

Increase in food intake

Many food consumption surveys throughout lactation have been published[20,91–95]. The average increases in energy intake during lactation varied widely from 0.2 MJ day^{-1} in a study with English women[94] to 2.5 MJ day^{-1} in Mexican women[91]. The average increase in energy intake in the longitudinal studies by peak lactation was 1.5 MJ day^{-1}. Because energy mobilisation from tissues is modest, it must be concluded that the energy cost of lactation is met primarily through dietary intake.

References

1 WHO. *Energy and Protein Requirements*. Report of a Joint FAO/WHO/UNU Expert Consultation. Technical Report Series No. 724. Geneva: World Health Organization, 1985.
2 WHO. Maternal Anthropometry and Pregnancy Outcomes – A WHO Collaborative Study. *Bulletin of the World Health Organization* 1995; **73**: S1–69.
3 WHO. *Physical Status: The Use and Interpretation of Anthropometry*. Geneva: WHO, 1995.
4 Kelly A, Kevany J, de Onis M, Shah PM. A WHO collaborative study of maternal anthropometry and pregnancy outcomes. *International Journal of Gynaecology and Obstetrics: the Official Organ of the International Federation of Gynaecology and Obstetrics* 1996; **53**: 219–33.
5 Martorell R, Delgado HL, Valverde V, Klein RE. Maternal stature, fertility and infant mortality. *Human Biology; an International Record of Research* 1981; **53**: 303–12.
6 Merchant KM, Villar J, Kestler E. Maternal height and newborn size relative to risk of intrapartum caesarean delivery and perinatal distress. *BJOG: an International Journal of Obstetrics and Gynaecology* 2001; **108**: 689–96.
7 Pickett KE, Abrams B, Selvin S. Maternal height, pregnancy weight gain, and birthweight. *American Journal of Human Biology: the Official Journal of the Human Biology Council* 2000; **12**: 682–7.
8 Institute of Medicine and Food and Nutrition Board. *Nutrition During Pregnancy*. Washington, DC: National Academy Press, 1990.
9 Kleinman J. *Maternal Weight Gain During Pregnancy: Determinants and Consequences*. Hyattsville, MD: National Center for Health Statistics, Public Health Service, US Department of Health and Human Services, 1990.
10 Abrams B, Altman SL, Pickett KE. Pregnancy weight gain: still controversial. *American Journal of Clinical Nutrition* 2000; **71**: S1233–41.
11 Hytten FE, Chamberlain G. *Clinical Physiology in Obstetrics*. Oxford: Blackwell Scientific Publications, 1991.
12 Blaxter K. *Energy Metabolism in Animals and Man*. Cambridge: Cambridge University Press, 1989.
13 Hytten FE. Nutrition. In: Hytten FE, Chamberlain G, eds. *Clinical Physiology in Obstetrics. Part 2. Nutrition and Metabolism*. Oxford: Blackwell Scientific Publications, 1980; 163–92.
14 MacGillivray I, Buchanan TJ. Total exchangeable sodium and potassium in non-pregnant women and in normal and pre-eclamptic pregnancy. *Lancet* 1958; **2**: 1090–3.
15 King JC, Calloway DH, Margen S. Nitrogen retention, total body ^{40}K and weight gain in teenage pregnant girls. *Journal of Nutrition* 1973; **103**: 772–85.
16 Emerson K Jr, Poindexter EL, Kothari M. Changes in total body composition during normal and diabetic pregnancy. Relation to oxygen consumption. *Obstetrics and Gynecology* 1975; **45**: 505–11.
17 Pipe NGJ, Smith T, Halliday D, Edmonds CJ, Williams C, Coltart TM. Changes in fat, fat-free mass and body water in normal human pregnancy. *British Journal of Obstetrics and Gynaecology* 1979; **86**: 929–40.
18 Forsum E, Sadurskis A, Wager J. Resting metabolic rate and body composition of healthy Swedish women during pregnancy. *American Journal of Clinical Nutrition* 1988; **47**: 942–7.
19 Butte NF, Hopkinson JM, Ellis K, Wong WW, Treuth MS, Smith EO. Composition of gestational weight gain impacts maternal fat retention and infant birth weight. *American Journal of Obstetrics and Gynecology* 2003; **189**: 1423–32.
20 Spaaij CJK. *The efficiency of energy metabolism during pregnancy and lactation in well-nourished Dutch women*. The Netherlands: University of Wageningen, 1993.
21 Durnin JVGA, McKillop FM, Grant S, Fitzgerald G. Energy requirements of pregnancy in Scotland. *Lancet* 1987; **2**: 897–900.
22 van Raaij JMA, Vermaat-Miedema SH, Schonk CM, Peek MEM, Hautvast JGAJ. Energy requirements of pregnancy in The Netherlands. *Lancet* 1987; **ii**: 953–5.
23 Thongprasert K, Tanphaichitre V, Valyasevi A, Kittigool J, Durnin JV. Energy requirements of pregnancy in rural Thailand. *Lancet* 1987; **2**: 1010–2.
24 Tuazon MA, van Raaij JM, Hautvast JG, Barba CV. Energy requirements of pregnancy in the Philippines. *Lancet* 1987; **2**: 1129–31.
25 Barba CVC. *Progress Report on Study on Maternal Energy Requirements During Pregnancy and Lactation of Rural Philippine Women*. Los Banos: Institute of Human Nutrition and Food, University of the Philippines, 1994.
26 Lawrence M, Coward WA, Lawrence F, Cole TJ, Whitehead RG. Fat gain during pregnancy in rural African women: the effect of season and dietary status. *American Journal of Clinical Nutrition* 1987; **45**: 1442–50.
27 Hopkinson JM, Butte NF, Ellis KJ, Wong WW, Puyau MR, Smith EO. Body fat estimation in late pregnancy and early postpartum: comparison of two-, three-, and four-component models. *American Journal of Clinical Nutrition* 1997; **65**: 432–8.
28 van Raaij JMA, Peek MEM, Vermaat-Miedema SH, Schonk CM, Hautvast JGAJ. New equations for estimating body fat mass in pregnancy from body density or total body water. *American Journal of Clinical Nutrition* 1988; **48**: 24–9.
29 Siri WE. Body composition from fluid spaces and density: an analysis of methods. In: Broszek J, Henschel A, eds. *Techniques for Measuring Body Composition*. Washington, DC: National Academy of Science-National Research Council, 1961.
30 Fuller NJ, Jebb SA, Laskey MA, Coward WA, Elia M. Four-component model for the assessment of body composition in humans: comparison with alternative methods, and evaluation of the density and hydration of fat-free mass. *Clinical Science* 1992; **82**: 687–93.
31 de Groot LCPGM, Boekholt HA, Spaaij CJK, van Raaij JMA, Drijvers JJMM, van der Heijden LJM, Hautvast JGAJ. Energy balances of Dutch women before and during pregnancy: limited scope for metabolic adaptations in pregnancy. *American Journal of Clinical Nutrition* 1994; **59**: 827–32.
32 Goldberg GR, Prentice AM, Coward WA, Davies HL, Murgatroyd PR, Wensing C, Black AE, Harding M, Sawyer M. Longitudinal assessment of energy expenditure in pregnancy by the doubly labelled water method. *American Journal of Clinical Nutrition* 1993; **57**: 494–505.
33 Koop-Hoolihan LE, Van Loan MD, Wong WW, King JC. Fat mass deposition during pregnancy using a four-component model. *Journal of Applied Physiology* 1999; **87**: 196–202.
34 Butte NF, Wong WW, Treuth MS, Ellis K, Smith EO. Energy requirements during pregnancy based on total energy

expenditure and energy deposition. *American Journal of Clinical Nutrition* 2004; **79**: 1078–87.
35 Kopp-Hoolihan LE, Van Loan MD, Wong WW, King JC. Longitudinal assessment of energy balance in well-nourished, pregnant women. *American Journal of Clinical Nutrition* 1999; **69**: 697–704.
36 Poppitt SD, Prentice AM, Jequier E, Schutz Y, Whitehead RG. Evidence of energy sparing in Gambian women during pregnancy: a longitudinal study using whole-body calorimetry. *American Journal of Clinical Nutrition* 1993; **57**: 353–64.
37 Prentice AM, Spaaij CJK, Goldberg GR, Poppitt SD, van Raaij JMA, Totton M, Swann D, Black AE. Energy requirements of pregnant and lactating women. *European Journal of Clinical Nutrition* 1996; **50**: S82–111.
38 Prentice AM, Goldberg GR, Davies HL, Murgatroyd PR, Scott W. Energy-sparing adaptations in human pregnancy assessed by whole-body calorimetry. *British Journal of Nutrition* 1989; **62**: 5–22.
39 Butte NF, Hopkinson JM, Mehta N, Moon JK, Smith EO. Adjustments in energy expenditure and substrate utilization during late pregnancy and lactation. *American Journal of Clinical Nutrition* 1999; **69**: 299–307.
40 Heini A, Schutz Y, Jéquier E. Twenty-four-hour energy expenditure in pregnant and nonpregnant Gambian women, measured in a whole-body indirect calorimeter. *American Journal of Clinical Nutrition* 1992; **55**: 1078–85.
41 Goldberg GR, Prentice AM, Coward WA, Davies HL, Murgatroyd PR, Sawyer MB, Ashford J, Black AE. Longitudinal assessment of the components of energy balance in well-nourished lactating women. *American Journal of Clinical Nutrition* 1991; **54**: 788–98.
42 Forsum E, Kabir N, Sadurskis A, Westerterp K. Total energy expenditure of healthy Swedish women during pregnancy and lactation. *American Journal of Clinical Nutrition* 1992; **56**: 334–42.
43 Heini A, Schutz Y, Diaz E, Prentice AM, Whitehead RG, Jequier E. Free-living energy expenditure measured by two independent techniques in pregnant and nonpregnant Gambian women. *American Journal of Physiology* 1991; **261**: E9–17.
44 Singh J, Prentice AM, Diaz E, Coward WA, Ashford J, Sawyer M, Whitehead RG. Energy expenditure of Gambian women during peak agricultural activity measured by the doubly-labelled water method. *British Journal of Nutrition* 1989; **62**: 315–29.
45 Panter-Brick C. Seasonality of energy expenditure during pregnancy and lactation for rural Napali women. *American Journal of Clinical Nutrition* 1993; **57**: 620–8.
46 Dufour DL, Reina JC, Spurr G. Energy intake and expenditure of free-living, pregnant Colombian women in an urban setting. *American Journal of Clinical Nutrition* 1999; **70**: 269–76.
47 Durnin JVGA. Energy metabolism in pregnancy. In: Cowett R, ed. *Principles of Perinatal-Neonatal Metabolism*. New York: Springer, 1992, 228–36.
48 Spaaij CJK, van Raaij JMA, van der Heijden LJM, Schouten FJM, Drijvers JJMM, de Groot LCPGM, Boekholt HA, Hautvast JGAJ. No substantial reduction of the thermic effect of a meal during pregnancy in well-nourished Dutch women. *British Journal of Nutrition* 1994; **71**: 335–44.
49 Nagy NE, King JC. Postprandial energy expenditure and respiratory quotient during early and late pregnancy. *American Journal of Clinical Nutrition* 1984; **40**: 1258–63.
50 Illingworth PJ, Jung RT, Howie PW, Isles TE. Reduction in postprandial energy expenditure during pregnancy. *British Medical Journal* 1987; **294**: 1573–6.
51 Schutz Y, Golay A, Jéquier E. 24 h energy expenditure (24-EE) in pregnant women with a standardized activity level. *Experientia* 1988; **44**: A31.
52 Contaldo F, Scalfi L, Coltorti A, Di Palo MR, Martinelli P, Guerritore T. Reduced regulatory thermogenesis in pregnant and ovariectomized women. *International Journal for Vitamin and Nutrition Research. Internationale Zeitschrift fur Vitamin- und Ernahrungsforschung. Journal International de Vitaminologie et de Nutrition* 1987; **57**: 299–304.
53 Blackburn MW, Calloway DH. Energy expenditure of pregnant adolescents. *Journal of the American Dietetic Association* 1974; **65**: 24–30.
54 Blackburn MW, Calloway DH. Basal metabolic rate and work energy expenditure of mature, pregnant women. *Journal of the American Dietetic Association* 1976; **69**: 24–8.
55 Seitchik J. Total body water and total body density of pregnant women. *Journal of Obstetrics and Gynaecology* 1967; **29**: 155–65.
56 Edward MJ, Metcalfe J, Dunham MJ, Maul MS. Accelerated respiratory response to moderate exercise in late pregnancy. *Respiration Physiology* 1981; **45**: 229–41.
57 Blackburn MW, Calloway DH. Heart rate and energy expenditure of pregnant and lactating women. *American Journal of Clinical Nutrition* 1985; **42**: 1161–9.
58 Durnin JVGA. Energy requirements of pregnancy. *Diabetes* 1991; **40**: 152–6.
59 van Raaij JMA, Schonk CM, Vermaat-Miedema SH, Peek MEM, Hautvast JGAJ. Energy cost of walking at a fixed pace and self-selected pace before, during and after pregnancy. *American Journal of Clinical Nutrition* 1990; **51**: 158–61.
60 Schoeller D. Limitations in the assessment of dietary energy intake by self-report. *Metabolism Clinical and Experimental* 1995; **44**: 18–22.
61 Lindsay CA, Huston L, Amini SB, Catalano PM. Longitudinal changes in the relationship between body mass index and percent body fat in pregnancy. *Obstetrics and gynecology* 1997; **89**: 377–82.
62 Institute of Medicine. *Nutrition Issues in Developing Countries*. Washington, DC: National Academy Press, 1992.
63 March of Dimes. *Nutrition Today Matters Tomorrow – A Report From the March of Dimes Task Force on Nutrition and Optimal Human Development*, 2002.
64 Kumbi S, Isehak A. Obstetric outcome of teenage pregnancy in Northwestern Ethiopia. *East African Medical Journal* 1999; **76**: 138–40.
65 Gortzak-Uzan L, Hallak M, Press F, Katz M, Shoham-Vardi I. Teenage pregnancy: risk factors for adverse perinatal outcome. *Journal of Maternal-fetal Medicine* 2001; **10**: 393–7.
66 Larsson J, Svanberg L. Teenage deliveries in a Swedish population in the 1970's. *Acta Obstetricia et Gynecologica Scandinavica* 1983; **62**: 467–72.
67 Bwibo N. Birthweights of infants of teenage mothers in Nairobi. *Acta Paediatrica Scandinavica Supplement* 1985; **319**: 89–94.
68 Lao T, Ho L. The obstetric implications of teenage pregnancy. *Human reproduction* 1997; **12**: 2303–5.
69 Jolly M, Sebire N, Harris J, Robinson S, Regan L. Obstetric risks of pregnancy in women less than 18 years old. *Obstetrics and Gynecology* 2000; **96**: 962–6.
70 Prentice A, Paul A, Black A, Cole T, Whitehead R. Cross-cultural differences in lactational performance. In: Hamosh M, Goldman AS, eds. *Human Lactation 2: Maternal and Environmental Factors*. New York: Plenum Press, 1986; 13–44.
71 WHO Expert Consultation. *Expert Consultation on the Optimal Duration of Exclusive Breastfeeding. Conclusions and Recommendations*. Geneva, Switzerland: WHO, 2001.
72 Brown K, Dewey KG, Allen L. *Complementary Feeding of Young Children in Developing Countries: a Review of*

Current Scientific Knowledge. Geneva: World Health Organization, 1998.

73 Garza C, Butte NF. Energy concentration of human milk estimated from 24-hour pools and various abbreviated sampling schemes. *Journal of Pediatric Gastroenterology and Nutrition* 1986; **5**: 943–8.

74 Prentice AM, Prentice A. Energy costs of lactation. *Annual Review of Nutrition* 1988; **8**: 63–79.

75 Thompson AM. The energy cost of human lactation. *British Journal of Nutrition* 1970; **24**: 565–74.

76 Frigerio C, Schutz Y, Prentice A, Whitehead R, Jequier E. Is human lactation a particularly efficient process? *European Journal of Clinical Nutrition* 1991; **45**: 459–62.

77 Butte NF, Wong WW, Hopkinson JM. Energy requirements of lactating women derived from doubly labelled water and milk energy output. *Journal of Nutrition* 2001; **131**: 53–8.

78 Butte NF, Barbosa L, Villalpando S, Wong WW, Smith EO. Total energy expenditure and physical activity level of lactating Mesoamerindians. *Journal of Nutrition* 1997; **127**: 299–305.

79 Brent NB, Redd B, Dworetz A, D'Amico F, Greenberg JJ. Breast-feeding in a low-income population. *Archives of Pediatrics and Adolescent Medicine* 1995; **149**: 798–803.

80 Lovelady CA, Meredith CN, McCrory MA, Nommsen LA, Joseph LJ, Dewey KG. Energy expenditure in lactating women: a comparison of doubly labelled water and heart-rate-monitoring methods. *American Journal of Clinical Nutrition* 1993; **57**: 512–8.

81 Sadurskis A, Kabir N, Wager J, Forsum E. Energy metabolism, body composition, and milk production in healthy Swedish women during lactation. *American Journal of Clinical Nutrition* 1988; **48**: 44–9.

82 Spaaij CJK, van Raaij JMA, de Groot LCPGM, van der Heijden LJM, Boekholt HA, Hautvast JGAJ. Effect of lactation on resting metabolic rate and on diet- and work-induced thermogenesis. *American Journal of Clinical Nutrition* 1994; **59**: 42–7.

83 Schutz Y, Lechtig A, Bradfield RB. Energy expenditures and food intakes of lactating women in Guatemala. *American Journal of Clinical Nutrition* 1980; **33**: 892–902.

84 Guillermo-Tuazon MA, Barba CVC, van Raaij JMA, Hautvast JGAJ. Energy intake, energy expenditure, and body composition of poor rural Philippine women throughout the first 6 mo of lactation. *American Journal of Clinical Nutrition* 1992; **56**: 874–80.

85 Illingworth PJ, Jung RT, Howie PW, Leslie P, Isles TE. Diminution in energy expenditure during lactation. *British Medical Journal* 1986; **292**: 437–41.

86 Motil KJ, Montandon CM, Garza C. Basal and postprandial metabolic rates in lactating and non-lactating women. *American Journal of Clinical Nutrition* 1990; **52**: 610–5.

87 Frigerio C, Schutz Y, Whitehead RG, Jéquier E. Postprandial thermogenesis in lactating and non-lactating women from the Gambia. *European Journal of Clinical Nutrition* 1992; **46**: 7–13.

88 van Raaij JMA, Schonk CM, Vermaat-Miedema SH, Pek MEM, Hautvast JGAJ. Energy cost of physical activity throughout pregnancy and the first year postpartum in Dutch women with sedentary lifestyles. *American Journal of Clinical Nutrition* 1990; **52**: 234–9.

89 Butte NF, Hopkinson JM. Body composition changes during lactation are highly variable among women. *Journal of Nutrition* 1998; **128**: S381–5.

90 Roberts SB, Paul AA, Cole TJ, Whitehead RG. Seasonal changes in activity, birth weight and lactational performance in rural Gambian women. *Transactions of the Royal Society of Tropical Medicine and Hygiene* 1982; **76**: 668–78.

91 Allen LH, Bakstrand JR, Chavez A, Pelto GH. *People Cannot Live by Tortillas Alone: The Result of the Mexico Nutrition CRSP*. Washington: Final report to the US Agency for International Development, 1992.

92 Black AE, Wiles SJ, Paul AA. The nutrient intakes of pregnant and lactating mothers of good socio-economic status in Cambridge, UK: some implications for recommended daily allowances of minor nutrients. *British Journal of Nutrition* 1986; **56**: 59–72.

93 English RM, Hitchcock NE. Nutrient intakes during pregnancy, lactation and after the cessation of lactation in a group of Australian women. *British Journal of Nutrition* 1968; **22**: 615–24.

94 Schofield C, Wheeler E, Stewart J. The diets of pregnant and post-pregnant women in different social groups in London and Edinburgh: energy, protein, fat and fibre. *British Journal of Nutrition* 1987; **58**: 369–81.

95 Whichelow MJ. Success and failure of breast-feeding in relation to energy intake. *Proceedings of the Nutrition Society* 1975; **35**: 62A–3A.

96 Lederman SA, Paxton A, Heymsfield SB, Wang J, Thornton J, Pierson RN Jr. Body fat and water changes during pregnancy in women with different body weight and weight gain. *Obstetrics and Gynecology* 1997; **90**: 483–8.

97 Sohlström A, Forsum E. Changes in total body fat during the human reproductive cycle as assessed by magnetic resonance imaging, body water dilution, and skinfold thickness: a comparison of methods. *American Journal of Clinical Nutrition* 1997; **66**: 1315–22.

98 Durnin JVGA, McKillop FM, Grant S, Fitzgerald G. Energy requirements of pregnancy in Scotland. *Lancet* 1987; **2**: 897–900.

99 de Groot LCPGM, Boekholt HA, Spaaij CJK, van Raaij JMA, Drijvers JJMM, van der Heijden LJM, Hautvast JGAJ. Energy balances of healthy Dutch women before and during pregnancy: limited scope for metabolic adaptations in pregnancy. *American Journal of Clinical Nutrition* 1994; **59**: 827–32.

100 Lawrence M, Whitehead RG. Physical activity and total energy expenditure of child-bearing Gambian village women. *European Journal of Clinical Nutrition* 1988; **42**: 145–60.

101 Wood CS, Isaacs PC, Jensen M, Hilton HG. Exclusively breast-fed infants: growth and caloric intake. *Pediatric nursing* 1988; **14**: 117–24.

102 Butte NF, Garza C, Smith EO, Nichols BL. Human milk intake and growth of exclusively breast-fed infants. *Journal of Pediatrics* 1984; **104**: 187–95.

103 Butte NF, Wong WW, Ferlic L, Smith EO. Energy expenditure and deposition of breast-fed and formula-fed infants during early infancy. *Pediatric Research* 1990; **28**: 631–40.

104 Dewey KG, Heinig MJ, Nommsen LA, Lonnerdal B. Adequacy of energy intake among breast-fed infants in the DARLING study: relationships to growth velocity, morbidity, and activity levels. *Journal of Pediatrics* 1991; **119**: 538–47.

105 Motil KJ, Sheng H-P, Montandon CM, Wong WW. Human milk protein does not limit growth of breast-fed infants. *Journal of Pediatric Gastroenterology and Nutrition* 1997; **24**: 10–7.