See corresponding editorial on page 933.

Energy requirements during pregnancy based on total energy expenditure and energy deposition[1–4]

Nancy F Butte, William W Wong, Margarita S Treuth, Kenneth J Ellis, and E O'Brian Smith

ABSTRACT

Background: Energy requirements during pregnancy remain controversial because of uncertainties regarding maternal fat deposition and reductions in physical activity.

Objective: This study was designed to estimate the energy requirements of healthy underweight, normal-weight, and overweight pregnant women and to explore energetic adaptations to pregnancy.

Design: The energy requirements of 63 women [17 with a low body mass index (BMI; in kg/m^2), 34 with a normal BMI, and 12 with a high BMI] were estimated at 0, 9, 22, and 36 wk of pregnancy and at 27 wk postpartum. Basal metabolic rate (BMR) was measured by calorimetry, total energy expenditure (TEE) by doubly labeled water, and activity energy expenditure (AEE) as TEE − BMR. Energy deposition was calculated from changes in body protein and fat. Energy requirements equaled the sum of TEE and energy deposition.

Results: BMR increased gradually throughout pregnancy at a mean (±SD) rate of 10.7 ± 5.4 kcal/gestational week, whereas TEE increased by 5.2 ± 12.8 kcal/gestational week, which indicated a slight decrease in AEE. Energy costs of pregnancy depended on BMI group. Although total protein deposition did not differ significantly by BMI group (mean for the 3 groups: 611 g protein), FM deposition did (5.3, 4.6, and 8.4 kg FM in the low-, normal-, and high-BMI groups; $P = 0.02$). Thus, energy costs differed significantly by BMI group ($P = 0.02$). In the normal-BMI group, energy requirements increased negligibly in the first trimester, by 350 kcal/d in the second trimester, and by 500 kcal/d in the third trimester.

Conclusion: Extra energy intake is required by healthy pregnant women to support adequate gestational weight gain and increases in BMR, which are not totally offset by reductions in AEE. *Am J Clin Nutr* 2004;79:1078–87.

KEY WORDS Pregnancy, energy requirements, total energy expenditure, basal metabolic rate, activity, body composition

INTRODUCTION

Extra dietary energy is required during pregnancy to make up for the energy deposited in maternal and fetal tissues and the rise in energy expenditure attributable to increased basal metabolism and to changes in the energy cost of physical activity. Weight gain during pregnancy results from products of conception (fetus, placenta, and amniotic fluid), increases in various maternal tissues (uterus, breasts, blood, and extracellular extravascular fluid), and increases in maternal fat stores. Hytten and Chamberlain (1) developed a theoretical model to estimate energy requirements during pregnancy, assuming an average gestational weight gain (GWG) of 12.5 kg (≈0.925 kg protein, ≈3.8 kg fat, and ≈7.8 kg water. This model was the basis of current recommendations for energy intakes in pregnant women (2, 3). Energy requirements during pregnancy remain controversial because of conflicting data on maternal fat deposition and putative reductions in the mother's physical activity as pregnancy advances (4).

Integral to the energy requirements of pregnancy is the determination of desirable GWG and the inevitable deposition of maternal fat. In 1990, the Institute of Medicine (IOM) recommended GWG ranges for women on the basis of body mass index (BMI; in kg/m^2): 12.5–18 kg for those with a low BMI (<19.8), 11.5–16 kg for those with a normal BMI (19.8–26.0), and 7.0–11.5 kg (overweight, BMI >26.0–29.0) or ≥6 kg (obese, BMI >29.0) for those with a high BMI (5). The recommended ranges were derived from the observed weight gains of women delivering full-term, healthy infants without complications. A systematic review showed that GWG within the recommended ranges was associated with the best outcome for both infants, in terms of birth weight, and for mothers, in terms of delivery complications and postpartum weight retention (6). Because GWG influences energy requirements, maternal BMI should be taken into account when making energy intake recommendations for pregnant women.

Traditionally, the energy requirements of pregnant women have been derived factorially from the increment in BMR and energy deposited in tissues. This factorial approach ignores potential changes in physical activity and the thermic effect of feeding. Alternatively, total energy expenditure (TEE) can be measured by the doubly labeled water (DLW) method, which captures BMR, activity energy expenditure (AEE), and thermic effect of food (7). Energetic adaptations to pregnancy may be a function of maternal BMI (4).

The purpose of this study was to define the energy requirements of healthy pregnant women with low, normal, or high BMIs. The specific objectives were to *1*) estimate energy depo-

[1] From the US Department of Agriculture/Agricultural Research Service Children's Nutrition Research Center, Department of Pediatrics, Baylor College of Medicine, Houston.

[2] The contents of this publication do not necessarily reflect the views or policies of the Army or the USDA, nor does mention of trade names, commercial products, or organizations imply endorsement by the US Government.

[3] Supported by the US Department of the Army (grant DAMD 17-95-1-5070) and the USDA/ARS (Cooperative Agreement 58-6250-6001).

[4] Address reprint requests to NF Butte, Children's Nutrition Research Center, 1100 Bates Street, Houston, TX 77030. E-mail: nbutte@bcm.tmc.edu.

Received October 9, 2003.
Accepted for publication December 18, 2003.

sition from changes in body protein and fat; *2*) measure changes in BMR, 24-h energy expenditure (24-h EE), AEE, and TEE throughout pregnancy and postpartum; *3*) determine the effect of BMI status, weight, and body-composition changes on BMR, 24-h EE, and TEE; *4*) determine the association between physical activity and weight and body-composition changes during pregnancy and postpartum; and *5*) define the energy requirements of healthy pregnant women on the basis of the sum of TEE and energy deposition.

SUBJECTS AND METHODS

Study design and subjects

Subjects were classified prepregnancy as underweight, normal weight, or overweight/obese into 1 of 3 BMI groups: low BMI (≤19.8), normal BMI (19.8–26.0), or high BMI (≥26). In the high-BMI group, 8 women were classified as overweight and 4 were classified as obese according to the IOM categories (5). To be eligible for enrollment, the subjects had to be nonsmokers, be aged 18–40 y, have a parity ≤ 4, and be moderately active (ie, 20–30 min of moderate exercise ≥3 times/wk) and to not be users of chronic medications or abusers of alcohol or drugs. At enrollment, the women were nonanemic, normoglycemic, and euthyroidic. A total of 124 healthy women were enrolled in the study at baseline. During the course of the study, 76 women became pregnant and 63 women delivered term, singleton infants with birth weights >2.5 kg. Gestational age was taken as reported in the hospital record or as determined with the Dubowitz test, from the last menstrual period, or from ultrasound. Twelve women were dropped from the study for the following reasons: 3 delivered sets of twins, 1 delivered a set of triplets, 5 delivered preterm infants, 2 had miscarriages, and 1 developed preeclampsia. In addition, one woman moved away from the Houston area. Anthropometry and body composition were measured in each woman before pregnancy; at 9, 22, and 36 wk of pregnancy; and at 2, 6, and 27 wk postpartum at the US Department of Agriculture/Agricultural Research Service Children's Nutrition Research Center, Houston. The average time between baseline measurements and conception was 179 ± 184 d. During this period, women recorded their weight weekly. Because weight changed >5%, pregravid anthropometric and body-composition measurements were repeated in 8 women. Because dual-energy X-ray absorptiometry (DXA) and total body nitrogen (TBN) measurements involve some radiation exposure, these measurements were made only before and after pregnancy. This study was approved by the Baylor Affiliates Review Board for Human Subject Research, recruitment was done through local newspapers and community fliers, and informed written consent was obtained from each woman.

Anthropometry and body composition

Body weight and height were measured with an electronic balance (Healthometer, Bridgeview, IL) and stadiometer (Holtain Limited, Crymych, United Kingdom), respectively. Total body potassium (TBK) was estimated from the ^{40}K naturally present in the body with the use of the Children's Nutrition Research Center whole-body counter (8). One gram of potassium emits γ rays (1.46 MeV) at a constant rate of 200.4 photons/min, which were detected by 30 NaI (Tl) detectors arranged in 2 arrays above and below the body. The detectors were inside a shielded room to reduce background interference. The precision for the TBK counter was ±1%. Total body water (TBW) was determined by dilution of an orally administered dose of deuterium oxide (40 or 100 mg ^2H_2O/kg) (Cambridge Isotope Laboratories, Andover, MA). At 0, 22, and 36 wk of pregnancy and at 27 wk postpartum, TBW was estimated by extrapolation to zero-time intercept from samples collected daily for 13 d as part of the DLW method. At 9 wk of pregnancy and at 2 and 6 wk postpartum, TBW was estimated with the plateau method from samples collected 4–6 h postdose. Saliva samples were stored frozen at −20 °C in o-ring sealed vials until analyzed for hydrogen isotope ratio measurements by gas-isotope-ratio mass spectrometry (9). Deuterium dilution space was converted to TBW by dividing by 1.04. Body density (D_b) was measured with an underwater weighing system with the use of force cube transducers (Precision Biomedical Systems Inc, State College, PA) (10). Body volume was corrected for residual lung volume, which was measured separately by the simplified nitrogen washout method (11). DXA (QDR2000, software version 5.56; Hologic Inc, Madison, WI) was used to measure total-body bone mineral content (BMC).

A four-component body-composition model using body weight (in kg), TBW (in L) from ^{2}H dilution, body volume (in L) from densitometry, and BMC from DXA was used to compute fat mass (FM; in kg) and fat-free mass (FFM; in kg) (12):

$$\text{FM} = 2.747\ \text{body volume} - 0.71\ \text{TBW} + 1.46\ \text{BMC} - 2.05\ \text{weight} \quad (1)$$

$$\text{FFM} = \text{weight} - \text{FM} \quad (2)$$

TBN was measured by prompt γ activation analysis. A shielded ^{241}AmBe source provided a collimated neutron beam through which the subject was scanned. Four large-volume NaI (Tl) detectors with neutron γ shielding were positioned at 90° to both the bed and source. Total body protein was computed as 6.25 × TBN. Changes in total body protein during pregnancy were estimated from the serial TBK measurements, assuming a whole-body ratio of potassium to nitrogen of 2.15 mEq/g (13). Changes in total body protein postpartum were estimated directly from the differences in TBN measurements.

Energy deposition or mobilization was computed from the changes in protein and FM between adjacent study intervals. The energy equivalents for protein and fat deposition or mobilization were taken as 5.6 and 9.2 kcal/g fat, respectively.

Respiration calorimetry

Oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) were measured continuously in 31-m^3 room calorimeters for 24 h. The performance of the respiration calorimeters was described in detail previously (14). Errors from 24-h infusions of nitrogen and carbon dioxide were −0.34 ± 1.24% for $\dot{V}O_2$ and 0.11 ± 0.98% for $\dot{V}CO_2$ (14). The average temperature and humidity within the calorimeter were 23.4 ± 0.3 °C and 47.4 ± 3.8%, respectively. All urine was collected during the 24-h calorimetry procedure. Urine samples were acidified with 6N HCl and refrigerated. Urinary volume was measured and nitrogen concentrations were determined by Kjeldahl digestion (Kjeltec Auto Analyzer 1030; Tecator, Hoganas, Sweden), which were followed by a phenol-hypochlorite colorimetric reaction (15). From the 24-h $\dot{V}O_2$, $\dot{V}CO_2$, and urinary nitrogen excretion, TEE was computed according to Livesey and Elia (16). All milk produced during the 24 h in the calorimeter was expressed with an electric breast pump. After each pumping session, the milk was weighed and a 10% aliquot was refrigerated and later pooled for analysis; milk was analyzed for energy content by adiabatic bomb calorimetry (Parr Instruments, Moline, IL).

Subjects adhered to a set schedule while in the calorimeter. Calorimetry began at 0800. Meals were served at 0830, 1200, and 1730, with a snack at 1830. No food was allowed after 1900; bedtime was at 2200. After fasting overnight for 12 h, the subjects were awakened at 0645, were asked to void, and returned to sleep. The subject was again awakened ≈30 min later. After it was confirmed that they were awake, BMR was measured for 40 min. BMR was calculated by using the Weir equation (17).

TEE calculated with the doubly labeled water method

TEE, which was used to define energy requirements, was measured with the DLW method (7). After a baseline saliva sample was collected, the women received by mouth 100 mg ^2H_2O and 125 mg $H_2{}^{18}O$ (both from Cambridge Isotope Laboratories) per kg body weight. One daily saliva sample was collected at the subjects' homes for the next 13 d and stored frozen at −20 °C in o-ring sealed vials. The time of collection was recorded.

Saliva samples were analyzed for hydrogen and oxygen isotope ratio measurements by gas-isotope-ratio mass spectrometry (9). For hydrogen isotope ratio measurements, 10 μL saliva without further treatment was reduced to hydrogen gas with 200 mg Zn reagent at 500 °C for 30 min (18). The $^2H/^1H$ isotope ratios of the hydrogen gas were measured with a Finnigan δ-E gas-isotope-ratio mass spectrometer (Finnigan MAT, San Jose, CA). For oxygen isotope ratio measurements, 100 μL saliva was allowed to equilibrate with 300 mbar CO_2 of known ^{18}O content at 25 °C for 10 h with a VG ISOPREP-18 water–carbon dioxide equilibration system (VG Isogas, Limited, Cheshire, United Kingdom). At the end of the equilibration, the $^{18}O/^{16}O$ isotope ratios of the carbon dioxide were measured with a VG SIRA-12 gas-isotope-ratio mass spectrometer (VG Isogas, Limited).

The isotope dilution spaces for ^2H (N_H) and ^{18}O (N_O) were calculated as follows:

$$N_H \text{ or } N_O \text{ (mol)} = d \times A \times E_a/a \times E_d \times 18.02 \qquad (3)$$

where d is the dose of ^2H_2O or $H_2{}^{18}O$ (in g), A is the amount of laboratory water (in g) used in the dose dilution, a is the amount of ^2H_2O or $H_2{}^{18}O$ (in g) added to the laboratory water in the dose dilution, E_a is the rise in ^2H or ^{18}O abundance in the laboratory water after the addition of the isotopic water, and E_d is the rise in ^2H and ^{18}O abundance over baseline values obtained from the zero-time intercepts of the ^2H and ^{18}O decay curves in the saliva samples.

$\dot{V}CO_2$ was calculated from the fractional turnover rates of ^2H (k_H) and ^{18}O (k_O) as follows:

$$\dot{V}CO_2 \text{ (mol/d)} = 0.4584 \times [(k_O \times N_O) - (k_H \times N_H)] \qquad (4)$$

In this equation, the in vivo isotope fractional factors (f) of 0.945 [f_1, $^2H_2O_{(liquid)} \leftrightarrow {}^2H_2O_{(gas)}$], 0.990 [$f_2$, $H_2{}^{18}O_{(liquid)} \leftrightarrow H_2{}^{18}O_{(gas)}$], and 1.039 [$f_3$, $H_2{}^{18}O_{(liquid)} + C^{16}O_{2(gas)} \leftrightarrow H_2{}^{16}O_{(liquid)} + C^{18}O_{2(gas)}$]—measured at 37 °C—were used (19–22). $\dot{V}CO_2$ was converted to TEE by using the Weir equation (17) as follows:

$$\text{TEE (kcal/d)} = 22.4 \times (1.106 \times \dot{V}CO_2 + 3.941 \times \dot{V}O_2) \qquad (5)$$

where $\dot{V}O_2$ was calculated from the food quotient (FQ) of 0.86 with the use of the relation $\dot{V}O_2 = CO_2/FQ$ according to Black et al (23). AEE was estimated from nonbasal energy expenditure as TEE − BMR. The physical activity level (PAL) was estimated as TEE/BMR.

TABLE 1
Subject characteristics

	Low BMI (n = 17)	Normal BMI (n = 34)	High BMI (n = 12)
Age (y)	30.8 ± 3.9[1]	30.3 ± 4.3	31.2 ± 4.5
Ethnicity (n)			
White	15	25	9
African American	0	4	2
Hispanic	1	4	1
Asian	1	1	0
Education (y)	17.6 ± 2.6	16.8 ± 2.2	16.2 ± 1.6
Income (n)			
<$20 000	0	1	1
$20 000–34 999	2	4	0
$35 000–49 999	0	3	2
>$50 000	15	24	9
Menarche (y)	13.4 ± 1.6	12.8 ± 1.4	12.3 ± 1.1
Gravidity	0 (0–3)[2]	1 (0–5)	1 (0–4)
Parity	0 (0–1)	0 (0–2)	1 (0–2)

[1] $\bar{x}$ ± SD (all such values).
[2] Median; range in parentheses (all such values).

Statistics

MINITAB (release 13; Minitab Inc, College Station, PA) was used for data description and statistical analysis, which included Pearson's correlations, paired t tests, chi-square tests, and linear regression. Repeated-measures analysis of variance (BMDP5V; BMDP Statistical Software, Berkeley, CA) was used to test for the effects of BMI groups and time; the model included a grouping factor (low, normal, or high BMI), a time factor (0, 9, 22, and 36 wk of pregnancy or 2, 6, and 27 wk postpartum), and interactions between BMI group and time. Post hoc pairwise comparisons between BMI groups or time intervals were performed by using Tukey's method.

RESULTS

Of the 63 pregnant women who completed the study, 17 were classified according to prepregnancy BMI as underweight, 34 as normal weight, and 12 as overweight/obese (**Table 1**). Prepregnancy BMI was highly correlated with prepregnancy percentage FM (%FM; $r = 0.79$, $P = 0.001$) and FM ($r = 0.94$, $P = 0.001$). There were no statistically significant differences in age, ethnicity, family income, attained level of education, gravidity, or parity in the low-, normal- and high-BMI groups. The mean age of the 3 groups was 31 ± 4 y (range: 21–39 y). Fifty-seven percent of the women were nulliparous, 35% had one child, and

TABLE 2
Maternal weight and body composition throughout a reproductive cycle[1]

	0 wk (baseline)	Pregnancy			Postpartum		
		9 wk	22 wk	36 wk	2 wk	6 wk	27 wk
Weight (kg)[2,3]							
Low BMI	49.9 ± 3.9	51.9 ± 5.5	57.7 ± 4.8	63.0 ± 4.7	54.8 ± 4.8	54.4 ± 5.4	51.9 ± 4.9
Normal BMI	59.3 ± 6.0	60.2 ± 6.4	65.1 ± 7.4	72.2 ± 8.4	64.8 ± 8.3	63.7 ± 8.8	61.5 ± 7.9
High BMI	77.3 ± 10.2	81.8 ± 11.2	85.8 ± 10.4	93.8 ± 10.1	84.6 ± 10.4	83.9 ± 10.8	81.9 ± 11.3
BMI[2,3]							
Low BMI	18.9 ± 0.8	19.7 ± 1.5	21.8 ± 1.4	23.6 ± 1.6	21.0 ± 1.6	20.8 ± 1.7	19.7 ± 1.3
Normal BMI	22.1 ± 1.5	22.3 ± 1.6	24.1 ± 2.0	26.8 ± 2.4	24.2 ± 2.5	23.8 ± 2.5	22.9 ± 2.2
High BMI	28.8 ± 2.6	30.2 ± 3.5	32.0 ± 3.0	34.9 ± 3.1	31.6 ± 3.0	31.4 ± 3.1	30.4 ± 3.5
Total body protein (kg)[2,4]							
Low BMI	6.9 ± 0.9	6.8 ± 0.6	6.9 ± 0.7	7.5 ± 0.8	7.0 ± 1.0	6.9 ± 0.9	6.8 ± 0.8
Normal BMI	7.6 ± 1.0	7.4 ± 1.0	7.5 ± 1.0	8.0 ± 1.1	7.6 ± 0.8	7.5 ± 0.9	7.6 ± 1.0
High BMI	7.9 ± 0.7	7.8 ± 0.9	8.2 ± 0.6	9.0 ± 0.7	8.1 ± 0.6	8.0 ± 0.8	8.0 ± 0.6
Fat-free mass (kg)[2,4]							
Low BMI	39.0 ± 3.8	39.6 ± 4.1	42.6 ± 4.7	46.9 ± 4.5	40.2 ± 4.1	39.5 ± 4.4	37.9 ± 3.6
Normal BMI	43.1 ± 4.7	43.0 ± 4.8	46.0 ± 5.2	51.4 ± 4.8	44.2 ± 4.3	43.5 ± 4.9	43.3 ± 4.8
High BMI	47.8 ± 6.3	48.9 ± 5.3	51.0 ± 4.4	56.9 ± 5.2	49.4 ± 5.0	48.6 ± 4.7	48.5 ± 5.2
Fat mass (kg)[2,3]							
Low BMI	10.9 ± 2.9	12.4 ± 2.7	15.1 ± 4.0	16.1 ± 3.8	14.7 ± 3.4	14.9 ± 4.5	13.9 ± 4.3
Normal BMI	16.8 ± 4.2	17.2 ± 3.7	19.1 ± 4.7	21.0 ± 5.6	20.6 ± 5.6	20.3 ± 5.7	18.2 ± 5.3
High BMI	30.9 ± 6.0	33.0 ± 8.3	34.8 ± 8.1	37.0 ± 8.4	35.2 ± 8.3	35.3 ± 8.8	33.7 ± 11.0
Fat mass (% by wt)[2,3]							
Low BMI	21.9 ± 5.1	23.7 ± 4.0	26.1 ± 6.1	25.3 ± 5.5	26.7 ± 5.3	27.2 ± 6.7	26.6 ± 6.7
Normal BMI	27.9 ± 5.9	28.5 ± 4.7	29.2 ± 5.4	28.6 ± 5.3	31.4 ± 5.5	31.4 ± 5.7	29.3 ± 6.1
High BMI	39.2 ± 4.5	39.9 ± 5.5	40.1 ± 5.3	39.1 ± 6.0	41.2 ± 6.2	41.6 ± 5.9	40.3 ± 8.2

[1] All values are $\bar{x}$ ± SD. Low BMI (n = 17), normal BMI (n = 34), high BMI (n = 12).
[2] Significant differences between BMI groups during pregnancy (P = 0.01–0.001) and between weeks of pregnancy (P = 0.001–0.002).
[3] Significant differences between BMI groups postpartum (P = 0.01–0.001).
[4] Significant differences between BMI groups postpartum (P = 0.01–0.001) and between weeks postpartum (P = 0.01–0.05).

8% had 2 children. Most of the women (87%) worked outside of the home: 44% were in business or administrative positions; 19% were teachers, professors, or students; 19% were healthcare providers; 5% were physical trainers; and 13% were homemakers. The mean numbers of hours worked outside the home were 42 ± 10, 38 ± 11, 37 ± 12, 38 ± 12, 8 ± 14, and 30 ± 17 h/wk at 0, 9, 22, and 36 wk of pregnancy and 6 and 27 wk postpartum, respectively.

Maternal weight and body-composition measures are summarized in **Table 2**. Mean (±SD) height did not differ significantly between BMI groups and averaged 163 ± 6 cm. Mean gestational duration was 38.3 ± 1.6, 39.3 ± 1.1, and 39.6 ± 1.2 wk in the low-, normal-, and high-BMI groups, respectively. Mean GWGs, computed as the difference in weight at delivery minus baseline, were 15.0 ± 3.8, 14.5 ± 4.5, and 17.9 ± 5.4 kg, and mean birth weights were 3.38 ± 0.44, 3.55 ± 0.39, and 3.82 ± 0.47 kg, respectively, in the low-, normal-, and high-BMI groups. In the low-BMI group, 2 (12%), 9 (53%), and 3 (18%) of the women gained below, within, and above the IOM recommendations for weight gain, respectively. In the normal-BMI group, 11 (32%), 11 (32%), and 12 (35%) of the women gained below, within, and above the IOM recommendations, respectively. In the high-BMI group, 100% of the women gained above the recommendations. Details on changes in body weight and composition and their influence on pregnancy outcome are published elsewhere (24). At 2, 6, and 27 wk postpartum, 55, 53, and 39 of the 63 women were breastfeeding, respectively.

Energy deposition estimated from changes in body protein and FM during the first, second, and third trimesters is summarized in **Table 3**. Total protein deposition did not differ significantly between BMI groups (611 g protein) and was highest in the third trimester. Total FM deposition differed significantly by BMI group (5.3, 4.6, and 8.4 kg FM in the low-, normal-, and high-BMI groups; P = 0.02) but not by trimester. Total energy deposition was higher in the high-BMI group than in the normal-BMI group (P = 0.02). Postpartum changes in total body protein were greater earlier (2–6 wk) than later (6–27 wk). Postpartum FM and energy deposition or mobilization did not differ significantly between BMI groups or time intervals.

BMR increased gradually throughout pregnancy at a mean (±SD) rate of 10.7 ± 5.4 kcal/gestational wk (mean regression coefficient of energy expenditure on gestational week determined for each woman): 8.8 ± 4.5 kcal/wk in the low-BMI group, 9.5 ± 4.6 kcal/wk in the normal-BMI group, and 16.3 ± 5.4 kcal/wk in the high-BMI group. Differences in BMR between BMI groups differed by time (group × time interaction, P = 0.002); at baseline, BMR differed between BMI groups (low-BMI group < normal-BMI group < high-BMI group). At 9, 22, and 36 wk of pregnancy, BMRs of the low- and normal-BMI groups were lower than BMR in the high-BMI group (**Table 4**). FFM and FM explained 69–72% of the variability in BMR. When adjusted for weight or FFM and FM, BMR did not differ significantly between BMI groups. Postpartum BMR did not differ significantly from pregravid BMR, with or without adjust-

TABLE 3
Energy deposition or mobilization on the basis of changes in body protein and fat during pregnancy and the postpartum period[1]

	Pregnancy			Postpartum	
	0–9 wk	9–22 wk	22–36 wk	2–6 wk	6–27 wk
Weight (g/d)[2]					
Low BMI	33.0 ± 42.1	66.8 ± 18.7	53.7 ± 20.6	−11.9 ± 41.3	−17.3 ± 13.8
Normal BMI	6.8 ± 46.6	52.7 ± 19.6	81.5 ± 21.3	−23.4 ± 55.9	−15.5 ± 20.0
High BMI	68.1 ± 69.1	71.0 ± 31.5	83.2 ± 37.7	−26.6 ± 53.2	−14.4 ± 25.3
Protein (g/d)[3]					
Low BMI	−2.8 ± 8.2	0.5 ± 4.3	4.8 ± 6.9	−6.1 ± 15.6	−0.1 ± 3.1
Normal BMI	−3.7 ± 6.1	1.5 ± 4.0	5.9 ± 6.3	−5.3 ± 13.5	1.1 ± 3.8
High BMI	−2.5 ± 10.0	4.0 ± 7.5	8.4 ± 3.1	−6.3 ± 24.3	1.0 ± 4.1
Fat mass (g/d)[4]					
Low BMI	16.5 ± 38.0	37.6 ± 30.7	18.2 ± 26.4	12.7 ± 84.6	−6.2 ± 13.7
Normal BMI	5.8 ± 49.3	20.0 ± 27.2	20.6 ± 31.4	−11.1 ± 59.1	−14.4 ± 20.4
High BMI	41.3 ± 60.3	43.5 ± 27.6	22.6 ± 29.2	−0.3 ± 90.5	−8.3 ± 34.5
Protein (kcal/d)[3]					
Low BMI	−16 ± 46	3 ± 24	27 ± 39	−34 ± 88	−1 ± 18
Normal BMI	−21 ± 34	9 ± 23	33 ± 36	−30 ± 76	6 ± 22
High BMI	−14 ± 57	22 ± 43	47 ± 18	−36 ± 137	6 ± 23
Fat mass (kcal/d)[4]					
Low BMI	153 ± 352	348 ± 284	168 ± 244	118 ± 783	−58 ± 127
Normal BMI	53 ± 456	186 ± 251	190 ± 290	−103 ± 546	−133 ± 189
High BMI	382 ± 558	402 ± 255	209 ± 270	−2 ± 837	−77 ± 319
Total energy deposition or mobilization (kcal/d)[4]					
Low BMI	137 ± 368	351 ± 276	181 ± 256	133 ± 782	−47 ± 139
Normal BMI	32 ± 461	207 ± 251	211 ± 297	−133 ± 568	−127 ± 193
High BMI	367 ± 585	425 ± 257	256 ± 270	−38 ± 895	−71 ± 327

[1] All values are $\bar{x}$ ± SD. Low BMI (n = 17), normal BMI (n = 34), high BMI (n = 12).
[2] BMI group × time interaction during pregnancy (P = 0.001): 0–9 wk of pregnancy, change in normal-BMI group < high-BMI group; 22–36 wk of pregnancy, change in low-BMI group < normal- and high-BMI groups; significant differences between weeks postpartum (P = 0.001).
[3] Significant differences between weeks of pregnancy (P = 0.001) and significant differences between weeks postpartum (P = 0.001).
[4] Significant differences between BMI groups during pregnancy (P = 0.02–0.03).

ment for weight or FFM and FM in all BMI groups. The absolute and relative changes in BMR from baseline are presented in **Table 5**.

24-h EE measured in the room calorimeter also increased gradually over gestation at a mean (±SD) rate of 11.3 ± 6.3 kcal/gestational wk in all women, 9.2 ± 5.5 kcal/wk in the low-BMI group, 10.3 ± 4.2 kcal/wk in the normal-BMI group, and 16.3 ± 9.2 kcal/wk in the high-BMI group. The rise in BMR accounted for most of the rise in 24-h EE. The mean 24-h EE/BMR in all women was 1.33 ± 0.07 during pregnancy. Differences in 24-h EE (kcal/d) between BMI groups were dependent on time (P = 0.04). 24-h EEs were lower in the low- and normal-BMI groups than in the high-BMI group at 0, 9, 22, and 36 wk of pregnancy. When adjusted for weight or FFM and FM in 2 analyses, 24-h EE differed by BMI group (P = 0.003 and 0.03) and time (P = 0.001 and 0.01). Postpartum 24-h EE did not differ significantly from pregravid 24-h EE, with and without adjustment for weight or FFM and FM. The absolute and relative changes in 24-h EE from baseline are provided in Table 5.

TEE measured by the DLW method is summarized in Table 4. During pregnancy, the isotope dilution spaces for ^{2}H and ^{18}O differed by BMI group (P = 0.001) and time (P = 0.001), with no significant group × time interaction. Fractional turnover rates of ^{2}H and ^{18}O did not differ significantly by BMI group or time. TEE (kcal/d) differed by BMI group (high-BMI group > normal-BMI and low-BMI groups; P = 0.001) at 0, 22, and 36 wk of pregnancy. TEE increased throughout pregnancy at a mean rate of 5.2 ± 12.8 kcal/gestational wk for all women. In the normal-BMI group, TEE increased linearly at a mean rate of 7.4 ± 10.2 kcal/gestational wk. In the low- and high-BMI groups, mean TEE decreased in the second trimester and then increased in the third trimester; the overall increases were 2.0 ± 15.1 and 2.9 ± 16.2 kcal/wk in the low- and high-BMI groups, respectively. When adjusted for weight, TEE did not differ significantly by BMI group or time; when adjusted for FFM and FM, TEE declined slightly through gestation in all BMI groups (P = 0.03).

AEE and PAL decreased across pregnancy (0, 22, 36 wk of pregnancy), displaying significant group x time interactions (P = 0.04). Further analysis indicated that AEE was significantly lower in the normal-BMI than the high-BMI group before pregnancy. No significant differences in PAL were found among BMI groups. PAL was significantly higher before pregnancy than in the third trimester in all BMI groups.

Postpartum TEE was lower in the low-BMI group than in the normal- and high-BMI groups (P = 0.001). No significant differences were apparent between BMI groups after adjustment for weight or FFM and FM. With or without adjustment for weight or FFM and FM, postpartum TEE, PAL, and AEE were significantly lower than pregravid values in the low-BMI group (P = 0.004) but not in the normal- and high BMI groups.

Absolute changes in BMR and 24-h EE in the first trimester (9 wk − baseline) were positively correlated with the corresponding change in weight and FFM (r = 0.28–0.44, $P \leq 0.05$) but not with FM. Changes in BMR and 24-h EE in the second

TABLE 4
Total energy expenditure measured by 24-h respiratory calorimetry and the doubly labeled water method during pregnancy and the postpartum period and estimated total energy costs[1]

		Pregnancy			Postpartum[2]
	0 wk (baseline)	9 wk	22 wk	36 wk	27 wk
BMR (kcal/d)[3]					
Low BMI	1201 ± 137	1234 ± 116	1330 ± 121	1573 ± 210	1254 ± 169
Normal BMI	1323 ± 127	1350 ± 158	1413 ± 142	1673 ± 172	1323 ± 136
High BMI	1505 ± 153	1600 ± 213	1693 ± 210	2016 ± 254	1505 ± 171
24-h EE (kcal/d)[4]					
Low BMI	1627 ± 171	1626 ± 156	1742 ± 162	2064 ± 285	1681 ± 188
Normal BMI	1760 ± 182	1771 ± 195	1854 ± 190	2164 ± 232	1784 ± 191
High BMI	2074 ± 220	2145 ± 261	2245 ± 274	2595 ± 340	2054 ± 288
N_H (kg)[5]					
Low BMI	29.8 ± 3.0	—	33.5 ± 3.8	36.1 ± 4.0	28.8 ± 2.5
Normal BMI	33.1 ± 4.0	—	35.2 ± 3.9	40.1 ± 4.1	33.0 ± 3.8
High BMI	36.9 ± 5.4	—	39.4 ± 3.9	44.5 ± 4.2	36.8 ± 4.2
N_O (kg)[5]					
Low BMI	29.0 ± 3.1	—	32.6 ± 3.8	35.1 ± 3.8	27.7 ± 2.4
Normal BMI	31.8 ± 4.0	—	34.4 ± 3.9	39.2 ± 4.2	32.1 ± 3.8
High BMI	35.9 ± 5.1	—	38.0 ± 3.6	43.6 ± 4.2	35.8 ± 4.2
N_H/N_O					
Low BMI	1.03 ± 0.01	—	1.03 ± 0.02	1.03 ± 0.01	1.04 ± 0.02
Normal BMI	1.03 ± 0.02	—	1.02 ± 0.02	1.02 ± 0.03	1.03 ± 0.02
High BMI	1.03 ± 0.02	—	1.03 ± 0.02	1.02 ± 0.01	1.03 ± 0.02
k_H (d^{-1})					
Low BMI	−0.100 ± 0.031	—	−0.100 ± 0.029	−0.098 ± 0.028	−0.132 ± 0.048
Normal BMI	−0.103 ± 0.035	—	−0.102 ± 0.040	−0.104 ± 0.034	−0.108 ± 0.039
High BMI	−0.111 ± 0.041	—	−0.099 ± 0.031	−0.104 ± 0.028	−0.105 ± 0.049
k_O (d^{-1})					
Low BMI	−0.128 ± 0.031	—	−0.125 ± 0.032	−0.122 ± 0.030	−0.160 ± 0.048
Normal BMI	−0.130 ± 0.038	—	0.127 ± 0.041	−0.127 ± 0.035	−0.135 ± 0.040
High BMI	−0.139 ± 0.042	—	−0.126 ± 0.034	−0.128 ± 0.030	−0.132 ± 0.053
AEE (kcal/d)[6]					
Low BMI	912 ± 228	—	720 ± 322	700 ± 446	602 ± 291
Normal BMI	868 ± 296	—	845 ± 330	752 ± 322	910 ± 331
High BMI	1142 ± 319	—	905 ± 348	693 ± 402	909 ± 275
PAL[7]					
Low BMI	1.97 ± 0.25	—	1.72 ± 0.28	1.63 ± 0.33	1.68 ± 0.30
Normal BMI	1.84 ± 0.25	—	1.78 ± 0.28	1.62 ± 0.24	1.88 ± 0.29
High BMI	1.96 ± 0.22	—	1.72 ± 0.25	1.49 ± 0.22	1.77 ± 0.19
TEE (kcal/d)[8]					
Low BMI	2348 ± 276	—	2272 ± 376	2439 ± 485	2020 ± 267
Normal BMI	2434 ± 368	—	2520 ± 381	2693 ± 372	2480 ± 410
High BMI	2940 ± 421	—	2887 ± 435	3020 ± 553	2708 ± 400
Total energy costs (kcal/d)[9]					
Low BMI	2348 ± 276	2497 ± 464	2542 ± 488	2658 ± 560	2042 ± 338
Normal BMI	2434 ± 368	2423 ± 637	2758 ± 415	2904 ± 438	2590 ± 454
High BMI	2940 ± 421	3308 ± 862	3381 ± 564	3280 ± 716	2815 ± 537

[1] All values are $\bar{x}$ ± SD. Low BMI (n = 17), normal BMI (n = 34), high BMI (n = 12). BMR, basal metabolic rate; EE, energy expenditure; N_H, ^{2}H dilution space; N_O, ^{18}O dilution space; k_H, ^{2}H turnover rate; k_O, ^{18}O turnover rate; rCO_2, carbon dioxide production rate; TEE, total energy expenditure; PAL, physical activity level; AEE, activity energy expenditure.

[2] Energy costs include changes in energy stores but do not include the energy cost of lactation.

[3] BMI group × time interaction during pregnancy (P = 0.002): baseline, BMR in low-BMI group < normal-BMI group < high-BMI group; 9, 22, and 36 wk of pregnancy, BMR in low- and normal-BMI groups < high-BMI group; significant differences between BMI groups postpartum (P = 0.001).

[4] BMI group × time interaction during pregnancy (P = 0.04): 24-h EE in low- and normal-BMI groups < high-BMI group at 0, 9, 22, and 36 wk of pregnancy; significant differences between BMI groups postpartum (P = 0.001).

[5] Significant differences between BMI groups during pregnancy (P = 0.001), significant differences between weeks of pregnancy (P = 0.001), and significant differences between weeks postpartum (P = 0.001).

[6] BMI group × time interaction during pregnancy (P = 0.04): AEE in normal-BMI group < high-BMI group at baseline; significant differences between BMI groups postpartum (P = 0.01).

[7] BMI group × time interaction during pregnancy (P = 0.04): PAL at baseline > 36 wk of pregnancy in all BMI groups.

[8] Significant differences between BMI groups during pregnancy (P = 0.001), significant differences between weeks of pregnancy (P = 0.02), and significant differences between weeks postpartum (P = 0.001).

[9] Significant differences between BMI groups during pregnancy (P = 0.02), significant differences between weeks of pregnancy (P = 0.001), and significant differences between weeks postpartum (P = 0.001).

TABLE 5
Changes (Δ) from baseline in energy expenditure and total energy costs during pregnancy and the postpartum period relative to prepregnancy baseline values[1]

	Pregnancy			Postpartum[2]
	Δ0–9 wk	Δ0–22 wk	Δ0–36 wk	Δ0–27 wk
ΔBMR (kcal/d)				
Low BMI	41 ± 109	123 ± 126	305 ± 119	4 ± 124
Normal BMI	32 ± 111	95 ± 110	359 ± 140	17 ± 104
High BMI	107 ± 115	237 ± 162	566 ± 194	55 ± 98
ΔBMR (%)				
Low BMI	4 ± 10	11 ± 14	25 ± 10	1 ± 11
Normal BMI	2 ± 8	7 ± 9	28 ± 11	2 ± 4
High BMI	7 ± 8	16 ± 11	38 ± 14	4 ± 7
Δ24-h EE (kcal/d)				
Low BMI	−15 ± 117	100 ± 181	336 ± 152	−6 ± 148
Normal BMI	16 ± 107	103 ± 101	405 ± 162	45 ± 92
High BMI	103 ± 165	251 ± 209	626 ± 275	68 ± 152
Δ24-h EE (%)				
Low BMI	−0.5 ± 7	7 ± 12	20 ± 9	0.3 ± 9
Normal BMI	1 ± 6	6 ± 6	23 ± 9	3 ± 5
High BMI	5 ± 8	13 ± 11	31 ± 15	4 ± 8
ΔTEE (kcal/d)				
Low BMI	—	−91 ± 442	41 ± 553	−411 ± 388
Normal BMI	—	123 ± 341	287 ± 377	84 ± 400
High BMI	—	16 ± 652	149 ± 571	−171 ± 433
ΔTEE (%)				
Low BMI	—	−3 ± 18	3 ± 23	−16 ± 15
Normal BMI	—	6 ± 14	13 ± 16	4 ± 17
High BMI	—	3 ± 23	6 ± 20	−5 ± 14
ΔTotal energy costs (kcal/d)				
Low BMI	137 ± 368	163 ± 512	294 ± 602	−530 ± 302
Normal BMI	32 ± 461	356 ± 416	496 ± 368	−33 ± 472
High BMI	367 ± 585	441 ± 755	434 ± 806	−276 ± 497
ΔTotal energy costs (%)				
Low BMI	6 ± 16	8 ± 22	14 ± 26	−21 ± 13
Normal BMI	1 ± 20	16 ± 17	22 ± 16	−0.4 ± 20
High BMI	12 ± 19	17 ± 28	17 ± 29	−8 ± 17

[1] All values are $\bar{x}$ ± SD. Low BMI (n = 17), normal BMI (n = 34), high BMI (n = 12). BMR, basal metabolic rate; EE, energy expenditure; TEE, total energy expenditure.

[2] Energy costs include changes in energy stores but do not include the energy cost of lactation.

trimester (22 wk − 9 wk) were positively correlated with the corresponding increment in weight (r = 0.35–0.52, $P \leq 0.01$) and FFM (r = 0.37–0.38, $P \leq 0.01$) but not with FM. Changes in BMR and 24-h EE in the third trimester (36 wk − 22 wk) were positively correlated with the corresponding increment in weight (24-h EE: r = 0.45, P = 0.001) and FFM (r = 0.26–0.46, $P \leq$ 0.05) but not with FM. Birth weight was positively correlated with the changes in BMR and 24-h EE, especially in the third trimester (r = 0.48–0.59, P = 0.001). Gestational changes in TEE did not correlate with the changes in weight or body composition.

First-trimester changes in BMR and 24-h EE relative to prepregnancy EE values (Table 5) were not related to prepregnancy BMI or %FM. Second-trimester absolute changes in BMR and 24-h EE relative to prepregnancy EE values were related to prepregnancy BMI and %FM (r = 0.26–0.30, $P \leq 0.04$). Third-trimester absolute and relative changes in BMR and 24-h EE relative to prepregnancy EE values also were related to prepregnancy BMI and %FM (r = 0.27–0.49, $P \leq 0.05$). Rates of change in BMR (10.7 ± 5.4 kcal/gestational wk) and 24-h EE (11.3 ± 6.3 kcal/gestational wk) across the entire pregnancy were positively correlated with GWG and FFM gain (r = 0.34–0.49, $P \leq$ 0.01) and with prepregnancy BMI and %FM (r = 0.30–0.42, $P \leq 0.02$). By multiple regression, GWG, FFM gain, and prepregnancy BMI and %FM accounted for 40% of the variability in BMR and 33% of the variability in 24-h EE. Absolute changes in TEE were positively correlated with FFM gain (r = 0.31, P = 0.02) but not with GWG and prepregnancy BMI or %FM.

Neither PAL nor AEE at 22 and 36 wk of pregnancy was shown to be associated with gestational changes in weight, FFM, or FM. PAL and AEE at 27 wk postpartum were not associated with postpartum changes in weight, FFM, or FM between 6 and 27 wk postpartum. PAL at 22 and 36 wk of pregnancy was negatively correlated with birth weight. By multiple regression, birth weight was significantly predicted from sex, gestational age, and PAL at 22 wk (PAL coefficient = −0.40, P = 0.038; R^2 = 0.31, P = 0.001) and 36 wk (PAL coefficient = −0.58, P = 0.007; R^2 = 0.28, P = 0.001).

Total energy costs derived from the sum of TEE and energy deposition or mobilization are summarized for the low-, normal-, and high-BMI groups in Table 4. TEE at 9 wk of pregnancy was assumed to be equal to baseline TEE. Total energy costs at 0, 9, 22, and 36 wk of pregnancy differed by BMI group ($P = 0.02$; low-BMI group < normal-BMI and high-BMI groups) and time ($P = 0.001$). Postpartum energy costs in the low-BMI group were lower than those in the normal- and high-BMI groups ($P = 0.001$) and lower than their own pregravid values ($P = 0.004$).

For the subset of women who gained within the IOM recommendations for GWG, energy deposition averaged 31, 278, and 98 kcal/d in the low-BMI group and −32, 256, and 227 kcal/d in the normal-BMI group; total energy requirements were 2427, 2602, and 2604 kcal/d in the low-BMI group and 2182, 2561, and 2723 kcal/d in the normal-BMI group during the first, second, and third trimesters, respectively. The values differed from prepregnancy energy requirements by 31, 205, and 175 kcal/d in the low-BMI groups and by −32, 301, and 510 kcal/d in the normal-BMI groups, respectively. All of the women in the high-BMI group gained above the IOM recommendations. Postpartum, an additional allowance is required to cover the costs of lactation. In those women who exclusively breastfed their children ($n = 6$), mean milk production was 820 g/d with an energy concentration of 0.63 kcal/g; therefore, an additional 531 kcal/d was required to cover their energy needs. In the women who partially breastfed their children ($n = 33$), an additional 413 kcal/d (mean: 664 g/d with 0.64 kcal/g) was needed.

DISCUSSION

This study determined the extra dietary energy needs during pregnancy from the sum of TEE and energy deposition and resolved uncertainties regarding maternal fat deposition and putative reductions in physical activity. However, recommendations for energy intake in pregnant women must be population-specific because of differences in body size and lifestyles. The extent to which women change their habitual activity patterns during pregnancy will be determined by socioeconomic and cultural factors specific to the population. The subjects in the current study were representative of healthy moderately active American women with low, normal, or high prepregnancy BMIs. As is characteristic of pregnant women (4, 25), high variability was seen in their rates of GWG, energy deposition, and energy expenditure, and thus, in their energy costs during pregnancy.

In our study, the energy deposited in maternal and fetal tissues as fat was estimated from a multicomponent body-composition model based on TBW, body volume, and BMC, and as protein from TBK measurements. Total fat accretion, the major contributor to energy deposition, averaged 3.7 kg (range: 2.4–5.9 kg) when measured by using valid body-composition models in many studies of well-nourished pregnant women (26–35). Mean fat gains in this study were 5.3, 4.6, and 8.4 kg for women in the low-, normal-, and high-BMI groups. For those women who gained within the IOM recommendations for GWG, the mean fat gains were 3.5 and 4.6 kg for women in the low- and normal-BMI groups. As described in our companion article about body composition (24), excessive GWG was attributed primarily to FM gain, not protein accretion, and is undesirable. Maternal fat retention at 27 wk postpartum was significantly higher in women who gained above IOM recommendations for GWG than in those who gained within or below recommendations.

As a result of increased tissue mass, the energy cost for maintenance rises during pregnancy. The increase in BMR is one of the major components of the energy cost of pregnancy. Several longitudinal studies have been published that measured changes in BMR throughout pregnancy (27–30, 36–38). In these studies, BMR increased over prepregnancy values by 5%, 11%, and 24% in the first, second, and third trimesters, which was similar to what was observed among our women in the low- and normal-BMI groups. However, striking variability in metabolic response was seen between the women in our study; BMR (and sleeping metabolic rate) decreased relative to pregravid values during the first and second trimesters in some women and increased steadily throughout pregnancy in the others. In the high-BMI group, the increase was greater (7%, 16%, and 38% in the first, second, and third trimesters, respectively), consistent with their greater GWG and FFM gain. We also found that the increments in BMR and 24-h EE in the second and third trimesters were correlated not only with changes in weight and FFM but also independently with prepregnancy BMI or %FM. Together, GWG, FFM gain, and prepregnancy BMI and %FM explained 33–40% of the variability seen in the overall changes in BMR and 24-h EE. In a cross-country comparison, cumulative increases in BMR were significantly correlated with total weight gain ($r = 0.79$, $P < 0.001$) and prepregnancy %FM ($r = 0.72$, $P < 0.001$) (4). This relation was also seen within populations in the United Kingdom (28, 39) and The Gambia (40).

Whole-room 24-h respiration calorimetry was performed in well-nourished pregnant women in only a few studies (29, 39, 41). 24-h Respiration calorimetry can demonstrate changes in the components of TEE under standardized protocols. The increment in 24-h EE observed during pregnancy was largely due to the increase in BMR. The mean ratio of 24-h EE to BMR or PAL was 1.33 and represents 24-h EE under sedentary conditions and may be considered the minimal daily energy expenditure for basic survival.

Free-living TEE was measured by DLW in a few longitudinal studies of well-nourished pregnant women (28, 38, 42, 43). In these studies, TEE increased on average by 1%, 6%, and 19% over pregravid values in the first, second, and third trimesters, respectively. BMR increased by 2%, 9%, and 24%, and AEE changed by −2%, 3%, and 6% relative to baseline. Because of the larger increment in BMR, PAL decreased from 1.73 to 1.60 at term in these studies. In the current study, TEE increased more modestly (3–13% by the third trimester), but baseline TEE and PAL were higher than in the other publications. Because of individual differences in physical activity, AEE is highly variable. The women in the low-BMI group conserved more AEE as pregnancy advanced; BMR and 24-h EE increased by 25% and 20%, but TEE increased by only 3% in the third trimester. AEE and PAL decreased in all BMI groups as pregnancy advanced. Activity records confirmed a decrease across all categories, ranging in intensity from occupational and home activities to sports. Although activity records provide insight into types of activities, they do not provide quantitative estimates of energy expenditure. The DLW method in conjunction with a measure of BMR provides a quantitative estimate of AEE—the amount of energy expended in physical activity. In the pregnant women in the current study, the energy conserved by the decrease in AEE did not totally compensate for the rise in BMR and energy deposited in maternal and fetal tissues.

We did not find that PAL or AEE was associated with gestational changes in weight, FFM, or FM. Interestingly, birth weight was inversely associated with PAL at 22 and 36 wk of pregnancy.

This is consistent with the negative effect of vigorous exercise on birth weight and gestational duration reported by others (44).

Recommendations for energy intake during pregnancy should be derived from healthy populations with favorable pregnancy outcomes. In the current study, the healthy well-nourished women in the normal-BMI group who delivered term infants with birth weights >2.5 kg form the basis of our recommendations. Special considerations should be given to the women with low and high BMI because energetic adaptations or responses to pregnancy may not reflect optimal nutritional conditions. In the current study, total energy costs of pregnancy were estimated from the sum of TEE and energy deposition in maternal and fetal tissues. GWG is a major determinant of the incremental energy needs during pregnancy, because it determines not only energy deposition but also the increase in BMR and TEE resulting from the energy cost of moving a larger body mass. Mean GWG in the low- and normal-BMI groups was within IOM recommendations; absolute and relative increases in BMR were similar, but the increase in TEE was less in the low- than in the normal-BMI group because of a greater conservation in AEE. GWG in the high-BMI group was excessive and should be discouraged to prevent poor maternal and fetal outcomes (5). On the basis of the women in the normal-BMI group, the incremental needs during pregnancy were negligible in the first trimester, 350 kcal/d in the second trimester, and 500 kcal/d in the third trimester over non-pregnant values. Because of higher GWGs, maternal fat depositions, and increments in BMR, these estimated energy requirements are higher than the 1985 FAO/WHO/UNU (2) and 1989 US recommendations for energy intakes in pregnant women (3). Reductions in physical activity do not totally compensate for increases in BMR and energy deposited in maternal and fetal tissues; thus, increases in dietary energy intakes are required as pregnancy progresses.

We thank the women who participated in this study and acknowledge the contributions of Carolyn Heinz and Marilyn Navarrete for study coordination, Sopar Seributra for nursing, Sandra Kattner for dietary support, and Maurice Puyau, Firoz Vohra, Anne Adolph, Roman Shypailo, JoAnn Pratt, and Shide Zhang for technical assistance.

NFB acted as the principal investigator of this study and oversaw the study design, data collection, and data analysis. WWW was responsible for the isotopic analysis. MST supervised the energy expenditure measurements. KJE was responsible for the body-composition measurements. EOS provided advice about the statistical analyses. The authors had no conflicts of interest.

REFERENCES

1. Hytten FE, Chamberlain G. Clinical physiology in obstetrics. Oxford, United Kingdom: Blackwell Scientific Publications, 1991.
2. FAO/WHO/UNU Expert Consultation. Energy and protein requirements. Geneva: World Health Organization, 1985.
3. National Research Council, Subcommittee on the 10th ed of the RDAs. Recommended dietary allowances. Washington, DC: National Academy Press, 1989.
4. Prentice AM, Spaaij CJK, Goldberg GR, et al. Energy requirements of pregnant and lactating women. Eur J Clin Nutr 1996;50:S82–111.
5. Institute of Medicine, Food and Nutrition Board. Nutrition during pregnancy, weight gain and nutrient supplements. Washington, DC: National Academy Press, 1990.
6. Abrams B, Altman SL, Pickett KE. Pregnancy weight gain: still controversial. Am J Clin Nutr 2000;71(suppl):1233S–41S.
7. International Dietary Energy Consulting Group. The doubly-labeled water method for measuring energy expenditure: technical recommendations for use in humans. In: Prentice AM, ed. Vienna: NAHRES-4 International Atomic Energy Agency, 1990.
8. Ellis KJ, Shypailo RJ. Whole-body potassium measurements independent of body size. In: Ellis KJ, Eastman JD, eds. Human body composition: in vivo methods, models, and assessment. New York: Plenum Press, 1993:371–5.
9. Wong WW, Lee LS, Klein PD. Deuterium and oxygen-18 measurements on microliter samples of urine, plasma, saliva, and human milk. Am J Clin Nutr 1987;45:905–13.
10. Akers R, Buskirk ER. An underwater weighing system utilizing "force cube" transducers. J Appl Physiol 1969;26:649–52.
11. Wilmore JH. A simplified method for determination of residual lung volumes. J Appl Physiol 1969;27:96–100.
12. 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. Clin Sci 1992;82:687–93.
13. King JC, Calloway DH, Margen S. Nitrogen retention, total body ^{40}K and weight gain in teenage pregnant girls. J Nutr 1973;103:772–85.
14. Moon JK, Vohra FA, Valerio Jimenez OS, Puyau MR, Butte NF. Closed-loop control of carbon dioxide concentration and pressure improves response of room respiration calorimeters. J Nutr 1995;125:220–8.
15. Wetherburn MW. Phenol-hypochlorite reaction for determination of ammonia. Anal Chem 1967;39:971.
16. Livesey G, Elia M. Estimation of energy expenditure, net carbohydrate utilization, and net fat oxidation and synthesis by indirect calorimetry: evaluation of errors with special reference to the detailed composition of fuels. Am J Clin Nutr 1988;47:608–28.
17. de Weir JB. New methods for calculating metabolic rate with special reference to protein metabolism. J Physiol 1949;109:1–9.
18. Wong WW, Clark LL, Llaurador M, Klein PD. A new zinc product for the reduction of water in physiological fluids to hydrogen gas for $^2H/^1H$ isotope ratio measurements. Eur J Clin Nutr 1992;46:69–71.
19. Wong WW, Cochran WJ, Klish WJ, Smith EO, Lee LS, Klein PD. In vivo isotope-fractionation factors and the measurement of deuterium- and oxygen-18-dilution spaces from plasma, urine, saliva, respiratory water vapor, and carbon dioxide. Am J Clin Nutr 1988;47:1–6.
20. Halliday D, Miller AG. Precise measurement of total body water using trace quantities of deuterium oxide. Biomed Mass Spectrom 1997;4:82–7.
21. Pflug KP, Schuster KD, Pichotka JP, Forstel H. Fractionation effects of oxygen isotopes in mammals. In: Klein ER, Klein PD, eds. Stable isotopes: Proceedings of the Third International Conference. New York: Academic Press, 1979:553–61.
22. Schoeller DA, Leitch CA, Brown C. Doubly labeled water method: in vivo oxygen and hydrogen isotope fractionation. Am J Physiol 1986;1:R1137–43.
23. Black AE, 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.
24. 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. Am J Obstet Gynecol 2003;189:1423–32.
25. Durnin JV. Energy requirements of pregnancy: an integration of the longitudinal data from the five-country study. Lancet 1987;2:1131–3.
26. 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. Br J Obstet Gynaecol 1979;86:929–40.
27. Forsum E, Sadurskis A, Wager J. Resting metabolic rate and body composition of healthy Swedish women during pregnancy. Am J Clin Nutr 1988;47:942–7.
28. Goldberg GR, Prentice AM, Coward WA, et al. Longitudinal assessment of energy expenditure in pregnancy by the doubly labeled water method. Am J Clin Nutr 1993;57:494–505.
29. de Groot LCPGM, Boekholt HA, Spaaij CJK, et al. Energy balances of healthy Dutch women before and during pregnancy: limited scope for metabolic adaptations in pregnancy. Am J Clin Nutr 1994;59:827–32.
30. Spaaij CJK. The efficiency of energy metabolism during pregnancy and lactation in well-nourished Dutch women. Wageningen, Netherlands: The University of Wageningen, 1993.
31. 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. Am J Clin Nutr 1988;48:24–9.
32. Lindsay CA, Huston L, Amini SB, Catalano PM. Longitudinal changes in the relationship between body mass index and percent body fat in pregnancy. Obstet Gynecol 1997;89:377–82.

33. 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. Obstet Gynecol 1997;90:483–8.
34. Kopp-Hoolihan LE, Van Loan MD, Wong WW, King JC. Fat mass deposition during pregnancy using a four-component model. J Appl Physiol 1999;87:196–202.
35. 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. Am J Clin Nutr 1997;66:1315–22.
36. Durnin JVGA, McKillop FM, Grant S, Fitzgerald G. Energy requirements of pregnancy in Scotland. Lancet 1987;2:897–900.
37. van Raaij JMA, Vermaat-Miedema SH, Schonk CM, Peek MEM, Hautvast JGAJ. Energy requirements of pregnancy in The Netherlands. Lancet 1987;2:953–5.
38. Kopp-Hoolihan LE, Van Loan MD, Wong WW, King JC. Longitudinal assessment of energy balance in well-nourished, pregnant women. Am J Clin Nutr 1999;69:697–704.
39. Prentice AM, Goldberg GR, Davies HL, Murgatroyd PR, Scott W. Energy-sparing adaptations in human pregnancy assessed by whole-body calorimetry. Br J Nutr 1989;62:5–22.
40. 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. Am J Clin Nutr 1987;45:1442–50.
41. Butte NF, Hopkinson JM, Mehta N, Moon JK, Smith EO. Adjustments in energy expenditure and substrate utilization during late pregnancy and lactation. Am J Clin Nutr 1999;69:299–307.
42. Goldberg GR, Prentice AM, Coward WA, et al. Longitudinal assessment of the components of energy balance in well-nourished lactating women. Am J Clin Nutr 1991;54:788–98.
43. Forsum E, Kabir N, Sadurskis A, Westerterp K. Total energy expenditure of healthy Swedish women during pregnancy and lactation. Am J Clin Nutr 1992;56:334–42.
44. Wolfe LA, Mottola MF. Aerobic exercise in pregnancy: an update. Can J Appl Physiol 1993;18:119–47.