Energy Requirements during Pregnancy and Consequences of Deviations from Requirement on Fetal Outcome

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Energy requirements as defined in the 1985 FAO/WHO/UNU report on Energy and Protein Requirements [1] should support a body size and composition and level of energy expenditure (EE) consistent with good health, and allow for economically necessary and socially desirable physical activity. In pregnancy, extra energy is needed to cover the costs of maternal and fetal tissue accretion, and the rise in EE attributable to basal metabolism and physical activity. Because of uncertainties regarding desirable gestational weight gain (GWG), maternal fat deposition, putative reductions in physical activity and energetic adaptations to pregnancy, controversy remains regarding energy requirements during pregnancy [2]. Dietary energy studies imply that the incremental needs of pregnancy are relatively low. Calorimetric studies have demonstrated energetic adaptations to pregnancy via suppression of basal metabolism and reduction in physical activity. Energy requirements during pregnancy have been based on immediate infant and maternal outcomes; the long-term consequences of inadequate and excess maternal energy intake on fetal growth and development are just now being recognized. The objectives of this chapter are to review: (1) energy requirements during pregnancy; (2) energetic adaptations to pregnancy, and (3) consequences of deviations from maternal energy requirement on fetal outcome.

Approaches to Defining Energy Requirements during Pregnancy

The 1985 FAO/WHO/UNU [1] recommendations for energy intake of pregnant women (1,200 kJ/day throughout pregnancy, or 840 kJ/day if healthy women
reduce their physical activity) are based on a theoretical model developed by Hytten and Chamberlain [3, 4]. Assumptions underlying this model were: a pre-pregnant body weight between 60 and 65 kg; an average GWG of 12.5 kg; maternal fat mass (FM) accretion of 3.8 kg, and an average infant birth weight of 3.4 kg. Hytten and Chamberlain’s model accounts for fat accretion and the rise in basal metabolism, but ignores potential changes in physical activity and the thermic effect of food (TEF). Alternatively, energy requirements can be derived from total EE (TEE) measured by the doubly labeled water (DLW) method which captures basal metabolic rate (BMR), energy expended in physical activity and TEF [5], plus an allowance for energy deposition, as in the Institute of Medicine (IOM) recommendations for energy intake of pregnant women [6].

**Gestational Weight Gain**

GWG is a major determinant of the incremental energy needs during pregnancy, since it determines not only energy deposition, but also the increase in BMR and TEE due to the energy cost of moving a larger body mass. GWG comprises the products of conception (fetus, placenta, amniotic fluid), the increases in various maternal tissues (uterus, breasts, blood, extracellular extravascular fluid), and the increases in maternal fat stores. Data from the WHO Collaborative Study on Maternal Anthropometry and Pregnancy Outcomes on 110,000 births from 20 different countries were used to define anthropometric indicators which are most predictive of fetal outcome (low birth weight, LBW; intrauterine growth retardation, and preterm birth) and maternal outcome (preeclampsia, postpartum hemorrhage, and assisted delivery) [7]. Birth weights between 3.1 and 3.6 (mean 3.3) kg were associated with a lower risk of fetal and maternal complications. The range of GWG associated with birth weights of >3 kg was 10–14 (mean 12) kg.

Because of the interaction between the pre-pregnancy body mass index (BMI) and GWG on birth weight, the IOM recommended different ranges of GWG for women with low BMI (BMI <19.8 kg/m²: 12.5–18 kg), normal BMI (19.8–26.0 kg/m²: 11.5–16 kg), and high BMI (overweight BMI >26.0–29.0: 7–11.5 kg, or obese BMI >29.0: at least 6 kg) [8]. The recommended ranges were derived from the 1980 US National Natality Survey and based on the observed GWG of women delivering full-term (39–41 weeks), normally grown (3–4 kg) infants without complications. A systematic review showed that GWG within the IOM’s recommended ranges was associated with the best fetal and maternal outcomes [9]. The recommended range of GWG for women with normal pre-pregnancy BMI was 11.5–16 (mean 13.8) kg.
Energy Deposition: Fat and Protein Accretion

Energy deposition during pregnancy is best estimated from fat and protein accretion. Because of gestational changes in the hydration and density of fat-free mass (FFM), basic assumptions used for more commonly available two-compartment models are not valid [10]; hence, estimation of the body composition of pregnant women should be based on three- or four-component models. Fat accretion during pregnancy estimated using valid techniques in normal-weight women is summarized in table 1. The 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, the 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 (range 10–14) kg observed in the WHO Collaborative Study [7] would be 3.7 (range 3.1–4.4) kg.

The most comprehensive body composition study was by Lederman et al. [11] who used a multi-compartment model to measure FM at 14 and 37 weeks of gestation in 200 women stratified by BMI. Weight gain was positively correlated with fat gain; mean FM gains were 4.8, 3.9 and 2.8 kg associated with weight gains of 12.6, 12.2, and 11.0 kg in the underweight, normal-weight, and overweight women, respectively. We [12] also estimated fat accretion using a multi-component body composition model in 63 women with low, normal and high pre-pregnancy BMI. Fat gains were 5.3, 4.6 and 8.4 kg for women in the low, normal and high BMI groups. Weight gain was linearly correlated with gains in total body water (TBW), total body potassium (TBK), protein, FFM and FM. For those women gaining 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, respectively. Excessive GWG was attributed primarily to FM gain, not FFM accretion. Maternal fat retention at 27 weeks postpartum was significantly higher in women who gained above the IOM recommendations for GWG compared with those who gained within or below the recommendations.

Protein is deposited predominantly in the fetus (42%), but also in the uterus (17%), blood (14%), placenta (10%), and breasts (8%) [4]. Protein is deposited unequally across pregnancy, predominantly in late pregnancy. Hytten and Chamberlain [4] estimated that 925 g protein are deposited in association with a 12.5-kg GWG. Protein deposition was distributed as 36, 129, 333 and 427 g for 0–10, 10–20, 20–30, and 30–40 weeks of pregnancy, respectively.

Protein deposition has been estimated indirectly from measurements of TBK 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 [12–17]. MacGillivray and Buchanan [13] studied 8 women in early pregnancy
### Table 1. Fat mass accretion during pregnancy in healthy, normal-weight women

<table>
<thead>
<tr>
<th>Reference</th>
<th>Multicomponent body composition model</th>
<th>Country</th>
<th>n</th>
<th>Initial measurement week of gestation</th>
<th>Final measurement week of gestation</th>
<th>Gestational weight gain kg</th>
<th>Gestational weight gain extrapolated kg</th>
<th>Fat mass gain kg</th>
<th>Fat mass gain extrapolated kg</th>
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</thead>
<tbody>
<tr>
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<td>TBW, TBK</td>
<td>UK</td>
<td>27</td>
<td>12</td>
<td>37</td>
<td>10.4</td>
<td>13.2</td>
<td>2.4</td>
<td>3.1</td>
</tr>
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<td>Forsum et al. [17], 1988</td>
<td>TBW, TBK</td>
<td>Sweden</td>
<td>22</td>
<td>0</td>
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<td>6.0</td>
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<td>TBW, TBK</td>
<td>UK</td>
<td>12</td>
<td>0</td>
<td>36</td>
<td>11.9</td>
<td>13.2</td>
<td>2.8</td>
<td>3.1</td>
</tr>
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<td>de Groot et al. [22], 1994</td>
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<td>USA</td>
<td>12</td>
<td>0</td>
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<td>11.7</td>
<td>13.8</td>
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<td>Spaaij [23], 1993</td>
<td>UWW</td>
<td>Netherlands</td>
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<td>Spaaij [23], 1993</td>
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<td>Netherlands</td>
<td>42</td>
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<td>3.5</td>
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<tr>
<td>Lindsay et al. [32], 1997</td>
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<td>14.6</td>
<td>5.9</td>
<td>6.8</td>
</tr>
<tr>
<td>Lederman et al. [11], 1997</td>
<td>TBW, UWW, BMC</td>
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<td>46</td>
<td>14</td>
<td>37</td>
<td>12.2</td>
<td>15.3</td>
<td>3.9</td>
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<td>Kopp-Hoolihan et al. [49], 1999</td>
<td>TBW, UWW, BMC</td>
<td>USA</td>
<td>9</td>
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<td>5–10 pp</td>
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<td>15.8</td>
<td>3.6</td>
<td>3.6</td>
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<tr>
<td>Butte et al. [12], 2003</td>
<td>TBW, UWW, BMC</td>
<td>USA</td>
<td>34</td>
<td>0</td>
<td>36</td>
<td>12.8</td>
<td>14.2</td>
<td>4.6</td>
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<td>11.9</td>
<td>13.8</td>
<td>3.7</td>
<td>4.3</td>
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</table>

TBW = Total body water; TBK = total body potassium; UWW = underwater weighing.
and another 16 in late pregnancy; since the same women were not studied repeatedly, the increase in TBK is unreliable. The results of Emerson et al. [15] based on a sample size of 5 women are questionable; the potassium per kilogram gained was high, and TBK did not decline in the postpartum period in 3 of the subjects. King et al. [14] observed a rate of 24 mEq/week between 26 and 40 weeks of gestation. Pipe et al. [16] found a 312 mEq K increase. Lower increments of 110 and 187 mEq at 36 weeks were found over pre-pregnancy values [12, 17]. Based on a K:N in fetal tissues of 2.15 mEq/g N, total protein deposition estimated from the longitudinal studies of King et al. [14], Pipe et al. [16], Forsum et al. [17] and Butte et al. [12] was 686 g. Protein is not deposited equally throughout pregnancy. Interesting, TBK and total body nitrogen measured by prompt-γ neutron activation did not differ significantly before and after pregnancy, indicating no net accretion of protein during pregnancy [12]. Based on the mean GWG of 12 kg in the WHO Collaborative Study on Maternal Anthropometry and Pregnancy Outcomes [7], total protein deposition would be 597 g, distributed as 1.3 and 5.1 g/day in the second and third trimesters.

**Changes in Energy Expenditure during Pregnancy**

*Basal Metabolism*

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
### Table 2. Protein accretion during pregnancy estimated from changes in total body potassium in healthy, normal-weight women

<table>
<thead>
<tr>
<th>Reference</th>
<th>n</th>
<th>Study interval weeks of pregnancy</th>
<th>TBK measurement mEq</th>
<th>Increase in TBK mEq</th>
<th>TBK mEq/day</th>
<th>TBK mEq/kg gained</th>
<th>Increment in protein g</th>
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<tr>
<td>MacGillivray and Buchanan [13], 1959</td>
<td>8</td>
<td>11.2–37.3</td>
<td>1,952</td>
<td>589</td>
<td>3.22</td>
<td>42.1</td>
<td>1,712</td>
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<tr>
<td></td>
<td>16</td>
<td>cross-sectional</td>
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<td>King et al. [14], 1973</td>
<td>10</td>
<td>26–40</td>
<td>24 mEq/week</td>
<td>336</td>
<td>3.41</td>
<td>44.3</td>
<td>977</td>
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<td></td>
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<td>longitudinal</td>
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<tr>
<td>Emerson et al. [15], 1975</td>
<td>5</td>
<td>20, 24, 28, 32, 35</td>
<td>2,712</td>
<td>480</td>
<td>3.43</td>
<td>86.5</td>
<td>1,395</td>
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<td>longitudinal</td>
<td>3,192</td>
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<td>Pipe et al. [16], 1979</td>
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<td>10–14, 24–28, 36–38</td>
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<td>1.78</td>
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<td>Forsum et al. [17], 1988</td>
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<td>2,397</td>
<td>110</td>
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<td>2,507</td>
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<tr>
<td>Butte et al. [12], 2003</td>
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<td>0–36</td>
<td>2,604</td>
<td>187</td>
<td>0.79</td>
<td>12.8</td>
<td>544</td>
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</tbody>
</table>
Energy Requirements during Pregnancy

energy cost of pregnancy. Several longitudinal studies have been published which measured changes in BMR throughout pregnancy (table 3) [17–24]. In these studies, BMR increased over pre-pregnancy values by 4, 10 and 24% in the first, second and third trimesters, respectively. In our study, BMR increased gradually throughout pregnancy at a mean rate of 45 ± 22 kJ/gestational week. Mean rates were 37 ± 19 kJ/week in the low BMI group, 40 ± 19 kJ/week in the normal BMI group and 68 ± 22 kJ/week in the high BMI group. 24-hour EE measured in the room calorimeter also increased gradually over gestation at a mean rate of 47 ± 26 kJ/gestational week in all women. The rise in BMR accounted for most of the rise in 24-hour EE.

Total Energy Expenditure

Free-living TEE has been measured by DLW in a few longitudinal studies of healthy pregnant women (table 4) [20, 23–26]. In these studies, TEE increased on average by 1, 6, and 19% over pre-gravid values in the first, second and third trimesters, respectively. Activity EE (AEE) changed by -2, 3 and 6% relative to baseline. Because of the larger increment in BMR, the physical activity level (PAL) declined from 1.73 to 1.60 at term in these studies.

In our study [24], TEE increased more modestly (3–13% by the third trimester), but baseline TEE and PAL were higher than in the other publications. TEE increased throughout pregnancy at a mean rate of 22 ± 54 kJ/gestational week for all women. In the normal BMI group, TEE increased linearly at a mean rate of 31 ± 43 kJ/gestational week. Because of individual differences in physical activity, AEE was highly variable. The women in the low BMI group conserved more AEE as pregnancy advanced; BMR and 24-hour EE increased by 25 and 20%, but TEE increased only by 3% in the third trimester. AEE and PAL declined in all BMI groups as pregnancy advanced. In these pregnant women, 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.

In our study, PAL and AEE at 22 and 36 weeks of pregnancy were not associated with gestational changes in weight, FFM or FM. Interestingly, birth weight was inversely associated with PAL at 22 and 36 weeks of gestation. Birth weight was significantly predicted from gender, gestational age, and PAL at 22 weeks (PAL coefficient −0.40, p = 0.038; r² = 0.31, p = 0.001) and at 36 weeks (PAL coefficient −0.58, p = 0.007; r² = 0.28, p = 0.001). This is consistent with the negative impact of vigorous exercise on birth weight and gestational duration reported by others [27].

Estimation of Energy Requirements during Pregnancy

Energy requirements of pregnancy in healthy, normal-weight women was estimated factorially from the increment in BMR and from the increment in
### Table 3. Changes in basal metabolic rate (BMR) during pregnancy in healthy women

<table>
<thead>
<tr>
<th>Reference</th>
<th>Country</th>
<th>n</th>
<th>Weight gain, kg&lt;sup&gt;a&lt;/sup&gt;</th>
<th>BMR, MJ/day</th>
<th>Cumulative increase values in BMR, MJ&lt;sup&gt;b&lt;/sup&gt;</th>
<th>% Change in BMR from pre-pregnancy values</th>
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<td></td>
<td></td>
<td>pre-pregnancy</td>
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<td>2nd trimester</td>
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<td>van Raaij et al.</td>
<td>Netherlands</td>
<td>57</td>
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<td>Forsum et al.</td>
<td>Sweden</td>
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<td>de Groot et al.</td>
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<td>6.0</td>
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</tr>
</tbody>
</table>

<sup>a</sup>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/week towards term [4].

<sup>b</sup>Calculated as cumulative increase in BMR over pregnancy using pre-pregnancy or early pregnancy values as baseline.
Table 4. Total energy expenditure measured by the doubly labeled water method in healthy, normal-weight women during pregnancy

<table>
<thead>
<tr>
<th>Reference</th>
<th>Country</th>
<th>n</th>
<th>Week of gestation</th>
<th>Weight kg</th>
<th>Height m</th>
<th>BMI</th>
<th>TEE MJ/day</th>
<th>BMR MJ/day</th>
<th>AEE MJ/day</th>
<th>PAL</th>
<th>Weight/ NP weight</th>
<th>TEE/ NPTEE</th>
<th>BMR/ NPBMR</th>
<th>AEE/ NPAAE</th>
<th>TEE MJ/kg/ day</th>
<th>BMR MJ/kg/ day</th>
<th>AEE MJ/kg/ day</th>
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<tbody>
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<td>5.86</td>
<td>3.92</td>
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<td>5.86</td>
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<td>1.04</td>
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BMI = Body mass index; TEE = total energy expenditure; BMR = basal metabolic rate; AEE = activity energy expenditure; PAL = physical activity level; NP = nonpregnant.
TEE, plus the energy deposition associated with a mean GWG of 13.8 kg (table 5). Energy deposition was derived from fat and protein accretion in well-nourished women. The two approaches gave similar results for the energy cost of pregnancy averaging 371 MJ, distributed as 430, 1,375 and 2,245 kJ/day for the first, second and third trimesters, respectively.

The incremental cost of pregnancy was also predicted for women with a mean GWG of 12.0 kg, as found in the WHO Collaborative Study on Maternal Anthropometry and Pregnancy Outcomes [7]. It was assumed that the increments in BMR and TEE were proportional to the weight gain. The incremental energy cost of pregnancy would be 323 MJ, distributed as 375, 1,200 and 1,950 kJ/day for the first, second and third trimesters, respectively.

Recommendations for dietary energy intake during pregnancy are generally based on mean estimates of healthy, normal-weight women. However, it is also important to recognize the high variability in energy requirements during pregnancy, as seen with underweight and overweight women, as well as normal-weight women. In our study, we estimated the energy cost of pregnancy in 63 women with a low, normal or high BMI [24]. In the normal BMI group, the incremental needs during pregnancy were negligible in the first trimester, 1,464 kJ/day in the second trimester, and 2,092 kJ/day in the third trimester [8]. Due to their higher GWG, maternal fat deposition and increments in BMR, these estimated energy requirements are higher than the 1985 FAO/WHO/UNU recommendations for energy intake of pregnant women [1]. Absolute and relative increases in BMR in the low BMI group were similar to the normal BMI group; however, the increase in TEE was less due to greater conservation in AEE. Consequently, the energy costs of pregnancy were lower at 573, 682 and 1,230 kJ/day across pregnancy. In the high BMI group, GWG exceeded

---

**Fig. 2.** Physical activity level (PAL), computed as total energy expenditure (TEE) divided by basal metabolic rate (BMR), of women with low, normal or high pre-pregnancy body mass index (BMI) while nonpregnant (NP), and at 22 and 36 weeks of pregnancy.
**Table 5.** Total energy requirements during pregnancy in healthy women

### A Rates of tissue deposition

<table>
<thead>
<tr>
<th></th>
<th>1st Trimester&lt;sup&gt;a&lt;/sup&gt;</th>
<th>2nd Trimester</th>
<th>3rd Trimester</th>
<th>Total deposition, g</th>
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</thead>
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<td>Weight gain, g/day&lt;sup&gt;b&lt;/sup&gt;</td>
<td>20</td>
<td>70</td>
<td>62</td>
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<td>Protein deposition, g/day&lt;sup&gt;b&lt;/sup&gt;</td>
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<tr>
<td>Fat deposition, g/day&lt;sup&gt;b&lt;/sup&gt;</td>
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### B Total energy cost of pregnancy estimated from the increment in basal metabolic rate and energy deposition

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<th>2nd Trimester</th>
<th>3rd Trimester</th>
<th>Total energy cost, kJ</th>
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<td>Fat deposition, kJ/day</td>
<td>232</td>
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<td>752</td>
<td>166,419</td>
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<tr>
<td>Increment in basal metabolic rate, kJ/day</td>
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<td>465</td>
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<td>Efficiency of energy utilization, kJ/day&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>Total energy cost of pregnancy, kJ/day</td>
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### C Total energy cost of pregnancy estimated from the increment in total energy expenditure and energy deposition

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<td>Protein deposition, kJ/day</td>
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<td>Fat deposition, kJ/day</td>
<td>232</td>
<td>841</td>
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<td>166,419</td>
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<tr>
<td>Increment in total energy expenditure, kJ/day</td>
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</table>

<sup>a</sup>Interval (79 days) computed from last menstrual period; total pregnancy (266 days).

<sup>b</sup>Total weight gain of 13.8 kg, protein deposition of 686 g, fat deposition 4.3 kg taken as 23.64 kJ/g for protein and 38.70 kJ/g for fat.

<sup>c</sup>Efficiency of energy utilization taken as 0.90.
the IOM recommendations, resulting in excessive energy costs of 1,536, 1,845 and 1,816 kJ/day for the three trimesters. Excessive GWG in overweight women should be discouraged to prevent poor maternal and fetal outcomes [8].

**Energetic Adaptations**

Energetic adaptations in basal metabolism, energetic efficiency and physical activity can occur to meet the increased energy needs of pregnancy under certain physiological circumstances, but this may reflect suboptimal nutrition.

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. [28]. In well-nourished women the BMR usually begins to rise soon after conception and continues to rise until delivery, although considerable variation is seen in the cumulative increase in BMR. Increased energetic efficiency in the basal state was seen in British [29], Dutch [21] and American [24] pregnant women. In the British study leaner women showed a depression in BMR, adjusted for FFM, up to 24 weeks of gestation [29]. Cumulative increases in BMR were found to be significantly correlated with total weight gain (r = 0.79; p < 0.001) and pre-pregnancy %FM (r = 0.72; p < 0.001) [28]. In contrast, no correlation was found between initial body fatness and changes in BMR in Scottish women [30]. In our study, BMR decreased relative to pre-gravid values during the first and second trimester in some, and increased steadily throughout gestation in other women in the low and normal BMI groups. In the high BMI group, the increase was greater (7, 16 and 38% in the first, second and third trimesters), consistent with their greater GWG and FFM gain. We also found that the

![Fig. 3. Mean basal metabolic rate (BMR) of women with low, normal or high pre-pregnancy body mass index (BMI) measured prior to pregnancy, and at 9, 22 and 36 weeks of pregnancy.](image-url)
increments in BMR and 24-hour EE in the second and third trimesters were correlated not only with changes in weight and FFM, but also independently with pre-pregnancy BMI or %FM. Together, GWG, FFM gain, pre-pregnancy BMI and %FM explained 33–40% of the variability seen in the overall changes in BMR and 24-hour EE. Of several fasting serum biochemistries explored, total triiodothyronine/thyroxine (T₃/T₄) was found to be associated with the changes in BMR and 24-hour EE throughout pregnancy ($r = 0.38–0.57; p < 0.005$). A significant effect of birth weight on the changes in BMR and 24-hour EE was seen in the third trimester ($r = 0.42–0.52; p < 0.002$).

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 [31]. As a result, the average BMR in pregnancy was even lower than before pregnancy.

The energetic efficiency of performing physical activities might be increased in pregnancy. Prentice et al. [28] 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. The net cost of non-weight-bearing activities 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

![Fig. 4.](image)

**Fig. 4.** Individual changes in basal metabolic rate (BMR) in women with low, normal or high pre-pregnancy body mass index (BMI) measured between 0–9, 0–22, and 0–36 weeks of pregnancy.
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.

The energy cost of physical activity also depends on duration, frequency and
intensity of performing various activities. Pregnant women may change their
daily activities or change the pace or intensity of the work performed. 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
[32]. A review of 122 studies found that in most societies, women were
expected to continue with partial or full duties throughout most of pregnancy
[33]. However, quantitative DLW studies in well-nourished pregnant women
showed a decline in AEE and PAL as pregnancy advanced (table 4). Free-
living TEE has been measured cross-sectionally in pregnant women relative
to controls from developing countries using DLW, activity diaries and heart
rate monitoring [34–37]. With the exception of the Gambian study by Singh
et al. [35], TEE and AEE declined throughout pregnancy relative to controls.
PAL in the nonpregnant-nonlactating 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 developing countries as well.

Energetic-sparing adaptations may protect the fetus from environmental
and nutritional stresses, but they may not totally prevent inadequate GWG
and adverse pregnancy outcomes [38]. Because fetal growth is slow and
gestational duration long in humans, the extra energy requirement for
pregnancy relative to maternal metabolic size is relatively low. Faced with the
energetic demands of pregnancy, undernourished women display energy-
sparing responses, whereas better-nourished women are more energy-
profligate. The wide range of total energy costs of pregnancy from −30 MJ in
unsupplemented Gambian women to 523 MJ in Swedish women illustrate
tremendous metabolic plasticity. Although this metabolic plasticity confers
an immediate survival advantage, there are long-term consequences with any
nutritional deprivation.

Consequences of Deviations from Maternal Energy
Requirement on Fetal Outcome

Negative deviations from maternal energy requirement (dietary energy
deficiency) can perpetuate low maternal weights and inadequate GWG.
Failure of the materno-placental supply to satisfy fetal energy and nutrient
requirements can result in intrauterine growth retardation, increased
perinatal and neonatal morbidity and mortality, and a range of adaptations
and developmental changes which may lead to permanent structural and
metabolic alterations which may influence metabolic diseases later in life. Epidemiological studies have shown an inverse relationship between birth weight and adult risk of chronic diseases such as obesity, coronary heart disease, stroke, type-2 diabetes, and some cancers [39].

Deviations from maternal energy requirement prior to conception as well as during pregnancy adversely affect the fetus. In the WHO Collaborative Study on Maternal Anthropometry and Pregnancy Outcomes on 110,000 births from 20 different countries, maternal anthropometric indicators (pre-pregnancy weight, GWG) were examined for their impact on pregnancy outcomes [40]. Mean maternal heights ranged from 148 to 163 cm, pre-pregnancy weights from 42.1 to 65.6 kg, and birth weights from 2.6 to 3.4 kg. Pre-pregnancy weight (OR = 2.38) and attained weight at 36 weeks gestation (OR = 2.59) were the most significant predictors of LBW.

Further evidence of the adverse consequences of inadequate GWG on fetal outcome is the effectiveness of maternal food supplementation trials (table 6). A meta-analysis of randomized control trials in a Cochrane review on balanced energy/protein maternal supplementation demonstrated a significant increase in birth weight (p = 0.05), and nonsignificant increases in head circumference and length. The incidence of small for gestational age (SGA) birth was reduced substantially (p = 0.0003). Also, reductions in stillbirth (p = 0.04), and neonatal deaths (p = 0.08), based on three trials appear important. Maternal supplementation was associated with modest increases in maternal weight gain (p = 0.03). Larger effects on fetal growth were seen with supplements that provided higher energy. In The Gambia, supplements providing 4,255 kJ and 22 g protein from mid-pregnancy reduced LBW prevalence by 39%, increased birth weight by 136 g after adjustments and reduced infant mortality by 40% [41].

Several recent studies corroborate the impact of the components of GWG on birth weight. Lederman et al. [42] found that maternal weight and TBW, but not FM at term, were significantly related to infant birth weight. In American women, maternal FM gain was not related to infant birth weight, but was positively correlated with maternal FM retained at 4–6 weeks postpartum [43]. In Swedish women, FFM gain, but not FM gain, in early pregnancy was correlated with birth weight [17]. In Chilean women, FFM was the most important component influencing birth weight (r = 0.38), followed by FM (r = 0.27) [44]. In Guatemalan women, FM gain before 30 weeks was associated with birth weight; however, the fat gain (6.23 kg) estimated by bioelectrical impedance was questionably high for a GWG of 10.0 kg [45]. The positive association between birth weight and FFM may be mediated by plasma volume expansion. Our results confirm the well-recognized association between birth weight and maternal pre-pregnancy weight (r = 0.34; p = 0.009) and GWG (r = 0.35; p = 0.006) [46]. Birth weight was also positively correlated with total gain in TBW, TBK and FFM, but not FM. In a multiple regression, 37.9% of the variability in birth weight was accounted for by
### Table 6. Studies in the Cochrane review of balanced protein/energy supplementation during pregnancy [54]

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<th>protein g</th>
<th>% protein</th>
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gestational age, pre-pregnancy weight and GWG. Infant body composition (FFM, FM, %FM) at 2 weeks of age was not correlated with maternal body composition prior to pregnancy or at 2 weeks postpartum. Total gestational gains in maternal weight, TBW, TBK, FFM and FM were not shown to have an effect on infant FFM, FM or %FM at 2 weeks of age.

Positive deviations from maternal energy requirement can result in excessive GWG. While inadequate GWG is associated with risk of LBW, excess GWG is associated with high birth weight, which can secondarily lead to prolonged labor, cesarean delivery, shoulder dystocia, birth trauma and asphyxia [8]. Women who are overweight are much more likely to have gestational diabetes and glucose intolerance, and in turn produce larger infants with a propensity to childhood obesity and adolescent-onset of type-2 diabetes. Based on the US Prevention Pregnancy Nutrition Surveillance System, LBW risk consistently decreased with increasing GWG for average weight women [47]. There was no reduction in LBW risk beyond GWG of 14–15 kg for overweight women and 7–9 kg for obese women. The incidence of high birth weight increased with GWG >16 kg for normal weight women, GWG >9–11 kg for overweight women, and across all GWG categories for obese women.

Although energetic-sparing adaptations can occur during pregnancy to protect the fetus from environmental and nutritional stresses, they may not totally prevent adverse maternal and fetal outcomes. Every effort should be made to provide pregnant women with sufficient but not excessive food to meet the substantial energy requirements of pregnancy.

References

Energy Requirements during Pregnancy

Dr. Di Renzo: Very nice presentation. I have 3 very sharp questions. First, how can gender modify your result especially on energy requirements? Is there any correlation with fetal gender? Does female or male make a difference?

Dr. Butte: You mean the effect of gender on energy requirements?

Dr. Di Renzo: Yes.

Dr. Butte: Absolute energy requirements differed by gender (boys > girls), but energy requirements adjusted for weight or fat-free mass did not differ between boys and girls. PAL was not significantly different between boys and girls.

Dr. Di Renzo: My second question is about excessive food. Can you quantify calories, for instance a cutoff for excessive food which you think may have an effect on weight and consequently some clinical outcome?

Dr. Butte: Yes, I think we could take some of these numbers and come up with what we think is excessive for a given woman. As I said, the women in the high body mass index (BMI) group all gained excessively and their energy requirements were up to 3,100 cal/day; so obviously they were consuming that amount to support their energy expenditure and excess fat deposition. Since energy requirements will depend...
on a woman’s body size, PAL and weight gain, monitoring weight gain provides an indicator of excessive energy intake.

Dr. Di Renzo: And finally, do you have any experience with twin pregnancies?

Dr. Butte: Actually in this study we had 2 or 3 sets of twins and 1 set of triplets, and the mothers continued through the study up until the second or third trimesters, but certainly that is not enough to publish, and they were eliminated from the data set. It would be fascinating to do a full study on twin pregnancies.

Dr. Pencharz: I am just wondering what explanation you have for the resting metabolic rate falling in the second trimester of some women?

Dr. Butte: We measured many hormones in the study with that mind, trying to understand the earlier observations of Prentice et al. [1], and it is interesting that the only correlate found was the T₃ to T₄ ratio with changes in basal metabolic rate.

Dr. Kramer: I have one comment and one question. The comment has to do with your slide that said something about reduced maternal energy intake and long-term consequences for adult chronic disease. As far as I know there is not a shred of evidence linking reduced maternal energy intake and adult chronic disease. So that must be an extrapolation from the association between small babies or small weight for dates and adult chronic disease.

Dr. Butte: Those last two slides I showed, the first one, which was looking at low gestational weight gain, really would refer to the infant where we have some evidence of that. The second slide was excess energy intake where I think there is evidence both for the infant and the adult that there is risk for later disease. So high gestational weight gain certainly can lead to gestational diabetes and later problems in the mother as well.

Dr. Kramer: The other question has to do with your data showing a negative correlation between maternal energy expenditure and birth weight. I wonder whether that correlation could be due to the fact that mothers who are having problems with their pregnancy reduce their physical activity. Either on medical advice or because they are not feeling well, perhaps they actually restricted their physical activity. Trials that have randomized women to increase or reduce their exercise have not shown any adverse effects of exercise [2]. They are small trials, but they are larger than your study and don’t show any adverse effects on fetal growth of increased physical activity.

Dr. Butte: The studies by Clapp et al. [3, 4] certainly show an effect on birth weight and gestational duration. The studies may not be strictly randomized but they consistently show an effect of recreational exercise on birth weight. In our study we had some women who had complications and dropped out of the study. We had a few women who were put to bed rest and just other complications of pregnancy, so the 63 that made up the study were considered healthy and delivered healthy term infants. For the most part these women tended to be working women, middle class, upper class women, many of them did recreational activities, many had small toddlers. So I would describe the data set as typical busy middle-class Westernized women. According to their exercise diaries, many decreased the intensity and sometimes changed the type of activity by the third trimester. So it was not so much that they were feeling bad, it was just that they decreased the intensity of exercise and sometimes the type.

Dr. Kramer: Then you are not concluding from your study that women should reduce their physical activity?

Dr. Butte: The inverse correlation between PAL and birth weight suggests that there may be a limit of physical activity above which birth weight might be compromised. Most women in the study spontaneously decreased their PAL by the third trimester.

Dr. Kramer: But I would argue that the evidence from randomized trials is much stronger, because without knowing why the women either were able to maintain or had

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to reduce their physical activity, it is very hard to make any conclusions about the causal
effects of physical activity on pregnancy outcome in an observational study like that.

Dr. Butte: I agree with that.

Dr. Uauy: So how do we match your very careful observations and the epidemi-
ologic data that we heard from Dr. Kramer? If women are consuming less than they
should yet they don’t achieve, we don’t observe an effect in the supplementation trials.
Are we not giving enough, should we actually give more or should we actually do this?
Maybe there is a problem with compliance, that people are given the food but they
don’t consume it. So how do we approach these needs for optimal whatever that is?

Dr. Butte: I think that is the question. Many of the trials have not been sufficient,
and it could be in the absolute amount that is supplemented and also the compliance.
The Gambian study [5] had tremendous success and that was across several villages
and delivering the supplement to the pregnant women. They made sure the women
ate the biscuits providing 4,255 kJ. The effect that they got in that study was very
impressive.

Dr. Uauy: Those women were getting 1,300 cal in their diet so supplements will
work commonly under conditions of semi starvation. So maybe we should actually
limit our interventions as you said, target women who are either wasted or for whom
we can document very low intakes. That obviously puts the public health intervention
into a very limited pool, rather than into everybody that has low birth weight, which
up to now has been the model for the intervention.

Dr. Butte: I think Prentice et al. [6] would be the first to say that they have proba-
bly underestimated intake from their earlier studies. We have all struggled with that
problem, so I doubt their intakes were quite as low as has been reported. I think the
best indicator is what the gestational weight gain of the women was. In women only
gaining 7, 8, 9 kg during pregnancy, dietary intake is probably inadequate. Instead of
trying to measure dietary intake, I would measure gestational weight gain to identify
at-risk populations.

Dr. Hornstra: These supplementation studies, were they started after conception
or before?

Dr. Butte: Maybe Dr. Kramer knows each one better. Usually they are started once
pregnancy had started. Are any of them before pregnancy, Dr. Kramer?

Dr. Kramer: In most of the supplementation studies, the supplement was started
in the second or third trimester. There is one study, the Taiwan study [7], that actu-
ally began supplementation with the birth of the previous offspring and continued all
the way through the following pregnancy, so that it included the inter-pregnancy
interval as well as the pre-conception period and the early index pregnancy. The mag-
nitude of the effect on fetal growth in the Taiwan trials was not larger than in other
trials, presumably because it did not get much of a net increase in energy intake, as
opposed to the Gambian trial which had a huge increase in intake. So there is not a lot
of evidence to go by, but the evidence that we have doesn’t suggest that starting sup-
plementation earlier or even pre-conceptionally is more effective than starting it later.

Dr. Hornstra: Have these infants been followed up for a longer period of time so
that if perhaps there is an effect it shows up later and not immediately as a difference
in birth weight. Is anything known about that?

Dr. Butte: You are referring to the supplementation trials in general?

Dr. Hornstra: Yes.

Dr. Butte: I think in the Gambian study those infants are being followed up, I think
Dr. Moore can speak about that.

Dr. Moore: Children born during the second Gambian supplementation study, in
which the mothers were supplemented between 1989 and 1994, have been followed
up but not to look at chronic disease outcomes, only to look at immune outcomes.
They are now approaching puberty, so I think we need to revisit them, and again it will be really interesting to follow up those children to look at the metabolic consequences. They were supplemented from 20 weeks of gestation until birth or in the control group it was 20 weeks following delivery.

Dr. Yajnik: Do you have any information on glucose, insulin and lipids in these women?

Dr. Butte: Yes, we studied all of them and many of the different hormones.

Dr. Yajnik: And what does it show? Because I think that it is an important determinant or confounder between maternal weight, the full intake and the outcome in the size of the baby at birth. What we would expect in general is that larger women eating more might be more glucose-intolerant.

Dr. Butte: None of them had gestational diabetes. So again we just see a continuum of higher insulin levels and the women in the high BMI group certainly had a higher insulin to glucose ratio and there was an effect of insulin fasting, insulin levels on the birth weight of the infants.

Dr. Yajnik: Do you have information on the triglycerides?

Dr. Butte: Yes, we measured triglyceride but I don’t recall the relationship. I can look at that.

Dr. Yajnik: One more point about birth weight and maternal size. Most of the studies which have shown a relationship between low birth weight and future problems relate to smaller babies born to larger mothers i.e. a low birth weight baby born to a larger mother is more at risk for future cardiovascular disease. There is little information for low birth weight babies born to smaller mothers except for one study in China, which was published in the *Annals of Internal Medicine* [8] and our studies in Pune, India. In Mysore, South India larger babies born to larger mothers went on to get diabetes [9]. So I think that has to be kept in mind when we are saying that birth weight predicts future problems, we are forgetting the mothers.

Dr. Moore: I noticed in one of your slides that although there wasn’t a significant difference between the low BMI mothers and the high BMI mothers in terms of gestational age, there was a slight association in that mothers who were bigger had a slightly longer gestational period than the mothers who were smaller. Recently we analyzed the data from the Gambia looking at the seasonality of birth weight (unpublished). It appears that more of the low birth weight in the hungry season is caused by reduced gestational age than we previously thought. I wonder if you know of any other studies that have looked at either pre-conceptionally low BMI or low weight gains in any of the 3 trimesters and how this relates to gestational age?

Dr. Butte: There certainly are a lot of studies that have looked at the effect of the gain in the second or third trimester and there are conflicting results on how it would affect birth weight. I don’t know that those studies have reported on the gestational duration. I am thinking of the studies of Abrams et al. [10] but I just don’t recall if they mentioned the duration. Dr. Kramer, do you know?

Dr. Kramer: I am pretty sure Abrams has looked at that, but I don’t recall any large effect of weight gain on gestational duration in those studies. A number of studies have shown a small effect of BMI.

Dr. Butte: I would say that our studies are simply not large enough to really say whether this has any statistical confidence. But some of the women in our group, not all of them, were avid exercisers and there were a couple who actually delivered preterm and were dropped from the final data set. They delivered before 37 weeks, and I know that they were exercising right up to delivery. We need a much larger sample to really be able to answer that completely.

Dr. Uauy: Regarding the long-term consequences: it might be interesting to comment on the trans-generational effect the data that are emerging from the Martorell follow-up studies [11].
Dr. Butte: Certainly there are both animal work and human studies showing that maternal malnutrition has an inter-generational effect.

Dr. Uauy: I think what is interesting, though in the recent follow-up of Martorell’s data it was shown that in fact there was almost no effect on birth weight but there was very significant effect on the growth over the first 3 years of life [12]. So somehow, although it was not measurable at birth, the child was able to grow I think about 5 cm more over the first 3 years of life. This tells us that birth weight and even birth length do not tell us the whole story of what will happen after birth. A word of caution regarding putting all the weight on birth measurements, somehow the follow-up is also important.

References
