THE EFFICIENCY OF ENERGY METABOLISM DURING PREGNANCY AND LACTATION IN WELL-NOURISHED DUTCH WOMEN

Caroline J.K. Spaaij

Promotor: dr. J.G.A.J. Hautvast
Hoogleraar voedingsleer en voedselbereiding

Co-promotor: dr. ir. J.M.A. van Raaij
Universitair Hoofddocent
Vakgroep Humane Voeding

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STELLINGEN

1. De efficiëntie van de energiestofwisseling verandert niet noemenswaardig tijdens zwangerschap.
   Dit proefschrift.

2. Door de grote verschillen tussen vrouwen in extra energiebehoefte tijdens zwangerschap en lactatie hebben algemene aanbevelingen voor extra energie-inneming weinig praktische waarde.
   Dit proefschrift.

3. Om te voorkomen dat in het lichaamsvetweefsel opgehoopte omgevingscontaminanten vrijkomen en in de moedermelk belanden, verdient het aanbeveling tijdens lactatie niet af te slanken.

4. Door implantatie van een bevruchte eicel in combinatie met hormoontherapie kunnen vrouwen ook na de menopauze kinderen krijgen (*Sauer, Paulson en Lobo. Lancet 1993; 341: 321-323*). Deze ontwikkeling is niet in het belang van de kinderen.

5. In obese vrouwen is het thermisch effect van de maaltijd positief gerelateerd aan de hoeveelheid visceraal vet.
   Leenen, van der Kooy, e.a. American Journal of Physiology: Endocrinology & Metabolism 1992; 263 (26): E913-E919.

6. The progress of science requires more than new data; it needs novel frameworks and contexts.
   Gould. The flamingo's smile. Reflections in natural history. W.W. Norton & Company, Inc. New York 1985: 138.

7. In de stad is de fiets een sneller vervoermiddel dan de auto of het openbaar vervoer.
   De Volkskrant, 17 mei 1993.

8. Bij gebruik van de 'shuffle'-functie van een CD-speler wordt de artistieke keuze van de kunstenaar veronachtzaamd.

9. Een iets geringere consumptie van vlees en zuivelprodukten en een grotere vraag naar biologisch geproduceerd voedsel kunnen ervoor zorgen dat de milieuschade door intensieve landbouw vermindert.
   Alders. De Volkskrant, 10 mei 1993.

10. Voor een goed begrip van 'verantwoorde' televisieprogramma's is grondige kennis van 'pulp' programma's tegenwoordig een vereiste.

11. In het land van melk, boter en kaas staan waarheden als koeien in hoog aanzien. Toch zijn er ook waarheden als lama's, als tijgers, ja, als eenhoorns en basilisken.
    Mulisch. Paniek der onschuld. De Bezige Bij, Amsterdam 1979: 137.

Stellingen behorend bij het proefschrift 'The efficiency of energy metabolism during pregnancy and lactation in well-nourished Dutch women' van Caroline Spaaij. Wageningen, 29 juni 1993.

ABSTRACT

The efficiency of energy metabolism during pregnancy and lactation in well-nourished Dutch women

Thesis by Caroline Spaaij,
Department of Human Nutrition,
Wageningen Agricultural University,
Wageningen, the Netherlands,
29 June 1993.

Pregnancy and lactation involve extra energy needs. As extra energy intakes over pregnancy and lactation are limited, and energy savings by reduced physical activity are assumed to be restricted, it has been postulated that during pregnancy and lactation, energy expenditure is further reduced by improved efficiency of energy metabolism. Such improved metabolic efficiency could be reflected in reduced diet-induced thermogenesis, and increased work efficiency. This hypothesis was addressed in a longitudinal study, including pre-pregnant baseline measurements, measurements in each trimester of pregnancy and measurements during lactation at 2 months post partum. No changes were observed in diet-induced thermogenesis or work efficiency during pregnancy (Chapters 2 and 3, respectively) and lactation (Chapter 5). The power of the study was sufficient to detect changes of physiologically importance in both parameters. As no metabolic adaptations appear to take place, we reassessed the magnitude of the imbalance between energy inputs and outputs during pregnancy and lactation. Pronounced underestimation of the energy savings by reduced physical activity might be the major cause of this imbalance (Chapter 4). Large differences in the changes in energy intake and in physical activity are observed between subjects. This high between-subject variability implies that energy intake recommendations based on group averages may have only limited value for individual women.

Aan mijn ouders

Contents

Chapter 1

INTRODUCTION

Human pregnancy and lactation impose large physiological stresses on the maternal body. Amongst the main nutritional interests are the energy requirements during pregnancy and lactation. Positive energy balances are needed to establish adequate weight gain of both mother and fetus during pregnancy and adequate breast milk production during lactation. Good understanding and quantification of energy costs and possible energy savings during pregnancy and lactation are needed to formulate recommendations for dietary energy intake throughout the reproductive cycle.

Pregnancy

To achieve an optimal outcome of pregnancy, nutrient and energy intakes should meet maternal and fetal requirements. The use of maternal weight gain during pregnancy as an indicator for maternal nutritional status and the progress of pregnancy has been subject to much investigation. The weight gain is positively related with birth weight[1-4], so that the risk of having a low-birth-weight infant decreases if a higher maternal weight gain is achieved. However, as weight gain is also positively associated with weight retention after delivery[5-8], excessive weight gains over pregnancy should be avoided to prevent the onset of obesity. High weight gain is furthermore associated with toxemia[9-11], but in this relationship, toxemia is probably rather the cause than the effect. Both low and high maternal weight gains are associated with increased neonatal mortality[12]. Therefore, monitoring weight gain over pregnancy is considered important for the evaluation of the progress of pregnancy.

During the last 10-15 years, much attention has been payed to the role of pre-pregnant body mass index in the relationship between maternal weight gain and fetal growth: in underweight women, fetal growth appears to be strongly related with maternal weight gain, whereas this relationship is weak or even absent in the very obese[4,13-15]. Therefore, recommended weight gain during pregnancy should be highest in thin women, whereas in the obese, low weight gains apparently do not affect pregnancy outcome.

Weight gain during pregnancy is made up of the increased weight of fetus, placenta, amniotic fluid, uterus, breasts, blood, maternal fat stores, and extracellular extravascular fluid. The energy cost involved with this tissue gain consists of the energy cost of fat and protein deposition, the energy content (i.e. protein and fat content) of these tissues, and the energy needed for maintaining these tissues. In general, no allowance is made for the increased energy cost of moving a heavier body mass, assuming that this expenditure is compensated by a reduction of physical activity.

The most valuable estimates of the energy costs of pregnancy are obtained with longitudinal study designs, preferably those that include measurements before conception. From 1987 onwards, several such longitudinal studies have been published[16-24]. There are pronounced differences between the estimates of the energy costs of human pregnancy in these studies **(Table 1)**.

To cope with the energy costs of pregnancy, women can either increase their energy intake or reduce their energy expenditure. In all the longitudinal studies[16,17,19,20,22,25-27] except one[18], the observed changes in energy intake over pregnancy appeared to be insufficient to meet the energy costs of pregnancy **(Table 1)**. This indicates that substantial energy savings must occur during human pregnancy.

One of the mechanisms to save energy is by reducing the amount and pace of physical activity. Various investigators have reported that pregnant women reduce the pace or intensity of activities[28-30]. Weight gain during pregnancy will cause an increase of the net cost of weight-bearing activity over pregnancy, which might be (partly) compensated by reducing walking pace. Nagy and King observed a 11% increase in the net cost of self-paced walking, with a 4% reduction of walking pace[28], whereas in a study by van Raaij *et al*[29] a 25% reduction of self-selected pace was observed in combination with a slight decrease of the net cost of the activity. The potential for energy savings over pregnancy by reduced physical activity appears to be limited. Using an activity-diary technique, estimates of the savings by Scottish[16], Gambian[19] and Dutch[31] women were respectively 109, 75 and 76 MJ. Although the latter figures must be treated as crude estimates, increased energy intake plus energy savings by reduced physical activity seem to be insufficient to meet all energy costs of pregnancy.

It has therefore been postulated that improved efficiency of energy metabolism may be involved in the conservation of energy by reducing energy expenditure. Such adaptation could be reflected in a reduction of diet-induced thermogenesis. So far, only

TABLE 1 Energy cost of pregnancy and cumulative increase in energy intake over pregnancy; estimates from longitudinal studies.

Country[ref]	N	Energy costs (MJ) *	Extra energy intake (MJ)
The Gambia[19]	23 †	-49	-123
The Gambia[19]	29 ‡	115	40
The Gambia[23]	21	144	-
The Philippines[20]	40	181	0
Thailand[18]	44	208	238
Scotland[16]	88	281	88
The Netherlands[17]	57	286	22
Scotland[25]	162	289	149
England[22]	12	293	203
Sweden[21]	22	578	-
Australia[26]	49	-	13
Canada[27]	16	-	28

* Estimated as the sum of the cumulative increase of maintenance costs over pregnancy, the energy cost of the gain in maternal fat stores (46 MJ/kg fat), plus the energy cost of remaining fat and protein deposition (42-49 MJ, dependent of birth weight of the baby).

† Women receiving no energy supplement.

‡ Energy-supplemented women.

one longitudinal study on a small group of women has been published, suggesting that the thermic effect of a meal is reduced by almost 30% in mid-pregnancy[32]. Improved metabolic efficiency might also result in a higher work efficiency. Changes in work efficiency over pregnancy could be evaluated as the net energy cost (energy cost minus basal or resting metabolic rate) of an exercise on which weight gain has no impact; standardized cycling exercise is generally assumed to meet this condition. Previous studies have shown that the net energy cost of cycling exercise are unchanged or even slightly reduced during pregnancy[33-38]. However, none of these studies evaluated whether the net costs of the exercise were truly independent of weight gain.

The study presented in this thesis was designed to investigate changes in diet-induced thermogenesis and work efficiency in human pregnancy, against the background of the energy balance of pregnancy of the subjects studied, characterized by their energy cost of pregnancy and their changes in energy intake and physical activity over pregnancy. In a subgroup of women respiration-chamber measurements were also carried out, to estimate 24-hour energy expenditure and the apparent digestibility and metabolizability of dietary energy. This combination of measurements provided a unique oppertunity to evaluate changes in energy expenditure over pregnancy.

Lactation

Compared with the energy cost of pregnancy, the energy cost of human lactation appear to be easier to calculate: extra energy needs during lactation depend solely on the volume and energy content of breast milk produced and on the energetic efficiency of milk production. WHO estimates the energy cost of human lactation to be on average 3.1 MJ/d, or about 2.6 times the average energy cost during pregnancy[39]. During lactation, energy intake is clearly elevated above the early-pregnant or post-lactating situation[40-42]. However, extra energy intakes appear to be insufficient to meet all the cost of lactation[40-43]. Body fat may also serve as an energy source during lactation. A tendency towards mobilization of body fat is observed in lactating women, as fat cells in the femoral region show a higher basal lipolysis and a lower lipoprotein lipase activity compared to non-pregnant non-lactating women and pregnant women[44]. In most[40,41,43], but not all[42] longitudinal studies body fat appears to be mobilized during lactation. Energy savings might furthermore be established by reduced physical activity. Such reduction has been observed with the activity-diary technique[40,42], and also in a study combining doubly-labelled water estimates of total daily energy expenditure with basal metabolic rate measurements[42].

For the lactating Dutch women studied previously in our department[41], extra energy intakes, fat mobilization and reduced physical activity seemed to be insufficient to meet the energy cost of lactation. Additional reductions of energy expenditure seem to be required to meet all the costs involved. Therefore, it has been postulated that metabolic adaptations occur during lactation, resulting in a reduction of diet-induced thermogenesis[45] and increased work efficiency. This hypothesis is addressed in this thesis.

Outline of the thesis

This thesis presents the results of a large longitudinal study including pre-pregnant baseline measurements, in which changes during pregnancy and early lactation in the thermic effect of a meal and work efficiency were investigated. The impact of pregnancy on the thermic effect of a standard meal is described in **Chapter 2**. Changes during pregnancy in work efficiency are discussed in **Chapter 3**. In this chapter, changes during pregnancy in the net cost of cycling exercise and in delta work efficiency are presented, and attention is payed to the impact of the weight gain during pregnancy on these costs. Furthermore, pregnancy-induced changes in the recovery cost after exercise and in heart rate during and immediately after cycling are discussed. A reassessment of the extra energy needs during pregnancy is given in **Chapter 4**. For this purpose, the results presented in Chapters 2 and 3 are combined with the measurements carried out in the respiration chamber[46] and with estimated changes in energy intake and physical activity. The effect of lactation on metabolic efficiency is discussed in **Chapter 5**. Finally, the overall conclusions and research suggestions are given in **Chapter 6**.

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der Heijden LJM, van der Heide D, Hautvast JGAJ. Energy balances of healthy Dutch women before and during pregnancy: no supportive evidence for metabolic adaptations in pregnancy. Submitted.

Chapter 2

NO SUBSTANTIAL REDUCTION OF THE THERMIC EFFECT OF A MEAL DURING PREGNANCY [1]

Caroline J.K. Spaaij, Joop M.A. van Raaij, Lidwien J.M. van der Heijden, Frans J.M. Schouten, José J.M.M. Drijvers, Lisette C.P.G.M. de Groot, Harry A. Boekholt and Joseph G.A.J. Hautvast

Abstract

To study changes in the thermic effect of a meal (TEM) during pregnancy, metabolic rate was measured in the fasting state and during the first 180 min after consumption of a standardized testmeal in 27 women before, and in each trimester of pregnancy. Resting metabolic rate (RMR) showed a steady increase during pregnancy, values in wk 24 and 35 of pregnancy were significantly higher than the pre-pregnancy baseline (Tukey's studentized range test). The pattern of changes of postprandial metabolic rate (PPMR) was similar to that of RMR. Consequently, the TEM (PPMR minus RMR) did not change during pregnancy; mean TEM-values before and in wk 13, 24 and 35 of pregnancy were, respectively 117.3 (SD 19.4) kJ/180min, 116.4 (SD 23.7) kJ/180min, 111.6 (SD 24.4) kJ/min and 111.5 (SD 26.7) kJ/min. We consider changes of TEM less than 15% to be physiologically of little importance. If true changes in TEM during pregnancy are 15% or more, we would have had an chance of 90% to observe significant changes in TEM in this study, given the number of subjects and the methods used. Therefore, we conclude that no substantial reduction of TEM occurs during pregnancy.

[1] Accepted for publication in the British Journal of Nutrition

Introduction

Longitudinal studies in various countries have shown that the energy costs of pregnancy are considerable[1-5]. In a previous study on the energy requirements of pregnancy, the question has been raised whether processes of metabolic adaptation, resulting in a lowering of metabolic rate, might occur during pregnancy[2]. Metabolic adaptation could be reflected in a reduction of the thermic effect of a meal. So far, one longitudinal study[6] and two cross-sectional studies[7,8] have been published on this issue, but the results were inconsistent.

In the present study we tried to investigate whether the thermic effect of the meal is reduced during pregnancy, using a longitudinal approach including baseline measurements which were carried out before the onset of pregnancy. The number of subjects in our study was calculated to be sufficient for detecting a 15% change in the thermic effect of the meal with a statistical power of 90%.

Subjects and methods

Study design

Resting metabolic rate (**RMR**), postprandial metabolic rate (**PPMR**) and body weight (**BWt**) were measured in 27 healthy Dutch women before, and in wk 13, 24 and 35 of pregnancy. The thermic effect of a meal was calculated as PPMR minus RMR. Metabolic rate measurements (RMR and PPMR) were carried out twice in each measurement period at two non-consecutive days within one wk. Before pregnancy, 22 out of the 27 women had a second measurement period (two more measurement days). Afterwards it appeared that half of the pre-pregnant measurement days fell in the preovulary and half in the postovulary phase of the menstrual cycle.

Each measurement day was preceded by 3 d with standardized food intake. At a measurement day the woman arrived fasting by car at the metabolic unit between 07.00 and 07.30 hours. BWt was measured after voiding. The woman was installed under a ventilated hood on a hospital bed. Data over the first 25 min were not used for analysis. After measurement of RMR (35 min), a liquid testmeal was consumed, followed by the PPMR measurement (180 min). Immediately after the PPMR measurement, urine was collected quantitatively.

Subjects

For the recruitment of subjects, advertisements in local newspapers, and posters spread in public buildings were used. They were living in the town of Wageningen and surrounding areas and reflected middle-upper socioeconomic stratum. Their ethnic background was Caucasian. They were non-smokers. Participants were judged to be healthy by medical histories and urine analysis. All women gave their informed consent. The study was approved by the Ethical Committee of the Department of Human Nutrition of the Wageningen Agricultural University.

TABLE 1 Subject characteristics (N=27).

	Mean	±	SD
Age (y) *	29.9	±	3.8
Height (cm)	169	±	7
Body weight (kg) †	62.8	±	8.5
Body mass index (kg/m^2) †	21.8	±	2.4
Body fat % (wt/wt %) †‡	28.7	±	5.2
Parity † §	0.8	±	0.9
Length of gestation (wk) ‖	40.0	±	1.3
Weight gain during pregnancy (kg) ¶	11.7	±	3.0
Placental weight (g)	657	±	114
Baby birth weight (g) **	3517	±	323
Baby length (cm) ** ††	51.0	±	5.1
Baby head circumference (cm) ** ††	36.6	±	3.2

* At onset of present pregnancy.

† Before present pregnancy.

‡ Estimated with densitometry using under water weighing.

§ Nulliparae: N=11; primiparae: N=13; multiparae: N=3.

‖ Length of gestation was derived from the first day of the woman's last reported menstrual period; classification according to Hytten[9]: 24 women "term" (259-293 d), 1 woman preterm (258 d), and 2 women postterm (296 and 299 d).

¶ Last recorded weight during pregnancy (1-7 d before delivery) minus pre-pregnant weight.

** Sex baby: female N=13; male N=14.

†† Number of days after delivery: mean 9 (SD 4) d.

Initially, 38 women participated in the study. We succeeded to collect data before and in every trimester of pregnancy from 28 women. One of these women developed gestational diabetes. This article is based on the results of the remaining 27 women. Some characteristics of these women are given in **Table 1**. Twenty-five infants were delivered normally and two by Caesarian section.

Measurements of metabolic rate

Ventilated hood device. Metabolic rate was measured by open-circuit indirect calorimetry using the ventilated hood technique. Two hoods were connected to one set of gas analyzers, so that two subjects could be measured simultaneously. A perspex hood (vol 30 L) with an air inlet on top and an air outlet at the right side, was placed over the head of the woman. Fresh filtered atmospheric air was drawn through the hood by negative pressure created by a pump downstream (Ocean SCL210, Dieren, the Netherlands). Airflow through the hood was maintained at 40 L/min by a control valve (Brooks 5837, Veenendaal, the Netherlands) and measured in the outlet airstream by a thermal mass flowmeter (Brooks 5812N, Veenendaal, the Netherlands). The mass flowmeter was calibrated at least once a year by the manufacturer. Flow readings from the mass flowmeter were directly converted to STPD conditions (standard temperature and pressure, dry air). A small and constant quantity of air (0.4 L/min) was continuously withdrawn by an airtight pump for O_2 and CO_2 analysis. Before gas analysis the sample was passed through the drying agent $CaCl_2$ (Merck 2387, Darmstadt, Germany). Through a system of computer driven valves (Bürkert 211A, Ingelfingen, Germany) either fresh filtered atmospheric air, or outlet air from the ventilated hood, or calibration gas was passed to the analyzers. Oxygen consumption and carbon dioxide production were calculated using the Haldane correction[10].

The zero and span point of the CO_2 analyzer (Analytical Development Company SS100, Hoddesdon, UK) were calibrated using standard gasses (for the zero point: 100% N_2 and for the span point: gas mixture containing 0.6% CO_2). The zero level (0% O_2) and the span point (20.95% O_2) of the O_2 analyzer (Servomex 1100A, Zoetermeer, The Netherlands) were calibrated with 100% N_2 standard gas and fresh filtered atmospheric air, respectively. These calibrations were carried out before the measurement of resting metabolic rate; the span point of the O_2 analyzer was recalibrated at least every 60 min.

Simultaneously with metabolic rate measurements, subject's movements were recorded as an index value by a load cell (Tokyo Sokki Kenkyujo TKA-200A, Tokyo, Japan) placed under one leg of the bed on which the woman lay during the measurement.

Actual analyses were integrated over 2 min and printed over 2.5 min intervals. If both hoods were used simultaneously, one value per 5 min of O_2 consumption (mL/min), CO_2 production (mL/min), and body movement index, was printed for each subject. If high O_2 consumption and CO_2 production values appeared in combination with a high body movement index, these values were excluded. Missing values also occurred when the span point of the O_2 analyzer was checked, or when the woman needed to visit the lavatory. Missing values were replaced by the mean of the 2 preceding and the 2 following values.

Variability. Ethanol combustion tests were carried out at least once per month to detect systematic deviations in the ventilated hood system. In each test about 25 g of ethanol was combusted in about 2 h. Instead of the ventilated hood, an airtight combustion chamber was linked to air inlet and air outlet. The reproducibility of the system was determined by 6 alcohol combustion tests for each ventilated hood device, carried out on separate days within a period of 2 wk. Day-to-day coefficients of variation were 2.1% for O_2 consumption, 1.9% for CO_2 production, 1.9% for respiratory quotient, and 1.9% for metabolic rate. These values agree very well with those presented by Bogardus *et al.*[11].

Measurement of N-excretion. Subjects voided immediately after arriving at the laboratory. Urine was collected quantitatively 4 hours later, when the PPMR measurement had finished. Urine was weighed and 2 samples were taken which were frozen at -20 °C. In these urine samples the urea concentration was determined (Boehringer Mannheim BV 396346 kit, Almere, The Netherlands)[12]. Urea-nitrogen excretion was calculated by multiplication of urine weight with urea concentration. To obtain total nitrogen (N) excretion, the assumption was made that 85% of urinary N is excreted as urea[13].

Calculation of metabolic rate and non-protein respiratory quotient. Metabolic rate (MR, in kJ/min) and non-protein respiratory quotient (npRQ) were calculated from O_2 consumed (VO_2, mL/min), CO_2 produced (VCO_2, mL/min) and N-excretion (mg/min), using formulae given by Jéquier[10]. Metabolic rate values were averaged to obtain one value per 5 min for each subject on each measurement day. These 5-min averages were used for further analyses.

Standardization of diet on days prior to measurements

During the 3 days preceding metabolic rate measurements, the woman followed strict guidelines for her dietary intake. Guidelines reflected the individual energy requirement of each subject as estimated by a 5-d weighed food record, carried out about 2 wk before the first measurement day. Between periods, guidelines were only changed at the woman's request, so that within each period the prescribed energy intake followed the subject's habitual intake. The proportions of protein, carbohydrate and fat were standardized at respectively 15, 50 and 35 energy%. Maximally one alcoholic beverage per day was allowed, replacing an equivalent amount of energy from carbohydrates. The standardization of energy intake was done because short term over- or underfeeding[14] as well as the macronutrient composition of the diet on days prior to measurement days[15] might influence both resting metabolic rate and the thermic effect of a standard meal.

Resting metabolic rate

Resting metabolic rate (RMR) was measured after 12 hours fasting. On the day before a measurement day, the woman refrained from intensive physical activity. During the measurement the woman was lying in supine semi-recumbent position, in complete physical rest, but awake, watching non-stressing video films.

Analysis of variance of measurements before and during pregnancy of 27 subjects with complete data, revealed that the within person day-to-day variation coefficient in RMR was 4.7%, which is within the normal range[11,16,17]. There was no systematic difference between the first and second day of measurement within the same week.

To investigate whether resting metabolic rate (RMR) was measured under steady state conditions, the 35 min period during which RMR was measured was divided into 7 periods of 5 min. Analysis of covariance with RMR as dependent variable and time as covariable revealed that there was no decrease in RMR throughout the 35 min of the measurement, and with Tukey's studentized range test it appeared that there were no differences between any pair of 5-min RMR values. Therefore we conclude that the duration of the period of rest preceding the RMR measurement (25 min) was sufficient for reaching the steady state.

Postprandial metabolic rate and thermic effect of a meal

Testmeal. The meal consisted of 375 g yoghurt-based liquid formula containing 1325 kJ (15 en% protein, 30 en% fat and 55 en% carbohydrate). The recipe was 581 g full-cream yoghurt, 323 g unsweetened orange juice, 65 g white sugar, 13 g sunflower oil and 18 g protein powder (Protifar®, Nutricia Nederland BV, Zoetermeer, The Netherlands) per 1000 g. The macronutrient composition per 100 g was 20.5 g dry matter, 0.7 g ash, 3.3 g protein (Kjeldahl method, nitrogen content was multiplied with 6.38 to obtain protein content), 3.0 g fat (Röse Gottlieb method) and 13.5 g carbohydrate (calculated by subtraction). Testmeals were prepared in bulk in three batches, and stored at -20°C.

Postprandial metabolic rate (PPMR) was measured during the first 180 min following consumption of the testmeal. The conditions of measurement were exactly the same as during the RMR measurement, except for the postprandial state. The thermic effect of the meal (TEM) was calculated as PPMR minus RMR and expressed as kJ/min in time-response curves, or as kJ/180 min if the cumulative TEM over 180 min is considered.

The within person day-to-day variation coefficient of PPMR was 3.9%, which resembles the value observed for RMR. The within person day-to-day variation coefficient of TEM was 22.6%. There was no systematic difference between PPMR or TEM values of the first and second day of measurement within the same week.

The duration and magnitude of the thermic effect of the meal increases with the energy content of the meal[18], thus meal size and duration of the measurement should be well-balanced to each other. We limited the postprandial period to 180 min to avoid stress caused by prolonged measurement, which might occur especially in late pregnancy. We choose a relatively small testmeal to ensure that a 3-h postprandial period would cover the main part of the thermic effect of the meal.

A side study in which 8 non-pregnant non-lactating (NPNL) women were measured at 3 non-consecutive days within a 2 wk period, following exactly the same procedures but now up to 300 min after the testmeal, revealed that 86% of the full TEM-response was covered during the first 180 min after consumption of the testmeal. The cumulative TEM over 300 min was 132 kJ (10% of the energy content of the testmeal); from 270 and 300 min after the meal PPMR was only slightly above RMR level (mean difference 0.14 (SEM 0.04) kJ/min). In late-pregnancy, some gastrointestinal responses to a meal are delayed[19], suggesting that the TEM-response might be spread over a longer period, and that the first 180 min after the meal might cover a smaller part of the TEM-response than in the non-pregnant state. Therefore, in a second cross-sectional study, metabolic rate was measured in the fasting state and in the period from 270 to 300 min after the meal, in 5 late-pregnant and 8 NPNL women at 3 non-consecutive days within a 2-wk period. No difference in TEM between 270 and 300 min after the meal was observed between late-pregnant women (mean 0.13 (SEM 0.08) kJ/min) and NPNL-women (mean 0.13 (SEM 0.05) kJ/min). This result does not indicate a prolonged TEM-response in late-pregnancy.

Statistics

Data analysis was carried out using the programme provided by SAS (SAS Institute, Inc, Cary, NC). Data are expressed as mean ± SD, unless stated otherwise. The Shapiro and Wilk test were used to test whether data were a random sample from a normal distribution. Tukey's studentized range test (significance level $\alpha = 0.05$) was used to investigate whether significant changes during pregnancy had occurred.

The statistical power (β) to detect the physiologically important change between two periods (Δ), if this change truly exists, was determined by calculating t_β [20]:

$$t_\beta = \{ \Delta \sqrt{N} / s_\Delta \} - t_\alpha,$$

where s_Δ is the estimated within-subject standard deviation in the change of the parameter and N is the number of subjects. At an α of 0.05, and a sample size of 26 ($df = 25$), t_α is 2.060 (two-tailed). The β of t_β is read from the one-tailed t-distribution table ($df = 25$).

Results

Resting metabolic rate and postprandial metabolic rate

Resting metabolic rate (RMR) increased from before pregnancy to 13 wk gestation (**Table 2**), but this increase did not reach statistical significance (mean difference 0.18 (SEM 0.05) kJ/min). In wk 24 of gestation RMR was significantly higher than in wk 13 (mean difference 0.34 (SEM 0.08) kJ/min). This increase was similar to that from wk 24 to wk 35 of gestation (mean difference 0.34 (SEM 0.07) kJ/min).

The differences in postprandial metabolic rate PPMR (average value of 180 min) were very similar to the differences in RMR observed between the values before and at each trimester of pregnancy (**Figure 1** and **Table 2**). There was a slight but non-significant increase in PPMR from pre-pregnant levels to the first trimester of pregnancy (mean difference 0.18 (SEM 0.05) kJ/min). The increase from wk 13 to wk 24 of

TABLE 2 Resting metabolic rate (RMR), postprandial metabolic rate (PPMR) and thermic effect of a meal (TEM) before and during pregnancy in 27 women.

Period	RMR	PPMR *	TEM †
	kJ/min	*kJ/min*	*kJ/180min*
Before pregnancy	3.76 ± 0.33 A‡	4.41 ± 0.30 A	117.3 ± 19.4 A
Pregnancy wk 13	3.94 ± 0.42 A	4.58 ± 0.41 A	116.4 ± 23.7 A
Pregnancy wk 24	4.28 ± 0.51 B	4.90 ± 0.53 B	111.6 ± 24.4 A
Pregnancy wk 35	4.62 ± 0.51 C	5.24 ± 0.46 C	111.5 ± 26.7 A

* Average metabolic rate during the first 180 min after the testmeal.

† Cumulative increase of metabolic rate above RMR level during the first 180 min after the testmeal ({PPMR minus RMR} * 180).

‡ Within each column, means with the same letter are not significantly different (Tukey's studentized range test).

gestation was almost twice as large (mean 0.32 (SEM 0.08) kJ/min) and an increase of 0.34 (SEM 0.07) kJ/min was found from wk 24 to wk 35.

Thermic effect of a meal

The time-response curves of TEM are given in **Figure 2.** There are only minor differences between the curves representing the pre-pregnant measurements and the measurements in wk 13 and 24 of gestation. In the third trimester of pregnancy, the first 100 min after the meal TEM tended to be slightly decreased compared to pre-pregnant values, whereas from 100 to 180 min after the meal both curves followed almost the same pattern. However none of these differences reached statistical significance. The cumulative TEM over 180 min did not change significantly during pregnancy **(Table 2)**: the change from before pregnancy to wk 13 of gestation was -0.9 (SEM 4.5) kJ/180min, the change from wk 13 to wk 24 of gestation was -4.9 (SEM 4.5) kJ/180min, and the change from wk 24 to wk 35 of gestation was -0.1 (SEM 6.0) kJ/180min.

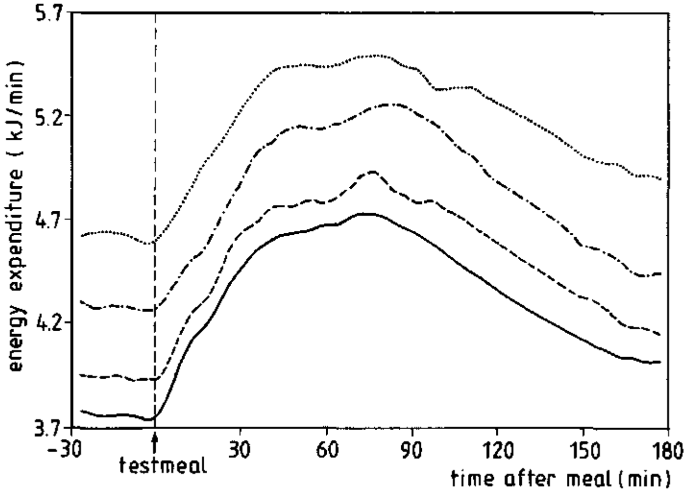

FIGURE 1 Metabolic rate before and after consumption of the testmeal in 27 women, before pregnancy (————), and in wk 13 (– – – –), in wk 24 (– · – · –), and in wk 35 (.............) of pregnancy.

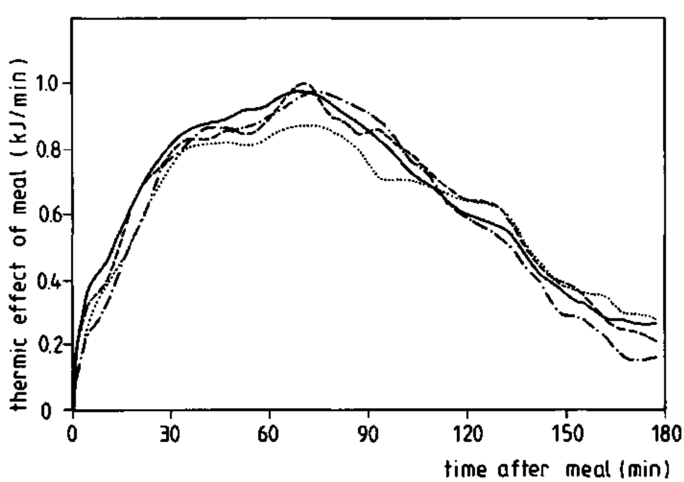

FIGURE 2 Thermic effect of a meal (TEM) in 27 women, before pregnancy (————), and in wk 13 (– – – –), in wk 24 (– · – · –), and in wk 35 (.............) of pregnancy.

Protein oxidation and non-protein respiratory quotient

N-excretion during the RMR- and PPMR-measurements diminished during pregnancy. Mean values of N-excretion were: before pregnancy 10.38 (SD 2.22) mg/min, at 13 wk gestation 9.48 (SD 1.38) mg/min, at 24 wk gestation 9.13 (SD 2.22) mg/min, and at 35 wk gestation 8.05 (SD 0.85) mg/min. The mean reduction of N-excretion from before pregnancy to wk 13 of gestation was 0.90 (SEM 0.45) mg/min and not significant (Tukey's standardized range test), but values at wk 24 and 35 of gestation were significantly below pre-pregnancy values: mean reductions were respectively 1.25 (SEM 0.42) mg/min and 2.33 (SEM 0.54) mg/min.

During the RMR-measurement non-protein respiratory quotient (npRQ) had a mean value of 0.88 before pregnancy as well as during pregnancy (**Table** 3). After consumption of the testmeal npRQ increased to a peak value at 60-90 min after the meal. Thereafter

TABLE 3 Non-protein respiratory quotient (npRQ)* before and during pregnancy.

	Before pregnancy	During pregnancy		
		Wk 13	Wk 24	Wk 35
Fasting state	0.88 ± 0.04 A†	0.88 ± 0.06 A	0.88 ± 0.05 A	0.87 ± 0.05 A
Postprandial state				
0-30 min ‡	0.88 ± 0.05 A	0.89 ± 0.06 A	0.90 ± 0.05 A	0.88 ± 0.05 A
30-60 min	0.96 ± 0.04 A	0.97 ± 0.06 A	0.96 ± 0.05 A	0.92 ± 0.04 B
60-90 min	0.97 ± 0.04 A	0.95 ± 0.05 A	0.95 ± 0.05 A	0.92 ± 0.04 B
90-120 min	0.94 ± 0.04 A	0.93 ± 0.04 AB	0.91 ± 0.05 BC	0.90 ± 0.04 C
120-150 min	0.92 ± 0.04 A	0.91 ± 0.05 AB	0.90 ± 0.04 B	0.90 ± 0.03 B
150-180 min	0.89 ± 0.04 A	0.87 ± 0.05 A	0.87 ± 0.05 A	0.87 ± 0.04 A

* npRQ was calculated as the ratio of CO_2-production and O_2-consumption after correction for the amounts of CO_2 and O_2 attributable to protein oxidation.

† Within each row, means with the same letter are not significantly different (Tukey's studentized range test).

‡ Time after consuming the testmeal.

npRQ decreased again. Non-protein RQ between 90 and 150 min after the meal was significantly reduced in wk 24 of gestation npRQ compared to the pre-pregnancy value: mean changes for the periods 90-120 min and 120-150 min after the meal were, respectively: -0.03 (SEM 0.01), and -0.03 (SEM 0.01). In wk 35 the peak value was even smaller, and values between 30 and 150 min after the meal were significantly below the pre-pregnant level: mean changes for the periods 30-60 min, 60-90 min, 90-120 min, and 120-150 min after the meal were, respectively: -0.04 (SEM 0.01), -0.05 (SEM 0.01), -0.04 (SEM 0.01), and -0.03 (SEM 0.01).

Discussion

The women in the present study were all healthy and well-nourished. Their weight gains during pregnancy and the birthweights of their children (**Table 1**) were as expected for western women eating without restriction[1,2,9]. The increase of RMR during pregnancy closely resembled the pattern observed in our previous study[21].

The macronutrient composition of our testmeal was representative for western countries, although the fat content was a bit lower than in the average Dutch diet (30 instead of 40 energy%). During the 180 min postprandial measurement period we covered the main part (86%) of the full thermic effect of this testmeal (see subjects and methods section). It seems therefore appropriate to extrapolate the TEM-results to total daily diet-induced thermogenesis. Still, some caution is needed as gastrointestinal responses to a liquid meal might differ from responses to the normal mixed diet.

Our results show that there is no change in the thermic effect of the meal (TEM) during pregnancy. Until now only one publication gives results on longitudinal changes in TEM during pregnancy[6]. In that study, TEM appeared to be reduced in the second (-28%), but not in the first (-1%) and third (-15%, NS) trimesters of pregnancy compared to post-lactational measurements. However, their study population was small ($N=7$) and maybe not representative, since RMR in wk 35 of gestation was only 7.9% higher than in the postlactational state, which is a small increase compared to the present study and to other longitudinal studies in well-nourished populations[1,2,5]. Two small cross-sectional studies have been published, in which TEM-values of pregnant women and non-pregnant control subjects were compared[7,8]. Nagy & King[8] did not observe any difference (4 late-pregnant, 6 early-pregnant and 6 non-pregnant women), but Contaldo *et al.*[7] found a significantly lower TEM (-35%) in 5 late-pregnant versus 5 non-pregnant women. Prentice *et al.*[22] studied metabolic rate in 8 women before and during their pregnancies with a whole body calorimeter. From 24-h metabolic rate, basal metabolic rate, and metabolic rate during exercise, they derived the energy costs of diet-induced thermogenesis plus minor physical movements, and found this factor to be constant throughout pregnancy.

The large within subject variation in TEM (22.6% in our study) might have caused the inconsistency of the previous studies[6-8,22], which all described groups of only 4 to 8 women. In the present study we were interested in a 15% reduction of TEM throughout pregnancy. With the mean pre-pregnancy energy intake of 9.6 (SEM 0.3) MJ/d in our women, such reduction would result in an energy saving of about 0.15 MJ/d. If a reduction in TEM of 15% really occurred, we in our study would have had a chance of 90% to find a significant reduction. Our results therefore suggest that it is unlikely that physiologically significant changes in diet-induced thermogenesis occur during pregnancy. More research is needed to investigate if other processes of metabolic adaptation occur during pregnancy.

The reduction of N-excretion during pregnancy indicates that protein oxidation is diminished. This was also found by De Benoist *et al.*[23] and Fitch & King[24]. The decrease of N-excretion might reflect the anabolic state of the body. On a daily basis, a reduction with on average 1.5 mg N/min could reflect accumulation of 13.5 g protein, which is equivalent to about 70 g lean tissue[25]. However, Hytten[9] estimated total protein accumulation during pregnancy to be only 925 g, or on average about 3.5 g/d. Therefore, the reduction of N-excretion appears to be far too high to be explained by protein accumulation. Possibly, it also reflects a shift from protein oxidation towards oxidation of carbohydrates and fats. This could be a usefull adaptation to the increased energy needs during pregnancy, because the net ATP-yield of protein is lower than the net ATP-yield of an energetically equivalent amount of carbohydrate or fat[26].

Fasting non-protein respiratory quotient (npRQ) was unchanged during pregnancy, suggesting that the proportion of oxidized carbohydrate to oxidized fat is unchanged in the fasting state. In contrast, a progressive reduction of postprandial npRQ was observed during pregnancy. This suggests that the postprandial increase in carbohydrate oxidation gets smaller when pregnancy advances: carbohydrates appear to be saved at the expense of fats. This fits with the findings of Williams *et al.*[27] that glucose uptake by adipose tissue diminishes and plasma levels of free fatty acids and glycerol increase steadily in pregnancy.

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Chapter 3

NO CHANGES DURING PREGNANCY IN THE NET COST OF CYCLING EXERCISE, NOR IN DELTA WORK EFFICIENCY

Caroline J.K. Spaaij, Joop M.A. van Raaij,
Lisette C.P.G.M. de Groot, Lidwien J.M. van der Heijden,
Harry A. Boekholt and Joseph G.A.J. Hautvast

Abstract

This study was carried out to investigate whether work efficiency improves during pregnancy. Resting metabolic rate (RMR), cycling metabolic rate (CMR) at workloads of 30, 45, 60 and 75 Watts, and post-cycling metabolic rate (PCMR) were measured in 26 women before the onset of pregnancy and in wk 13, 24 and 35 of gestation. RMR, CMR and PCMR increased significantly and to a similar extent during pregnancy, so that the net energy costs of cycling activity (CMR minus RMR) and the net recovery costs after exercise (PCMR minus RMR) were unchanged. Delta work efficiency did not change during pregnancy, implying that changes in CMR during pregnancy were similar at all workloads. We conclude that during pregnancy no clear changes in work efficiency occur.

Introduction

Hytten[1] estimated the total energy costs of pregnancy, defined as protein and fat accumulation in fetus and mother plus the increase of maintenance metabolism, to be 335 MJ. Longitudinal studies in various countries[2-6] have confirmed that pregnancy involves considerable energy costs. The hypothesis has been raised that physiological and metabolic adaptations, resulting in a lowering of metabolic rate, might occur during pregnancy[2]. The present study was carried out to explore whether the energy costs of standardized physical activity change during pregnancy, and comparisons are made with values obtained in the same women before pregnancy. Cycling exercise was chosen to avoid confounding by gestational weight gain: work load during cycling exercise is assumed to be largely independent of body weight.

Several studies have been published about pregnancy-induced changes in metabolic rate or oxygen consumption during standardized cycle ergometer exercise[7-14]. In previous longitudinal studies, measurements during pregnancy were compared with post partum values, including data of lactating mothers[7-13]. This cannot be considered appropriate, as lactation might involve changes in energy metabolism[15]. The present study is unique in its use of pre-pregnant measurements as baseline.

Subjects and methods

Study design

Metabolic rate and heart rate during and immediately after cycle ergometer exercise, resting metabolic rate, body weight, and leg circumferences were measured in 26 healthy Dutch women before, and in wk 13, 24 and 35 of pregnancy. Metabolic rate, heart rate and body weight measurements were carried out twice in each measurement period at two non-consecutive measurement days within one wk. Twenty-two out of the 26 women had a second measurement period before pregnancy (two more measurement days). Afterwards it appeared that about half of the pre-pregnant measurement days fell in the preovulary and half in the postovulary phase of the menstrual cycle.

At a measurement day the woman arrived fasting by car at the metabolic unit between 0700 and 0730. After voiding, body weight was measured. The woman was installed under a ventilated hood on a hospital bed, and after a 25 min period in which metabolic rate reached a steady state, resting metabolic rate was measured during 35 min. The rest of the morning was used for measurements of resting metabolic rate in the postprandial state (data not included in this article). After the postprandial measurements, the woman was allowed to drink one or two cups of tea with or without sugar. The woman was then re-installed under the ventilated hood, and performed a 25.5 min cycle-ergometer exercise programme (4 different work loads), immediately followed by a 10.5 min post-cycling period (still seated on the cycle ergometer, but without body movements). Then the subject received a lunch. On one of the two measurement days within the same period, leg anthropometry was performed after lunch.

Subjects

For the recruitment of subjects, advertisements in local newspapers and posters spread in public buildings were used. All participants were judged to be healthy by medical history and urine analysis. They were all non-smokers. They were living in the town of Wageningen and surrounding areas and reflected middle-upper socioeconomic stratum. Their ethnic background was Caucasian. Further subject characteristics are given in **Table 1**. All women gave their informed consent. The study was approved by the Ethical Committee of the Department of Human Nutrition of the Wageningen Agricultural University.

Cycle ergometer

We used a cycle ergometer with a maximum work load of 250 W (type RH, Lode BV, Groningen, the Netherlands). The electro-magnetic brake in this cycle ergometer consists of a disk rotating in a magnetic field with such high speed, that the work load is largely independent of the rotation frequency of the pedals[17]. A digital voltmeter (type DPM 339, Display Elektronika, Utrecht, the Netherlands) was connected to the ergometer to allow for more accurate adjustments of the work load (accuracy 1 mV ~ 0.25 Watts). The work load at the crank of the ergometer was checked once a year and the ergometer was readjusted if necessary. The position of the saddle was adjusted to the height of the woman, so that her back was straight, and her knee slightly bent when the peddle was at its lowest position. The woman was instructed to rotate the peddles with a frequency of 60 rotations per minute.

TABLE 1 Subject characteristics (N=26).

	Mean	±	SD
Age *(y)* *	30.0	±	3.9
Height *(cm)*	169	±	7
Body weight *(kg)* †	62.4	±	8.5
Body mass index *(kg/m²)* †	21.8	±	2.4
Body fat % *(wt/wt %)* † ‡	27.5	±	4.9
Parity † §	0.7	±	0.8
Length of gestation *(wk)* ‖	40.2	±	1.1
Weight gain during pregnancy *(kg)* ¶	11.8	±	3.0
Placental weight *(g)*	654	±	117
Birth weight *(g)* **	3512	±	333
Baby length *(cm)* ** ††	51.3	±	5.0
Baby head circumference *(cm)* ** ††	36.7	±	3.2

* At onset of present pregnancy.

† Before present pregnancy.

‡ Estimated with densitometry using under water weighing.

§ Nulliparae: N=11; primiparae: N=13; multiparae: N=2.

‖ Length of gestation was derived from the first day of the woman's last reported menstrual period; classification according to Hytten[16]: 24 women "term" (259-293 d) and 2 "postterm" (296 and 299 d). Twenty-four infants were delivered normally and 2 by Caesarian section.

¶ Last recorded weight during pregnancy (1-7 d before delivery) minus pre-pregnant weight.

** Sex baby: female: N=13, male: N=13.

†† Number of days after delivery: 11 ± 7 d.

Metabolic rate

Ventilated hood device. Metabolic rate during rest and cycle ergometer exercise was measured by open-circuit indirect calorimetry using the ventilated hood technique. A perspex hood (vol 30 L) with an air inlet on top and an air outlet at the right side, was placed over the head of the woman. Mean values of O_2 consumption (VO_2, mL/min) and CO_2 production (VCO_2, mL/min) were printed every 2.5 min during resting metabolic rate measurements, and every 1.5 min during cycling and post-cycling metabolic rate measurements. The zero and span points of the O_2 and CO_2 analyzers were calibrated just before the measurements of resting metabolic rate and just before start of the cycling programme, using standard gases (for the zero points 100% N_2, for the span point of the CO_2 analyzer a gas mixture containing 0.6% CO_2) and fresh filtered atmospheric air (for the span point of the O_2 analyzer).

Ethanol combustion tests were carried out at least once per mo to validate the ventilated hood system. In each test about 25 g of ethanol was combusted in about 2 h. Instead of the ventilated hood, an airtight combustion chamber was linked to air inlet and air outlet. The reproducibility of the system was determined by 6 alcohol combustion tests for each ventilated hood device, carried out on separate days within a period of 2 wk. Day-to-day coefficients of variation were 1.9% for metabolic rate and 1.9% for respiratory quotient. These values agree very well with those presented by Bogardus *et al.*[18]. Metabolic rate (MR, in kJ/min) was calculated from oxygen consumption (VO_2, in L/min) and carbon dioxide production (VCO_2, in L/min) using Weir's formula[19]: $MR = 16.3\ VO_2 + 4.6\ VCO_2$. Respiratory quotient (RQ) was calculated as VCO_2 divided by VO_2.

Resting metabolic rate. Resting metabolic rate (**RMR**) was measured after 12 hours fasting. On the day before a measurement day, the woman refrained from intensive physical activity. During the measurement the woman was lying in supine semi-recumbent position, and was in complete physical rest, but awake, watching non-stressing video films.

Cycling metabolic rate. The cycling programme consisted of 25.5 min cycling exercise: for 7.5 min at 30 W, for 6 min at 45 W, for 6 min at 60 W, and for 6 min at 75 W. To ensure that the O_2- and CO_2-concentrations in the air coming out of the ventilated hood remained within the range required for gas analysis, the flow rate of air through the ventilated hood was increased with work load: 120 L/min at a work load of 30 W, 140 L/min at 45 W, 180 L/min at 180 W and 200 L/min at a work load of 75 W. Only results from the last 3 min at each work load were used for calculation of gross cycling metabolic rate (**CMR_{gross}**). Net cycling metabolic rate (**CMR_{net}**) was calculated as CMR_{gross} minus RMR. Delta work efficiency (**dWE**) is defined by Gaesser and Brooks[20] as: $dWE = 100 * \Delta workload / \Delta CMR_{gross}$. We estimated delta work efficiency as the inverse slope from linear regression of CMR_{gross} on work load, but only if CMR_{gross}-

values at all 4 work loads were obtained. Regression lines were calculated for each subject individually.

Post-cycling metabolic rate. After finishing the cycling programme the subject remained seated on the cycle ergometer for another 10.5 min during which the post-cycling metabolic rate ($PCMR_{gross}$) was measured. After the first 4.5 min in this period, flow rate of air through the ventilated hood was reduced from 200 L/min to 120 L/min. This influenced gas exchange measurements in the following 1.5 min, so that VO_2- and VCO_2-values over the period 4.5-6 min after cycling had to be replaced by the average of the values obtained 3-4.5 min and 6-7.5 min after cycling. Net post-cycling metabolic rate ($PCMR_{net}$) was calculated as $PCMR_{gross}$ minus RMR.

Heart rate

Heart rate was registered during exercise and the subsequent recovery period (type Sporttester PE-3000, Polar Electro KY, Kempele, Finland). Heart rate was measured by an electrode belt, connected around the trunk of the subject, and then transmitted to a wrist receiver, that stored one value every 15 sec. Heart rate values were averaged and analyzed over the same time periods as metabolic rate values.

Body weight and leg anthropometry

Body weight was measured in the laboratory on an electronic balance (Berkel ED60-T, Rotterdam, The Netherlands), or at home on a spring balance (Seca 760, Lameris Instruments BV, Utrecht, The Netherlands).

Body height and sitting height (total height when seated minus seat height) were measured with a microtoise to the nearest 1 mm. Leg length was calculated as body height minus sitting height. Circumferences of the leg were measured with a plastic tape to the nearest 1 mm, at three sites: directly below the gluteal fold (thigh circumference), halfway between the ilia-crest and the patella (upper leg circumference) and at the broadest part of the calf (calf circumference). At each of these sites, the cross-sectional area was calculated as circumference square divided by 4π. The mean of these three cross-sectional area's was called "leg cross-sectional area". Leg index was obtained by multiplication of "leg cross-sectional area" by leg length.

Statistics

Data are expressed as mean ± *SD*. Data analysis was carried out using the programme provided by SAS (SAS Institute, Inc, Cary, NC). The Shapiro and Wilk test was used to evaluate whether the data are a random sample from a normal distribution. Tukey's studentized range tests were used to analyze whether significant changes during pregnancy had occurred (significance level $\alpha=0.05$). Pearson correlation coefficients (r) and p-values were used to described associations between pairs of variables (null hypothesis $r=0$). If a parameter was correlated with more than one variable, the general linear models (GLM) procedure of the SAS-package was used to investigate the association with the combination of variables.

Results

Body weight and leg anthropometry

Body weight increased steadily during pregnancy (**Table 2**) to a mean gestational

TABLE 2 Body weight and leg anthropometry before and during pregnancy.

	Before pregnancy	During pregnancy		
		wk 13	wk 24	wk 35
Body weight *(kg)*	62.4 ± 8.5 ^{A*}	63.5 ± 8.6 ^{B}	68.0 ± 8.7 ^{C}	72.6 ± 9.1 ^{D}
Leg circumferences *(cm)*:				
Thigh	58.3 ± 4.1 ^{A}	58.7 ± 4.4 ^{A}	59.9 ± 4.6 ^{B}	60.6 ± 4.9 ^{B}
Upperleg	55.8 ± 4.4 ^{A}	56.0 ± 4.6 ^{A}	56.7 ± 4.6 ^{AB}	57.5 ± 4.4 ^{B}
Calf	36.4 ± 2.2 ^{AB}	36.1 ± 2.3 ^{A}	36.6 ± 2.4 ^{B}	37.2 ± 2.3 ^{C}
Leg index *(dm^3)* †	16.6 ± 2.7 ^{A}	16.7 ± 2.8 ^{A}	17.3 ± 2.9 ^{B}	17.7 ± 3.0 ^{C}

* On each row means sharing the same letter are not significantly different (Tukey's studentized range test, N=26).

† Leg index was calculated as the mean of thigh, upper leg, and calf cross-sectional area's (dm^2) times leg length (leg length = height - [{height when seated} - {seat height}]; mean ± SD: 7.94 ± 0.41 dm).

weight gain of 11.8 kg (**Table 1**). In wk 35 of gestation, body weight was 10.3 ± 2.2 kg (16.5%) above the pre-pregnant value. Leg circumferences at thigh, upper leg and calf sites showed small but significant increases during pregnancy (**Table 2**). Leg index was calculated from these 3 leg circumferences and from leg length, and showed a significant increase as well (**Table 2**). In wk 35 of gestation, leg index was 1.1 ± 0.9 dm^3 (7%) above the pre-pregnant value.

TABLE 3 Gross and net metabolic rates before and during pregnancy.

	Before pregnancy	During pregnancy		
		Wk 13	Wk 24	Wk 35
<u>Gross metabolic rates</u> (*kJ/min*)				
RMR (26)*	3.84 ± 0.33 ^{A†}	4.01 ± 0.43 ^{A}	4.35 ± 0.51 ^{B}	4.70 ± 0.51 ^{C}
CMR_{gross} 30W‡ (26)	14.3 ± 1.2 ^{AB}	14.1 ± 0.9 ^{A}	14.7 ± 1.4 ^{BC}	15.2 ± 1.4 ^{C}
CMR_{gross} 45W (25)	17.3 ± 1.3 ^{A}	17.2 ± 1.7 ^{A}	17.8 ± 1.5 ^{AB}	18.2 ± 1.6 ^{B}
CMR_{gross} 60W (24)	20.9 ± 1.6 ^{AB}	20.6 ± 2.1 ^{A}	21.4 ± 1.8 ^{AB}	21.7 ± 1.9 ^{B}
CMR_{gross} 75W (21)	24.5 ± 1.8 ^{AB}	24.2 ± 2.8 ^{A}	25.6 ± 1.7 ^{BC}	25.7 ± 2.1 ^{C}
PMR_{gross} § (20)	8.4 ± 0.8 ^{A}	8.6 ± 1.1 ^{A}	9.1 ± 1.2 ^{B}	9.7 ± 1.0 ^{C}
<u>Net metabolic rates</u> (*kJ/min*) ‖				
CMR_{net} 30W (26)	10.5 ± 1.0 ^{A}	10.1 ± 1.3 ^{A}	10.4 ± 1.1 ^{A}	10.5 ± 1.1 ^{A}
CMR_{net} 45W (25)	13.5 ± 1.1 ^{A}	13.2 ± 1.5 ^{A}	13.5 ± 1.1 ^{A}	13.5 ± 1.4 ^{A}
CMR_{net} 60W (24)	17.0 ± 1.5 ^{A}	16.6 ± 2.0 ^{A}	17.1 ± 1.4 ^{A}	17.0 ± 1.7 ^{A}
CMR_{net} 75W (21)	20.6 ± 1.6 ^{A}	20.2 ± 2.6 ^{A}	21.2 ± 1.2 ^{A}	20.9 ± 2.0 ^{A}
PMR_{net} (20)	4.5 ± 0.7 ^{A}	4.5 ± 0.8 ^{A}	4.7 ± 0.8 ^{A}	4.9 ± 0.8 ^{A}

* Group size between brackets.

† On each row, means sharing the same letter are not significantly different (Tukey's studentized range test).

‡ Work load during cycling.

§ Postcycling metabolic rate, measured during the first 10.5 min after cycling.

‖ Net metabolic rate is calculated as gross metabolic rate minus resting metabolic rate (RMR).

Metabolic rate

Resting metabolic rate (RMR) increased steadily during pregnancy up to a 22% increase over the pre-pregnant value in wk 35 of gestation (**Table 3**). The gross costs of cycle ergometer exercises (CMR_{gross}) tended to be below pre-pregnant values in wk 13 of gestation, but at none of the four work loads, this decrease reached statistical significance (**Table 3**). From wk 13 onwards, CMR_{gross} increased steadily, and at every work load the value in wk 35 of gestation was significantly higher than in wk 13 (**Table 3**). Gross post-cycling metabolic rate ($PCMR_{gross}$) showed a steady increase from the pre-pregnancy state onwards (**Table 3**). CMR_{net} (CMR_{gross} - RMR) did not change significantly during pregnancy (**Table 3**), but values in wk 13 of pregnancy tended to be lower than pre-pregnancy values (difference 0.3 to 0.4 kJ/min, NS). At the work loads 30, 45 and 60 Watt, CMR_{net}-values in wk 24 and 35 of gestation were identical to pre-pregnancy values; CMR_{net}-values at the highest work load (75 W) tended to be somewhat higher in wk 24 and 35 of gestation than before pregnancy, but this increase was statistically not significant. $PCMR_{net}$ ($PCMR_{gross}$ minus RMR) showed a non-significant 8% increase in wk 35 of gestation, compared with pre-pregnant values (+0.34 ± 0.79 kJ/min, **Table 3**).

From 21 women, delta work efficiency (dWE) values were obtained in each measurement period. Their pre-pregnancy value was 27.1 ± 2.7 %, and values in wk 13, 24 and 35 of gestation were respectively: 27.5 ± 4.9 %, 25.3 ± 1.1 %, and 26.5 ± 3.4 %. None of the differences between measurement periods were statistically significant (Tukey's studentized range test).

In the pre-pregnancy period, at every work load CMR_{gross} was significantly correlated with RMR, with body weight (**BWt**) and with legindex. CMR_{net}-values were significantly correlated with BWt and legindex as well; however, a significant correlation between CMR_{net} and RMR was only observed at the lowest work load (30 W). Similar associations existed in the measurement periods during pregnancy. Within each measurement period RMR, legindex and BWt were significantly correlated. We choose pre-pregnant CMR at a work load of 60 W to describe the associations in more detail. RMR, BWt and legindex explained respectively 20%, 28% and 32% of the variance in CMR_{gross}, and when these three variables were combined, the explained variance was 35%. RMR explained only 6% of the variance in CMR_{net}, but BWt and legindex respectively 20% and 24%; addition of BWt or RMR to legindex did not further increase

TABLE 4 Respiratory quotients before and during pregnancy.

Measurement condition	Before pregnancy	During pregnancy		
		Wk 13	Wk 24	Wk 35
At rest (26)*	0.85 ± 0.03 A†	0.85 ± 0.04 A	0.85 ± 0.03 A	0.85± 0.04 A
Cycling 30W‡ (26)	0.84 ± 0.04 AB	0.86 ± 0.03 A	0.84 ± 0.04 B	0.82± 0.02 B
Cycling 45W (25)	0.87 ± 0.03 AB	0.88 ± 0.03 A	0.87 ± 0.03 AB	0.85± 0.03 B
Cycling 60W (24)	0.89 ± 0.03 AB	0.90 ± 0.03 A	0.89 ± 0.04 AB	0.88± 0.03 B
Cycling 75W (21)	0.90 ± 0.03 A	0.90 ± 0.03 A	0.90 ± 0.04 A	0.89± 0.04 A
Postcycling§ (20)	0.92 ± 0.05 A	0.92 ± 0.05 A	0.91 ± 0.05 A	0.89± 0.04 A

* Group size between brackets.

† On each row, means sharing the same letter are not significantly different (Tukey's studentized range test).

‡ Work load during cycling.

§ Postcycling metabolic rate, measured during the first 10.5 min after cycling.

R^2. Thus, legindex seemed to be the strongest determinant of CMR_{gross} and CMR_{net}.

Respiratory quotient

The respiratory quotient during cycle ergometer exercise (RQ_C) increased with work load (**Table 4**): within each measurement period, significant differences in RQ_C existed between 30 W and all higher work loads, as well as between 45 W and the two higher work loads (60 and 75 W) (Tukey's studentized range test). Although no changes during pregnancy were found in the respiratory quotient under resting conditions (RQ_R), the respiratory quotient during cycle ergometer exercise (RQ_C) decreased during pregnancy: at the three lower work loads the decrease of RQ_C from wk 13 to 35 of pregnancy was statistically significant (**Table 4**). Post-cycling respiratory quotient (RQ_P) tended also to decrease during pregnancy, but the changes did not reach statistical significance (**Table 4**).

TABLE 5 Heart rate before and during pregnancy.

Measurement condition	Before pregnancy	During pregnancy		
		Wk 13	Wk 24	Wk 35
Cycling 30W* (26)†	99 ± 11 AB‡	96 ± 9 A	99 ± 9 A	102 ± 10 B
Cycling 45W (25)	110 ± 12 A	108 ± 10 A	108 ± 9 A	109 ± 17 A
Cycling 60W (24)	122 ± 15 A	120 ± 14 A	119 ± 11 A	121 ± 14 A
Cycling 75W (21)	134 ± 16 A	132 ± 16 A	133 ± 12 A	133 ± 16 A
Postcycling§ (20)	95 ± 13 A	95 ± 13 A	95 ± 8 A	98 ± 11 A

* Work load during cycling.

† Group size between brackets.

‡ On each row, means sharing the same letter are not significantly different (Tukey's studentized range test).

§ Postcycling metabolic rate, measured during the first 10.5 min after cycling.

Heart rate

Heart rate during cycling exercise at a work load of 30 W increased significantly during pregnancy (**Table 5**). However, at none of the other work loads a change in HR_C during pregnancy was observed. Heart rate in the post-cycling recovery period (HR_P) did not change either.

Discussion

The women in the present study were all healthy and well-nourished. Their weight gains during pregnancy and the birthweights of their children (**Table 1**) were as expected for western women eating without restriction[2,3,16]. The increase in RMR closely resembled the pattern observed in our previous study[21].

Metabolic rate during cycling exercise

We observed a small but steady increase of gross cycling metabolic rate (CMR_{gross}) during pregnancy (**Table 3**). This agrees with findings in other studies (**Table 6**): from mid-pregnancy onwards, CMR_{gross}-values were above the non-pregnant baseline in all studies [7,8,10-14], except for a study involving pregnant adolescents instead of adults[9]. The changes during pregnancy in cycling metabolic rate disappeared when resting metabolic rate (RMR) was subtracted from CMR_{gross}: no significant changes during pregnancy in CMR_{net} were observed. With our study design, we had a chance of 90% to detect a 4% change in CMR_{net}, if such change truly occurs. The constancy of CMR_{net} indicates that the increase in CMR_{gross} was caused by the increase in RMR, which is supported by the association between CMR_{gross} and RMR. No significant association was observed between the change in CMR_{gross} from pre-pregnancy to wk 35 of pregnancy (ΔCMR_{gross}) and the corresponding change in RMR (ΔRMR), but the larger measurement error of the delta's, compared to the original values, might have attenuated this correlation. **Table 6** shows that in most previous longitudinal studies, CMR_{net} appears to be unchanged or slightly reduced in all but the last four weeks of gestation[7-9,11-13].

No significant increase in delta work efficiency (dWE) occurred during pregnancy. Changes in CMR_{gross} as a result of a specific increase of work load, were not significantly influenced by gestation. Thus, the increase during pregnancy in CMR_{gross} reflected a change in metabolic rate which is independent of work load.

Methodological considerations

Instead of pre-pregnancy baseline values, other longitudinal studies used post partum values as baseline. From a group of 22 women we collected data at 9 wk after delivery, which enables us to compare our pre-pregnancy baseline with the post partum value (**Table 7**). Post partum CMR_{gross} was somewhat below the pre-pregnant value (−0.38 ± 2.07 kJ/min, paired *t*–test: $p = 0.40$). Thus, the increase in CMR_{gross} during pregnancy would have been somewhat larger if post partum values instead of pre-pregnancy values had been used as a baseline. RMR appeared to be higher post partum than before pregnancy (+0.13 ± 0.34 kJ/min, paired *t*–test: $p = 0.08$), the increase during pregnancy in RMR would thus have been smaller if post partum values instead of pre-pregnancy values were used as a baseline. In wk 24 and 35 of gestation, CMR_{net} was slightly higher than the post partum value but slightly lower than the pre-pregnancy baseline. We

TABLE 6 Chronologic overview of longitudinal studies on changes in cycling metabolic rate during pregnancy.

Ref*	N	Measurement periods		RMR (*kJ/min*)		CMR (*kJ/min*)			
		Baseline	Pregnancy	$RMR_{baseline}$	ΔRMR	Load (freq)†	$CMR_{baseline}$	ΔCMR_{gross}	ΔCMR_{net}
7	6	7 wk pp‡	wk 22 wk 30 wk 39	4.62	+0.76 +1.01 +1.77	100 *kpm* (?)	15.4	+0.3 +0.7 +2.2	-0.5 -0.3 +0.4
8	13	6 wk pp	wk 24	3.78	+1.23	50 *W* (60 *rpm*)	21.0	+0.7	-0.5
9	7	10 wk pp	wk 34	3.98	+0.67	50 *W* (?)	17.3	-0.6	-1.3
10	12	13 wk pp	wk 24 wk 35 wk 40	5.18	+0.57 +1.01 +1.74	50 *W* (45 *rpm*)	21.3	+0.9 +2.1 +3.1	+0.3 +1.1 +1.4
11	16§	10 wk pp	wk 24 wk 33 wk 40	3.31	+0.71 +1.17 +1.30	50 *W* (?)	16.7	-0.5 +1.2 +3.5	-1.2 0 +2.2
12	16	12 wk pp	wk 38	6.12	+0.99	50 *W* (?)	17.8	+2.6	-0.2
13	20	13 wk pp	wk 28	3.99	+1.09	50 *W* (?)	17.7	+0.8	-0.3

* Reference number.

† Load: work load at cycle ergometer; freq: pedalling frequency.

‡ pp: post partum.

§ In this study, the number of subjects differed between measurement periods: baseline, N=16; wk 24 gestation N=11, wk 33 gestation, N=10; wk 40 gestation, N=6.

conclude that studies using a post partum baseline tend to overestimate the difference in CMR_{net} between pregnant and non-pregnant state.

Cycling is generally assumed to be a weight-independent activity. We assumed that leg mass might influence cycling metabolic rate, as the legs have to be rotated. Our data confirmed this hypothesis: CMR was significantly associated with our index of leg mass and this association was stronger than the association between CMR and body weight. Thus, cycling exercise is dependent of the weight of the legs rather than total body weight. We assume that leg weight influences the work output during cycling exercise. Therefore, part of the increase during pregnancy in CMR_{gross} might have been the result of the increased leg mass, inducing increased work load. CMR_{net} was unchanged during pregnancy despite the increased leg mass, and might have decreased if leg mass had not changed. However, because of the small change in legindex during pregnancy (gestation wk 35 minus pre-pregnancy: +1.1 ± 0.9 dm^3) as well as the small regression coefficient for the effect of legindex on CMR (before pregnancy, legindex was estimated to influence $CMR_{gross,60W}$ and $CMR_{net,60W}$ with respectively 0.33 and 0.27 kJ/min per dm^3), the effect on CMR will have been limited.

TABLE 7 Longitudinal changes in cycling metabolic rate during pregnancy (N=22): comparison of changes relative to pre-pregnant versus post partum baseline.

Measurement periods		RMR (*kJ/min*)		CMR at 60 *W* (*kJ/min*)		
Baseline	Pregnancy	$RMR_{baseline}$	ΔRMR	$CMR_{baseline}$	ΔCMR_{gross}	ΔCMR_{net}
	wk 13		+0.17		-0.5	-0.6
Pre-pregnant	wk 24	3.84	+0.51	21.0	+0.4	-0.1
	wk 35		+0.86		+0.7	-0.2
	wk 13		-0.01		-0.2	-0.2
9 wk pp	wk 24	3.98	+0.36	20.7	+0.8	+0.4
	wk 35		+0.78		+1.1	+0.4

The relationship between CMR and RMR, body weight or legindex underlines the importance of collecting data longitudinally: in a cross-sectional analysis, differences in CMR between groups could result from pregnancy-induced changes in CMR, but also from differences in leg mass, inducing differences in work load between groups.

Metabolic rate during recovery after cycling, and heart rate during and after cycling

Post-cycling metabolic rate ($PCMR_{gross}$) increased during pregnancy to a level 1.2 ± 0.9 kJ/min (14.8%) above pre-pregnancy value in wk 35 of gestation. The corresponding increase in $PCMR_{net}$ ($PCMR_{gross}$ minus RMR) was smaller (0.3 ± 0.8 kJ/min or 7.4%) and statistically not significant (**Table 3**). $PCMR_{net}$ reflects the extra oxygen uptake after exercise, eliminating the oxygen debt which is built up during the cycling programme. This oxygen debt is the result of anaerobic energy-yielding processes, which occur especially during the first minutes of exercise. Thus, the oxygen debt built up during exercise does not change substantially, and recovery of exercise does not cost more energy during pregnancy.

The increase in gross metabolic rate during pregnancy involves increased oxygen transport from lungs to tissues. As plasma haemoglobin is rather decreased than increased during pregnancy[22], an increase in blood circulation (heart rate and/or stroke volume) would be expected during pregnancy. Stroke volume has been reported to be increased[24,25], as well as decreased[23] during pregnancy. We observed a small but significant increase during pregnancy in heart rate during cycling exercise (H_C) at the lowest work load (30 W), but not at the higher work loads (**Table 3**). This is in line with previous studies, in which heart rates at rest[12,23] and during 0 and 30 W cycling exercises[23] were reported to be increased during pregnancy, whereas heart rates at higher work loads[8,12,23,24] as well as maximal heart rate[23] seemed to be unchanged during pregnancy. Thus, the increase in blood circulation during pregnancy might (partly) be realized by increased heart rate under resting conditions or during minor exercise, but not during moderate or heavy exercise.

During the recovery period heart rate (HR_P) was slightly higher (NS) in wk 35 of gestation compared to values earlier in pregnancy and before pregnancy (**Table 5**). Significantly higher recovery heart rates during pregnancy have previously been observed, the differences being comparable to differences in heart rate under resting conditions [10,23].

We conclude that the changes during pregnancy in gross cycling metabolic rate are independent of work load and attributable to changes in resting metabolic rate. Thus, pregnancy does not involve a work-specific change in metabolic rate. Furthermore, the amount of energy needed for recovery after exercise appeared not to change during pregnancy, or only to a very limited extent. We therefore conclude that work efficiency is not substantially improved during pregnancy.

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Chapter 4

CRITICAL REASSESMENT OF THE EXTRA ENERGY NEEDS DURING PREGNANCY

Caroline JK Spaaij, Joop MA van Raaij,
Lisette CPGM de Groot, Joseph GAJ Hautvast

Abstract

Energy costs of pregnancy in 26 Dutch women, calculated as cumulative increase of RMR during pregnancy (ΔRMR_{CUM}: 189 MJ) plus energy cost of increased maternal fat stores (97 MJ) and gain in other tissues (49 MJ), were 335 MJ. The efficiency of energy metabolism appeared to be unchanged during pregnancy, because both the thermic effect of a meal and work efficiency were constant. Energy savings by reduced physical activity (120–261 MJ) appeared to be higher than earlier estimates (100 MJ). These behavioural adaptations plus increased energy intake (43 MJ) accounted for 163–304 MJ. As slight over-estimation of ΔRMR_{CUM} and slight under-estimation of the increase in energy intake during pregnancy cannot be excluded, our study suggests that during pregnancy extra energy needs may be met by increased energy intake plus behavioural adaptations. As a result of the large between-subject variability in both factors, energy intake recommendations for well-nourished pregnant women seem to have limited value.

Introduction

Several longitudinal studies have been published in which the energy costs of pregnancy were estimated, along with changes in energy intake and physical activity during pregnancy[1-8]. Most of these studies confirmed that pregnancy involves considerable energy costs[1-3,5-8], but failed to demonstrate a sufficient increase in energy intake during pregnancy [1,2,4,5,7]. A reduction of physical activity could lower energy expenditure during pregnancy, but the amount of energy saved by such behavioural adaptation is generally assumed to be limited to a maximum of about 100 MJ over the entire pregnancy[1,4,9]. In a previous study in our laboratory the estimated increase in energy intake during pregnancy (48 MJ)[2] and estimated energy savings by reduced physical activity (76 MJ)[9], were together much below the estimated energy costs of pregnancy (286 MJ)[2]. This discrepancy between the extra demands and the extra supplies of energy during pregnancy has been subject to much debate[1,2,7,8,10].

In the study presented here, several options are addressed which could reduce or eliminate this discrepancy. Over-estimation of the energy cost of pregnancy, under-estimation of the increase in energy intake and under-estimation of the energy savings by reduced activity could all explain (part of) the discrepancy. However, if the increase in energy intake and energy savings by behavioural adaptations together, are truly below the energy costs of pregnancy, it would be reasonable to assume that extra reductions of energy expenditure during pregnancy occur. Such further reductions of energy expenditure might be established by metabolic adaptations, which could result in reduced diet-induced thermogenesis and in improved work efficiency.

Our results on longitudinal changes during pregnancy in the thermic effect of a meal[11], the energy cost of cycle ergometer exercise[12], and 24-hour metabolic rate[13] were described separately in more detail. In this publication, all these metabolic rate measurements are combined, and presented along with changes in energy intake and physical activity during pregnancy. After evaluating possible explanations for the difference between the demand- and supplies-sides of the energy balance equation of pregnancy, the implications of these findings for energy intake recommendations are discussed.

Subjects and methods

Study design

In 26 women, measurements of resting metabolic rate (**RMR**), postprandial metabolic rate (**PPMR**), cycling metabolic rate (**CMR**) and body weight (**Wt**) were carried out before pregnancy and in wk 13, 24 and 35 of gestation, on two non-consecutive days within one week. In 22 of these women two more pre-pregnant measurement days were accomplished. Afterwards it appeared that about half of the pre-pregnant measurement days were carried out in the preovulatory and half in the postovulatory phase of the menstrual cycle. Body fat mass (**FM**) was estimated on one of the two measurement days within the same week. Energy intake (**EI**) and habitual physical activity (**PA**) were determined at about 2 wk before the first pre-pregnant measurements and at 1 or 2 wk after the measurement weeks during pregnancy.

In a subgroup of 10 women, measurements of 24-hour metabolic rate (**24hMR**) were carried out on two consecutive days before pregnancy, and in wk 12, 23 and 34 of gestation.

Subjects

For the recruitment of subjects, advertisements in local newspapers, and posters spread in public buildings were used. All participants were judged to be healthy by medical histories and urine analysis. They were all non-smokers. They were living in the town of Wageningen and surrounding areas and reflected middle-upper socioeconomic stratum. Their ethnic background was Caucasian. Further subject characteristics are given in **Table 1**. All women gave their informed consent. The study was approved by the Ethical Committee of the Department of Human Nutrition of the Wageningen Agricultural University.

Metabolic rate

Metabolic rate (MR, in kJ/min) was calculated from oxygen consumption (VO_2, in L/min) and carbon dioxide production (VCO_2, in L/min) using Weir's formula[14]: MR = 16.3 VO_2 + 4.6 VCO_2.

Ventilated hood measurements. RMR, PPMR and CMR were measured by open-circuit indirect calorimetry using ventilated hood equipment as described previously[11].

TABLE 1 Characteristics of the study subjects.

	Full group	Subgroup
Number of women	26	10
Parity *	0.7 ± 0.9	0.4 ± 0.5
Nulliparae *(N)*	12	6
Primiparae *(N)*	11	4
Multiparae *(N)*	3	0
Age *(y)* †	29.9 ± 3.9	29.2 ± 2.8
Height *(cm)*	169 ± 7	169 ± 6
Body weight *(kg)* *	62.6 ± 8.6	61.6 ± 9.6
Body mass index *(kg/m²)* *	21.9 ± 2.5	21.4 ± 3.2
Body fat % *(wt/wt %)* *‡	27.7 ± 5.2	28.4 ± 5.9
Length of gestation *(wk)* §	40.2 ± 1.1 ‖	40.5 ± 1.2 ¶
Gestational weight gain *(kg)* **	11.7 ± 3.0	12.2 ± 2.9
Girls/boys	12/14	6/4
Birth weight *(g)*	3517 ± 329	3523 ± 237
Placental weight *(g)*	654 ± 119	661 ± 111
Baby length *(cm)*	51.3 ± 5.0 ††	52.8 ± 1.5 ‡‡
Baby head circumference *(cm)*	36.7 ± 3.2 ††	36.2 ± 1.1 ‡‡

* Before present pregnancy.

† At onset of present pregnancy.

‡ Estimated with densitometry using under water weighing.

§ Length of gestation was derived from the 1st d of the woman's last reported menstrual period.

‖ 24 women delivered at term (length of gestation 259–293 d, as defined by Hytten, ref. 24) and 2 women postterm (296 and 299 d); 24 infants were delivered normally and 2 by Caesarian section.

¶ 9 women delivered at term (259–293 d) and 1 woman postterm (296 d); all infants were delivered normally.

** Last recorded weight during pregnancy (1–7 d before delivery) minus pre-pregnant weight.

†† One to 2 wk (11 ± 7 d) after delivery.

‡‡ One to 2 wk (13 ± 7 d) after delivery.

During the measurements the woman watched non-stressing video films. The day-to-day coefficient of variation of MR, determined by ethanol combustion tests, was 1.9%[11].

RMR was measured during 35 min after 12 h fasting, while the woman was lying in supine semi-recumbent position, in complete physical rest, but awake[11]. The within-subject day-to-day coefficient of variation for RMR, as calculated from all pairs of measurement days in the same week, was 4.6% (*SD* 0.19 kJ/min).

PPMR was measured during the first 180 min following consumption of a testmeal. The conditions of the PPMR measurement were exactly the same as during the RMR measurement, except for the postprandial state. The within-subject day-to-day coefficient of variation for PPMR was 3.8% (*SD* 0.18 kJ/min). The testmeal consisted of 375 g yoghurt-based liquid formula containing 1325 kJ (15 energy% protein, 30 energy% fat and 55 energy% carbohydrate)[11]. The thermic effect of the meal (TEM) was calculated as PPMR minus RMR. The within-subject day-to-day coefficient of variation for TEM was 21.5% (*SD* 0.14 kJ/min). For the extrapolation of the TEM-response to daily diet-induced thermogenesis (DIT), we assumed that our postprandial measurement covered 85% of the total thermic effect of the testmeal[11], that within subjects, the thermic effect of a meal was proportional to its energy content[15], and that differences in composition between testmeal and diet did not result in different thermic effects. Thus, DIT was estimated from TEM and total daily energy intake (for free-living conditions we used the 5-d weighed record estimate, see further, and for respiration-chamber conditions we used the energy content of the supplied diet, see further).

CMR was measured during the last 3 min of a 6-min period during which the woman was performing cycle ergometer exercise at a work load of 45 Watts and 60 rotations per min. The women cycled with her back straight, and knees slightly bent with the peddle at its lowest position[12]. Net cycling metabolic rate (netCMR) was calculated as CMR minus RMR. Within-subject day-to-day coefficients of variation for CMR and netCMR were 3.1% and 4.1% (*SD*'s 0.54 and 0.55 kJ/min).

Respiration chamber measurements. Detailed descriptions of the respiration chamber system[16] and the measurement procedure[13] are given elsewhere. Gas-exchange measurements were made during two consecutive 24-h periods, beginning and ending at 0800. During days spent in the respiration chamber and the 6 preceding days, diet was supplied to the women. The energy content of the diet was tuned to each woman's individual pre-pregnant energy requirement[13]. The energy content was kept constant throughout pregnancy, because previous longitudinal studies failed to show a significant change in energy intake during pregnancy[2,10]. The macronutrient composition of the diet was 15 energy% protein, 35 energy% fat and 50 energy% carbohydrate.

The woman entered the respiration chamber on the day preceding the first 24hMR-measurement at about 2300 and left the chamber after the third night in the chamber. A standardized light activity schedule was followed in the respiration chamber: time from 2345 to 0815 was spent in bed, meals were consumed at 0900, 1300 and 1830, there were five 15-min cycling periods per day (work load 15 Watts, 50 rotations per min) and the remaining time was spent with sitting activities[13]. The within-subject day-to-day coefficient of variation for 24hMR was 2.1% (*SD* 0.19 MJ/d).

Body weight and body fat mass

Body weight was measured in the laboratory on an electronic balance (Berkel ED60–T, Rotterdam, The Netherlands), or at home on a spring balance (Seca 760, Lameris Instruments BV, Utrecht, The Netherlands). The density of the body was determined from Wt and body volume obtained by the under-water weighing technique. FM was calculated from body density using the Siri equation for pre-pregnant and post partum measurements[17] and using recently developed equations for measurements during pregnancy[18]. Within-subject day-to-day coefficient of variation in FM estimated by hydrodensitometry was 7.0% (*SD* 1.17 kg). Fat deposition in maternal stores during pregnancy was also estimated from the sum of four skinfold thicknesses before pregnancy and 4 wk after delivery[19]. Within-subject day-to-day coefficient of variation in FM estimated from Σ 4 skinfolds was 12.6% (*SD* 2.28 kg). Finally, fat deposition during pregnancy in maternal fat stores was also estimated from factorial analysis of total gestational weight gain (at 40 wk gestation) and from factorial analysis of weight retention at 4 wk post partum[20].

Energy intake

Food consumption was recorded over 5 consecutive days (Wednesday through Sunday) by the individual weighed-inventory technique as described earlier[3,21,22]. Basically this consists of weighing each item of food or drink immediately before consumption and repeating the procedure on leftovers. Weighing and recording was done by the woman herself using electronic scales incorporating a zeroing button and having a digital read out (type 1203 MP, Sartorius GMBH, Göttingen, FRG; weighing range 0–4000 g, accuracy 1 g). Attention was drawn to the prime importance of not interfering with normal eating patterns. All food items recorded were converted into food codes according to the Dutch food encoding system[23], the quantity per day was calculated, and the Dutch computerized food composition table was used[23] for conversion to EI. Within-subject day-to-day coefficient of variation in EI was 19.6% (*SD* 1.89 MJ/d).

Activity pattern

On the days of the weighed food consumption record, the woman recorded the times of rising and going to bed, as well as the duration of any period spent lying during the day. From this we calculated active time, which was defined as the total period (min/d) during which the subject was not lying. On the same days, the woman carried a pedometer (Kasper & Richter, Uttenreuth, Germany) and recorded the read-out both when rising and when going to bed. Step size was not individually adjusted, but fixed at 0.75 m/step, because of its variability during mixed activities. Walking activity is defined as the mean number of steps per day. Within-subject day-to-day coefficients of variation for active time and walking activity were 11.0% and 38.9%.

Calculation of cumulative changes during pregnancy

For the calculation of cumulative or average changes during pregnancy we had to extrapolate the measurements during pregnancy to the full period of pregnancy. We assumed that values did not change during the first 3 weeks after the onset of the last menstruation preceding conception: the first 2 weeks are preconceptual and it takes several days after conception before the embryo becomes implanted in the wall of the uterus. Thus, to calculate the cumulative change in RMR, 24hMR and EI during pregnancy, changes relative to pre-pregnancy values in the three gestational periods are averaged and extrapolated over 261 days (38 weeks minus 5 days, since implantation of the embryo in the uterus is assumed to take place about 5 days after ovulation).

Statistics

Data are presented as mean ± *SD* and refer to the group of 26 women, unless stated otherwise. Data analysis was carried out using the programme provided by SAS (SAS Institute, Inc, Cary, NC). Paired *t*-tests were used to analyze whether a response parameter changed significantly compared to its pre-pregnancy value (significance level $\alpha=0.05$). Pearson correlation coefficients (r) and p-values were used to describe associations between pairs of variables (null hypothesis $r=0$). If a parameter was correlated with more than one variable, the general linear models (GLM) procedure of the SAS-package was used to investigate the association with the combination of variables.

To partition the total variability in the cumulative change during pregnancy (s^2_{Δ}) into a between-subjects component ($s^2_{\Delta S}$) and a random component ($s^2_{\Delta R}$), this random component was estimated from the random variance for single measurements (s^2_R = within-subject day-to-day variance) using the following formula:

$$s^2_{\Delta R} = \frac{s^2_R * 261^2}{m_{pre}} + \frac{s^2_R * 87^2}{m_{wk13}} + \frac{s^2_R * 87^2}{m_{wk24}} + \frac{s^2_R * 87^2}{m_{wk35}}$$

where m_{pre}, m_{wk13}, m_{wk24} and m_{wk35} = the number of measurement days within that measurement period, and where 261 and 87 represent the number of days over which the measurement value was extrapolated when calculating the cumulative change. By subtracting $s^2_{\Delta R}$ from the total variance in the cumulative change of the parameter (s^2_{Δ}), we obtained an estimate of 'true' between-subject variability in the change of the parameter during pregnancy.

Results

After presenting data on the energy costs of pregnancy (fat gain, cumulative increase of RMR), and on relations of these costs with pre-pregnant subject characteristics, data on the cumulative increases in energy intake and on energy savings by reduced physical activity during pregnancy are given.

The energy costs of pregnancy

Gain in body fat mass. We used five approaches to estimate the gain in fat mass during pregnancy (**Table 2**). The estimates varied between 1.33 kg (Σ4skinfolds, fat retention at 4 wk post partum) and 2.41 kg (hydrodensitometry, fat retention at 9 wk post partum; 2 women not measured). The average value of four estimates, both hydrodensitometry estimates and the two estimates through factorial approaches, was 2.10 ± 2.18 kg. Assuming that deposition of 1 kg fat takes 46 MJ (the energy content of

TABLE 2 Estimates of gain in maternal fat stores during pregnancy.

Method and calculation	Weight	Fat stores
	kg	*kg*
Fat gain from hydrodensitometry at wk 35 of gestation		
Fat gain at 35 wk of gestation *	2.37 ± 2.23	
minus fat gain in tissues other than fat stores †	0.5	
Gain in maternal fat stores		1.87 ± 2.23
Factorial analysis of weight gain at 40 wk gestation		
Weight gain at 40 wk gestation *	11.71 ± 2.95	
minus birthweight baby	3.52 ± 0.33	
minus weight placenta	0.65 ± 0.12	
minus 4.77 kg †‡	4.77	
Gain in adipose tissue (80% fat)	2.78 ± 3.00	
Gain in maternal fat stores		2.22 ± 2.40
Factorial analysis of weight retention at 4 wk post partum		
Weight retention at 4 wk post partum *	2.94 ± 3.37	
minus gain in breast mass †	0.4	
Gain in adipose tissue (80% fat)	2.54 ± 3.38	
Gain in maternal fat stores		2.03 ± 2.70
Fat gain from Σ4skinfolds at 4 wk post partum		
Fat retention at 4 wk post partum *	1.33 ± 2.67	
Gain in maternal fat stores		1.33 ± 2.67
Fat gain from hydrodensitometry at 9 wk post partum		
Fat retention at 9 wk post partum * §	2.41 ± 2.68	
Gain in maternal fat stores		2.41 ± 2.68

* Change relative to pre-pregnancy value.

† Values given by Hytten (23).

‡ Sum of increased weights of uterus, breasts, blood, extravascular extracellular and amniotic fluids (23).

§ N=24.

TABLE 3 Energy cost of pregnancy.

Factor	Full group ($N=26$)	Subgroup ($N=10$)
	MJ	
Energy cost of tissue gain:		
Gain in maternal fat stores *†	97 ± 100	127 ± 80
Gain in other tissues *‡	49	49
Cumulative change in metabolic rate:		
ΔRMR_{CUM}	189 ± 106	239 ± 98
ΔDIT_{CUM}	-6 ± 60	11 ± 59
$\Delta 24hMR_{CUM}$		150 ± 118
Total energy costs of pregnancy:		
Tissue gain + ΔRMR_{CUM}	335 ± 154	415 ± 147
Tissue gain + ΔRMR_{CUM} + ΔDIT_{CUM}	329 ± 160	426 ± 135
Tissue gain + $\Delta 24hMR_{CUM}$		326 ± 137

* Values of 29 and 46 kJ were applied as the energy needed for depositing each g of protein and fat, respectively, allowing for both the energy content of the tissue and the energy cost of deposition[2].

† Fat gain during pregnancy: the average value of 4 estimates.

‡ The amounts of protein and fat deposited in tissues other than maternal fat mass were assumed to be 925 g and 480 g.[23]

fat plus the energy cost of its deposition), this gain in body fat mass costs 97 ± 100 MJ **(Table 3)**.

Cumulative increase in resting metabolic rate. Resting metabolic rate (RMR) increased significantly during pregnancy **(Table 4)**. The cumulative increase in RMR during pregnancy (ΔRMR_{CUM}) was estimated to be 189 ± 106 MJ **(Table 3)**. About 22.5% of the variance in ΔRMR_{CUM} was attributable to random measurement error, suggesting that the main part (77.5%) of the variance in ΔRMR_{CUM} was caused by between-subject differences in the increase of RMR during pregnancy.

Cumulative change in diet-induced thermogenesis. No significant changes during pregnancy were observed in the thermic effect of the meal (TEM) **(Table 4).** On average, TEM decreased with 0.03 ± 0.12 kJ/min. The main part (58.6%) of the variance in $\Delta TEM_{average}$ was attributable to random measurement error. Within each measurement period, diet-induced thermogenesis (DIT) was estimated for each woman from her TEM-response and habitual daily energy intake (5-d weighed record). The cumulative change of DIT during pregnancy (ΔDIT_{CUM}) was estimated to be –6 ± 60 MJ (p=0.55) **(Table 3).**

Change in net cycling metabolic rate. Net metabolic rate during standardised cycle ergometer exercise (netCMR) tended to decrease at 13 wk gestation, but was close to pre-pregnancy level at wk 24 and wk 35 of gestation **(Table 4).** On average, netCMR

TABLE 4 Changes during pregnancy relative to pre-pregnant value.

Component	Pre-pregnancy value	Change *		
		wk 13	wk 24	wk 35
			MJ/d	
24hMR †	8.56 ± 0.82	+0.10 ± 0.56	+0.37 ± 0.52 ‡	+1.27 ± 0.43 §
			kJ/min	
Gross metabolic rates				
RMR ‖	3.82 ± 0.35	+0.16 ± 0.27 §	+0.48 ± 0.40 §	+0.87 ± 0.42 §
PPMR ‖	4.46 ± 0.33	+0.16 ± 0.25 §	+0.45 ± 0.39 §	+0.83 ± 0.36 §
CMR ‖	17.28 ± 1.24	–0.11 ± 1.49	+0.48 ± 1.38	+0.85 ± 1.45 §
Net metabolic rates				
TEM ‖	0.64 ± 0.11	–0.01 ± 0.13	–0.04 ± 0.15	–0.04 ± 0.17
NetCMR ‖	13.45 ± 1.13	–0.27 ± 1.43	–0.00 ± 1.33	–0.02 ± 1.49

* Value during pregnancy minus pre-pregnancy value.

† Data from the subgroup of 10 women.

‡ Significantly different from zero with paired t-test: 0.01≤p≤0.05.

§ Significantly different from zero with paired t-test: p≤0.01.

‖ Data from the full group of 26 women.

diminished with 0.10 ± 1.22 kJ/min during pregnancy ($p=0.69$). The variance of $\Delta netCMR_{CUM}$ was largely (for 91.1%) attributable to true between-subject differences in the response to pregnancy, only 8.9% of the variance appeared to be caused by measurement error.

Cumulative increase of 24-hour metabolic rate. Twenty-four-hour metabolic rate increased steadily from 8.56 ± 0.82 MJ/d before pregnancy to 9.83 ± 0.96 MJ/d at gestation wk 35 ($N=10$) (**Table 4**). The increase was significant in wk 24 ($p=0.05$) and wk 35 ($p<0.0001$) of gestation. The cumulative increase in 24hMR was estimated to be 150 ± 118 MJ ($p=0.003$) (**Table 3**). Only 10.8% of the total variance in $\Delta 24hMR_{CUM}$ was attributable to random measurement error, the remaining 89.1% of the variance appeared to represent true between subject differences.

Total energy costs of pregnancy and relationship with pre-pregnant characteristics

The sum of energy deposition in tissues and the cumulative increase of the maintenance costs of the body (ΔRMR_{CUM}) amounted to 335 ± 154 MJ during pregnancy (**Table 3**). The total costs of pregnancy were hardly affected if the change in DIT during pregnancy was taken into account as well (**Table 3**). In the subgroup of women that was measured in the respiration chamber, ΔRMR_{CUM} was substantially higher than in the total group of 26 women (**Table 3**). Their change in 24hMR during pregnancy appeared to be 37% lower than ΔRMR_{CUM} (**Table 3**).

A strong positive association was observed between ΔRMR_{CUM} and pre-pregnant body fat percentage ($r=0.50$, $p=0.01$) (**Figure 1a**). The total cost of pregnancy, calculated as tissue gain plus ΔRMR_{CUM}, was significantly related with pre-pregnant body fat percentage ($r=0.46$, $p=0.02$) as well (**Figure 1b**). However, pre-pregnant body fat percentage was not related with fat gain during pregnancy ($r=0.18$, $p=0.38$), birthweight of the baby ($r=0.33$, $p=0.10$), $\Delta TEM_{average}$ ($r=-0.34$, $p=0.09$), $\Delta netCMR_{average}$ ($r=-0.12$, $p=0.57$), or $\Delta 24hMR_{CUM}$ ($r=-0.09$, $p=0.81$, $N=10$). Neither age, nor parity appeared to influence (components of) the energy costs of pregnancy.

Change in habitual physical activity during pregnancy

Active time diminished from a pre-pregnant value of 915 ± 35 min/d with 42 ± 44 min/d at wk 13 of gestation ($p<0.0001$), with 42 ± 55 min/d at wk 24 of gestation ($p=0.0007$), and with 87 ± 54 min/d at wk 35 of gestation ($p<0.0001$). The average

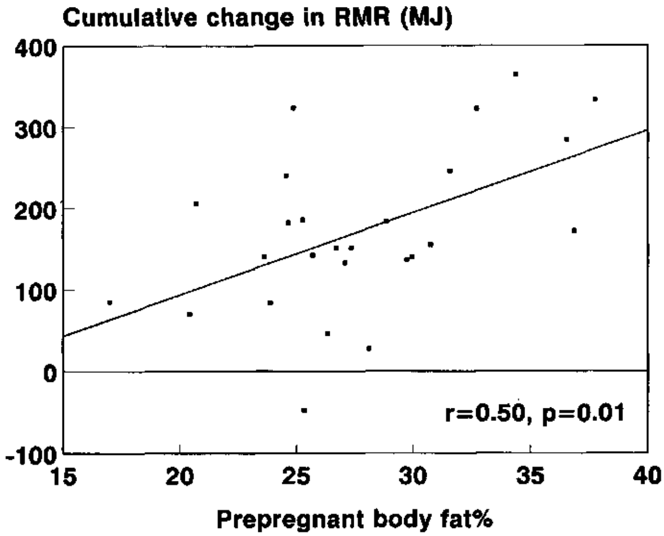

FIGURE 1a Relationship of pre-pregnant body fatpercentage with the cumulative increase of resting metabolic rate during pregnancy.

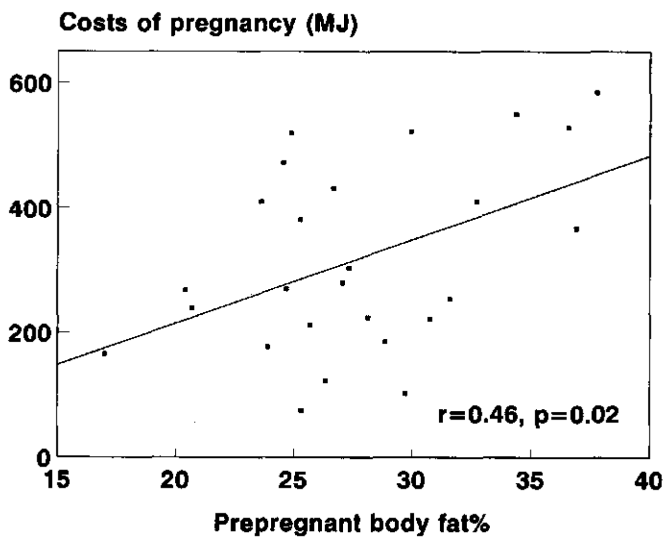

FIGURE 1b Relationship of pre-pregnant body fat% with the total energy cost of pregnancy.

reduction of active time during pregnancy was 57 ± 41 min/d ($p<0.0001$). Step count diminished from a pre-pregnant value of 11.4 ± 3.1 thousand steps per day with 1.2 ± 2.5 thousand steps/d at wk 13 of gestation ($p=0.03$), with 0.7 ± 3.8 thousand steps/d at wk 24 of gestation ($p=0.38$), and with 2.4 ± 3.7 thousand steps/d at wk 35 of gestation ($p=0.002$). The average reduction of walking activity during pregnancy was 1.4 ± 2.7 thousand steps per day ($p=0.01$).

Cumulative change in energy intake during pregnancy

No significant increase of energy intake was observed in these women. Energy intake was 9.50 ± 1.64 MJ/d before the onset of pregnancy, and changes in wk 13, 24 and 35 of gestation were respectively -0.13 ± 1.46 MJ/d ($p=0.65$), +0.13 ± 1.67 MJ/d ($p=0.70$), and +0.50 ± 1.65 MJ/d ($p=0.13$). Thus, the cumulative increase in energy intake was only 43 ± 349 MJ during pregnancy ($p=0.54$).

Discussion

Methodological considerations

For the amounts of protein and fat deposited in fetus, placenta, uterus, breasts, blood volume, volume of amniotic fluid and other extracellular extravascular fluids, we used Hytten's estimates, i.e. 925 g protein and 480 g fat[24]; assuming that protein and fat deposition cost respectively 29 and 46 kJ/g[1], the estimated energy cost of this factor is 49 MJ. We consider Hytten's estimate appropriate for our study population because the birthweights and placental weights in our women (3517 and 654 g) were similar to the values on which Hytten based his estimates (respectively 3400 and 650 g). Quantitative knowledge about the relationship of birthweight plus placenta weight (together about 75% of these costs) with weight gains of uterus, breasts, blood, amniotic fluid and other extracellular extravascular fluids is limited. Furthermore, the amounts of protein and fat in these tissues are probably not proportional to the tissue weight. Because of these two reasons, we preferred using the same value (49 MJ) for all women to making individual estimates for this factor.

From our 5 estimates of gain in maternal fat stores during pregnancy, we used the average of only four (from hydrodensitometry and factorial methods) when calculating the energy costs of pregnancy. These four estimates where based on "whole-body" measurements, whereas the fifth estimate, the skinfold estimate, was based on the amount of fat at only 4 subcutaneous sites of the body. The validity of the post partum estimate of fat mass from the sum of four skinfolds might be reduced because of site-specific changes in skinfold thicknesses[25,26,27] and fat cell metabolism during pregnancy[28].

The cumulative change in RMR during pregnancy (ΔRMR_{CUM}) was calculated as the average RMR (MJ/d) during pregnancy minus the average pre-pregnant RMR times 261 days. Pre-pregnant RMR-measurements can be affected by the menstrual cycle[29-31]. However, as pre-pregnant RMR-estimates were based on measurements at 4 (sometimes 2) separate days in our study, the menstrual-cycle effects are neglectable. The question remains whether the mean of measurements in wk 13, 24 and 35 of gestation (only three timepoints) is a valid estimator of the average RMR throughout gestation. In a recent publication[7], the mean of BMR-values at wk 12, 24 and 36 of gestation appeared to be 2% higher than the mean of BMR-values at wk 6, 12, 18, 24, 30 and 36. We therefore admit that our estimate of ΔRMR_{CUM} might be slightly too high.

For the extrapolation of the TEM-response to total daily diet-induced thermogenesis (DIT), we assumed that, per kJ consumed, the thermic effect of the regular diet was similar to that of the testmeal, despite small differences in macronutrient composition. Yet, differences in physical state were more pronounced and might have influenced the thermic effects. In our study, however, changes in TEM rather than the TEM as such were investigated, and it seems improbable that the thermic effect of a mixed meal would change during pregnancy if the thermic effect of the testmeal is unchanged. For the calculation of DIT, we furthermore assumed that TEM is proportional to energy intake. Therefore, under- or over-estimation of energy intake would cause similar estimation errors of DIT. However, as changes in DIT were studied rather than DIT as such, and as TEM appeared to be unchanged during pregnancy, estimation errors in changes of energy intake, but not in energy intake as such, appear to reduce the validity of estimated changes in DIT.

The validity of estimated changes in energy intake is only reduced if the extent of over- or under-reporting is affected by repeating the measurement. Increasing under-reporting has been observed in two previous studies[32,33], however, in another study good agreement was observed when repeating a dietary record[34]. With present knowledge, we cannot exclude the possibility that increasing levels of under-reporting mask true increases in energy intake during pregnancy.

Actual energy costs of pregnancy

Gestational weight gain, birth weight and placental weight in our women were as expected for western women eating without restriction[1,2,6,7,24]. Our estimate of ΔRMR_{CUM} (189 MJ) was within the upper range of values from other longitudinal studies in western countries: values of women in Schotland[1], Sweden[6], England[7], the Netherlands[20], and the USA[35] were, respectively: 126 MJ, 210 MJ, 124 MJ, 144 MJ, and 113 MJ. As described earlier, we cannot exclude that our estimate of ΔRMR_{CUM} was somewhat too high, although, the estimate was within the range normally observed. The gain in maternal fat stores during pregnancy, calculated as the average of four estimates (the hydrodensitometric and factorial estimates), was 2.1 ± 2.2 kg. This finding is consistent with results of most previously published longitudinal studies carried out in western countries: 2.3 kg[1], 2.0 kg[20], 2.3 kg[7]; however, in Swedish women, a substantially larger fat deposition during pregnancy was observed (3.8[6] or 5.8[36] kg, depending on the methodology used), but their average gestational weight gain was also higher (13.6 kg).

We studied the possibility of increased metabolic efficiency during pregnancy. Our results strongly suggest that no important changes in TEM-response occur during pregnancy, a finding which was presented earlier in more detail[11]. Energy intakes did not change substantially either, therefore, total daily diet-induced thermogenesis appeared to be unchanged during pregnancy in these women. A previous publication showed a significant TEM-decrease in mid-pregnancy[37], but the group size was small; two small cross-sectional studies showed conflicting results[38,39]. If metabolic efficiency would have been increased during pregnancy, this could have also resulted in improved work efficiency during pregnancy. However, the lack of a change in the net cost of cycling exercise, a non-weight-bearing activity, suggested that work efficiency was unchanged. The pattern and magnitude of changes in cycling metabolic rate were similar at three other work loads[12], and consistent with results of other studies[40-45]. The lack of changes in TEM and netCMR during pregnancy indicate that in well-nourished women, pregnancy does not affect metabolic efficiency.

The high variability in ΔRMR_{CUM} was probably largely attributable to true between subject differences. Although age, nor parity influenced ΔRMR_{CUM}, a significant association was observed with pre-pregnant body fat percentage. The total energy costs of pregnancy appeared to be positively related with pre-pregnant body fat percentage as well. The relationship between ΔRMR_{CUM} and pre-pregnant body fat percentage was earlier described by Prentice *et al.*[46] (r=0.84, p<0.005, N=8), and certainly warrants further investigation. Neither age, nor parity appeared to influence (components of) the energy costs of pregnancy. As a result of the smaller increase of RMR during pregnancy in thinner women (**Figure 1a**), their total energy costs of pregnancy are lower compared to fatter women (**Figure 1b**). This relationship was not the result of an association of birthweight with body fat percentage. Therefore, the lower ΔRMR_{CUM} in thinner women suggests that the efficiency of energy metabolism was inversely related with pre-pregnant body fat percentage.

Role of activity pattern in reducing energy expenditure

Especially at the end of pregnancy when weight gain is large, the net cost of weight-bearing activities, such as walking, might increase[47]. As metabolic efficiency does not improve during pregnancy, changes in total daily energy expenditure are caused by changes in RMR, changes in activity pattern and changes in the net cost of weight-bearing activity.

Our women significantly reduced their free living physical activity during pregnancy: active time reduced with 57 min/d and walking activity with 1.4 thousand steps/d, which was consistent with earlier observations in another group of Dutch women (active time: -70 min/d)[9]. If per day a woman would replace 1 h of sitting activity (about 6 kJ/min) or moderate exercise (about 15 kJ/min) by rest (about 4 kJ/min), energy savings between about 120–660 kJ/d could be established, which is in line with the general assumption of 360 kJ/d[48]. However, combination of 24hMR-, RMR- and DIT-data of a subgroup of 10 women revealed that for the days in the respiration chamber, when changes in the time spent sleeping or in supine rest were not allowed, the net cost of physical activity (netPA) decreased with about 308 kJ/d (-13%) or 80 MJ over the entire pregnancy (p=0.02) (**Figure 2**). This suggests that the amount and/or intensity of physical activity was reduced and is consistent with the observed reduction of Doppler- and Actometer counts during days in the respiration chamber[13]. Under free living conditions, the pre-pregnant netPA was about 3 MJ/d, or 30% higher than in the respiration chamber. This might imply that under free living conditions, larger energy savings by reduced activity could be established than in the respiration chamber. Subtraction of the energy savings by reduced active time (120–660 kJ/d) from pre-pregnant netPA (3 MJ/d), leaves 2.88–2.34 kJ/d. If changes in the type and intensity of these remaining

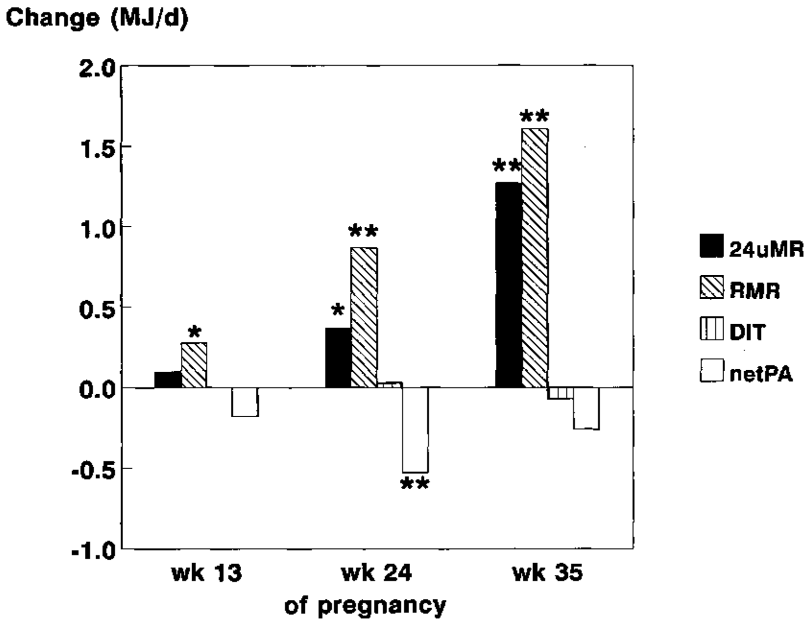

FIGURE 2 Changes during pregnancy in 24hMR (measured) and each of its three components: RMR (measured), DIT (calculated from TEM-measurement and energy intake from the supplied diet in respiration chamber) and the net cost of physical activity (netPA, by subtraction). Pre-pregnancy values of 24hMR, RMR, DIT and netPA were, respectively: 8.56, 5.32, 0.89, and 2.35 MJ/d.

activities result in another 13% reduction of the net costs, as observed in the respiration chamber (370–300 kJ/d), the total savings by behavioural adaptations (reduced activity and changes in type and intensity of remaining activity) could amount to 490–960 kJ/d, or 127–250 MJ over the entire pregnancy. Thus, the average amount of energy saved by reduced physical activity might be substantially higher than the usual assumption of 100 MJ. Because of the large between-subject variation in changes of physical activity during pregnancy, some women might even fully compensate the energy costs of pregnancy by reduced physical activity.

Longitudinal studies using the doubly labelled water ($^2H_2{}^{18}O$) method could possibly give definite answers about the amount of energy saved by reduced physical activity. So far, two doubly-labelled water studies with conflicting results have been published[7,36]: the results of one study suggested that the net cost of physical activity were increased during pregnancy[7], whereas in the other study these costs appeared to be unchanged[36].

The role of increased energy intake

The small increase of energy intake in our women (43 ± 349 MJ over the entire pregnancy) is consistent with previous estimates for Dutch (22 MJ)[2] and Scottish women (57 MJ, ref. 10), yet, the increase was much higher in 12 English women (203 MJ)[7]. The overall variability in the cumulative increase of energy intake is extremely high, and even if the impact of the large within-subject day-to-day variability in energy intake on this cumulative change is subtracted from the total variance, the variance remains high (*SD* 221 MJ). This suggests that profound between-subject differences in the increase in energy intake during pregnancy exist. Some women might pay the energy costs of pregnancy largely by increased energy intakes.

Conclusions

The generally accepted assumptions about energy savings by reduced physical activity are probably too low. For the entire pregnancy, we estimated that energy savings by behavioural adaptation (127–250 MJ) plus increased energy intake (43 MJ) could amount to 170–293 MJ. The upper range of this estimate comes close to the estimated energy cost of pregnancy (335 MJ). As the energy costs of pregnancy might be slightly over-estimated and the increase in energy intake during pregnancy might be slightly under-estimated, our study suggests that the energy costs of pregnancy may be met by increased energy intakes plus energy savings by reduced physical activity.

Changes during pregnancy in both energy intake and physical activity show very large between-subject variability. It seems reasonable to assume that women cope with the energy costs of pregnancy by either of these mechanisms or by a combination of the two. We conclude that as a result of the large differences between subjects in the way they cope with the energy costs of pregnancy, general energy intake recommendations for pregnancy are of limited use. Obviously, in obstetrical practice, deviations of body weight gain from the desired weight change could give rise to individual energy intake recommendations.

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Chapter 5

THE EFFECT OF LACTATION ON RESTING METABOLIC RATE AND ON DIET- AND WORK-INDUCED THERMOGENESIS

Caroline J.K. Spaaij, Joop M.A. van Raaij,
Lisette C.P.G.M. de Groot, Lidwien J.M. van der Heijden,
Harry A. Boekholt and Joseph G.A.J. Hautvast

Abstract

Energy metabolism was measured in 24 women before pregnancy and during lactation, 2 months post partum. Resting metabolic rate (RMR) increased with 0.17 ± 0.38 kJ/min during lactation, and postprandial metabolic rate (PPMR) showed a similar increase (0.17 ± 0.45 kJ/min). Thus, the thermic effect of the meal (PPMR minus RMR) was not affected by lactation. During lactation gross cycling metabolic rates (CMR) were slightly reduced. Net cycling metabolic rate (CMR minus RMR) tended to decrease with 0.6 kJ/min at each work load, however, only at the the lowest work load (30 W) the change was statistically significant. Changes in metabolic rate during the recovery period after exercise were not significant, but resembled changes in RMR rather than changes in CMR. Thus, no major changes in metabolic efficiency occurred during lactation. The lactation-induced increase in RMR appeared to be positively related with body mass index, suggesting that the efficiency of breast milk production might related to body mass index.

Introduction

Lactation causes substantial energy stress. WHO estimates the energy cost of lactation to be almost 3 MJ/d[1]. In a group of 40 lactating Dutch women, basal metabolic rate appeared to be reduced with 0.3 kJ/min at 9 wk after delivery compared to 12 wk gestation[2]. The hypothesis was raised that the efficiency of energy metabolism could be improved during lactation. However, in other longitudinal studies no such decrease in resting metabolic rate during lactation was observed[3-6]. The present study was carried out to investigate whether any of the three components of energy metabolism (resting metabolic rate, diet-induced thermogenesis and work-induced thermogenesis) show signs of metabolic adaptation during lactation. Pre-pregnant measurements were used as a baseline. Measurements were repeated at 2 mo after delivery, during lactation.

Subjects and methods

Study design

Resting metabolic rate (**RMR**), postprandial metabolic rate (**PPMR**), cycling metabolic rate (**CMR**), post-cycling metabolic rate (**PCMR**), heart rate during and after cycling exercise (**HR**$_C$ and **HR**$_P$), body weight (**BWt**), body fat mass (**FM**), energy intake, and habitual physical activity were measured in 24 healthy Dutch women before pregnancy and during lactation (9 wk post partum). Metabolic rate, heart rate and body weight measurements were carried out on two (N=5) or four (N=19) non-consecutive days before pregnancy and on two non-consecutive days after delivery. Afterwards it appeared that about half of the pre-pregnant measurement days fell in the preovulary and half in the postovulary phase of the menstrual cycle. Each measurement day was preceded by 3 days, during which energy intake was kept relatively constant (maximal variation 1 MJ/d), and macronutrient composition of the diet was standardized at 15 energy% protein, 50 energy% carbohydrate and 35 energy% fat. Body composition measurements, using under-water weighing and skinfold techniques, were performed on one out of two measurement days. At 4 wk post partum body weight and skinfold measurements were performed at the woman's home. Energy intake and habitual physical activity were determined about 2 wk preceding the first pre-pregnant measurement day, and in the week following the post partum measurement days (10 wk post partum). At 10 wk post partum, breast milk intake of the infants was determined as well.

At a measurement day the woman arrived fasting by car at the metabolic unit between 0700 and 0730. After voiding, body weight was measured. The woman was installed under a ventilated hood on a hospital bed, and after a 25 min period in which metabolic rate reached a steady state, RMR was measured during 35 min. A liquid meal was given and PPMR was measured during the subsequent 3 h. The woman was allowed to drink one or two cups of tea with or without sugar during a 20-30 min pause. She was then re-installed under the ventilated hood, and CMR and HR_C were measured during a 25 min cycling programme. Throughout the subsequent 10.5 min, the woman remained seated on the cycle ergometer, but without body movements. In this period PCMR and HR_P were measured. The subject had lunch, on one out of two measurement days followed by body composition measurements.

Subjects

For the recruitment of subjects, advertisements in local newspapers, and posters spread in public buildings were used. Participants were judged to be healthy by medical histories and urine analysis. They were all non-smokers. They were living in the town of Wageningen and surrounding areas and reflected middle-upper socioeconomic stratum. Their ethnic background was Caucasian. Further subject characteristics are given in **Table 1**. All women gave their informed consent. The study was approved by the Ethical Committee of the Department of Human Nutrition of the Wageningen Agricultural University.

Infant breast milk intake

The amount of breast milk ingested over a 5-d period was determined by weighing the infant before and after each feeding (test-weighing procedure) on an automatic, electronic balance (Babyscale model MBS 201, Weightec Ltd, New Haven UK; range 0–10 kg). The mothers were instructed not to change the infant's diapers or clothes between the weight measurements before and after the feeding.

Metabolic rate and respiratory quotient measurements

Ventilated hood device. Metabolic rate was measured by open-circuit indirect calorimetry using the ventilated hood technique. A perspex hood (vol 30 L) with an air

TABLE 1 Subject characteristics ($N=24$).

	Mean	± SD
Age *(y)* *	29.8	± 3.7
Height *(cm)*	170	± 7
Body weight *(kg)* †	62.5	± 8.7
Body mass index *(kg/m²)* †	21.7	± 2.3
Body fat % *(wt/wt %)* † ‡	27.6	± 5.2
Parity † §	0.6	± 0.7
Length of gestation *(wk)* ‖	40.3	± 1.2
Weight gain during pregnancy *(kg)* ¶	11.3	± 3.1
Placental weight *(g)*	640	± 95
Birth weight *(g)* **	3496	± 282
Baby length *(cm)* ** ††	51.2	± 5.3
Baby head circumference *(cm)* ** ††	36.7	± 3.4

* At onset of present pregnancy.

† Before present pregnancy.

‡ Estimated with densitometry using under water weighing.

§ Nulliparae: N=12; primiparae: N=11; multiparae: N=1.

‖ Length of gestation was derived from the first day of the woman's last reported menstrual period; classification according to Hytten[7]: 22 women "term" (259–293 d) and 2 women "postterm" (296 and 299 d). Twenty-three infants were delivered normally and 1 by Caesarian section.

¶ Last recorded weight during pregnancy (1–7 d before delivery) minus pre-pregnant weight, N=22 (same subjects as in Table 2).

** Sex baby: female: N=13, male: N=11.

†† Number of days after delivery: 12 ± 7 d (N=22).

inlet on top and an air outlet at the right side, was placed over the head of the woman. During metabolic rate measurements the woman watched non-stressing video films. Mean values of O_2 consumption (VO_2 in mL/min) and CO_2 production (VCO_2 in mL/min) were printed every 2.5 min (RMR and PPMR measurements) or every 1.5 min (CMR and PCMR measurements). The zero and span points of the O_2 and CO_2

analyzers were calibrated just before RMR and CMR measurements, using standard gasses (for the zero points 100% N_2, for the span point of the CO_2 analyzer a gas mixture containing 0.6% CO_2) and fresh filtered atmospheric air (for the span point of the O_2 analyzer).

Metabolic rate (MR, in kJ/min) was calculated from oxygen consumption (VO_2, in L/min) and carbon dioxide production (VCO_2, in L/min) using Weir's formula[8]: MR = 16.3 VO_2 + 4.6 VCO_2. Respiratory quotient (RQ) was calculated as VCO_2 divided by VO_2.

Ethanol combustion tests were carried out at least once per month to validate the ventilated hood system. In each test about 25 g of ethanol was combusted in about 2 h. Instead of the ventilated hood, an airtight combustion chamber was linked to air inlet and air outlet. The reproducibility of the system was determined by 6 alcohol combustion tests for each ventilated hood device, carried out on separate days within a period of 2 wk. Day-to-day coefficients of variation were 1.9% for MR and 1.9% for RQ.

Measurement conditions of gross metabolic rates and respiratory quotients. RMR was measured during 35 min after 12 h fasting. On the day before a measurement day, the woman refrained from intensive physical activity. During the measurement the woman was lying in supine semi-recumbent position, and was in complete physical rest, but awake. The 25 min of rest preceding the RMR measurement appeared to be sufficient for reaching steady state level.

PPMR was measured during the first 180 min following consumption of a testmeal. The conditions of the PPMR measurement were exactly the same as during the RMR measurement, except for the postprandial state. The testmeal consisted of 375 g yoghurt-based liquid formula containing 1325 kJ (15 energy% protein, 30 energy% fat and 55 energy% carbohydrate). The recipe was 581 g full-cream yoghurt, 323 g unsweetened orange juice, 65 g white sugar, 13 g sunflower oil and 18 g protein powder (Protifar®, Nutricia Nederland BV, Zoetermeer, The Netherlands) per 1000 g. Testmeals were prepared in bulk in three batches, and stored at -20°C.

The cycling programme consisted of 25.5 min cycling exercise: for 7.5 min at 30 W, for 6 min at 45 W, for 6 min at 60 W, and for 6 min at 75 W. Only results from the last 3 min at each work load were used for calculation of gross cycling metabolic rate (CMR_{gross}). The women rotated the peddles with a frequency of 60 per minute. The women cycled with her back straight, and knees slightly bent with the peddle at its lowest

lowest position. Our cycle ergometer (type RH, Lode BV, Groningen, the Netherlands) was connected to a digital voltmeter (type DPM 339, Display Elektronika, Utrecht, the Netherlands) to facilitate accurate adjustments of work load. The ergometer was checked once a year and readjusted if necessary.

Gross post-cycling metabolic rate (**$PCMR_{gross}$**) was measured during the first 10.5 min after finishing the cycling programme, while the subject remained seated on the cycle ergometer.

Calculation of net metabolic rates. Thermic effect of the meal (**TEM**), net cycling metabolic rate (**CMR_{net}**), and net post-cycling metabolic rate (**$PCMR_{net}$**) were calculated by subtracting RMR from respectively PPMR, CMR_{gross} and $PCMR_{gross}$.

Measurement of heart rate

Heart rate was registered during the cycling programme and the subsequent recovery period. Heart rate was measured by an electrode belt, connected around the trunk of the subject, and transmitted to a wrist receiver, storing one value every 15 sec (type Sporttester PE-3000, Polar Electro KY, Kempele, Finland). Heart rate values were averaged and analyzed over the same time periods as cycling metabolic rates and post-exercise metabolic rate.

Body weight and fat mass

Body weight was measured on an electronic balance (Berkel ED60-T, Rotterdam, The Netherlands). The density of the body was determined from body weight and body volume obtained by the underwater weighing technique, or estimated from the sum of four skinfolds (triceps, biceps, subscapular and supra-iliac)[9]. Body fat mass was calculated from body density, using the Siri equation[10].

Energy intake

Food consumption was recorded over 5 consecutive days (Wednesday through Sunday) by the individual weighed-inventory technique as described earlier[2,11]. Basically this consists of weighing each item of food or drink immediately before consumption and repeating the procedure on leftovers. Weighing and recording was done by the woman herself using electronic scales incorporating a zeroing button and having a digital read out (type 1203 MP, Sartorius GMBH, Göttingen, FRG; weighing range 0-4000 g, accuracy 1 g). Attention was drawn to the prime importance of not interfering with normal eating patterns. All food items recorded were converted into food codes according to the Dutch food encoding system[12], the quantity per day was calculated, and the Dutch computerized food composition table was used[12] for conversion to energy intake.

Activity pattern

On the days of the weighed food consumption record, the woman recorded the times of rising and going to bed, as well as the duration of any period spent lying during the day. From this we calculated active time, which was defined as the total period (min/d) during which the subject was not lying. On the same days, the woman carried a pedometer (Kasper & Richter, Uttenreuth, Germany) and recorded the read-out both when rising and when going to bed. Step size was not individually adjusted, but fixed at 0.75 m/step, because of its variability during mixed activities. Walking activity is defined as the mean number of steps per day.

Statistics

All data are presented as mean ± SD. Data analysis was carried out using the programme provided by SAS (SAS Institute, Inc, Cary, NC). Shapiro and Wilk tests were used to evaluate whether data are normally distributed. Changes between pre-pregnant and post partum values were evaluated with paired *t*-tests (significance level $\alpha=0.05$). Body weight and body composition were determined in 3 instead of 2 measurement periods. Therefore, Tukey's studentized range tests ($\alpha=0.05$) were used to evaluate changes in these parameters. Pearson correlation coefficients (r) were calculated to examine associations between pairs of variables. If a parameter was correlated with more than one variable, the general linear models (GLM) procedure of the SAS-package was used to investigate the association with the combination of variables.

Results

Breast milk output

Breast milk consumption of the 2 month old babies was 718 ± 145 g/d ($N=23$, 1 missing value, range: 566 to 969 g/d). Mothers fed their babies 5.4 ± 0.8 times per day.

TABLE 2 Body weight and fat mass before pregnancy and after delivery (N=22).

	Before pregnancy	4 wk after delivery	9 wk after delivery
		kg	
<u>Body weight</u>	62.5 ± 8.7 [A*]	65.4 ± 9.6 [A]	64.7 ± 9.6 [A]
<u>Body fat mass</u>			
under-water weighing	17.6 ± 4.9 [A]	-	19.9 ± 6.3 [B] †
sum of four skinfolds	17.6 ± 4.9 [A]	18.8 ± 5.2 [B]	18.3 ± 5.3 [AB] †

* On each row, means sharing the same letter are not significantly different (comparisons of 3 periods: Tukey's studentized range tests; comparisons of 2 periods: paired t-tests).

† Significant difference between fat mass estimated with under-water weighing and skinfold techniques at 9 wk post partum (paired t-test; p=0.03).

Body weight and body fat mass

Body weight at 9 wk after delivery (64.4 ± 9.2 kg) was significantly above pre-pregnant body weight (62.4 ± 8.5 kg) (paired t-test: p=0.002). In 2 women we failed to determine body weight and body composition at 4 wk post partum. Results of the remaining 22 women are presented in **Table 2.** Their weight retention at 9 wk post partum (2.1 ± 2.4 kg) was similar to that in the whole group (2.0 ± 2.7 kg).

At 4 wk after delivery weight retention was 2.8 ± 2.8 kg. Body weight reduced significantly over the second month post partum (change from 4 to 9 wk after delivery: −0.7 ± 1.5 kg). At 4 wk after delivery, body fat mass estimated from the sum of 4 skinfolds was significantly higher than the pre-pregnant value (+1.3 ± 2.3 kg, **Table 2**). From 4 to 9 wk after delivery, a significant reduction in the fat mass estimated from skinfolds was observed (−0.6 ± 1.1 kg).

In the pre-pregnancy period, fat mass estimates from skinfold and under-water weighing techniques were similar, however, at 9 wk post partum, fat mass estimated from skinfolds was significantly lower than fat mass estimated by under-water weighing (paired

t-test, $p=0.03$). Fat retention at 9 wk post partum was estimated to be 2.3 ± 2.5 kg with the under-water weighing technique and 0.7 ± 2.2 kg with the skinfold technique.

At 4 wk post partum, body fat retention (skinfold technique) was significantly correlated with weight retention ($r=0.86$, $p=0.0001$). Similar associations were observed for the increases of fat mass and body weight at 9 wk post partum above pre-pregnancy values (under-water weighing technique: $r=0.87$, $p=0.0001$; skinfold technique: $r=0.91$, $p=0.0001$).

TABLE 3 Metabolic rates before pregnancy and during lactation.

Measurement condition	Before pregnancy	During lactation	Change
		kJ/min	
Gross metabolic rates			
RMR	3.80 ± 0.35	3.98 ± 0.40	+0.17 ± 0.37 *
PPMR	4.45 ± 0.35	4.61 ± 0.46	+0.17 ± 0.45
CMR_{gross} 30 W	14.5 ± 1.1	14.1 ± 1.2	−0.4 ± 1.0
CMR_{gross} 45 W	17.5 ± 1.2	17.1 ± 1.4	−0.4 ± 1.4
CMR_{gross} 60 W	21.0 ± 1.5	20.6 ± 1.7	−0.5 ± 2.1
CMR_{gross} 75 W †	24.9 ± 1.6	24.4 ± 1.9	−0.5 ± 2.3
$PCMR_{gross}$ †	8.5 ± 0.9	8.7 ± 1.0	+0.2 ± 0.9
Net metabolic rates			
TEM	0.64 ± 0.11	0.64 ± 0.15	−0.01 ± 0.20
CMR_{net} 30 W	10.7 ± 1.0	10.1 ± 1.0	−0.6 ± 1.0 *
CMR_{net} 45 W	13.7 ± 1.1	13.1 ± 1.2	−0.6 ± 1.5
CMR_{net} 60 W	17.2 ± 1.4	16.6 ± 1.6	−0.6 ± 2.1
CMR_{net} 75 W †	21.0 ± 1.5	20.4 ± 1.7	−0.6 ± 2.3
$PCMR_{net}$ †	4.6 ± 0.7	4.7 ± 0.9	+0.1 ± 1.0

* Paired t-test: $p < 0.05$.

† N = 20 (4 women had missing value).

Metabolic rate, heart rate and respiratory quotient

Metabolic rates are presented in **Table 3**. During lactation, resting metabolic rate (RMR) was significantly higher than before pregnancy (+0.17 ± 0.37 kJ/min; p=0.03), and a similar, but insignificant increase was observed in postprandial metabolic rate (PPMR) (+0.17 ± 0.45 kJ/min; p=0.09). The increase in PPMR was strongly correlated with the increase in RMR (r=0.88, p=0.0001). Gross post-cycling metabolic rate ($PCMR_{gross}$) tended to be increased as well (+0.22 ± 0.92 kJ/min), but the increase was not significant (p=0.29) nor related with the increase in RMR (r=-0.10, p=0.64). During lactation, gross metabolic rates during cycling exercise (CMR_{gross}) tended to decrease, but the decrease was statistically not significant (for work loads from 30 to 75 W, p-values were respectively: 0.08, 0.20, 0.29 and 0.34).

No changes were observed in the thermic effect of the meal (TEM), nor in the net recovery costs after the cycling programme ($PCMR_{net}$). The net costs of cycling exercise (CMR_{net}) tended to diminish with 0.6 kJ/min during lactation (**Table 3**), however, only at the lowest work load the change was statistically significant (from 30 to 75 W, p-values were respectively: 0.01, 0.07, 0.16 and 0.24).

TABLE 4 Respiratory quotients before pregnancy and during lactation.

Measurement condition	Before pregnancy	During lactation	Change
At rest, fasting state	0.85 ± 0.03	0.82 ± 0.03	–0.03 ± 0.04 *
At rest, first 3h after meal	0.89 ± 0.02	0.86 ± 0.02	–0.03 ± 0.03 *
Cycling at work load 30 W	0.84 ± 0.04	0.83 ± 0.04	–0.01 ± 0.03
Cycling at work load 45 W	0.86 ± 0.03	0.85 ± 0.04	–0.01 ± 0.03
Cycling at work load 60 W	0.89 ± 0.03	0.88 ± 0.05	0.00 ± 0.04
Cycling at work load 75 W †	0.90 ± 0.03	0.89 ± 0.04	0.00 ± 0.04
Post–cycling 0–10.5 min †	0.93 ± 0.05	0.91 ± 0.06	–0.02 ± 0.06

* Paired t-test: $p < 0.001$.

† N = 20 (4 women had missing value).

TABLE 5 Heart rates before pregnancy and during lactation.

Measurement condition	Before pregnancy	During lactation	Change
		beats/min	
Cycling at work load 30 W *	99 ± 13	97 ± 12	–2 ± 9
Cycling at work load 45 W *	111 ± 14	110 ± 14	–2 ± 9
Cycling at work load 60 W *	124 ± 16	124 ± 17	0 ± 11
Cycling at work load 75 W †	133 ± 14	136 ± 15	+2 ± 14
Post-cycling 0–10.5 min †	94 ± 12	94 ± 11	0 ± 10

* N = 20 (4 women had missing value).
† N = 17 (7 women had missing value).

ΔRMR was significantly correlated with the body mass index at 9 wk post partum (r=0.43, p=0.04). However, neither body mass index (r=0.12, p=0.59), nor ΔRMR (r=–0.22, p=0.31) were significantly related with breast milk output. A similar association was observed between ΔPPMR and body mass index (r=0.43, p=0.03).

RQ was significantly below the pre-pregnant value during lactation under resting conditions in both the fasting state (–0.03 ± 0.04; p=0.0003) and the postprandial state (–0.03 ± 0.03; p=0.0001). However, no significant changes in RQ were observed during cycling exercise, nor during the recovery period after the cycling programme (**Table 4**).

During lactation, heart rates during and after cycling exercise were similar to pre-pregnant values (**Table 5**).

Habitual energy intake and physical activity

Energy intake was 9.61 ± 1.77 MJ/d before pregnancy and 10.24 ± 1.93 MJ/d during lactation. Thus, the women tended to increase their energy intake during lactation with 0.63 ± 2.52 MJ/d (p=0.23).

A significant reduction of active time occurred during lactation (before pregnancy: 912

± 37 min/d; during lactation: 868 ± 72 min/d; change: -45 ± 57 min/d, p=0.001). Walking activity decreased significantly as well (before pregnancy: 11.4 ± 3.5 10^3steps/d; during lactation: 9.3 ± 3.6 10^3steps/d; change: 2.1 ± 4.2 10^3steps/d, p=0.02).

Discussion

The women in the present study were all healthy and well-nourished. Their weight gains during pregnancy (11.3 kg), length of gestation (40.3 wk), and the birth weights of their children (3496 g) were as expected for western women eating without restriction[7,11]. Breast milk output at 9 wk after delivery (718 ± 145 g/d) was within the normal range[1,13-15] and similar to the value in a group of Dutch women studied previously (745 ± 131 g/d, N=40)[2]. Assuming that energy content of breast milk is 3 kJ/g and that the efficiency of conversion is 80%[1], lactation cost these women 2.69 ± 0.54 MJ/d, or 26.3% of their mean daily energy intake (10.24 MJ/d). Thus, the extra energy requirement during lactation was considerable in these women.

Part of this extra energy requirement seemed to be realized by increased energy intake. Furthermore, the women appeared to save energy by reducing their physical activities during lactation. With the skinfold technique, body fat mobilization over the second month after delivery was estimated to be 0.55 kg over a 5-wk period, or 15.7 g/d, and thus might have yielded about 0.6 MJ/d, assuming that the energy equivalent of fat mass is 37.7 kJ/g[16]. The question remains whether improved efficiency of energy metabolism could be another way by which women meet the energy costs of lactation.

Resting metabolic rate (RMR) increased with 4.5% after delivery. In a Swedish study, a similar (5%) increase in RMR above pre-pregnant baseline measurements was observed in 23 lactating women at 2 mo after delivery[5], but in two other longitudinal studies RMR-values during lactation were similar to those after lactation had stopped[3,4]. The increase in RMR was significantly associated with post partum body mass index, but not with breast milk output. This suggests that in thinner women, the increase in RMR associated with breast milk production is lower than in fatter women. This finding needs further investigation.

Postprandial metabolic rate (PPMR) showed changes similar to changes in RMR. As a result of this, the thermic effect of the meal (TEM) was unchanged, indicating that metabolic efficiency is not improved during lactation. Previous studies on the effect of lactation on thermic effect of a meal were relatively small and showed conflicting results[4,17,18].

No significant changes in the gross metabolic rate during cycle ergometer exercise (CMR_{gross}) were observed between the pre-pregnant and post partum period, although CMR_{gross} decreased at each work load. During lactation, the net costs of the cycling exercise (CMR_{net}) tended to decreased with 0.6 kJ/min at each work load, but the decreases was only statistically significant at the lowest work load. Such small changes in CMR_{net} cound not bring about major energy savings on a daily basis.

No significant changes were observed during lactation in the metabolic rate during the recovery period after the cycling program ($PCMR_{gross}$), but the mean change in $PCMR_{gross}$ (+0.22 kJ/min) resembled the change in RMR (+0.17 kJ/min). The net recovery costs ($PCMR_{net}$) during lactation were very similar to pre-pregnancy value.

The average energy output of breast milk was estimated to be 2.15 MJ/d (breast milk output 718 g/d, energy content of breast milk 3 kJ/g)[1]. The increase in RMR during lactation was 0.17 kJ/min or 0.25 MJ/d. Energy expenditure increased to a similar extend in the postprandial and post-exercise states and tended to decrease rather than increase during physical activity. We therefore do not expect that 24-h energy expenditure increases more than RMR. If we define the energy costs of lactation as the sum of the energy content of the breast milk and the increase of resting metabolic rate during lactation, the energy costs of lactation were 2.40 MJ/d or less. The efficiency of breast milk production, defined as the energy content of the breast milk divided by the total energy costs of lactation times 100%, was estimated to be 90% or higher.

We conclude that healthy, normal-weight, lactating women seem to cope with the energy requirements of lactation by fat mobilization, by increasing energy intake and by reducing their physical activity. No general improvement of metabolic efficiency was observed, but the efficiency of breast milk production might related to body mass index.

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Chapter 6

GENERAL DISCUSSION

The primary aim of the present study was to investigate whether the efficiency of energy metabolism improves during pregnancy and lactation, which could be reflected by reduced diet-induced thermogenesis or improved work efficiency. Such metabolic adaptations would lower energy expenditure and could consequently help to explain the discrepancy observed between extra energy needs and extra energy intakes during pregnancy and lactation.

In the present study, data were collected in well-nourished Dutch women. As a consequence of our recruitment procedure and of the large investment of time and effort required from the women, the participants of the study had a higher-than-average educational level, were from middle-upper socio-economic class, and had a relatively large interest in nutritional issues (about one out of three participants was educated and/or working in the field of medicine, nursing or dietetics). It seems reasonable, however, to assume that the physiological/metabolic changes during pregnancy which were the main interests in this study, are largely independent of these factors.

Changes in metabolic efficiency during pregnancy and lactation

The results of the present study strongly indicate that throughout the reproductive cycle, diet-induced thermogenesis remains unchanged compared to the pre-pregnant baseline value (Chapters 2 and 5). The study was designed to have a sufficient statistical power to detect a change of 15% in the thermic effect of the meal with 90% confidence. A 15% reduction would result in an energy saving of about 0.15 MJ/d, which is of modest physiological importance if compared to the energy costs of pregnancy (1.2 MJ/d) and lactation (3.1 MJ/d)[1]. However, the mean changes in the thermic effect of the meal observed in the present study were only 5% or lower.

The study also indicates that no major changes in work efficiency occur during pregnancy (Chapter 3) and lactation (Chapter 5). Although the net cost of cycling exercise tended to be reduced in early pregnancy and during lactation, none of these changes were statistically significant. In mid- and late-pregnancy the net costs of cycling exercise were similar to the pre-pregnant baseline. These results were in line with previous findings[2-7].

Standardized cycling exercise is generally considered a weight-independent activity. This assumption is of crucial importance to draw conclusions about changes in metabolic efficiency during advanced pregnancy: with a weight-independent activity, gestational weight gain will not interfere with effects of metabolic or physiological changes on the energy cost of the activity. Clearly, in early pregnancy and after delivery, when differences with pre-pregnant body weight are relatively small, this assumption is less important than in late-pregnancy. The results described in Chapter 3 show that the net cost of cycling exercise were positively related with body weight ($r=0.53$) and leg size ($r=0.57$). Therefore, the increases of body weight and leg size during pregnancy would be expected to cause increases in the net cost of cycling exercise. As no such change was observed in mid- and late-pregnancy, this might indicate that metabolic efficiency is somewhat improved. Yet, the practical importance of such improved metabolic efficiency, if present, is limited, because even with cycling activity, which is still relatively independent of body weight, no reduction in the net cost is observed. One would expect such small improvements of metabolic efficiency to be insufficient to compensate the impact of gestational weight gain on the net cost of weight-bearing activities such as walking. Still, an earlier study from our laboratory showed only a slight increase of the net cost of standardized treadmill exercise in late-pregnancy, but not in early- and mid-pregnancy[8].

As neither diet-induced thermogenesis nor work efficiency appeared to change during pregnancy and lactation, our study indicates that no metabolic adaptations take place during the reproductive cycle. This leads us back to the initial question: to what extent are the energy costs of pregnancy and lactation met by increased energy intakes, by energy savings through behavioral adaptations and, in lactation, by body fat mobilization.

Energy cost and energy balance during pregnancy

The estimated energy cost of pregnancy were 335 MJ in our women (Chapter 4). The cumulative increase of resting metabolic rate and the gain in maternal fat stores accounted for respectively 56% and 29% of the total costs, leaving only 15% for the 'obligatory' component of the energy cost of pregnancy: the energy needed for growth of fetus, placenta, uterus, breast, blood, extravascular extracellular and amniotic fluids. As a result of extrapolating only three resting metabolic rate measurements during pregnancy to the entire pregnancy, the cumulative increase in the maintenance costs during pregnancy may have been over-estimated to some extent; even so, it seems unlikely that the energy costs of pregnancy in our subjects were below earlier observations[9,10].

As in previous studies, the cumulative increase in energy intake (43 MJ) was insufficient to meet these costs[9-15]. The variability of the increase in energy intake during pregnancy was very high: the standard deviation was 349 MJ. Certainly, part of this variability must have resulted from the high within-subject day-to-day variability in energy intake. Still, after extrapolating this 'random variance of single measurement days' to the cumulative increase in energy intake during pregnancy, and subtracting this variance from the total variance in extra energy intake, a large variance remained (*SD* 221 MJ), indicating profound between subject differences in the cumulative change in energy intake during pregnancy. We conclude that some of the women may have increased their energy intake enough to meet almost all the energy costs of pregnancy, whereas the increases in energy intakes of others were far below their additional energy needs.

Energy savings during pregnancy by reduced physical activity were probably highly variable as well, although only crude indications can be obtained from our data. Our unique combination of energy expenditure measurements enabled us to estimate energy savings by reduced physical activity during days spent in the respiration chamber. Although the activity pattern on these days was more or less standardized, women were able to save about 0.3 MJ/d by changes in type and pace of activities. Under free-living conditions, women spent on average 1 hour more in bed during pregnancy than before pregnancy. Therefore, it seems reasonable to assume that under free-living conditions the reduction of physical activity could result in larger daily energy savings than observed in the respiration chamber, on average possibly about 0.7 MJ/d. With substantial between-subject differences in the changes in physical activity during pregnancy, behavioural adaptations might be almost sufficient for some women to cope with the energy cost of pregnancy, whereas others may save only little this way.

Recommended energy intake during pregnancy

The two main mechanisms by which women deal with the energy cost of pregnancy (increased energy intake and reduced physical activity) are both extremely variable, and the energy cost of pregnancy show considerable between-subject variability as well. As a result, it is difficult, if not impossible to formulate useful recommendations for additional energy intake during pregnancy. Energy intake recommendations based on group averages might be far too high or too low for a specific woman. From a point of view of energy balance, it might be most appropriate to formulate energy intake recommendations on basis of a comparison of the observed gestational weight gain with the desired weight gain.

The role of pre-pregnant body fat percentage

Based on potential benefits and risks for fetal growth, perinatal mortality, and obesity onset, it seems useful to differentiate recommendations for gestational weight gain according to body mass index[16]. The importance of establishing sufficient weight gain during pregnancy appears to be inversely related with pre-pregnant body mass index. The weakening of the relationship between gestational weight gain and birth weight with increasing body mass index[17-20], indicates that in heavy women, energy supplies to the fetus are generally sufficient, whereas in thin women, fetal growth is more dependent of maternal nutrition. In other words: energy balance appears to be more vulnerable in thinner than in fatter women.

In our group of Dutch women (Chapter 4), and in a group of English women[21], the cumulative increase of resting metabolic rate during pregnancy appeared to be positively associated with pre-pregnant body fat percentage. This association was not attributable to differences in birthweight, and therefore suggests that changes in metabolic efficiency during pregnancy might be inversely related with pre-pregnant body fat percentage. However, pre-pregnant body fat percentage appeared not to be associated with the change in the thermic effect of a meal or the changes in the net cost of cycling exercise during pregnancy.

Energy cost and energy balance during lactation

The energy costs of lactation consist of the energy content of the milk secreted plus the energy required to produce it. By weighing the baby before and after each feed, breast milk output at two months post partum was estimated to be 718 g/d. For calculating the energy cost of lactation, the energy content of the milk was assumed to be 3 kJ/g and the conversion efficiency 80%[1]. Thus, lactation cost our women on average 2.7 MJ/d, which is within the normal range for western populations[22-25], and about twice as high as their average daily energy cost of pregnancy.

Energy intake tended to be increased above pre-pregnant energy intake during lactation (+0.6 MJ/d), but the change was statistically not significant. Body fat mobilization appeared to supply energy as well (0.6 MJ/d), which fits with the observation that during lactation, adipose tissue metabolism is directed towards fat mobilization[26]. Furthermore, a significant reduction in physical activity compared to the pre-pregnant situation was observed.

The increase of resting metabolic rate during lactation was positively related with the body mass index in the post partum period, and this relationship was not attributable to differences in breast milk output. This finding resembles the positive association between the cumulative increase of resting metabolic rate during pregnancy and pre-pregnant body fat percentage, and certainly warrants more research.

Recommended energy intake during lactation

As extra energy requirements are higher during lactation than in pregnancy, it is difficult, or maybe impossible for lactating women to compensate all extra energy needs by reduced physical activity. More energy supplies are needed during lactation, which could be established by increased energy intake or by body fat mobilization. Fat mobilization during lactation could help to return to pre-pregnant body weight, and thus to prevent the onset of maternal obesity. However, from a toxicological point of view this fat losses during lactation might be unfavourable. Some environmental contaminants such as polychlorinated biphenyls[27,29], and dioxins[28,29] have been observed in breast milk. Their adverse effects do not outweigh the nutritional advantages of breast milk over bottle milk, however concentrations should be minimized as far as possible[29]. As these contaminants are fat soluble, they accumulate in adipose tissue. Maternal fat loss during lactation could therefore increase the concentration of these contaminants in breast milk[27]. Little is known about this relationship, but it might be desirable to avoid weight loss during lactation by means of a sufficient increase of energy intake.

Suggestions for future research

We observed that the energy costs of pregnancy and the mechanisms by which women cope with these costs are highly variable. It is of interest to investigate if these aspects of the energy balance of pregnancy are associated with the characteristics of the subjects such as age, body mass index, and socio-economic status. Establishing the desired pregnancy outcome, especially those women with relatively high extra energy needs and/or little possibility to reduce their physical activity will depend on increases in energy intakes during pregnancy. To identify the characteristics of these women, large populations should be studied. Determination of the separate components of energy balance of pregnancy would be too expensive and time-consuming with such large study groups, and would interfere with the need for a heterogeneous study group. In a large epidemiological study, gestational weight gain could be a useful indicator for the energy balance during pregnancy: the characteristics of women with insufficient weight gains during pregnancy would implicitly distinguish those who could benefit most from increased energy intakes during pregnancy.

Epidemiological data suggest that in obese women, gestational weight gain has little or no impact on fetal growth. To prevent these women from further weight gain, it could therefore be useful to aim with energy intake recommendations for obese women at maintaining constant body weight throughout gestation. However, before such recommendations could be made, more knowledge on the effects of energy intake and weight gain on pregnancy outcome in obese women is needed.

From all aspects of the energy balance of pregnancy, estimates of the demand-side (the costs) are probably more reliable than those at the supplies-side of the balance (changes in energy intake and physical activity). Both changes in energy intake and in physical activity are known to be highly variable from day to day and it is difficult to obtain valid estimates of these factors without interfering with normal patterns. Therefore, the validity of estimated changes in energy intake and in physical activity warrants more research.

During lactation, mother and child appear to have conflicting interests if maternal body fat mobilisation is concerned. Maternal body fat loss during lactation might increase the concentration of contaminants in breast milk, which could have adverse health effects for the breast-fed baby. The relationship between maternal fat loss and the concentration of contaminants in breast milk should be addressed in future research. As environmental contaminants gradually accumulate in adipose tissue, fat stores of older mothers might contain more contaminants than stores of younger mothers. Thus, when studying this relationship, confounding by age should be avoided. It is also of interest to study whether the adverse effect of fat mobilization during lactation is more pronounced in older versus younger mothers. The lipolytic activity in adipose tissue seems to be increased during lactation. As a result of this metabolic change, lactation appears to be a period in which it might be relatively easy for the mother to bring her amount of body fat back to pre-pregnant size. Therefore, fat mobilisation during lactation might be important for the prevention of gestational onset obesity. More knowledge about this latter factor is required as well. For the formulation of energy intake requirements during lactation, the pros and cons of maternal fat mobilization have to be weighed carefully against each other.

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Summary

Pregnancy and lactation involve extra energy needs, respectively to establish and maintain adequate weight gain, and to establish adequate breast milk production. Results of most previous studies show only small increases in energy intake during pregnancy. A reduction in physical activity could lower energy expenditure, however, such energy savings are assumed to be limited. Together, these two factors appeared to be insufficient to meet all energy costs of pregnancy. It has therefore been postulated that during pregnancy, energy expenditure is further reduced by improved efficiency of energy metabolism. Such improved metabolic efficiency could be reflected in reduced diet-induced thermogenesis, and increased work efficiency.

The latter hypothesis was studied using a longitudinal study design. Changes in the thermic effect of a meal and in the net cost of cycling exercise were estimated in a group of 26 women, along with their energy costs of pregnancy and lactation, and with changes in energy intake and physical activity. Baseline values were obtained before conception, and the measurements were repeated in wk 12-14, 23-25 and 34-36 of gestation, and at 9-10 wk after delivery. In a subgroup of 10 women, additional measurements of 24-hour metabolic rate were carried out in each period except post partum.

The results showed no changes in diet-induced thermogenesis or work efficiency during pregnancy (Chapters 2 and 3) and lactation (Chapter 5), in other words, no signs of metabolic adaptation were observed. Taking the statistical power of the study into account, it seems highly improbable that physiologically important changes in either of these two parameters occur during pregnancy and lactation.

As no metabolic adaptations appear to take place during pregnancy, the magnitude of the imbalance between the energy costs of pregnancy on the one hand, and extra energy intakes and energy savings through behavioural adaptations on the other hand (Chapter 4) was re-evaluated. The estimated total energy cost of pregnancy was 335 MJ. The cumulative increase of resting metabolic rate during pregnancy and the gain in maternal fat stores accounted for respectively 56% and 29% of the total costs, leaving only 15% for growth of fetus, placenta, uterus, breast, blood, extravascular extracellular and amniotic fluids. The cumulative increase in energy intake (45 MJ) was insufficient to meet these costs. Combining all energy measurements lead to the suggestion that the energy savings during pregnancy by reduced physical activity might be higher (125-250

MJ) than the usual assumption of 100 MJ. Extra energy intakes plus behavioural adaptation might thus together amount to 170-295 MJ. The upper range of this estimate is only slightly below the estimated energy cost of pregnancy (335 MJ).

The energy costs of lactation were estimated to be 2.7 MJ/d. During lactation, energy intake tended to increase above pre-pregnant energy intake (+0.6 MJ/d), though the change was statistically not significant. Body fat mobilization appeared to supply energy as well (0.6 MJ/d, statistically not significant). A significant reduction in physical activity compared to the pre-pregnant period was observed. As described above, energy saving up to about 1 MJ/d might be established by such behavioural adaptation. Together, these three factors might account for about 2.2 MJ/d, which is only slightly below the estimated energy cost of lactation.

We cannot exclude that the increase in energy intake during pregnancy and lactation might be slightly under-estimated, as under-reporting of dietary intakes might become more pronounced when dietary records are repeated. Therefore, the observed differences between the energy costs of pregnancy and lactation on the one hand, and extra energy intakes plus energy savings by reduced physical activity on the other hand, might in reality be non-existent.

The energy cost of pregnancy and lactation vary substantially between women, and the two main mechanisms by which women deal with these costs (extra energy intake and reduced physical activity) show large between subject variability as well. Therefore, energy intake recommendations based on group averages may be far too high or too low for a specific woman. The identification of parameters by which more homogeneous subgroups of women could be characterised, might lead to improved recommendations for energy intake for these subgroups of women.

Samenvatting

Tijdens de zwangerschap en de lactatie (het geven van borstvoeding) is de energiebehoefte verhoogd: tijdens de zwangerschap is energie nodig voor het bewerkstellingen en handhaven van de gewenste gewichtstoename en tijdens de lactatie is energie nodig voor de aanmaak van moedermelk. Uit voorgaand onderzoek is gebleken dat vrouwen tijdens de zwangerschap hun energieinneming nauwelijks verhogen. Door vermindering van lichamelijke activiteit kan het energieverbruik verlaagd worden, maar algemeen wordt aangenomen dat dergelijke besparingen beperkt zijn. Deze twee factoren, extra energieinneming en energiebesparingen via een verlaagd activiteitenpatroon, lijken tezamen onvoldoende energie op te leveren om in de extra energiebehoefte tijdens de zwangerschap ('de kosten') te voorzien. Een dergelijke discrepantie is ook geconstateerd tussen enerzijds de kosten van de lactatie, en anderzijds de extra energieinneming, de energie die beschikbaar komt door verbranding van lichaamsvet, en energie-besparingen via vermindering van activiteit. Daarom is gesuggereerd dat het energieverbruik tijdens de zwangerschap en de lactatie mogelijk verder wordt gereduceerd via een verhoogde efficiëntie van de energiestofwisseling. Een dergelijke 'metabole adaptatie' zou kunnen blijken uit een verlaging van de 'door voeding geïnduceerde thermogenese' (de energie die nodig is om een maaltijd te verteren en verwerken) of uit een verhoogde arbeidsefficiëntie.

Het in dit proefschrift beschreven longitudinale onderzoek is opgezet om de bovenstaande hypothese te toetsen. Bij een groep van 26 vrouwen werd bestudeerd of de 'door voeding geïnduceerde thermogenese' en de arbeidsefficiëntie veranderden tijdens de zwangerschap en na de bevalling ten opzichte van de periode vóór conceptie. Bij deze vrouwen werden tevens de kosten van de zwangerschap, veranderingen in energieinneming en veranderingen in lichamelijke activiteit geschat. Metingen werden verricht vóór de zwangerschap, in de weken 12-14, 23-25 en 34-36 van de zwangerschap en tenslotte 9-10 weken na de bevalling. Bij een subgroep van 10 vrouwen werd ook het totale dagelijkse energieverbruik gemeten in de meetperiodes vóór en tijdens de zwangerschap, echter niet ná de bevalling.

De onderzoeksresultaten lieten tijdens de zwangerschap géén veranderingen zien in de 'door voeding geïnduceerde thermogenese' (Chapter 2) en in de arbeidsefficiëntie (Chapter 3). Ook tijdens lactatie bleven beide factoren onveranderd (Chapter 5). Gezien de onderzoeksopzet, de gebruikte meettechniek en het relatief grote aantal vrouwen waarop de resultaten gebaseerd zijn, is er slechts een kleine kans dat de energiestofwisseling in werkelijkheid wél efficiënter wordt tijdens de zwangerschap en/of de lactatie, terwijl dat in dit onderzoek niet gevonden werd. Geconcludeerd wordt dat er waarschijnlijk géén metabole adaptaties van belang optreden tijdens zwangerschap en lactatie.

Gezien deze onderzoeksresultaten is opnieuw het verschil geschat tussen enerzijds de kosten van de zwangerschap en anderzijds de extra energieinneming en besparingen via verlaagde activiteit. De totale kosten van de zwangerschap werden geschat op 335 MJ (Chapter 4). De cumulatieve stijging van de ruststofwisseling over de zwangerschap en de toename van de vetreserve van de moeder hadden een aandeel van respectievelijk 56% en 29% in deze kosten. Slechts 15% van de kosten kwamen voor rekening van de groei van baby, placenta, baarmoederweefsel, borstweefsel, bloed en vruchtwater. De totale extra energieinneming werd geschat op 45 MJ, en leek dus ook bij deze vrouwen onvoldoende om de kosten van de zwangerschap te dekken. Door combinatie van alle energieverbruiksmetingen werden aanwijzingen verkregen dat de besparingen door verlaagde fysieke activiteit mogelijk groter zijn (125-250 MJ) dan voorheen werd aangenomen (100 MJ). Tezamen zouden de extra energieinneming en de activiteitsverandering 170-295 MJ op kunnen leveren. De bovengrens van deze nieuwe schatting ligt dicht bij de geschatte kosten van de zwangerschap.

De kosten van de lactatie werden geschat op 2.7 MJ/d. Tijdens de lactatie leek de energieinneming verhoogd ten opzichte van vóór het begin van de zwangerschap, de geschatte extra energieinname was 0.6 MJ/d, maar deze stijging was statistisch niet significant. Ook leek tijdens de lactatie mobilisatie van lichaamsvet op te treden (statistisch niet significant), hetgeen naar schatting eveneens 0.6 MJ/d opleverde. De lichamelijke activiteit was significant verlaagd ten opzichte van de periode vóór aanvang van de zwangerschap. Zoals hierboven beschreven, lijken dergelijke gedragsadaptaties aanzienlijke besparingen op te kunnen leveren, tot circa 1 MJ/d. Door extra energieinneming, mobilisatie van lichaamsvet en energie-besparingen via verminderde activiteit kwam in totaal 2.2 MJ/d beschikbaar, hetgeen slecht iets lager is dan de kosten van de lactatie.

Het kan niet worden uitgesloten dat de toename van de energieinneming tijdens de zwangerschap en de lactatie licht onderschat is: eerder onderzoek heeft aangetoond dat bij het herhalen van voedselconsumptieonderzoek de onderrapportage toe kan nemen. Daarom lijkt het aannemelijk dat vrouwen in werkelijkheid volledig kunnen voorzien in de kosten van de zwangerschap en de lactatie door extra energieinneming, energie-besparingen door vermindering van fysieke activiteit en, tijdens de lactatie, door het aanspreken van de vetreserves van het lichaam.

Tussen vrouwen onderling bestaan aanzienlijke verschillen in de energiekosten van zwangerschap en lactatie. Ook de twee belangrijkste mechanismen waarmee vrouwen in deze kosten voorzien (extra energieinneming en vermindering van activiteit) lijken sterk te verschillen. Daarom zullen aanbevelingen voor energieinneming tijdens zwangerschap en lactatie, wanneer deze gebaseerd zijn op dergelijke heterogene groepen, voor de ene vrouw te hoog zijn en voor de andere te laag. In de praktijk zullen aanbevelingen voor energieinneming tijdens zwangerschap en lactatie pas bruikbaar zijn als deze gericht zijn op meer homogene groepen. Vervolgonderzoek is nodig om dergelijke groepen te karakteriseren.

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CURRICULUM VITAE

Caroline Spaaij werd geboren op 1 mei 1964 te Sittard. Van 1976 tot 1982 volgde zij haar middelbare school opleiding (Atheneum B) aan het Eykhagencollege te Landgraaf. Zij begon haar studie in Wageningen aan de toenmalige Landbouwhogeschool in augustus 1982. In januari 1988 behaalde zij de titel van landbouwkundig ingenieur in de afstudeerrichting Human Voeding, met als hoofdvakken Voedingsleer en Toxicologie. Van januari tot juli 1988 werkte zij als redactioneel assistent bij de vakgroep Proefdierkunde van de Rijksuniversiteit Utrecht. Het in dit proefschrift beschreven onderzoek werd uitgevoerd van augustus 1988 tot augustus 1992 aan de vakgroep Humane Voeding van de Landbouwuniversiteit, waar zij als Onderzoeker in Opleiding was aangesteld door de Nederlandse organisatie voor Wetenschappelijk Onderzoek.