Effect on 24-h energy expenditure of a moderate-fat diet high in monounsaturated fatty acids compared with that of a low-fat, carbohydrate-rich diet: a 6-mo controlled dietary intervention trial[1–3]

Lone G Rasmussen, Thomas M Larsen, Pia K Mortensen, Anette Due, and Arne Astrup

ABSTRACT

Background: Dietary fat has a lower thermogenic effect than does carbohydrate. A moderate-fat diet, high in monounsaturated fatty acids (MUFA diet), may decrease energy expenditure (EE) and thereby induce weight gain.

Objective: We aimed to compare changes in 24-h EE and substrate oxidation after a 6-mo controlled dietary intervention with either a MUFA or a low-fat (LF) diet.

Design: Twenty-seven overweight [body mass index (in kg/m^2): 28.1 ± 0.4] nondiabetic subjects aged 18–36 y followed an 8-wk low-calorie diet and a 2-wk weight-stabilizing diet and then were randomly assigned to a MUFA ($n = 12$) or LF ($n = 15$) diet for 6 mo. Substrate oxidation and 24-h EE were measured by whole-body indirect calorimetry. The first measurement (0 mo) was taken during the weight-stabilizing diet, and the second measurement was taken after the 6-mo intervention.

Results: A tendency was seen toward a lower 24-h EE with the MUFA than with the LF diet ($P = 0.0675$), but this trend did not remain after adjustment for the initial loses of fat mass and fat-free mass ($P = 0.2963$). Meal-induced thermogenesis was significantly ($P < 0.05$) lower with the MUFA than with the LF diet, but no time × treatment interaction was found. A significant ($P = 0.0456$) treatment × time interaction was found for spontaneous physical activity.

Conclusion: Despite a slightly lower meal-induced thermogenesis, the MUFA diet had an effect on 24-h EE that was not significantly different from that of the LF diet after a 6-mo controlled dietary intervention. *Am J Clin Nutr* 2007;85:1014–22.

KEY WORDS Obesity, energy expenditure, moderate-fat diet, dietary intervention, substrate oxidation, monounsaturated fatty acids

INTRODUCTION

The increasing prevalence of obesity and type 2 diabetes is causally related to physical inactivity and excessive energy intake (1–3). It is controversial whether a high dietary content of fat contributes significantly to the development of obesity. The concept that a reduction in dietary fat causes a modest, dose-dependent decrease in body weight is supported by some prospective observational studies (4) and meta-analyses of short-term intervention studies (1, 3, 5, 6). High-fat diets may play a role in promoting weight gain by inducing an unintentional, passive overconsumption of energy (7–10). However, Willett and Leibel (11) and Willett (12) conducted a meta-analysis of trials lasting ≥1 y and concluded that fat intake between 18% and 40% of energy had little effect on body fat. Willett and Leibel (11) suggested that a compensatory or adaptation mechanism occurs when dietary composition is changed. The diverging views may be due to a lack of longer-term trials with a strict adherence to the stipulated dietary composition.

Diet composition can affect energy balance by influencing appetite and energy intake, by differences in digestibility, or by affecting energy expenditure (EE). After the ingestion of food, EE increases for 4–8 h, depending on the amount of food and on the macronutrient composition of the diet (13–15). Meal-induced thermogenesis (MIT) constitutes ≈10% of the daily EE, but there is great intraindividual variation (14). There is a large difference in the effect of the 3 macronutrients on MIT: ≈8%, 2%, and 20–30% of the energy intake from carbohydrate, fat, and protein, respectively, is spent as MIT (14, 16). Raben et al (17) examined the postprandial MIT of the 3 macronutrients and found significantly higher EE after a protein-rich meal than after a carbohydrate- or fat-rich meal. In another study, Raben et al (18) found no differences in the effects of a starch-, fat-, or sucrose-rich diet on MIT. Westerterp et al (19) found that MIT was higher after a protein- and carbohydrate-rich meal than after a high-fat meal. However, no significant difference was found in 24-h EE between the 2 groups.

[1] From the Department of Human Nutrition, Faculty of Life Sciences, University of Copenhagen, Frederiksberg, Denmark.

[2] Supported by the H A Foundation, Danish Heart Association, Danish Diabetes Association, the Centre for Advanced Food Research, State Research Councils, and the Danish Pork Council. The foods in the supermarket and the low-calorie diets were donated by Nutrillett, the H A Foundation, Copenhagen Wholesale Market/DEG Green Team, the Danish Pork Council, Danisco, Co-op Denmark, Arla Foods, the Danish Heart Association, the Centre For Advanced Food Research Foundation, 3-Star, Aarhus United, Allara, Ardo/Frigodan, Beauvais, Bæchs Confectionery, Bähncke, Cadiso, Cerealia, Daloon, Danisco, Flensted, Frisko, G-Potatoes, Gamba Food, Jan Import, Kellogg's, Kims, Kraft Foods, Kryta, Danish Livestock and Meat Board, LCH Food Services, Lykkeberg, Malaco Leaf, Nutana, Nutrillett, Odense Marcipan, Polar Is, Puratos, Rose Poultry, Rynkeby, Saeby, Santa Maria, Schulstad, Svansø, South Jutland Cabbage, Tholstrup Cheese, Toms, Tulip, Unilever, Urtekram, and Wasa.

[3] Reprints not available. Address correspondence to LG Rasmussen, Department of Human Nutrition, Faculty of Life Sciences, University of Copenhagen, Rolighedsvej 30, DK-1958 Frederiksberg C, Denmark. E-mail: logr@life.ku.dk.

Received March 28, 2006.

Accepted for publication October 23, 2006.

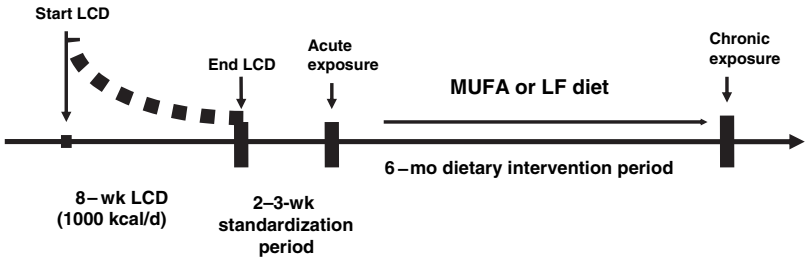

FIGURE 1. Timeline of the Mono Unsaturated Fatty acids in Obesity Study and the scheduled chamber measurements. LCD, low-calorie diet; MUFA diet, moderate-fat diet high in monounsaturated fatty acids; LF, low-fat.

It would be interesting to clarify whether a specific dietary composition influences EE favorably and could thus prevent weight gain. Long-term studies are needed to clarify whether diet composition also can affect long-term energy balance. A high degree of compliance with the diet is necessary to obtain valid results, which requires study designs with strict control of the diet. Existing studies are mostly of relatively short duration, and they are rarely as long as 6 mo. The purpose of the present study was to compare the effect of a moderate-fat diet, high in monounsaturated fatty acids (MUFAs), and a low-fat diet on EE and macronutrient oxidation before and after a 6-mo controlled dietary intervention.

SUBJECTS AND METHODS

Subjects

A dietary intervention study, the Mono Unsaturated Fatty acids in Obesity (MUFObes) Study, is ongoing at the Department of Human Nutrition, Faculty of Life Sciences, University of Copenhagen, (Frederiksberg, Denmark). The subjects in the present study were a subgroup made up of ≈20% of the total number of participants in the MUFObes Study ($n = 169$), which is being conducted in our department (ClinicalTrials.gov Identifier NCT00274729; for further information on the MUFObes Study, *see* www.mufobes.dk). The aim of the 4-y controlled dietary intervention trial, the MUFObes Study, was to compare the long-term effects of a MUFA diet and an LF diet on body weight, body composition, and risk factors for development of diet-related diseases (results to be published later). Subjects were randomly assigned to the 2 diets through a simple block randomization procedure with sex and initial BMI (below or above BMI 32) as stratification criteria. Subjects were randomly assigned to subgroup A or B, which determined the type of clinical examination that subjects should undergo at 0 mo and after the 6-mo intervention. This report discusses data from subjects randomly assigned to the MUFA or LF diet and to subgroup A, who underwent respiration chamber measurements of EE. Subgroup B was subjected to a meal test and underwent flow-mediated dilation measurements (results to be published later).

Thirty-seven subjects underwent respiration chamber measurement at 0 mo, and 27 of these subjects ($n = 12$ and 15 for the MUFA and LF diets, respectively) also underwent the 6-mo measurement. All subjects were recruited from the Copenhagen area by various methods, such as advertisements in local newspapers and on television and radio; notices placed in educational establishments and on homepages; and contacts with colleagues.

The inclusion criteria for the study were age 18–35 y, BMI 28–36, body weight fluctuations of ≤ 3 kg over the previous 2 mo, and a nonsmoking status. Subjects were healthy, their systolic and diastolic blood pressures were <180 mm Hg and <100 mm Hg, respectively, and they took no regular medicine other than contraceptive pills. Subjects had no psychological disorders, no known or presumed abuse of alcohol, no allergies to any food, and no special dietary restrictions (eg, vegetarian) or particular food dislikes. Female subjects were required not to be pregnant or lactating and to have no plans for pregnancy within 18 mo after enrollment.

All subjects gave oral and written informed consent after the experimental procedure had been explained to them. The Ethics Committee of the Municipalities of Copenhagen and Frederiksberg approved the study according to the Helsinki Declaration.

Experimental design

The study was designed as a parallel intervention trial with 2 groups who were assigned to 1 of 2 diets for 6 mo. A schematic presentation of the study design is given in **Figure 1**. After an initial 8-wk low-calorie diet (800–1000 kcal/d), the subjects were randomly assigned, through a simple block randomization procedure with sex and an initial body mass index (BMI; in kg/m^2) of ≤ 32 as stratification criteria, to either a moderate-fat diet high in monounsaturated fatty acids (MUFA diet) or a low-fat, high-carbohydrate diet (LF diet). After randomization, the participants completed a 2–3-wk standardization period eating a diet, resembling the average Danish diet according to nutritional surveys (20). This step was taken to ensure proper standardization before the respiration chamber measurements at 0 mo. The energy level of the diet during both the standardization period and the 6-mo postrandomization period corresponded to the individually estimated energy requirements, calculated by using World Health Organization equations (21) in combination with the participant's self-reported physical activity level (PAL). During the standardization period, in which all the subjects consumed the same standardized diet, and the 6-mo postrandomization dietary intervention period, the subjects obtained their food from the supermarket at the department. Respiration chamber measurements were conducted at 0 mo (the end of the standardization period) to test the acute exposure to the MUFA or the LF diet. Respiration chamber measurements were repeated after the 6-mo period of following the MUFA or the LF diet. Dual-energy X-ray absorptiometry (DXA) scanning was also carried out at 0 mo and after the 6-mo intervention.

Experimental diets

To mimic free-living conditions, the 6-mo dietary intervention was based on an ad libitum design. The MUFA diet was designed to be moderate in fat (35–45% of energy), high in MUFAs

(>20% of energy), and moderate in carbohydrate (40–50% of energy). The LF diet was low in fat (20–30% of energy) and high in carbohydrate (55–65% of energy). Both diets were moderate in protein (10–20% of energy). Alcohol consumption was allowed in accordance to the current guidelines issued by the Danish National Board of Health—ie, <14 units/wk and <21 units/wk (1 unit = 12 g alcohol) for women and men, respectively. Subjects were instructed to maintain their habitual PAL to achieve energy balance and weight maintenance. All subjects were allowed a 3-wk break from the project, during which no recording of the dietary intake was required.

Supermarket foods, the computer program, and shopping sessions

To provide the subjects with all necessary foods and to accomplish a total recording of the food consumed, a validated supermarket model (22) was established at the department. Throughout the 6-mo intervention, the subjects obtained all foods and beverages at the study supermarket, free of charge, and they were instructed to consume only these foods. The supermarket had a floor area of ≈70 m^2, distributed in 2 rooms, with 9 refrigerators of 400 L, 7 deep-freezers of 600 L, and ≈27 m^2 shelf space for items stored at room temperature.

A DOS-based computer program (MUFObes, version 7.5; Scientific Nutrition Supervision, Greve, Denmark) was constructed for recording of foods (product database) and for the calculation of nutrient composition of each shopping session (MUFObes shopping calculation software). The computer program used was similar to the programs used in previous supermarket dietary intervention studies carried out at the department (22, 23), but with improvements and adjustments designed specifically to handle the diets in this study. Local food manufacturers donated most products. Additional products were purchased to ensure an appropriate assortment to cover the dietary needs and the variability required by both diet groups throughout the 6-mo period. The product database covered the most common food items; alcohol and soft drinks were not included. All of the ≈700 different food items available in the supermarket were bar-coded and recorded according to their content of fat, carbohydrate, protein, fatty acids, and all vitamins and minerals available in the current official national food tables (24). Values for various nutrients in products not available in the food tables were estimated from other similar products found in the food table; for some products, nutrient information from the food manufacturers' labeling or from other sources was used. An estimated loss or gain of weight of each food due to preparation or cooking procedures was embedded in the program. In addition, a list of ≈380 food items that were not available from the study supermarket (termed "nonshop foods") was recorded in the computer program. These products were incorporated in the computer program to allow a complete recording of the foods and beverages from outside the study supermarket that the study participants consumed.

During each shopping session, all products were recorded with a bar-code scanner (Intermec 9170; Intermec Corporation, Everett, WA). All food items were weighed individually, with the weight of the packaging subtracted, on a digital scale (Sartorius IP65; Sartorius AG, Goettingen, Germany) that was connected to the 3 computers (each containing the shopping calculation software) that made up the checkout stations in the supermarket. At the beginning of each shopping session, waste and leftovers from the previous shopping session were recorded, and then the actual shopping event commenced. Every food item was recorded in a subject's profile. During the shopping session, the percentage of energy from fat, carbohydrate, and protein and the content of MUFAs, polyunsaturated fatty acids (PUFAs), and saturated fatty acids (SFAs), fiber, and added sugar were visible to both the study participant and the investigator, which allowed adjustment of the purchase by the addition or subtraction of various food items to achieve the optimal composition. To ensure that the shopping was ad libitum, the total energy content of the foods was visible only to the investigator, who thus also was able to estimate whether the total amount of energy provided was within reasonable limits. The total amount of energy was based on the number of days of the participant's diet that the foods obtained in one shopping session should provide, on the age and body weight of the participant, and on the participant's self-reported PAL (set at a maximum of 2.0).

Indirect calorimetry measurements

The indirect calorimetry measurements were carried out in respiration chambers, as described by Astrup et al (25). Gas exchange in the chamber was calculated by measuring the concentrations of oxygen and carbon dioxide at the outlet of the chamber (25), and EE and substrate partitioning were calculated by using equations of Elia and Livesey (26).

Subjects were instructed not to perform any strenuous physical activity during the 2 d before the chamber measurements. To accustom them to the chamber and to diminish stress during the 24-h measuring period, subjects slept in the chamber, with the door open, the night before the actual measurement. The measurements started at 0900 and ended 22 h later (ie, at 0700). This 22-h measuring period was converted into 24-h data by dividing the measurements by 22 and multiplying that value by 24. The basal metabolic rate (BMR) was measured during the last hour of the chamber stay (ie, 0600 to 0700), when the subjects were resting and fasting.

Subjects were instructed to consume all of the food and drinks served. Any leftovers during the first measurement (0 mo) were recorded and the portions served at the 6-mo measurement were adjusted accordingly. Other than the 3 subjects who left negligible amounts, all subjects consumed the same amount of food in the same dietary composition at both measurements. Spontaneous physical activity (SPA) was assessed by 2 microwave radar detectors (Sisor Mini-Radar; Statistic Input System SA, Lausanne, Switzerland), which continuously emitted and received a signal. The radar detected whether the subject was moving, and a signal was generated and received by the transceiver. SPA measurements indicated the percentage of time that the subject was detectably active. A laboratory technician kept the subject under surveillance during daytime, and a trained medical student kept the chamber under surveillance during the night.

Design of the diets consumed during chamber stays

The amount of energy provided during the chamber stay was individually calculated on the basis of age, sex, and body weight by using World Health Organization equations (27) and setting the physical activity at a fixed level at 1.5 PAL for all subjects. The total energy intake of the 3 meals consumed at 0 mo and at the 6-mo measurement was distributed with 20% at breakfast, 33% at lunch and 47% at dinner. The macronutrient composition

TABLE 1
The macronutrient composition of the 3 meals served to the 2 diet groups during both chamber stays[1]

	MUFA diet group (n = 12)			LF diet group (n = 15)		
	Breakfast	Lunch	Dinner	Breakfast	Lunch	Dinner
Weight of meals (g)[2]	464	647	1123	485	703	1153
Energy density (kJ/g)[3]	4.3	5.1	4.2	4.1	4.7	4.1
Carbohydrate + fiber (% of energy)	45.0	45.0	45.0	59.9	60.0	60.0
Total fat (% of energy)	40.0	40.0	40.0	25.1	25.0	24.9
Saturated fatty acids	4.1	5.0	5.2	6.4	5.5	9.4
Monounsaturated fatty acids	28.2	22.7	20.5	12.2	10.7	9.0
Polyunsaturated fatty acids	5.5	9.0	9.1	4.9	6.4	4.2
Protein (% of energy)	15.1	15.0	14.9	15.0	15.0	15.1
Fiber (g/MJ)	3.6	5.1	3.0	4.5	4.5	2.9
Added sugar (% of energy)	0	0	0	0	2.9	0

[1] MUFA diet, moderate-fat diet high in monounsaturated fatty acids (MUFAs); LF diet, low-fat diet. Both diets had a 10 MJ/d energy requirement. Dietary intake was energy adjusted, and calculations were made with DANKOST 3000, based on the food tables from The National Food Agency of Denmark.
[2] Including water or other drinks for an estimated energy provision of 10 MJ/d.
[3] Including water and other drinks.

of the diets is shown in **Table 1**. Dietary calculations were made with a computer database (DANKOST, version 3000; The National Food Agency of Denmark, Copenhagen, Denmark; 28) and the composition of the 3 daily meals consumed by the 2 groups is shown in **Table 2**.

Anthropometric measurements

Body weight was measured on an electronic scale while the subjects were wearing only light clothing and no shoes. Body composition was measured by using DXA scanning (Lunar Radiation Co, GE, Madison, WI), and fat-free mass (FFM) was calculated as total body mass − fat mass (FM). The measurements were performed in the morning after termination of the 24-h respiratory chamber measurements, when the subjects were fasting. Height was measured to the nearest 0.5 cm by using a wall-mounted stadiometer while the subjects were barefoot.

Statistical analysis

Mixed linear models was used to assess the main effects of time and treatment and the time × treatment interaction for the variables MIT during the 3 h after a meal ($MIT_{0-3\ h}$), RQ at a mean of 3 h after lunch ($RQ_{postprandial}$), BMR, RQ (BMR), 24-h

TABLE 2
The dietary composition of the 3 meals served to the 2 diet groups during both chamber stays[1]

Meal	MUFA diet group (10 MJ)	LF diet group (10 MJ)
Breakfast (≈2 MJ)		
	33 g oatmeal	67 g oatmeal
	8 g raisins	8 g raisins
	33 g hazelnuts	10 g hazelnuts
	40 g apple	50 g apple
	230 g skim milk (0.1% fat)	200 g low-fat milk (1.5% fat)
	120 g water	150 g water
Lunch (≈3.3 MJ)		
	137 g rye bread	94 g rye bread
	24 g turkey fillet	50 g white bread
	38 g shrimp (frozen)	31 g marinated herring
	30 g boiled egg	5 g onion
	100 g avocado	20 g low-fat cheese (30%)[2]
	18 g mayonnaise	30 g red pepper
	30 g red pepper	24 g smoked pork
	70 g fresh tomato	12 g mayonnaise
	200 g water	61 g potato (raw)
		70 g tomato
		106 g banana
		200 g water
Dinner (≈4.7 MJ)		
	454 g meat sauce (based on turkey and beans)	411 g meat sauce (based on beef, 11% fat)
	97 g brown rice (dry weight)	106 g pasta (dry weight)
	35 g pine nuts	50 g white bread
	350 g water	148 g banana
		150 g skim milk (0.1% fat)
		259 g water

[1] MUFA diet, moderate-fat diet high in monounsaturated fatty acids; LF diet, low-fat diet.
[2] "30%" indicates the fat content as a percentage of dry weight (or 27% of the total fat content of the cheese).

TABLE 3
Characteristics of subjects in the 2 diet groups at 0 mo and changes (Δ) after 6 mo of dietary intervention[1]

	MUFA diet group (n = 12)	LF diet group (n = 15)	P[2]
Men/women	4/8	8/7	0.259
Age (y)	28.0 ± 5.8[3]	28.7 ± 4.7	0.746
Height (cm)	170.0 ± 10.2	175.7 ± 6.8	0.097
Body weight at 0 mo (kg)	80.0 ± 12.3	86.0 ± 8.8	0.107
ΔBody weight (kg)	1.2 ± 3.9	1.0 ± 4.2	0.302
BMI (0 mo) (kg/m^2)	27.3 ± 2.2	27.8 ± 2.0	0.589
ΔBMI	0.8 ± 1.3	0.3 ± 1.4	0.381
FFM at 0 mo (kg)	54.9 ± 12.2	60.2 ± 9.1	0.175
ΔFFM (kg)	0.2 ± 1.0	0.4 ± 1.4	0.423
FM at 0 mo (kg)	25.1 ± 6.8	25.8 ± 8.1	0.916
ΔFM (kg)	1.0 ± 4.8	0.6 ± 3.4	0.278

[1] MUFA diet, moderate-fat diet high in monounsaturated fatty acids; LF diet, low-fat diet; FFM, fat-free mass; FM, fat mass. Body weight, FFM, and FM were assessed by dual-energy X-ray absorptiometric scanning.
[2] Test for difference between groups by chi-square test.
[3] $\bar{x}$ ± SD (all such values).

EE, 24-h SPA%, 24-h RQ, and macronutrient oxidation with subject number as random factor. The analyses were based on the 27 subjects (n = 12 and 15 for the MUFA and LF diets, respectively) who completed the respiratory chamber measurements both at 0 mo and after the 6-mo dietary intervention period. We tested whether sex, age, initial loss of FM and FFM after the 8-wk low-calorie diet (LCD), and current FFM and FM had a significant effect on the EE or RQ. When appropriate, variables that significantly affected EE or RQ were used as covariates in the MIXED analyses. The covariates that were used are the initial losses of FM and FFM and the current FM and FFM.

Statistical analyses were performed with SAS for WINDOWS software (version 9.1; SAS institute Inc, Cary, NC), and the level of significance was $P < 0.05$.

RESULTS

The physical characteristics of the 27 subjects who completed the respiratory chamber measurements are presented in **Table 3**. The change in body weight or in body fat did not differ significantly between the 2 groups after 6-mo ad libitum intake of the experimental diets.

Dietary intake

The intervention period was designed to be a period of ≈6 mo (including the days spent on vacation, etc). The number of days that the subject spent in the intervention period is calculated from the first day of the randomized diet to the day on which the 6-mo measurements were conducted minus the number of days reported as vacation time, time off, etc. No significant difference was observed between the MUFA and the LF diet groups regarding the number of days spent following the specific diet.

Actual dietary intake complied with the stipulated diet in both groups (**Table 4**). There were the expected differences between the 2 diets regarding dietary composition and energy density. However, the percentage of energy from protein was slightly, but significantly, higher in the LF group. Alcohol consumption was below the current official guidelines, and there was no difference between groups.

Meal-induced thermogenesis and respiratory quotient after the lunch meal

There was no time × treatment interaction for $MIT_{0-3\ h}$, but the main effect of time was significant ($P = 0.0480$): $MIT_{0-3\ h}$ at 0 mo was higher than that at 6 mo. The main effect of treatment was also significant ($P = 0.0435$): the $MIT_{0-3\ h}$ was lower on the MUFA diet than on the LF diet after adjustment for FFM and FM (**Table 5**). Furthermore, there was a significant main effect of treatment for $RQ_{postprandial}$ ($P < 0.0001$): the MUFA diet had a lower $RQ_{postprandial}$ than did the LF diet after adjustment for FFM and FM (Table 5).

TABLE 4
Energy intake, energy density, and mean dietary macronutrient composition during the 6-mo dietary intervention period[1]

	MUFA diet group (n = 12)	LF diet group (n = 15)	P[2]
Energy intake (MJ/d)	10.18 ± 1.65[3]	11.47 ± 2.45	0.131
Energy density (kJ/g)	4.76 ± 0.83	3.77 ± 0.40	< 0.0001
Carbohydrate + fiber (% of energy)	43.0 ± 2.0	57.2 ± 1.8	< 0.0001
Fiber (g/10 MJ)	37.3 ± 4.7	38.6 ± 2.5	0.266
Added sugar (% of energy)	6.2 ± 2.0	6.5 ± 1.7	0.661
Total fat (% of energy)	38.2 ± 1.6	23.2 ± 1.2	< 0.0001
Saturated fatty acids	7.0 ± 1.0	7.5 ± 0.7	0.134
Monounsaturated fatty acids	19.9 ± 1.2	8.2 ± 0.7	< 0.0001
Polyunsaturated fatty acids	7.8 ± 0.6	5.1 ± 0.5	< 0.0001
Protein (% of energy)	15.0 ± 1.1	16.0 ± 1.0	0.021
Alcohol (% of energy)	2.5 ± 1.9	2.4 ± 1.8	0.823
Intervention period (d)[4]	148 ± 16	155 ± 27	0.404

[1] MUFA diet, moderate-fat diet high in monounsaturated fatty acids; LF diet, low-fat diet. Data are based on the sum of energy provided from foods collected in the supermarket and from foods acquired outside the supermarket.
[2] ANOVA.
[3] $\bar{x}$ ± SD (all such values).
[4] Excluding days away from the study protocol because of a holiday, illness, etc.

TABLE 5
Values at 0 mo and 6 mo and changes (Δ) between 0-mo and 6-mo measurements in the 2 diet groups, as well as the main effects of time and treatment and time × treatment interaction for each variable[1]

			P[2]		
	MUFA diet group (n = 12)	LF diet group (n = 15)	Main effect of time	Main effect of treatment	Time × treatment interaction
$MIT_{0–3}$ h (kJ/min)[3,4]			0.0480	0.0435	0.5775
0 mo	6.9 ± 1.1[5]	7.6 ± 0.7			
6 mo	6.8 ± 1.0	7.6 ± 0.6			
$\Delta Time_{0–6\ mo}$	−0.13 ± 0.35	−0.05 ± 0.31			
RQ (meal)			0.7689	< 0.0001	0.3274
0 mo	0.822 ± 0.024	0.871 ± 0.033			
6 mo	0.817 ± 0.026	0.881 ± 0.033			
$\Delta Time_{0–6\ mo}$	−0.005 ± 0.035	0.010 ± 0.042			
BMR (kJ/min)[4]			0.0159	0.3612	0.1392
0 mo	5.2 ± 0.6	5.6 ± 0.5			
6 mo	5.0 ± 0.8	5.5 ± 0.4			
$\Delta Time_{0–6\ mo}$	−0.26 ± 0.43	−0.05 ± 0.41			
RQ (BMR)			0.3256	0.8080	0.4174
0 mo	0.867 ± 0.047	0.863 ± 0.059			
6 mo	0.869 ± 0.044	0.882 ± 0.051			
$\Delta Time_{0–6\ mo}$	0.002 ± 0.052	0.019 ± 0.055			
24-h EE (MJ/24 h)[6]			0.1783	0.2963	0.6465
0 mo	9.4 ± 1.4	10.2 ± 0.9			
6 mo	9.3 ± 1.4	10.1 ± 0.8			
$\Delta Time_{0–6\ mo}$	−0.1 ± 0.6	−0.01 ± 0.4			
24-h EE (MJ/24 h)			0.5496	0.0675	0.6530
0 mo	9.4 ± 1.4	10.2 ± 0.9			
6 mo	9.3 ± 1.4	10.1 ± 0.8			
$\Delta Time_{0–6\ mo}$	−0.1 ± 0.6	−0.01 ± 0.4			
SPA (24-h %)			< 0.0001	0.7865	0.0456
0 mo	9.2 ± 1.7	8.6 ± 1.5			
6 mo	7.8 ± 1.2	8.0 ± 1.4			
$\Delta Time_{0–6\ mo}$	−1.5 ± 1.4	0.03 ± 0.52			
$SPA_{day\ (0900–2300)}$ (%)			0.0001	0.6288	0.1093
0 mo	12.4 ± 2.44	11.55 ± 2.06			
6 mo	10.5 ± 1.6	10.7 ± 1.9			
$\Delta Time_{0–6\ mo}$	−1.9 ± 2.1	−0.9 ± 1.1			
$SPA_{night\ (2300–0600)}$ (%)			0.1527	0.1313	0.0876
0 mo	1.56 ± 0.63	1.68 ± 0.75			
6 mo	1.18 ± 0.49	1.71 ± 0.55			
$\Delta Time_{0–6\ mo}$	−0.39 ± 0.71	0.03 ± 0.52			
24-h RQ[4]			0.5562	0.0028	0.4540
0 mo	0.914 ± 0.023	0.943 ± 0.031			
6 mo	0.912 ± 0.028	0.953 ± 0.036			
$\Delta Time_{0–6\ mo}$	−0.002 ± 0.032	0.009 ± 0.041			
CHO oxidation (MJ/d)[4]			0.6147	0.0013	0.3419
0 mo	3.8 ± 0.6	4.8 ± 1.0			
6 mo	3.7 ± 0.8	5.1 ± 1.1			
$\Delta Time_{0–6\ mo}$	−0.07 ± 0.64	0.29 ± 1.15			
Fat oxidation (MJ/d)[4]			0.3552	0.0137	0.5622
0 mo	4.7 ± 1.0	3.9 ± 1.0			
6 mo	4.5 ± 1.0	3.6 ± 1.0			
$\Delta Time_{0–6\ mo}$	−0.04 ± 0.86	−0.27 ± 1.13			
Protein oxidation (kJ/d)[4]			0.3995	0.0022	0.6942
0 mo	1.1 ± 0.2	1.2 ± 0.3			
6 mo	1.2 ± 0.3	1.4 ± 0.3			
$\Delta Time_{0–6\ mo}$	0.005 ± 0.22	−0.37 ± 0.32			

[1] MUFA diet, moderate-fat diet high in monounsaturated fatty acids; LF, low-fat; $MIT_{0–3\ h}$, meal-induced thermogenesis during the 3 h after a meal; RQ, respiratory quotient; BMR, based metabolic rate; EE, energy expenditure; SPA, spontaneous physical activity; CHO, carbohydrate.
[2] Statistical analyses were carried out by using PROC MIXED.
[3] Postprandial (mean of 3 h after lunch).
[4] Adjusted for fat-free mass and fat mass.
[5] $\bar{x}$ ± SD (all such values).
[6] Adjusted for the initial losses of fat mass and fat-free mass and for fat mass and fat-free mass.

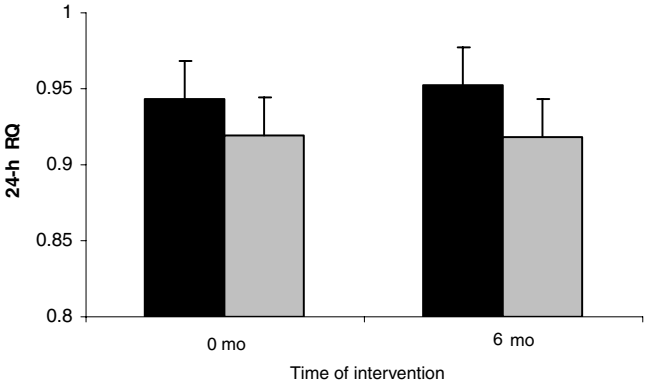

FIGURE 2. Mean (±SD) 24-h respiratory quotient (RQ) values obtained during chamber measurements at 0 mo—before the MUFA diet (moderate-fat diet high in monounsaturated fatty acid; ▨; $n = 15$) and the low-fat diet (■; $n = 12$)—and at 6 mo. There was a significant effect of diet, $P < 0.005$ (ANOVA). There was no significant time × treatment interaction.

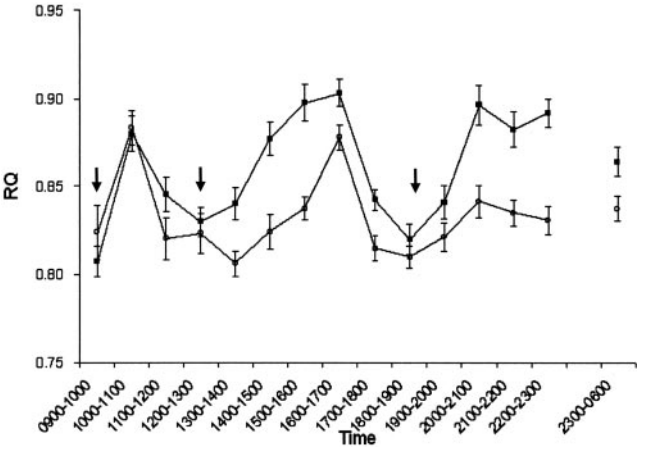

FIGURE 3. Mean (±SEM) respiratory quotient (RQ) values obtained during chamber measurements at 0 mo in subjects assigned to the low-fat diet (■; $n = 15$) or the MUFA diet (moderate-fat diet high in monounsaturated fatty acids; ○; $n = 12$). The last time marker (2300–0600) represents an interval of 7 h. Arrows indicate the times when meals were served.

Basal metabolic rate, 24-h energy expenditure, and spontaneous physical activity

The main effect of time for BMR was significant ($P = 0.0159$) after adjustment for FFM and FM, which indicated that the BMR at 0 mo was significantly higher than that at 6 mo (Table 5). There was no main effect of treatment or time × treatment interaction. For RQ there was no time × treatment interaction and no main effect of time or treatment. There was a tendency toward a lower 24-h EE on the MUFA than on the LF diet ($P = 0.0675$), but this trend did not remain after adjustment for the initial losses of FM and FFM ($P = 0.2963$) (Table 5).

There was a treatment × time interaction for SPA (24-h SPA%) ($P = 0.0456$). The reduction in SPA from 0 mo to 6 mo tended ($P = 0.0876$) to be greater on MUFA than LF diet, and most of the effect was found during sleep.

24-h Respiratory quotient and macronutrient oxidation

Substrate oxidation (24-h RQ) reflected the dietary macronutrient composition. The MUFA diet produced a significantly ($P = 0.0028$) smaller increase in carbohydrate oxidation that did the LF diet (Table 5), as shown in **Figure 2**. There was no time × treatment interaction for 24-h RQ.

The RQ profile from 0900 to 0600 at 0 mo is shown in **Figure 3**. Meals were served at 0900, 1300, and 1900 (arrows); at 1000 and 1600, the subjects had a 15-min episode of using a bicycle ergometer at an effect of 75 W. The RQ in the MUFA group was 0.850 after breakfast, and it was consistently significantly lower than that in the LF group throughout the chamber stay.

For the carbohydrate ($P = 0.013$), fat ($P = 0.0137$), and protein ($P = 0.022$) oxidation rate, the main effect of treatment was significant when adjusted for FFM and FM, because the LF diet produced a higher carbohydrate and protein oxidation and a lower fat oxidation. There was no main effect of time or time × treatment interaction.

DISCUSSION

The major finding of the present 6-mo controlled dietary intervention was a tendency toward a lower 24-h EE with the MUFA diet than with the LF diet, but this trend did not remain after adjustment for changes in FM and FFM. However, the LF diet produced a significantly greater MIT than did the MUFA diet, both acutely and after the 6-mo chronic exposure. Moreover, there was a slight decline in SPA in both diet groups, with a trend toward a greater decline in the MUFA group than in the LF group, particularly during sleep. BMR was unaffected by the diet.

Acute exposure to the randomized diets at 0 mo showed that MIT was greater with the low-fat diet than with the moderate-fat diet in the first 3 h after lunch, and the same tendency was found at the respiratory chamber measurement after the 6-mo intervention. In a study by Brehm et al (29), the MIT in response to low-fat (69%, 11%, and 20% of energy from carbohydrate, protein, and fat, respectively) and high-fat (5%, 26%, and 69% of energy from carbohydrate, protein, and fat, respectively) breakfasts, matched in calories, was assessed over 5 h at baseline, at 2 mo, and at 4 mo. They found that an LF meal caused a significantly greater 5-h increase in MIT than did a high-fat meal. These findings are consistent with the theory of larger costs of absorption, metabolism, and storage of carbohydrates than of fat (14, 16).

There was no time × treatment interaction for BMR before or after adjustment for FFM and FM. However, there was a significant main effect of time for BMR, which could be explained by a larger FFM in the diet groups at 0 mo, just after the 8-wk low-calorie diet, because FFM is the major determinant of BMR (16, 30, 31).

A study by Pereira et al (32) determined the effect of an energy-restricted LF diet and a low-glycemic-load (LGL) diet on resting EE (REE) by using indirect calorimetry. The macronutrient composition was 65%, 17%, and 18% and 43%, 27%, and 30% for carbohydrate, protein, and fat in the LF and LGL diets, respectively. After a 10-wk intervention period, Pereira et al found a significantly smaller decrease in REE in the LGL group than in the LF group. However, the protein content of the LGL diet was significantly higher than that of the LF diet, a difference that is likely to have influenced the result, and, therefore, such a comparison of the 2 diets is questionable.

The present study found a tendency toward a lower 24-h EE with the MUFA diet than with the LF diet, but, because this trend did not remain after adjustment for changes in FM and FFM,

neither diet had an effect on 24-h EE at 0 mo or after the 6-mo controlled dietary intervention. Furthermore, no chronic adaptation of 24-h EE to the 2 diets was found. In the present study, the MUFA diet did not decrease EE, and the effect on weight maintenance or weight loss did not differ significantly between the MUFA and the LF diets. However, the present study was not powered to detect possible effects on body weight, and thus, these small, insignificant changes in body weight and composition were regarded as potential confounders in the analyses of the EE and substrate oxidations.

Our findings seem to corroborate previous studies (18, 33–36); however, the methods used for assessment of control of dietary intake are diverse. In a study by Verboeket-van de Venne et al (36), subjects had access to either full-fat or reduced-fat products. Three-day dietary recordings at 3 timepoints during the 6-mo intervention period assessed energy and macronutrient intake. Other studies showed that dietary records are inaccurate in determining dietary intake (37, 38). However, the chamber diets corresponded to the subjects' specific randomized diets and no difference were found between the 2 groups at baseline or at the 6-mo measurements, which supports the findings of the present study.

The 6-mo dietary intervention study by Vasilaras et al (39) used a supermarket model similar to ours, and they found no difference in 24-h EE between the 3 diets (LF diet, simple-carbohydrate diet compared with LF diet, and complex-carbohydrate diet compared with high-fat control diet) when tested after the 6-mo dietary intervention. The macronutrient composition of the carbohydrate-rich diets and the control diet was 55% and 25% carbohydrates and 45% and 35% fat, respectively, which is fairly comparable with the diets in the present study. Our findings support the results of Vasilaras et al. The macronutrient oxidation pattern during the chamber reflected dietary composition; ie, the MUFA diet produced a smaller increase in fat oxidation, but no time × treatment interaction was seen.

There was a treatment × time interaction for SPA, and the reduction in SPA observed from 0 mo to 6 tended to be greater with the MUFA diet than with the LF diet; most of the effect was found during sleep. Although the subjects enter the chamber the night before the 0-mo measurements in an effort to diminish any stress, the situation is still unfamiliar and the subjects may be more comfortable at the 6-mo measurements, which could explain the lower SPA. Furthermore, an LF diet has been found in some studies to increase sympathetic activity in subjects with reduced obesity (40); thus, we speculate as to whether the MUFA reduced sympathetic activity slight more than did the LF diet, an effect that could translate into a lower SPA during sleep. An alternative explanation is that the LF diet group had a higher SPA than did the MUFA diet group from the beginning of the trial, which would make the finding a matter of chance.

A major strength of the present study is the use of the supermarket model, which ensures a high degree of compliance with the diets. The supermarket system is assumed to be one of the most valid methods for assessing dietary intake under ad libitum, free-living conditions, although the method is not without some uncertainty (22). There is no guarantee that the subjects actually consume the foods that they select in the supermarket. No measurements of compliance other than the supermarket diet recordings were applied during the 6-mo intervention period, and hence no objective indicators of the subjects' actual dietary intakes are available.

This randomized, long-term, intervention study found that, despite a slightly lower MIT and SPA, the MUFA and the LF diets had effects on 24-h EE during a 6-mo controlled dietary intervention that did not differ significantly. The reason for this lack of difference could be either a compensatory increase in EE in the fasting, resting state or simply a failure of the system to detect such small effects on 24-h EE. We cannot distinguish between these 2 possibilities, but we conclude that the effects are at best of minor importance for daily energy balance.

Thus, any significant differences in long-term body-weight regulation shown between MUFA and LF diets must be caused by differences in effects on appetite or satiety or by differences in nutrient digestibility. The substudy reported here was not statistically powered to detect a possible difference in weight loss, and thus any weight changes were simply regarded as confounders that had to be controlled for in the analyses of EE and RQ. Further long-term studies are needed to evaluate the long-term (>6 mo) effects of these diets.

We thank Walter C Willett (Harvard University of School of Public Health, Cambridge, MA) and David Ludwig (Children's Hospital, Boston, MA) for their help with the study design. We also thank the technical staffs at the Department of Human Nutrition for help with data collection, the kitchen staff for their help with the diets and in the supermarket, and the subjects for their endurance throughout the study. We thank the sponsors for their donations of foods and beverages to the supermarket.

AA was responsible for the study protocol; LGR, TML, PKM, and AD were responsible for the conduct of the trial and for data collection; LGR and PKM were responsible for data analysis; LGR wrote the draft of the manuscript; and AA and TML contributed to revisions of the manuscript. None of the authors had a personal or financial conflict of interest.

REFERENCES

1. Bray GA, Popkin BM. Dietary fat intake does affect obesity! Am J Clin Nutr 1998;68:1157–73.
2. Flatt JP. Dietary fat, carbohydrate balance, and weight maintenance: effects of exercise. Am J Clin Nutr 1987;45:296–306.
3. Astrup A, Ryan L, Grunwald GK, et al. The role of dietary fat in body fatness: evidence from a preliminary meta-analysis of ad libitum low-fat dietary intervention studies. Br J Nutr 2000;83(suppl):S25–32.
4. Paeratakul S, Popkin BM, Keyou G, Adair LS, Stevens J. Changes in diet and physical activity affect the body mass index of Chinese adults. Int J Obes Relat Metab Disord 1998;22:424–31.
5. Astrup A, Grunwald GK, Melanson EL, Saris WH, Hill JO. The role of low-fat diets in body weight control: a meta-analysis of ad libitum dietary intervention studies. Int J Obes Relat Metab Disord 2000;24:1545–52.
6. Yu-Poth S, Zhao G, Etherton T, Naglak M, Jonnalagadda S, Kris-Etherton PM. Effects of the National Cholesterol Education Program's Step I and Step II dietary intervention programs on cardiovascular disease risk factors: a meta-analysis. Am J Clin Nutr 1999;69:632–46.
7. Lawton CL, Burley VJ, Wales JK, Blundell JE. Dietary fat and appetite control in obese subjects: weak effects on satiation and satiety. Int J Obes Relat Metab Disord 1993;17:409–16.
8. Lissner L, Levitsky DA, Strupp BJ, Kalkwarf HJ, Roe DA. Dietary fat and the regulation of energy intake in human subjects. Am J Clin Nutr 1987;46:886–92.
9. Prentice AM. Manipulation of dietary fat and energy density and subsequent effects on substrate flux and food intake. Am J Clin Nutr 1998;67(suppl):535S–41S.
10. Stubbs RJ, Harbron CG, Murgatroyd PR, Prentice AM. Covert manipulation of dietary fat and energy density: effect on substrate flux and food intake in men eating ad libitum. Am J Clin Nutr 1995;62:316–29.
11. Willett WC, Leibel RL. Dietary fat is not a major determinant of body fat. Am J Med 2002;113(suppl):47S–59S.

12. Willett WC. Dietary fat plays a major role in obesity: no. Obes Rev 2002;3:59–68.
13. Poehlman ET, Horton ES. Energy needs: assessment and requirements in humans. In: Shills ME, Olson JA, Shike M, Ross AC, eds. Modern nutrition in health and disease. Baltimore, MD: Lippincott Williams and Wilkins 2004:95–104.
14. Schuts Y, Jéquier E. Resting energy expenditure, thermic effect of food, and total energy expenditure. In: Bray GA, Bouchard C, eds. Handbook of obesity, etiology and pathophysiology. New York, NY: Marcel Dekker, Inc, 2004:615–31.
15. Tataranni PA, Larson DE, Snitker S, Ravussin E. Thermic effect of food in humans: methods and results from use of a respiratory chamber. Am J Clin Nutr 1995;61:1013–9.
16. Jequier E, Acheson K, Schutz Y. Assessment of energy expenditure and fuel utilization in man. Annu Rev Nutr 1987;7:187–208.
17. Raben A, Agerholm-Larsen L, Flint A, Holst JJ, Astrup A. Meals with similar energy densities but rich in protein, fat, carbohydrate, or alcohol have different effects on energy expenditure and substrate metabolism but not on appetite and energy intake. Am J Clin Nutr 2003;77:91–100.
18. Raben A, Macdonald I, Astrup A. Replacement of dietary fat by sucrose or starch: effects on 14 d ad libitum energy intake, energy expenditure and body weight in formerly obese and never-obese subjects. Int J Obes Relat Metab Disord 1997;21:846–59.
19. Westerterp KR, Wilson SA, Rolland V. Diet induced thermogenesis measured over 24h in a respiration chamber: effect of diet composition. Int J Obes Relat Metab Disord 1999;23:287–92.
20. Andersen NL, Fagt S, Groth MV et al. Danskernes Kostvaner 1995. Hovedresultater. (Dietary habits of the Danes, 1995. Main results.) Danish National Food Agency, Ministry of Health publication no. 235. Rødovre, Denmark: Quickly Tryk A/S, 1995.
21. World Health Organization Energy and protein requirements. Report of a joint FAO/WHO/UNU Expert Consultation. World Health Organ Tech Rep Ser 1985;724:1–206.
22. Skov AR, Toubro S, Raben A, Astrup A. A method to achieve control of dietary macronutrient composition in ad libitum diets consumed by free-living subjects. Eur J Clin Nutr 1997;51:667–72.
23. Saris WH, Astrup A, Prentice AM, et al. Randomized controlled trial of changes in dietary carbohydrate/fat ratio and simple vs complex carbohydrates on body weight and blood lipids: the CARMEN study. The Carbohydrate Ratio Management in European National diets Int J Obes Relat Metab Disord 2000;24:1310–8.
24. Danish National Food Institute, The Technical University of Denmark. The Danish Food Composition Databank, revision 5.0. Internet: http://www.foodcomp.dk/fvdb_default.htm. 2006 (accessed on 15 December 2005).
25. Astrup A, Thorbek G, Lind J, Isaksson B. Prediction of 24-h energy expenditure and its components from physical characteristics and body composition in normal-weight humans. Am J Clin Nutr 1990;52:777–83.
26. Elia M, Livesey G. Energy expenditure and fuel selection in biological systems: the theory and practice of calculations based on indirect calorimetry and tracer methods. World Rev Nutr Diet 1992;70:68–131.
27. Sandström BM, Aro A, Becker W, Lyhne N, Pedersen JI, Pórsdóttir I. Nordiska näringsrekommendationer 1996. (The Nordic Nutrition Recommendations 1996.) Copenhagen, Denmark: Nordisk Ministerråd, 1996 (in Danish).
28. DANKOST 3000. Herlev, Denmark: Dansk Catering Center, 2006.
29. Brehm BJ, Spang SE, Lattin BL, Seeley RJ, Daniels SR, D'Alessio DA. The role of energy expenditure in the differential weight loss in obese women on low-fat and low-carbohydrate diets. J Clin Endocrinol Metab 2005;90:1475–82.
30. Ravussin E, Lillioja S, Anderson TE, Christin L, Bogardus C. Determinants of 24-hour energy expenditure in man. Methods and results using a respiratory chamber. J Clin Invest 1986;78:1568–78.
31. Weyer C, Snitker S, Rising R, Bogardus C, Ravussin E. Determinants of energy expenditure and fuel utilization in man: effects of body composition, age, sex, ethnicity and glucose tolerance in 916 subjects. Int J Obes Relat Metab Disord 1999;23:715–22.
32. Pereira MA, Swain J, Goldfine AB, Rifai N, Ludwig DS. Effects of a low-glycemic load diet on resting energy expenditure and heart disease risk factors during weight loss. JAMA 2004;292:2482–90.
33. Hill JO, Peters JC, Reed GW, Schlundt DG, Sharp T, Greene HL. Nutrient balance in humans: effects of diet composition. Am J Clin Nutr 1991;54:10–7.
34. Shetty PS, Prentice AM, Goldberg GR, et al. Alterations in fuel selection and voluntary food intake in response to isoenergetic manipulation of glycogen stores in humans. Am J Clin Nutr 1994;60:534–43.
35. Thomas CD, Peters JC, Reed GW, Abumrad NN, Sun M, Hill JO. Nutrient balance and energy expenditure during ad libitum feeding of high-fat and high-carbohydrate diets in humans. Am J Clin Nutr 1992;55:934–42.
36. Verboeket-van de Venne WP, Westerterp KR, Hermans-Limpens TJ, de Graaf C, het Hof KH, Weststrate JA. Long-term effects of consumption of full-fat or reduced-fat products in healthy non-obese volunteers: assessment of energy expenditure and substrate oxidation. Metabolism 1996;45:1004–10.
37. Mertz W, Tsui JC, Judd JT, et al. What are people really eating? The relation between energy intake derived from estimated diet records and intake determined to maintain body weight. Am J Clin Nutr 1991;54:291–5.
38. Schoeller DA. How accurate is self-reported dietary energy intake? Nutr Rev 1990;48:373–9.
39. Vasilaras TH, Raben A, Astrup A. Twenty-four hour energy expenditure and substrate oxidation before and after 6 months' ad libitum intake of a diet rich in simple or complex carbohydrates or a habitual diet. Int J Obes Relat Metab Disord 2001;25:954–65.
40. Astrup A, Buemann B, Christensen NJ, Madsen J. 24-hour energy expenditure and sympathetic activity in postobese women consuming a high-carbohydrate diet. Am J Physiol 1992;262:E282–8.