Energy density but not fat content of foods affected energy intake in lean and obese women[1–3]

Barbara J Rolls, Elizabeth A Bell, Victoria H Castellanos, Mosuk Chow, Christine L Pelkman, and Michelle L Thorwart

ABSTRACT

Background: Studies have shown that energy intake increases when both the fat content and energy density of the entire diet increases. When the fat content and energy density vary independently of one another, however, energy density, but not fat content, influences intake.

Objective: The present study examined whether energy intake in lean and obese women is affected when either the energy density or the fat content of a portion of the diet is manipulated and palatability is held constant.

Design: In a within-subjects design, 17 lean and 17 obese women consumed meals in the laboratory for four, 4-d test periods. In 3 of these test periods the energy density (4.4 and 6.7 kJ/g) or the fat content (16% and 36% of energy) of compulsory entrées representing 50% of each subject's usual energy intake was manipulated. Additional self-selected foods were consumed ad libitum at meals and as snacks.

Results: There were no systematic differences in palatability of the manipulated foods across conditions. Obese and lean participants responded similarly to the dietary manipulations. Intake of self-selected foods at meals was reduced significantly by 16% for both lean and obese subjects in the low- compared with the high-energy-density condition. The fat content of the compulsory foods had no significant effect on energy intake. Ratings of hunger did not differ between diets.

Conclusion: These results indicate that when a portion of the diet was manipulated, the energy density, but not the fat content, of the foods affected total energy intake at meals in both lean and obese women. Am J Clin Nutr 1999;69:863–71.

KEY WORDS Energy density, fat intake, human food intake, macronutrients, obesity, satiety, weight management, women

INTRODUCTION

Several studies have shown that energy intake increases as the proportion of fat in the diet increases (1–4). In those studies, however, the fat content of foods varied directly with energy density (kJ/g) and thus, the effects of fat content could not be separated from those of energy density. Although the fat content of foods can influence energy density, it is not the only determinant. In fact, examination of diet records showed only modest correlations between the fat content and energy density (5). Other factors such as the water and fiber content influence the energy density of foods. Thus, it is possible to manipulate the fat content and the energy density of foods independently to examine their separate effects on energy intake.

Some studies have examined the effects of fat content by manipulating the ratio of fat to carbohydrate in diets while keeping energy density constant. Results of these studies indicated that fat content, per se, did not affect energy intake (6–8). To investigate the independent effects of energy density of food on energy intake, investigators in one study manipulated the energy density of diets while keeping macronutrient content and palatability constant (9). Results from that study clearly showed that the energy density of food can have a significant effect on energy intake independently of either macronutrient content or palatability.

In the studies cited above, researchers manipulated either the energy density or fat content of entire diets and subjects were instructed not to consume foods other than those included in the experimental regimen. In real-life situations, however, individuals will likely choose to incorporate only some low-fat or low-energy-density foods in their diets and will also consume high-fat and high-energy-density foods. Additionally, investigators have not examined the independent effects of both fat content and energy density on intake within the same individuals. Thus, it is not possible to directly compare the effects of manipulations of dietary fat and energy density. Furthermore, none of the previously cited studies systematically examined whether lean and obese individuals respond differently to manipulations of fat and energy density. This is important because obese individuals may differ from lean individuals in their ability to adjust subsequent intake to compensate for energy derived from fat in foods (10).

[1] From the Nutrition and Statistics Departments, The Pennsylvania State University, University Park, and the Department of Dietetics and Nutrition, Florida International University, Miami.

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[3] Address reprint requests to BJ Rolls, Nutrition Department, 226 Henderson Building, The Pennsylvania State University, University Park, PA 16802-6501. E-mail: bjr4@psu.edu.

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TABLE 1
Compulsory foods served at each meal during the 3 experimental conditions[1]

Meal	Monday	Tuesday	Wednesday	Thursday
Breakfast	Bagels with cream cheese; mandarin oranges in light syrup	Waffles with butter and syrup; sliced peaches in light syrup	English muffins with butter and jam; pineapple tidbits	Pancakes with butter and syrup; pear halves in light syrup
Lunch	Roll with sliced ham, mustard, mayonnaise, lettuce, and tomato; raw carrot sticks	Pita pizza (toppings included shredded cheese, green peppers, and diced tomatoes)	Roll with sliced turkey, cheese, mustard, mayonnaise, lettuce, and tomato; raw carrot sticks	Pita bread with chicken salad and lettuce; unsweetened apple sauce
Dinner	Turkey and stuffing bake; corn and green beans	Chicken-rice Florentine	Burritos filled with refried beans, rice, and cheese; salsa, lettuce, tomatoes, green peppers, and sour cream	Italian pasta bake

[1] For each compulsory food, 3 versions were developed: condition 1, low-fat diet of low energy density; condition 2, low-fat diet of high energy density; condition 3, high-fat diet of high energy density. All recipes are available from the author.

The purpose of this experiment was to determine whether energy intake in lean and obese individuals was affected when 50% of each participant's habitual energy intake was varied. Within the same individuals, we examined the independent effects of both the energy density and fat content of foods on energy intake when only a portion of the diet was manipulated and other foods could be consumed ad libitum.

SUBJECTS AND METHODS

Subjects

We recruited subjects through advertisements in local and university newspapers and through posters and mailings. Potential subjects, who were females between 18 and 45 y of age, were initially screened through a telephone interview to determine that they ate 3 meals/d, did not smoke, did not have any food allergies or restrictions, were not athletes in training, were not dieting, and were not taking any medications or dietary supplements that would affect appetite. Subjects were excluded if they reported being unwilling to consume the foods offered in the test meals. Potential subjects were measured for weight and height and completed the following questionnaires in our laboratory: the Eating Attitudes Test (EAT; possible score: 0–140), which detects symptoms of an eating disorder (11); the Eating Inventory (12), which measures dietary restraint (possible score: 0–21), perceived hunger (possible score: 0–14), and disinhibition (possible score: 0–16); the Beck Depression Inventory (13; possible score: 0–63) and the Zung Self-Rating Questionnaire (14; possible score: 20–80), both of which detect depression; the Binge Eating Scale (15; possible score: 0–46); a detailed demographic inquiry; and a family weight history. Potential subjects were excluded if they scored ≥40 on the Zung or ≥10 on the Beck questionnaires, or ≥30 on the EAT. Subjects were also excluded if they ate <1255 kJ at breakfast or lunch, or <2510 kJ at dinner during a baseline testing period. Participants were defined as lean if their body mass index (BMI; in kg/m^2) was between 20 and 25 or obese if their BMI was between 28 and 48. All subjects were weight-stable within the 6 mo before the study began and had no known health problems.

Fifty subjects began participation in the study; however, 16 subjects were dropped: 8 because of noncompliance, 2 because they did not meet the minimum requirement for energy intake during baseline, 2 because they became pregnant during the study, 3 for unrelated illnesses, and 1 because of scheduling conflicts. Thus, the final sample consisted of 17 lean and 17 obese females. All aspects of the study were approved by the Institutional Review Board of The Pennsylvania State University.

Study design

This experiment used a within-subjects design. Subjects came to the laboratory for 4 consecutive days (ie, Monday–Thursday) during 5 test weeks to eat breakfast, lunch, and dinner. During the first week (baseline), subjects were served a variety of foods that they could consume ad libitum. Baseline was used to establish habitual energy intakes at breakfast, lunch, and dinner. During 1 of the remaining 4 wk (control), subjects were served meals identical to baseline and foods were again consumed ad libitum.

During 3 test weeks (experimental), a portion of each meal was manipulated and required to be consumed in full (compulsory). Compulsory food items (**Table 1**) varied in energy density or fat content and contained ≈50% of each subject's average energy intake at the respective meal (ie, breakfast, lunch, or dinner) during baseline. Three versions of the compulsory foods were developed: 1) low-fat, low energy density; 2) low-fat, high energy density; and 3) high-fat, high energy density (**Table 2**). Thus, the effects of energy density on intake could be assessed by comparing conditions 1 and 2. Likewise, the effects of fat content could be assessed by comparing conditions 2 and 3. In addition to the compulsory foods, subjects also received a variety of entrées and side dishes that were consumed ad libitum. Test weeks were separated by 10-d washout periods and the presentation of treatments was counterbalanced across subjects.

TABLE 2
Macronutrient composition, energy density, and moisture content of compulsory foods[1]

	Condition		
	1	2	3
Fat (% of energy)	16.9	16.4	36.5
Carbohydrate (% of energy)	66.9	67.3	47.5
Protein (% of energy)	16.2	16.4	16.0
Energy density			
(kJ/g)	4.4	6.7	6.6
(kcal/g)	1.1	1.6	1.6
Moisture (%)	71.9	57.4	62.7

[1] Average of all compulsory entrees. Condition 1, low-fat diet of low energy density; condition 2, low-fat diet of high energy density; condition 3, high-fat diet of high energy density.

Procedures

Before the beginning of the study, waist, hip, and percentage body fat measurements (Body Composition Analyzer; Biodynamics Corporation, Seattle) were taken. Also, subjects who were not taking hormonal contraceptives (n = 21) were instructed on the use of ovulation detection kits (OvuQuick OS; Quidel Corporation, San Diego). We tracked subjects' menstrual cycles and found that phase of the menstrual cycle was evenly distributed across conditions.

Subjects were asked to refrain from drinking alcohol and to maintain exercise at a consistent level on the day before and during each test day. All subjects were weighed without shoes before breakfast on the first day of each 4-d study session. Subjects then consumed breakfast, lunch, and dinner in the laboratory Monday–Thursday. On Friday, subjects were weighed and completed a brief questionnaire.

Foods and macronutrients

Test meals

Subjects were seated in individual cubicles and were periodically monitored to assess compliance with the experimental protocol through use of concealed video cameras. During each meal, a variety of main entrées, side dishes, beverages, and appropriate condiments were served. Chilled water was the only beverage served with lunch and dinner. Across all 5 conditions, beverages and condiments did not vary in amount or type. During the baseline and control conditions, large servings of the same entrées and side dishes were offered and subjects were allowed to consume these foods ad libitum. During the 3 experimental conditions, compulsory foods and side dishes to be eaten ad libitum were served on separate trays. Subjects were instructed to consume the compulsory foods completely and were given small, rubber spatulas to scrape serving dishes clean. Because the compulsory portion of each meal constituted 50% of the subject's habitual intake, side dishes consumed ad libitum were also an integral part of each meal. Care was taken to ensure that subjects had a suitable variety of foods available to choose from at each meal. For example, during dinner on Tuesday, subjects received a compulsory serving of chicken-rice Florentine (Table 1). In addition to condiments and dessert items, subjects were also served chicken breast, potatoes, broccoli and cauliflower, salad, rolls, and butter. The side dishes served at each meal were identical during each of the 3 experimental conditions.

For foods that were eaten ad libitum (during the baseline, control, and experimental conditions), we presented more food than subjects were likely to consume to avoid the possibility of subjects eating to "clean their plates." These foods varied in fat, carbohydrate, and protein contents to allow subjects to vary energy intake and proportions of macronutrients consumed. Foods were weighed (±0.1 g) before and after the meal to obtain the amount consumed. Energy and macronutrient intakes from foods that were consumed ad libitum were calculated by using information provided by manufacturers and Bowes and Church's Food Values of Portions Commonly Used (16). A complete listing of all foods served is available from the corresponding author on request.

Compulsory foods

We manipulated the macronutrient content and energy density of the compulsory portion of the 3 experimental diets by changing proportions of specific ingredients or substituting high-fat items with their reduced-fat or fat-free counterparts. The compulsory portion of the low-fat and low-energy-density diet (condition 1) contained more fruit and vegetables and less pasta, rice, or other bread products than the diet low in fat with high energy density (condition 2). Thus, in effect, manipulations of energy density were accomplished primarily by varying the water and fiber contents such that foods that were lower in energy density contained more water and fiber than foods that were higher in energy density. The compulsory portion of the high-fat and high-energy-density diet (condition 3) contained greater proportions of butter, oil, and full-fat products than the low-fat and high-energy-density diet (condition 2). Commercially produced low-fat, reduced-fat, and fat-free products were used to lower the fat content of the compulsory foods served in condition 2. For example, a combination of reduced-fat and full-fat cream cheeses was spread on bagels served at breakfast on Monday (Table 1) during condition 2, whereas only full-fat cream cheese was used in condition 3. Because fat was added to the compulsory portions of foods served during the high-fat condition, more fruit and vegetables were also added to match the energy density to that of the low-fat condition.

As described previously, compulsory foods served at each meal during experimental conditions 1, 2, and 3 represented 50% of each subject's energy intake at that meal during the baseline condition. For example, if a subject consumed on average 3350 kJ (800 kcal) at dinner during baseline, she would receive a compulsory portion of food at dinner that contained one-half that amount of energy (1675 kJ, or 400 kcal). We developed recipes for the compulsory foods in increments of 209 kJ (50 kcal). Thus, the energy content of the compulsory portion of the diet contained 50% ±105 kJ (25 kcal) of the subject's habitual intake.

The initial formulation of recipes was based on information obtained from food labels. Before the start of the study, analysis of the protein, fat, moisture, and ash contents of the compulsory foods was performed by The Pennsylvania State University Crop Quality Laboratory using methods of the Association of Official Analytical Chemists (AOAC; 17). Carbohydrate content was calculated as the difference between total weight and the sum of the protein, fat, moisture, and ash contents. Adjustments were made in recipe formulation or serving size, based on the results of these analyses, for 8% of the foods submitted. Final results from the proximate analyses for the versions used in this study showed that the high-fat compulsory foods (condition 3) contained 37% fat, whereas the low-fat foods (conditions 1 and 2) contained ≈16% fat.

Energy content was determined on the basis of the Atwater constants (37.7 kJ/g fat, 16.7 kJ/g carbohydrate, and 16.7 kJ/g protein). The compulsory foods of high energy density (conditions 2 and 3) contained ≈6.6 kJ/g, whereas the compulsory foods of low energy density (condition 1) contained 4.4 kJ/g (Table 2). Analysis of dietary fiber content was conducted by General Mills, Inc, using AOAC methods (17). These analyses did not allow for the determination of specific types of fiber contained in the foods. The compulsory foods of high energy density (conditions 2 and 3) contained less than half the fiber (13 ± 1 g) of the compulsory foods of low energy density (condition 1; 30 ± 1 g).

Snacks

Subjects were allowed to consume foods and beverages as desired outside the laboratory. They were given portable scales and were instructed to weigh and record all foods and beverages consumed outside of the laboratory, during test weeks, in the diaries we provided. Before the study, a registered dietitian demonstrated how to weigh single and mixed foods and subjects practiced with their scales. Subjects were asked to bring "Nutrition Facts" labels to the laboratory for each food and beverage consumed. They presented snack diaries and labels on arrival for each meal. Snack diaries were reviewed by experimenters daily and, if needed, subjects were asked to give further information. Data from "Nutrition Facts" labels and the database NUTRITIONIST IV (version 3.5; N-Squared Computing, San Bruno, CA) were used to calculate the energy and macronutrient contents of snacks.

Visual analogue scales

Before and after each meal, subjects rated their hunger, thirst, nausea, fullness, and prospective consumption (how much food they thought they could eat) on visual analogue scales (VAS). For example, hunger was rated on a 100-mm line preceded by the question, "How hungry are you right now?" and anchored on the left by "not at all hungry" and "extremely hungry" on the right. Other anchors consisted of the phrases "not at all…" and "extremely…" combined with the adjectives "...thirsty", "...nauseated", and "...full". At the beginning of the meal, subjects rated the taste of each compulsory entrée on a 100-mm line, preceded by the question "How pleasant is the taste of this food right now?" anchored on the left by "not at all pleasant" and "extremely pleasant" on the right.

Questionnaires

Before breakfast on each test day subjects completed a brief questionnaire (developed by the laboratory) to assess compliance with the experimental protocol. Subjects also completed the Eating Inventory (12) on each Thursday of testing. On each Friday of testing, subjects reported to the laboratory to complete a questionnaire assessing whether foods were appetizing or especially liked or disliked, and overall perceptions of hunger and fullness during the test week.

Debriefing

At the end of the study, subjects completed a discharge questionnaire. This questionnaire asked subjects to state what they believed the purpose of the study was, to state whether they detected any differences between the compulsory foods, and to share other comments relevant to the study.

Data analysis

Data were analyzed by using SAS-PC for WINDOWS (version 6.10; SAS Institute Inc, Cary, NC). Baseline subject characteristics were analyzed between groups with a t test adjusted for unequal variance, as appropriate. Results were considered significant at $P < 0.05$. All other analyses (eg, food intake and visual analogue ratings) were conducted by using the mixed procedure. The residuals for total daily energy intake were examined for normality and equality of variance by using the univariate procedure. Studentized residuals were examined for the presence of outliers. The influence of each observation on the regression function was examined by using DFFITS (an approximation of the number of SDs that a fitted value changes when a particular observation is removed from the data set). Observations with $P < 0.001$ for the studentized residual and $|DFFITS| > 2$ were considered to be significant outliers.

This experiment was designed to investigate the effects of the energy density (conditions 1 and 2) and fat content of food (conditions 2 and 3) on intake for lean and obese women. Thus, planned comparisons were used to test the effects of condition. The control condition was excluded from the analyses for the planned comparisons involving the effects of energy density and fat content. Least-squares means were used to examine pair-wise differences between conditions by group. A Bonferroni multiple comparison procedure was used to maintain family-wise α at 0.05 (18). Thus, in each pair-wise comparison (condition 1 versus 2 and condition 2 versus 3), α was set to 0.025 for models examining the effects of energy density and fat content, for the lean and obese groups separately. Baseline measures of disinhibition, cognitive restraint, hunger, eating attitudes, binge eating, and depression were tested as covariates in the mixed model. To compare each diet with the control condition, all conditions were included in the analyses and the general linear models procedure was used with Dunnett's post hoc test to examine differences between means. We also examined differences between lean and obese women with respect to energy intake and meal patterns for the control condition.

Food intake

Analyses of food intake (energy and weight) were conducted with and without the compulsory portions of food and snacks, and also with and without beverages. Percentage of energy from macronutrients was analyzed by using an equivalent multiple analysis of variance procedure.

Visual analogue scale ratings

Palatability ratings of the compulsory entrées were analyzed for each meal and also as an average across conditions. Ratings of hunger and fullness before meals and changes in ratings of such sensations (premeal ratings subtracted from postmeal ratings), for example, were analyzed by using the mixed model described above.

Body weight

Change in body weight was calculated by subtracting the subject's weight at the start of each diet period (Monday) from her weight at the end of each diet period (Friday). This change score was analyzed by using the mixed model described previously.

Questionnaires

To test for effects of condition or time, scores for the 3 factors of the Eating Inventory (12) (cognitive restraint, disinhibition, and hunger) were analyzed by using the mixed model described above with group and condition or group and week entered as factors.

RESULTS

Results of the univariate analysis procedure for food intake showed that the residuals were normally distributed with equal variance. One lean subject was found to be an outlier with respect to total daily energy intake (studentized residual = $3.9_{(30)}$, $P < 0.001$; DFFITS = 3.0) and was removed from all subsequent analyses. No significant covariates were found in any of the analyses.

Participant characteristics

Participant characteristics are given in **Table 3**. Subjects in the obese group had a significantly higher BMI, percentage body fat, and waist-to-hip ratio, as well as a higher score for disinhi-

TABLE 3
Subject characteristics[1]

	Lean (n = 16)	Obese (n = 17)
Age (y)	27.6 ± 1.9	29.3 ± 1.9
BMI (kg/m²)	22.5 ± 0.4	34.3 ± 1.5[2]
Percentage body fat (%)	29.1 ± 0.6	40.8 ± 1.4[2]
Waist-to-hip ratio	0.7 ± 0.01	0.8 ± 0.03[2]
Eating Inventory[3]		
Cognitive restraint	6.7 ± 1.1	6.5 ± 1.1
Disinhibition	5.3 ± 0.9	7.9 ± 0.9[2]
Hunger	4.4 ± 0.6	5.1 ± 0.8
Depression		
Beck[4]	3.3 ± 0.7	4.8 ± 0.8
Zung[5]	30.1 ± 1.3	31.1 ± 1.0
EAT[6]	6.6 ± 0.9	9.4 ± 1.4
Binge eating[7]	6.0 ± 1.2	9.6 ± 1.6

[1] $\bar{x}$ ± SEM.
[2] Significantly different from lean, P < 0.05.
[3] Eating Inventory (12).
[4] Beck Depression Inventory (13).
[5] Zung Self-Rating Questionnaire (14).
[6] Measured by the Eating Attitudes Test (11).
[7] Measured by the Binge Eating Scale (15).

bition than subjects in the lean group (P < 0.05). Cognitive restraint, disinhibition, and hunger scores on the Eating Inventory did not vary across conditions or over time for lean or obese subjects.

Food intake

Effects of energy density of compulsory foods (comparison of conditions 1 and 2)

Energy density of the compulsory foods affected total daily energy intake for the obese women only and energy consumed ad libitum from side dishes at meals for both the lean and the obese (**Figure 1** and **Table 4**). Lean women consumed on average 556 kJ/d less from side dishes on the diet of low energy density (condition 1) than on the diet of high energy density (condition 2). Obese women consumed 723 kJ less from side dishes and 774 kJ less energy per day during condition 1 than during condition 2. There was no evidence that obese subjects compensated over the 4 d because they consumed less energy on each day of the diet of low energy density; the difference between the 2 conditions was 322 kJ on Monday, 473 kJ on Tuesday, 787 kJ on Wednesday, and 1523 kJ on Thursday for a total cumulative difference of 3105 kJ over 4 d. Energy density of the compulsory foods did not affect significantly the amount of energy consumed as snacks between meals (Table 4) or the percentages of energy consumed daily from macronutrients (**Table 5**) for lean or obese subjects.

Energy density of the compulsory foods also affected the weight of food (g) consumed (Table 4). Lean women ate 11% less food ad libitum during meals (including beverages) during condition 1 (1410 ± 104 g) than during condition 2 (1593 ± 111 g; P < 0.01). Obese subjects ate 9% less food from side dishes (condition 1: 1689 ± 110 g; condition 2: 1860 ± 125 g; P < 0.01). When the weight of the compulsory foods was added to the weight of food from side dishes consumed ad libitum, the obese women ate a greater total weight of food at meals with the diet of low energy density (condition 1: 2920 ± 132 g) than with the diet of high energy density (condition 2: 2670 ± 137 g, P < 0.0004). A trend was found for lean women to consume more food with the diet of low energy density (condition 1: 2348 ± 111 g; condition 2: 2210 ± 113 g, P < 0.052). These results are not surprising because the required foods in condition 1 weighed 52% more than those in condition 2. With beverages excluded, similar results were found—intake of solid foods from side dishes was less for obese women during condition 1 than during condition 2 (P < 0.004) and a trend for a reduction in intake for lean women was found (P < 0.049).

Energy density of the compulsory foods did not affect the weight of food consumed as snacks for the lean or obese women. Also, there were no significant differences in the amount of fluids consumed in the laboratory during meals or as snacks between meals, or in the total of all beverages consumed per day. There was a trend for both lean and obese subjects to take longer to consume meals in the laboratory during condition 1 than during condition 2. Lean women took 43 and 40 min/d to consume meals during conditions 1 and 2, respectively (P < 0.08), whereas obese women took 47 min/d during condition 1 and 44 min/d during condition 2 (P < 0.04).

Effects of fat content of compulsory foods (comparison of conditions 2 and 3)

No significant differences were found for total energy or weight of food consumed per day between the high-fat and low-fat conditions for lean or obese subjects (Figure 1 and Table 4). Likewise, there were no significant differences in the amount (energy and weight) consumed ad libitum from side dishes, snacks, or beverages. Both lean and obese women consumed a greater daily percentage of energy as fat and a lower percentage of energy as carbohydrate during the high-fat diet (condition 3) than during the low-fat diet (condition 2) (Table 5). There were no significant differences in the macronutrient contents of side dishes or snacks. Thus, the observed differences were due solely to the differences in the macronutrient content of the compulsory portion of the diet.

Comparisons with control diet

Total daily energy intake and the weight of food consumed for the 3 experimental conditions was similar to the control diet for both lean and obese subjects (Table 4). The percentage of energy consumed as fat was lower for the 2 low-fat diets (conditions 1 and 2) and higher for the high-fat diet (condition 3), relative to the control condition, for both groups of subjects (Table 5). Similarly, the percentage of energy consumed as carbohydrate was higher for conditions 1 and 2 and lower for condition 3 than for the control condition.

Fiber intake

Average daily fiber intake was greater during the diet of low energy density (condition 1) than during the 2 diets of high energy density (conditions 2 and 3) or during the control diet for both lean and obese subjects (Table 4). This was not surprising because the compulsory foods of low energy density contained approximately twice as much fiber (30 g) as the compulsory foods of high energy density (13 g) (Table 4).

Visual analogue scale ratings and questionnaires

Palatability ratings of the compulsory foods are presented in **Table 6**. Significant differences between conditions were found

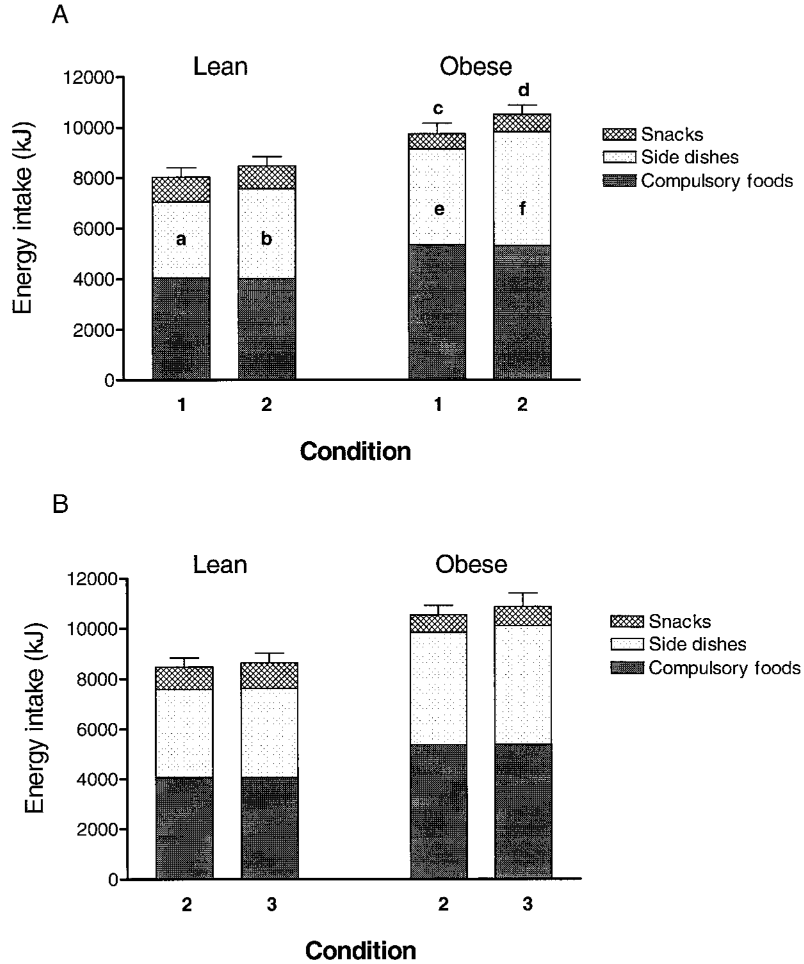

FIGURE 1. Effects of energy density (A) and fat content (B) on mean (±SEM) energy intake over the 4 test days for lean (n = 16) and obese (n = 17) women. Condition 1: low-fat diet of low energy density; condition 2: low-fat diet of high energy density; condition 3: high-fat diet of high energy density. Within each weight group, means with different superscript letters are significantly different, $P < 0.05$.

for some of the required foods; however, these differences were small and were not systematic. Overall, the foods were well liked—mean ratings were 71 ± 2, 73 ± 2, and 75 ± 2 mm for conditions 1, 2, and 3, respectively.

Ratings of hunger, fullness, prospective consumption, nausea, and thirst made before meals did not vary significantly between conditions for lean or obese subjects. Average ratings (across meals and conditions) were 63 mm for hunger and prospective consumption, 62 mm for thirst, 3 mm for nausea, and 24 mm for fullness. Significant effects were noted for changes in ratings from before to after meals for thirst and nausea in obese subjects; however, these differences were small. For changes in thirst, a larger decrease was found for condition 3 (53 mm) than for condition 2 (44 mm, $P < 0.014$) and for nausea a larger increase was noted for condition 1 (−3.8 mm) than for condition 2 (−1.7 mm, $P < 0.013$). No significant differences were found for the lean group.

Body weight

No significant changes in body weight were found in response to the experimental conditions for either lean or obese subjects. Average weight changes were −0.1 ± 0.1 kg during condition 1, 0.0 ± 0.1 kg during condition 2, and 0.1 ± 0.1 kg during condition 3.

Group effects

Analyses of group differences were performed for the control condition only. Average daily energy intake was greater for obese than for lean individuals (10 095 ± 305 and 8425 ± 217 kJ for the obese and lean subjects, respectively; $P < 0.02$). Lean individuals consumed more energy per kilogram body weight than did obese individuals (lean: 137 ± 6.2 kJ/kg; obese: 109 ± 6.1 kJ/kg; $P < 0.003$). Both groups consumed similar proportions of energy from macronutrients per day (the ratio of fat to carbohydrate to protein was 28:59:13 and 30:57:13 for lean and obese subjects, respectively) as well as similar amounts of snacks (as energy and weight). The pattern of energy intake was also similar between groups. Lean individuals consumed 26% of their energy at breakfast, 29% at lunch, 34% at dinner, and 11% as snacks between meals. Obese individuals consumed 26% of their energy at breakfast, 31% at lunch, 36% at dinner, and 7%

TABLE 4
Average daily intake over 4 test days[1]

	Lean (n = 16)				Obese (n = 17)			
	Control	Condition 1	Condition 2	Condition 3	Control	Condition 1	Condition 2	Condition 3
Side dishes[2,3]								
Energy intake (kJ)	7496 ± 378	2957 ± 213[4]	3513 ± 184	3558 ± 22	9309 ± 515	3751 ± 237[4]	4474 ± 237	4723 ± 313
Amount consumed (g)	2213 ± 119	1410 ± 104[4]	1593 ± 111	1514 ± 114	2584 ± 171	1689 ± 110[4]	1860 ± 125	1832 ± 128
Fiber (g)	16 ± 0.9	5 ± 0.6[4]	7 ± 0.7	7 ± 0.5	17 ± 1.2	5 ± 0.5[4]	7 ± 0.7	7 ± 0.8
Compulsory foods[5]								
Energy intake (kJ)	NA	4087 ± 159	4061 ± 157	4066 ± 157	NA	5403 ± 271	5365 ± 268	5373 ± 268
Amount consumed (g)	NA	938 ± 37	617 ± 24	630 ± 25	NA	1231 ± 60	810 ± 40	826 ± 40
Fiber (g)	NA	25 ± 1.0	11 ± 0.4	11 ± 0.4	NA	34 ± 1.6	15 ± 0.7	14 ± 0.7
Snacks[2,3]								
Energy intake (kJ)	919 ± 187	986 ± 194	898 ± 208	1017 ± 222	786 ± 268	595 ± 132	684 ± 180	758 ± 266
Amount consumed (g)	691 ± 153	622 ± 145	664 ± 155	700 ± 150	489 ± 121	402 ± 90	509 ± 125	522 ± 152
Fiber (g)	1 ± 0.4	1 ± 0.2	1 ± 0.2	2 ± 0.5	1 ± 0.3	1 ± 0.2	1 ± 0.3	1 ± 0.6
Total daily[3]								
Energy intake (kJ)	8415 ± 412	8030 ± 370	8471 ± 368	8641 ± 382	10095 ± 531	9748 ± 421[4]	10522 ± 381	10854 ± 542
Amount consumed (g)	2904 ± 205	2970 ± 192	2875 ± 214	2844 ± 197	3073 ± 222	3322 ± 172	3179 ± 186	3180 ± 218
Fiber (g)	17 ± 0.9	31 ± 1.1[4,6]	19 ± 0.8	19 ± 0.8[6]	18 ± 1.2	39 ± 1.8[4,6]	23 ± 1.1[6]	22 ± 1.2[6]

[1] $\bar{x}$ ± SEM. Condition 1, low-fat diet of low energy density; condition 2, low-fat diet of high energy density; condition 3, high-fat diet of high energy density. NA, not applicable.
[2] Consumed ad libitum.
[3] Includes beverages.
[4] Significantly different from condition 2, $P < 0.025$.
[5] Required to be consumed in full.
[6] Significantly different from control, $P < 0.05$ (Dunnett's post hoc test).

as snacks between meals. No differences were found between groups in ratings of, for example, hunger and fullness, and both groups spent similar amounts of time eating meals in the laboratory. Average meal times were 14 ± 1 min/meal for the lean individuals and 16 ± 1 min/meal for the obese individuals.

Debriefing

Thirty-five percent of the subjects reported noticing a difference in the size of the compulsory entrées and 21% stated that sometimes the portions of required entrées were large. Three subjects reported noticing a difference in the fat content of some of the compulsory foods. None of the subjects noted that the differences occurred for all the compulsory foods served within each test week and none correctly stated the purpose of the study.

DISCUSSION

This study showed that when half of an individual's energy intake was systematically varied, the energy density, but not the fat content, of the foods significantly affected energy intake during meals for both lean and obese women. The current study extends our previous findings that the energy density of foods affected energy intake when the whole diet was manipulated (9). In that study, normal-weight women were served meals varying in energy density for 2 d. The manipulated foods were similar in palatability and macronutrient content. We found that the normal-weight women ate a constant weight of food at each meal so that daily energy intakes varied directly with the energy density of the diets. The present study differs from that study in that only half of each subject's habitual intake was manipulated and subjects were allowed to consume other foods ad libitum. This experimental design more closely resembles real-life situations in which a person who is concerned about his or her food intake may select some foods that are reduced in fat or energy content but may also consume high-fat or high-energy foods. Our results showed that when half of what was consumed at every meal was of low energy density, both lean and obese women reduced their

TABLE 5
Percentages of total daily energy intake from macronutrients[1]

	Lean (n = 16)				Obese (n = 17)			
	Control	Condition 1	Condition 2	Condition 3	Control	Condition 1	Condition 2	Condition 3
	%				%			
Fat	27.5 ± 1.4	23.1 ± 1.3[2]	22.1 ± 1.1[2]	31.8 ± 1.1[2,3]	29.5 ± 1.2	23.9 ± 0.7[2]	23.5 ± 0.9[2]	33.9 ± 0.7[2,3]
Carbohydrate	58.7 ± 1.4	63.4 ± 1.3[2]	64.2 ± 1.1[2]	54.9 ± 1.2[2,3]	56.9 ± 1.3	61.9 ± 0.8[2]	62.3 ± 0.9[2]	52.2 ± 0.7[2,3]
Protein	13.9 ± 0.4	13.5 ± 0.3	13.7 ± 0.4	13.3 ± 0.4	13.5 ± 0.5	14.2 ± 0.4	14.2 ± 0.4	14.0 ± 0.3

[1] $\bar{x}$ ± SEM; average of 4 d. Condition 1, low-fat diet of low energy density; condition 2, low-fat diet of high energy density; condition 3, high-fat diet of high energy density.
[2] Significantly different from control, $P < 0.05$ (Dunnett's post hoc test).
[3] Significantly different from condition 2, $P < 0.025$.

TABLE 6
Palatability ratings of compulsory foods by visual analogue scale[1]

	Lean (n = 16)			Obese (n = 17)		
	Condition 1	Condition 2	Condition 3	Condition 1	Condition 2	Condition 3
Monday						
Breakfast	65 ± 7	58 ± 7	62 ± 8	66 ± 4	68 ± 5	70 ± 5
Lunch	85 ± 2	74 ± 6	76 ± 6	79 ± 4	73 ± 5	86 ± 3[2]
Dinner	70 ± 5[2]	82 ± 3	83 ± 5	66 ± 5[2]	76 ± 4	77 ± 5
Tuesday						
Breakfast	83 ± 3	78 ± 4	77 ± 5	76 ± 4	79 ± 4	75 ± 4
Lunch	84 ± 4	80 ± 4	88 ± 2	74 ± 6	79 ± 3	81 ± 5
Dinner	70 ± 6	67 ± 6	60 ± 7	51 ± 7	55 ± 7	60 ± 7
Wednesday						
Breakfast	68 ± 4[2]	79 ± 5	77 ± 4	71 ± 5	79 ± 3	73 ± 4
Lunch	83 ± 3	77 ± 6	82 ± 6	76 ± 4	78 ± 4	82 ± 3
Dinner	69 ± 6	63 ± 7	70 ± 5	68 ± 5	67 ± 4	79 ± 5[2]
Thursday						
Breakfast	70 ± 7[2]	82 ± 3	75 ± 5	78 ± 3	84 ± 3	79 ± 3
Lunch	79 ± 4	74 ± 5	76 ± 4	71 ± 6	75 ± 5	72 ± 4
Dinner	60 ± 7	60 ± 5	68 ± 6	52 ± 6	66 ± 5	66 ± 5

[1] $\bar{x}$ ± SEM. Condition 1, low-fat diet of low energy density; condition 2, low-fat diet of high energy density; condition 3, high-fat diet of high energy density.
[2] Significantly different from condition 2, $P < 0.025$.

intake during meals.

It is likely that the more accurate compensation for manipulations in diet composition seen in several other studies is related at least in part to the smaller magnitude of the manipulation in those studies (19). Many involved changes in a food or foods at a single meal. The present study and another with a similar design (20) showed that a large decrease in the energy density of a significant portion of the diet across an entire day was associated with incomplete compensation.

There are several possible explanations for why accurate compensation did not occur and specifically why subjects consumed less energy during meals of low energy density than during those of high energy density. We made no attempt to conceal the apparent differences in portion size between the low- and high-energy-density conditions. Compulsory foods of low energy density weighed more and were larger in size than isoenergetic foods of high energy density. Thus, how much additional food subjects chose to consume could have been influenced by their knowledge of culturally acceptable portion sizes (21), knowledge of portion sizes adequate to satisfy hunger (19), and beliefs about the energy or fat content of foods (22, 23). It is also possible that the volume of food consumed and its energy density could affect intake through differential stimulation of gastric and postgastric compartments. Previous studies conducted in humans and rats showed that the stomach is sensitive to cues related to volume and that manipulation of gastric distension affects food intake (24, 25).

Results of a study completed recently in our laboratory (26) showed that the volume of food consumed can affect satiety. In that study, men were served milk-based preloads varying in volume (300, 450, and 600 mL), but not in energy (2088 kJ), macronutrient content, or palatability. Volume of the preloads, and thus energy density, affected intake at lunch and dinner such that energy intake was greater after the low-volume preload (300 mL, high energy density) than the high-volume preload (600 mL, low energy density). These results suggest that the volume or weight of food consumed may contribute to the effects of energy density on food intake. Further studies, however, are needed to characterize the specific mechanisms mediating the effects of the energy density of foods on intake.

In the present study, the compulsory foods varied in both water and fiber content between the conditions of high- and low energy density. Thus, it is not possible to separate the effects of water from the effects of fiber on intake because they covaried between conditions. Fiber has been shown to decrease hunger and food intake and to increase weight loss in previous studies (27). Results from a recent study showed that the effects of the energy density of food on food intake were not due solely to differences in the fiber content of foods (9). In that study, the energy density of food affected energy intake even though fiber intake varied by only 2 g between conditions. Further research is needed to study the independent as well as the possible synergistic effects of water and fiber content of foods and how they contribute to the effects of energy density on intake.

Results of studies in which the fat content of a preload was varied, while energy density was held constant, indicated that in some individuals fat suppressed intake less at the subsequent meal than an isoenergetic amount of carbohydrate, but this effect was modest (10, 19). In longer-term studies, when the fat content of the entire diet was manipulated independent of energy density, fat content had no significant effect on daily intake (7, 8). The results of the present study are consistent with those findings in that we found no significant effect of fat content on energy intake when half of an individual's typical daily energy intake was varied.

In the present study, energy density of the foods but not fat content affected intake for both lean and obese women. In both groups the women consumed 16% less energy from side dishes at meals when the compulsory foods were lower in energy density than when they were higher in energy density. Reported intakes of snacks were similar across conditions and between groups. Several studies (28, 29) indicated that obese individuals underreport their intakes to a greater extent than do normal-weight individuals. Although this may also be true of our subjects, there is no evidence to suggest that the degree of underreporting differed between dietary conditions, which was the primary comparison of interest.

The fact that the obese subjects showed a reduction in intake at meals including foods of low energy density suggests that these foods could be useful for weight management. There was no indication that subjects ate more of the noncompulsory foods over the 4 d of the present study to compensate for the reduction in daily energy intake that occurred. This suggests that it would be worthwhile to examine the effects of low-energy-density diets on food intake and body weight of obese individuals over longer periods of time. Although there are no long-term, controlled studies examining the effects of energy density independent of the fat content of the diet, studies of experimental diets based on reductions in both fat and energy density have been conducted. In these studies, which ranged in length from 2 wk (1, 3, 4) to 11 wk (2), subjects could eat ad libitum but only foods that had a controlled amount of fat and energy. The subjects consumed similar weights of the different diets so that when the fat content and energy density were reduced, total daily intakes were also reduced. The reduction in energy intake persisted during the studies, although in the study lasting 11 wk (2) daily intakes were starting to converge.

In the present investigation, hunger did not differ between the dietary conditions despite the reduction in food intake during the diet of low energy density. It will be important to determine in future studies whether hunger can be effectively controlled over long periods of time despite the reductions in energy intake experienced with diets of low energy density.

In conclusion, the results of the present study indicated that when palatability was controlled, the energy density of food but not the fat content affected energy intake in both lean and obese women. The results confirm earlier findings that the fat content of food, independent of changes in energy density, did not affect energy intake. Furthermore, this study extends previous work by showing that the energy density of food affected intake when 50% of the diet was varied. Therefore, this study provides preliminary evidence that reducing the energy density of a portion of the diet may contribute to a significant decrease in energy intake.

REFERENCES

1. 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.
2. Kendall A, Levitsky DA, Strupp BJ, Lissner L. Weight loss on a low-fat diet: consequence of the imprecision of the control of food intake in humans. Am J Clin Nutr 1991;53:1124–9.
3. Stubbs RJ, Ritz P, Coward WA, Prentice AM. Covert manipulation of the ratio of dietary fat to carbohydrate and energy density: effect on food intake and energy balance in free-living men eating ad libitum. Am J Clin Nutr 1995;62:330–7.
4. 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.
5. Seagle HM, Davy BM, Grunwald G, Hill JO. Energy density of self-reported food intake: variation and relationship to other food components. Obes Res 1997;5:87S (abstr).
6. van Stratum P, Lussenburg RN, van Wezel LA, Vergroesen AJ, Cremer HD. The effect of dietary carbohydrate:fat ratio on energy intake by adult women. Am J Clin Nutr 1978;31:206–12.
7. Stubbs RJ, Harbron CG, Prentice AM. Covert manipulation of the dietary fat to carbohydrate ratio of isoenergetically dense diets: effect on food intake in feeding men ad libitum. Int J Obes Relat Metab Disord 1996;20:651–60.
8. Saltzman E, Dallal GE, Roberts SB. Effect of high-fat and low-fat diets on voluntary energy intake and substrate oxidation: studies in identical twins consuming diets matched for energy density, fiber, and palatability. Am J Clin Nutr 1997;66:1332–9.
9. Bell EA, Castellanos VH, Pelkman CL, Thorwart ML, Rolls BJ. Energy density of foods affects energy intake in normal-weight women. Am J Clin Nutr 1998;67:412–20.
10. Rolls BJ, Kim-Harris S, Fischman MW, Foltin RW, Moran TH, Stoner SA. Satiety after preloads with different amounts of fat and carbohydrate: implications for obesity. Am J Clin Nutr 1994;60:476–87.
11. Garner DM, Garfinkel PE. The Eating Attitudes Test: an index of the symptoms of anorexia nervosa. Psychol Med 1979;9:273–80.
12. Stunkard AJ, Messick S. The three-factor eating questionnaire to measure dietary restraint, disinhibition, and hunger. J Psychosom Res 1985;29:71–83.
13. Beck AT, Beamesdorfer A. Assessment of depression: the Depression Inventory. In: Pinchot P, ed. Psychological measurements in psychopharmacology, modern problems in pharmacopsychiatry. Vol. 7. Basel, Switzerland: Karger, 1974:151–69.
14. Zung WWK. A self-rating depression scale. Arch Gen Psychiatry 1970;12:63–70.
15. Gormally J, Black S, Daston S, Rardin D. The assessment of binge eating severity among obese persons. Addict Behav 1982;7:47–55.
16. Pennington JAT. Bowes and Church's food values of portions commonly used. Philadelphia: JB Lippincott Company, 1994.
17. AOAC. Official methods of analysis of AOAC International. Arlington, VA: AOAC International, 1995.
18. Keppel G. Design and analysis. Englewood Cliffs, NJ: Prentice-Hall, 1982.
19. Rolls BJ, Hammer VA. Fat, carbohydrate, and the regulation of energy intake. Am J Clin Nutr 1995;62(suppl):1086S–95S.
20. Foltin RW, Rolls BJ, Moran TH, Kelly TH, McNelis AL, Fischman MW. Caloric, but not macronutrient, compensation by humans for required-eating occasions with meals and snack varying in fat and carbohydrate. Am J Clin Nutr 1992;55:331–42.
21. Rozin P. Sociocultural influences on human food selection. In: Capaldi ED, ed. Why we eat what we eat. Washington, DC: American Psychological Association, 1996:233–63.
22. Caputo FA, Mattes RD. Human dietary responses to perceived manipulation of fat content in a midday meal. Int J Obes Relat Metab Disord 1993;17:237–40.
23. Shide DJ, Rolls BJ. Information about the fat content of preloads influences energy intake in healthy women. J Am Diet Assoc 1995;95:993–8.
24. Geliebter A. Gastric distension and gastric capacity in relation to food intake in humans. Physiol Behav 1988;44:665–8.
25. Davis JD, Smith GP, Sayler JL. Reduction of intake in the rat due to gastric filling. Am J Physiol 1997;272:R1599–605.
26. Rolls BJ, Castellanos VH, Halford JC, et al. Volume of food consumed affects satiety in men. Am J Clin Nutr 1998;67:1170–7.
27. Levine AS, Billington CJ. Dietary fiber: does it affect food intake and body weight? In: Fernstrom JD, Miller GD, eds. Appetite and body weight regulation: sugar, fat, and macronutrient substitutes. Boca Raton, FL: CRC Press, 1994:191–200.
28. Lissner L, Heitmann BL, Lindroos AK. Measuring intake in free-living human subjects: a question of bias. Proc Nutr Soc 1998;57:333–9.
29. Lavienja AJ, Braam LM, Ocké MC, Bueno-de-Mesquita HB, Sei-