

Energy density of foods affects energy intake in normal-weight women¹⁻³

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ABSTRACT This study examined the effect of energy density, independent of fat content and palatability, on food and energy intakes. With use of a within-subjects design, normal-weight women ($n = 18$) were provided with meals for 2 d during each of three test sessions. During lunch, dinner, and an evening snack, subjects were given free access to a main entree varying in energy density (low, medium, or high). The manipulated main entrees were similar in palatability to their counterparts across conditions. Low-energy compulsory (consumption required) side dishes accompanied each meal. Subjects also consumed a standard, compulsory breakfast. Results showed that subjects consumed a similar amount of food (by weight) across the three conditions of energy density. Thus, significantly more energy was consumed in the condition of high energy density (7532 ± 363 kJ, or 1800 ± 86 kcal) than in the medium- (6356 ± 281 kJ, or 1519 ± 67 kcal) and low- (5756 ± 178 kJ, or 1376 ± 43 kcal) energy-density conditions ($P < 0.0001$). There were no differences in hunger or fullness before meals, after meals, or over the 2 d across conditions. The results from this study indicate that energy density affects energy intake independent of macronutrient content or palatability, suggesting that the overconsumption of high-fat foods may be due to their high energy density rather than to their fat content. *Am J Clin Nutr* 1998;67:412-20.

KEY WORDS Caloric density, energy density, energy intake, fat, human food intake, macronutrients, satiation, women

INTRODUCTION

The high consumption of dietary fat has been linked to adverse health outcomes, including obesity and associated disorders such as type 2 diabetes mellitus, cardiovascular disease, and certain forms of cancer (1). Approximately 34% of energy intake in the United States is derived from fat, despite recommendations that this be reduced to 30% (2). Dietary fat may be overeaten for several reasons, including high palatability, high energy density, and insensitivity to the satiety value of fat (3).

Dietary fat may affect satiation, the processes involved in the termination of a meal (4). Some investigators suggest that fat is overeaten because it is not as satiating as the other macronutrients, especially carbohydrate (5, 6). On the other hand, it has been suggested that dietary fat may be overeaten because of its high energy density (the energy content per weight of food) (7). Dietary fat provides more than twice as much energy per gram as either carbohydrate or protein. A high-fat food or meal is usually much smaller in weight than an isoenergetic high-carbohydrate food or meal.

Therefore, if individuals consume a constant amount of food, the high energy density of fat, rather than the fat content, could be a key factor in its overconsumption (8). Fat can also improve the texture and flavor of foods, thereby increasing palatability (9). This influence of fat on the sensory properties of foods could be an important determinant of satiation and food intake (10).

Previous studies have investigated the effects of dietary fat on food intake by manipulating the ratio of fat to carbohydrate in diets while holding energy density constant. Thus, the effects of macronutrient composition were studied apart from the effects of energy density on food intake. In one of the first studies, van Stratum et al (11) used liquid diets varying in fat content (24% and 47% of energy) but similar in energy density. Subjects were allowed 25% of their energy from standardized snacks. Over 2 wk with each diet, a constant weight of the liquid diet was consumed and energy intake remained constant, suggesting that energy intake was not affected by the fat content. In another study, Stubbs et al (12) compared energy intakes from diets containing solid foods varying in fat content (20%, 40%, and 60%) but similar in energy density. Six men consumed ad libitum each of the three diets for 14 d. Within each diet, all foods were of the same macronutrient composition. Energy intakes from the three diets were similar. Although results from both of these studies imply that fat content, independent of its effects on energy density, does not affect energy intake, the interpretation and application of the findings are limited because liquid diets were used in one study and in both studies palatability of foods was not shown to be well-matched.

In two recent comprehensive reviews (7, 13), the authors concluded that the overconsumption of energy from a high-fat diet is a result of the diet's high energy density rather than the diet's fat content. Most conclusions related to energy density and its effects on food intake are based on experiments in which individuals were provided with low- or high-fat diets varying in energy density. In studies by Duncan et al (14), Kendall et al (15), Lissner et al (16), Stubbs et al (17, 18), and Tremblay et al (19), subjects consumed significantly more energy from the diets high in fat content and energy density. One may conclude from these studies that diets high in both fat and energy density result

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in greater energy intake. However, it is not possible to separate the effects of energy density from the effects of macronutrient content (fat) on food or energy intake because fat content and energy density were related. The possibility also exists that palatability might have affected food intake because palatability tends to increase in direct relation to fat content (9).

The present experiment investigates the effect of energy density on food intake while specifically controlling for the potential effects of macronutrient content (ie, fat) and palatability on food and energy intakes. This study was designed to test the hypothesis that individuals are not sensitive to energy density cues. That is, individuals will consume a constant weight or amount of food, regardless of changes in energy density, thus resulting in variations in energy intake.

SUBJECTS AND METHODS

Subjects

Eighteen healthy, normal-weight women successfully completed this study. We chose to conduct this study in women because a greater percentage of the American adult female population than of the adult male population is overweight (2). Volunteers were recruited via advertisement from The Pennsylvania State University community. On response to the advertisement, individuals completed a standard telephone interview to ensure that they met the general criteria for inclusion in the study: 20–45 y of age, nonsmoking, in good health, not dieting, not in athletic training, not pregnant or lactating, no chronic health problems, not using medications known to affect food intake or appetite, consuming meals (including breakfast) at regularly scheduled intervals, no weight gain or loss (± 10 lbs or 4.5 kg) in the previous 6 mo, and no food allergies or food restrictions.

After the initial telephone interview, potential subjects were measured for weight and height and were asked to complete several screening questionnaires, including the Eating Inventory (EI) (20), which assesses dietary restraint, disinhibition, and hunger; the Eating Attitudes Test (EAT) (21), which detects aberrant attitudes toward food and eating; and the Beck Depression Inventory (BDI) (22), which detects cognitive indicators of depression. Only normal-weight women [body mass index (BMI; in kg/m²): 19–26] who scored <30 on the EAT and <10 on the BDI were included in the study. Scores on the EI were not used as inclusion or exclusion criteria.

Each subject signed a consent form acknowledging receipt of a description of the experimental procedures and participation in the study. Each subject received financial compensation for her participation in the study. To prevent experimental bias, the consent form indicated that the experiment sought to examine people's perceptions of different types of food products. The study was approved by The Pennsylvania State University Institutional Review Board.

Twenty-three subjects began participation in this study. Two subjects were selected for the study and were dropped when it was recognized that they had elevated scores on the BDI. Two subjects consumed the entire amount of food offered during the evening snack and were dropped from the study because we could not be certain that the amount of food offered did not limit consumption. One subject withdrew from the study for personal reasons. Therefore, a total of 18 subjects ($\bar{x} \pm \text{SEM}$: aged 25.5 \pm 1.4 y with a BMI of 23.0 \pm 0.4) completed the study. Mean (\pm

SEM) scores on the EI for cognitive restraint, disinhibition, and hunger were 7.2 \pm 1.1, 4.4 \pm 0.6, and 4.6 \pm 0.6, respectively.

Procedures

A within-subjects, repeated-measures design was used in this experiment. Subjects participated in three, 3-d test sessions. Order of presentation of the conditions was counterbalanced across subjects.

During the first 2 d of the test sessions, subjects ate breakfast, lunch, and dinner in our laboratory and were provided with take-home evening snacks. On the third day subjects completed a brief questionnaire. Breakfast was standard across conditions and was required to be consumed in full. Lunch, dinner, and the evening snack consisted of one main entree that varied across three conditions of energy density and several low-energy side dishes that were standard (in type and amount) across dietary treatments. Subjects consumed the main entrees ad libitum and were required to consume the side dishes in full. Large servings (lunch: >1000 g; dinner: >1500 g; snack: >600 g) of the main entrees were provided so that food intake was not limited by portion size. Small amounts of the compulsory side dishes were served (Table 1). Therefore, the study was designed so that the majority of both daily food and energy intake was derived from the manipulated main entrees. Four different 2-d menus were created using combinations of the two possible lunches and two possible dinners (Table 1). These menus were randomly assigned to the subjects.

Study sessions were scheduled on the same days of alternate weeks for 5 wk (ie, Tuesday, Wednesday, and Thursday of every other week). During the test days, subjects were instructed to consume only foods and beverages provided by the laboratory, with the exception of nonenergetic beverages. Beverage intake was recorded by subjects and verified for compliance with the experiment protocol. Subjects were asked to refrain from drinking alcohol during the 24 h preceding and throughout test sessions and to maintain similar exercise schedules during test sessions. On arrival at the laboratory in the morning of each test day, subjects completed a brief questionnaire to assess compliance with the experimental protocol. Meals were scheduled at approximately the same time during the day across all conditions with a minimum of 3.5 h between breakfast and lunch, and lunch and dinner.

Subjects were seated in individual cubicles and were not allowed to read during meals. Before service of each meal and again after the consumption of the meal, subjects completed a series of 100-mm visual analogue scales (VAS) rating their degree of hunger, thirst, fullness, perception of how much they could eat (prospective consumption), and nausea. Also, before and after lunch and dinner, subjects were presented with a sample (10 g) of the main entree and were asked to complete the following questions on 100-mm VAS: "How pleasant is the taste of this food right now?", "How pleasant is the texture of this food right now?", "How much of this food do you think you could eat right now?", and "How many calories do you think this food has?". After dinner, subjects were provided with their evening snack. Subjects returned food packages, including uneaten food, from the evening snack to the laboratory the following morning.

On the third day of each session, subjects completed a brief questionnaire with open-ended questions about their experiences in the laboratory during the previous 2 d. Subjects also retrospectively rated their hunger between meals and their fullness

TABLE 1
One sample menu order¹

Day and meal	Amount		Day and meal	Amount	
	By weight	By energy		By weight	By energy
	<i>g</i>	<i>kJ (kcal)</i>		<i>g</i>	<i>kJ (kcal)</i>
Day 1			Day 2		
Breakfast			Breakfast		
Bagel ²	57.0	670 (160)	Bagel	57.0	670 (160)
Cream cheese ³	16.0	146 (35)	Cream cheese	16.0	146 (35)
Peaches, canned ⁴	124.0	259 (62)	Pears, canned ¹³	124.0	259 (62)
Water, tea, or coffee (ad libitum)			Water, tea, or coffee (ad libitum)		
Lunch, A			Lunch, B		
Pasta salad with Italian dressing (ad libitum)			Pasta salad with yogurt dressing (ad libitum)		
Cracked pepper crackers ⁵	13.0	218 (52)	Golden crackers ¹⁴	12.0	216 (52)
Chocolate chip cookies ⁶	6.7	125 (30)	Cinnamon graham snacks ¹⁵	6.0	92 (22)
Water (ad libitum)			Water (ad libitum)		
Dinner, B			Dinner, A		
Italian pasta bake (ad libitum)			Chicken noodle casserole (ad libitum)		
Dinner roll ⁷	35.0	335 (80)	Dinner roll	35.0	335 (80)
Carrot sticks ⁸	18.0	32 (8)	Carrot sticks	18.0	32 (8)
Celery sticks ⁹	16.0	10 (2)	Celery sticks	16.0	10 (2)
Devil's food cookie cake ¹⁰	16.0	209 (50)	Strawberry gelatin ¹⁶	92.0	42 (10)
Water (ad libitum)			Whipped topping ¹⁷	4.0	42 (10)
Evening snack			Water (ad libitum)		
Pasta salad (same variety as lunch)			Evening snack		
Peaches or pears, canned ¹¹	113.0	236 (57)	Pasta salad (same variety as lunch)		
Wheat crackers ¹²	15.0	251 (60)	Peaches or pears, canned	113.0	236 (57)
			Wheat crackers	15.0	251 (60)

¹ Although lunch and dinner menus were counterbalanced across subjects, food items in the menus remained constant.

² Lender's Bagels, Lender's Bagel Bakery, Rye Brook, NY.

³ Philadelphia Light Cream Cheese, Kraft, Inc, Glenview, IL.

⁴ Del Monte Lite Peaches, Del Monte Foods, San Francisco.

⁵ Snackwell's Cracked Pepper Crackers, Nabisco Foods, East Hanover, NJ.

⁶ Snackwell's Chocolate Chip Cookies, Nabisco Foods.

⁷ Bread du Jour Italian Roll, Interstate Brands Corporation, Kansas City, MO.

⁸ Wm Bolthouse Farms, Inc, Bakersfield, CA.

⁹ Calcel Marketing, Inc, Oxnard, CA.

¹⁰ Snackwell's Devil's Food Cookie Cakes, Nabisco Foods.

¹¹ Del Monte Fruit Cup, Del Monte Foods.

¹² Snackwell's Wheat Crackers, Nabisco Foods.

¹³ Del Monte Lite Pears, Del Monte Foods.

¹⁴ Snackwell's Classic Golden Crackers, Nabisco Foods.

¹⁵ Snackwell's Cinnamon Graham Snacks, Nabisco Foods.

¹⁶ Jell-O Sugar Free Gelatin Snack, Kraft General Foods, Inc, White Plains, NY.

¹⁷ Cool Whip Lite Whipped Topping, Kraft General Foods.

over the previous 2 d on the VAS. 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 to be and gave subjects the opportunity to share other comments relevant to the study.

Manipulated main entrees

Only commercially available ingredients were used in the manipulated entrees. Lunch and dinner entrees were formulated to vary across three levels of energy density. Lunch entrees consisted of pasta salad with Italian dressing and pasta salad with yogurt dressing. Dinner entrees were Italian pasta bake and chicken noodle casserole. Evening snacks consisted of smaller portions of the entrees served for lunch. Information on the macronutrient and energy contents of the entrees is provided in **Table 2**.

Variation in energy density of the entrees was accomplished primarily by manipulating the proportion of low-fiber vegetables and pasta, such that the entrees that were low in energy density contained more vegetables and less pasta than the entrees that were higher in energy density. In effect, entrees of low energy density had greater water content than entrees of higher energy density. The entrees were formulated by using NUTRITIONIST IV (version 3.5; N-Squared Computing, San Bruno, CA) on the basis of nutrient composition data from manufacturers and *Bowes and Church's Food Values of Portions Commonly Used* (23). Recipes for the entrees may be obtained by contacting the first author.

Analysis of the protein, fat, moisture, and ash contents of the entrees was conducted by The Pennsylvania State University Crop Quality Laboratory by using methods of the Association of Official Analytical Chemists (24). Carbohydrate content was cal-



TABLE 2

Composition of manipulated entrees per 100 g¹

Food	Fat	Carbohydrate	Protein	Fiber ²	Energy ³	Energy density	Moisture
	g (% of energy)	g (% of energy)	g (% of energy)	g	kJ (kcal)	kJ/g (kcal/g)	%
Pasta salad with Italian dressing ⁴							
Low energy density	1.7 (19)	12.4 (61)	4.2 (20)	1.5	343 (82)	3.4 (0.8)	79.7
Medium energy density	1.7 (14)	17.8 (65)	5.6 (20)	1.4	456 (109)	4.6 (1.1)	72.9
High energy density	2.5 (16)	22.7 (64)	7.1 (20)	1.3	590 (141)	5.9 (1.4)	65.7
Pasta salad with yogurt dressing ⁴							
Low energy density	2.2 (27)	10.6 (58)	2.9 (16)	1.5	306 (73)	3.1 (0.7)	82.6
Medium energy density	2.7 (26)	14.0 (59)	3.8 (16)	1.2	400 (96)	4.0 (1.0)	77.7
High energy density	2.8 (22)	17.8 (62)	4.6 (16)	1.1	482 (115)	4.8 (1.2)	73.0
Italian pasta bake							
Low energy density	2.3 (22)	13.8 (58)	4.8 (20)	1.5	399 (95)	4.0 (1.0)	76.6
Medium energy density	2.4 (19)	18.3 (62)	5.7 (19)	1.5	491 (117)	4.9 (1.2)	71.1
High energy density	3.8 (25)	20.2 (57)	6.5 (18)	1.3	592 (141)	5.9 (1.4)	66.5
Chicken noodle casserole							
Low energy density	2.5 (28)	10.8 (54)	3.7 (19)	1.4	338 (81)	3.4 (0.8)	81.4
Medium energy density	2.6 (24)	13.7 (56)	5.1 (21)	1.5	410 (98)	4.1 (1.0)	77.1
High energy density	3.5 (24)	19.6 (58)	6.1 (18)	1.5	564 (135)	5.6 (1.3)	68.7

¹ Serving dishes were filled to similar volumes.² Calculated based on information from manufacturers and from *Bowes and Church's Food Values of Portions Commonly Consumed* (23).³ Atwater constants [38 kJ/g (9 kcal/g) for fat; 17 kJ/g (4 kcal/g) for carbohydrate; and 17 kJ/g (4 kcal/g) for protein] were used to determine energy content.⁴ Lunch entrees were provided as the entree in the take-home evening snacks. Evening snack servings were ≈600 g.

culated as the difference between the total weight and the sum of protein, fat, moisture, and ash contents. The entrees were on average 22% fat, 59% carbohydrate, and 19% protein. Average values for the energy density of the entrees were 3.5 kJ/g (0.8 kcal/g), 4.4 kJ/g (1.1 kcal/g), and 5.6 kJ/g (1.3 kcal/g) for the conditions of low, medium, and high energy density, respectively (Table 2). These values reflect reductions in energy density of the entrees of ≈20% between conditions such that the entrees of low energy density contained ≈40% less energy per gram than the entrees of high energy density. Dietary fiber content was calculated from fiber information from manufacturers and from *Bowes and Church's Food Values of Portions Commonly Used* (23).

To ensure that manipulated entrees were equally well liked and perceived as having similar energy contents as their counterparts in different conditions, a preliminary taste test was conducted. In a within-subjects, repeated-measures design, 22 women rated the pleasantness of taste and perceived energy content of the entrees. During three test sessions, separated by ≥1 d, subjects were seated in individual cubicles and presented with randomly numbered samples (10 g) of both dinner and lunch entrees with one of the three energy densities. With use of a 100-mm VAS, subjects were asked to complete the following questions: "How pleasant is the taste of this food right now?" and "How many calories do you think this food has?" Results indicated that there were no significant differences in either pleasantness of taste or perceived energy content across conditions for any entree ($P > 0.05$). Individuals who participated in the taste test were excluded from participation in the present study.

All foods were weighed (± 0.1 g) before service and then reweighed after the subjects had eaten to obtain the amount consumed of each food. Energy and macronutrient intakes were calculated by using nutrition information from the proximate analysis described above for the entrees and manufacturers' nutrition information for the side dishes.

Data analysis

All data were analyzed by using SAS-PC for Windows (version 6.10; SAS Institute, Cary, NC). Results were considered significant at $P < 0.05$. Tukey's honestly significant difference test was used for post hoc comparisons of significant effects.

Food and energy intakes

Food (g) and energy (kJ) intakes were analyzed by analysis of variance (ANOVA) using the General Linear Model procedure with adjusted error terms for the within-subject, repeated-measures design. Condition (high, medium, or low energy density) was entered as the within-subjects factor. Where appropriate, the main effect of test day (day 1 or 2) and the interaction between test day and condition were also tested in the model. Session (1, 2, or 3) was tested as a covariate on gram intake.

Energy density and macronutrient composition (percentage of energy) of diets and fiber intake

Energy density and macronutrient composition of the diets and fiber intake were calculated on the basis of subjects' food intake (in g) of main entrees and side dishes.

Analysis of visual analog ratings

Ratings of the manipulated foods (ie, pleasantness of taste) and ratings of subjective sensations (ie, hunger) were analyzed by using ANOVA with the energy density as the within-subjects factor. Where appropriate, the main effect of day (1 or 2) and the interaction between day and condition were added to the model.

Power analysis

A power analysis (version 2.0; STAT-POWER, Scientific Software, Portland, OR) using estimated variances and effect sizes derived from previous experiments with lean women in our laboratory determined that a sample size of 18 was needed to detect

differences between conditions ($\alpha = 0.05$; $1 - \beta = 0.80$). Post hoc analyses were conducted with data from the current study to determine whether we had adequate power to detect hypothetical differences in the amount of food consumed if individuals had varied their intake to adjust for changes in energy density.

RESULTS

Food and macronutrient intakes

Weight of food consumed

There was no effect of energy density on the amount of food consumed. Cumulative intake (by meals) did not differ across conditions (**Figure 1**). Mean (\pm SEM) daily intakes were 1350.1 ± 39.6 , 1302.2 ± 48.4 , and 1334.1 ± 46.3 g/d for the low, medium, and high-energy density conditions, respectively. Subjects consumed a greater amount of food on day 1 (1368.6 ± 35.1 g) than on day 2 (1289.0 ± 37.3 g) ($F_{[1,17]} = 4.46$, $P < 0.05$). This effect was the same across conditions. Session (1, 2, or 3) was found to be a significant covariate on average daily gram intake ($F_{[1,33]} = 6.27$, $P < 0.02$, $\beta = -63.50$), with subjects consuming less food over time (mean daily intake \pm SEM: session 1, 1384.7 ± 48.4 g; session 2, 1344.1 ± 54.0 g; and session 3, 1257.7 ± 65.2 g). This did not alter the effect of energy density on the amount of food consumed. The amount (in g) of water consumed in the laboratory did not vary by day or across conditions.

Energy consumed

Subjects consumed significantly more energy in the high-energy density condition than in the medium and low conditions. This effect was seen after consumption of the first manipulated meal (day 1 lunch) ($F_{[2,34]} = 10.92$, $P < 0.0002$) and continued throughout the study (**Figure 2**). There was no effect of test day (ie, day 1 or 2) on energy intake and no interaction between test day and condition. Because there was no effect of test day, this factor was dropped from the model and further analyses were conducted by using mean daily energy intakes. Subjects consumed significantly more energy daily in the condition of high energy density (7532 ± 363.2 kJ, or $1800 \pm$

86.8 kcal) than in the medium (6356 ± 280.7 kJ, or 1519 ± 67.1 kcal) and low (5756 ± 178.2 kJ, or 1376 ± 42.6 kcal) conditions ($F_{[2,34]} = 20.08$, $P < 0.0001$). The difference in total energy intake (entrees and side dishes) across conditions was due to a difference in energy intake from the main entrees ($F_{[2,34]} = 20.57$, $P < 0.0001$).

Energy density and macronutrient composition of diets and fiber intake

Energy density and macronutrient composition of the diets (main entrees and side dishes) and fiber intake were calculated on the basis of intakes of manipulated entrees and compulsory foods. Mean energy density values were 5.61 kJ/g (1.34 kcal/g), 4.90 kJ/g (1.17 kcal/g), and 4.27 kJ/g (1.02 kcal/g) for the high, medium, and low conditions, respectively. The percentages of energy from carbohydrate, fat, and protein, respectively, for the conditions were $65.7 \pm 0.4\%$, $16.0 \pm 0.2\%$, and $20.4 \pm 0.3\%$ for low energy density; $66.1 \pm 0.5\%$, $14.9 \pm 0.3\%$, and $21.2 \pm 0.3\%$ for medium energy density; and $65.4 \pm 0.5\%$, $15.8 \pm 0.3\%$, and $20.8 \pm 0.3\%$ for high energy density. Average daily fiber intakes were 17.4 ± 0.6 , 16.1 ± 0.7 , and 15.08 ± 0.6 g for the low-, medium-, and high-energy density conditions, respectively. The small differences in macronutrient composition and fiber intake across conditions were, arguably, too small to affect human food intake.

VAS ratings

Hedonic ratings

There were no differences in ratings of pleasantness of taste or texture, prospective consumption, or perceived energy content for the three versions of each of the manipulated entrees before meals (**Table 3**). Likewise, there were no differences in these ratings after meals. These data confirm that entrees were equally well-liked and did not vary systematically in sensory properties with changes in energy density.

Hunger ratings

There were no main effects of energy density on ratings of hunger, fullness, thirst, prospective consumption, or nausea

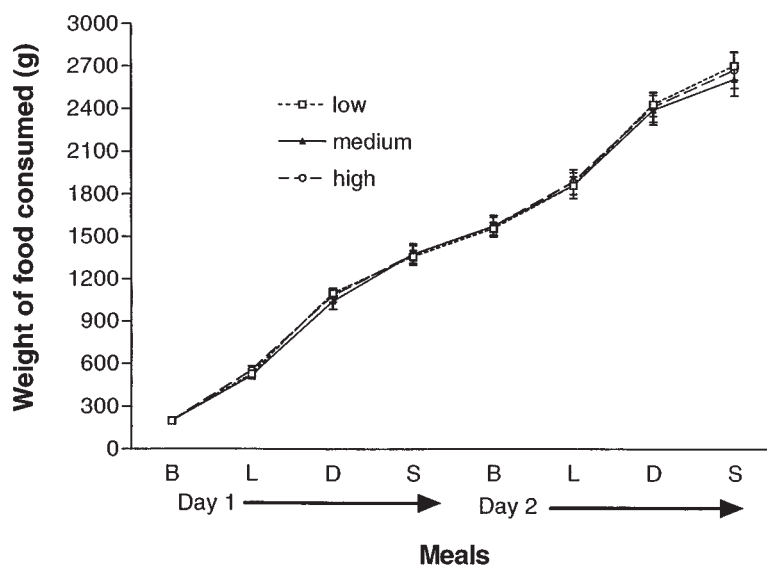


FIGURE 1. Cumulative food consumption by condition. Energy densities of the diets (main entrees and side dishes): low, 4.3 kJ/g (1.02 kcal/g); medium, 4.9 kJ/g (1.17 kcal/g); and high, 5.61 kJ/g (1.34 kcal/g). B, breakfast; L, lunch; D, dinner; S, evening snack. $\bar{x} \pm$ SEM.

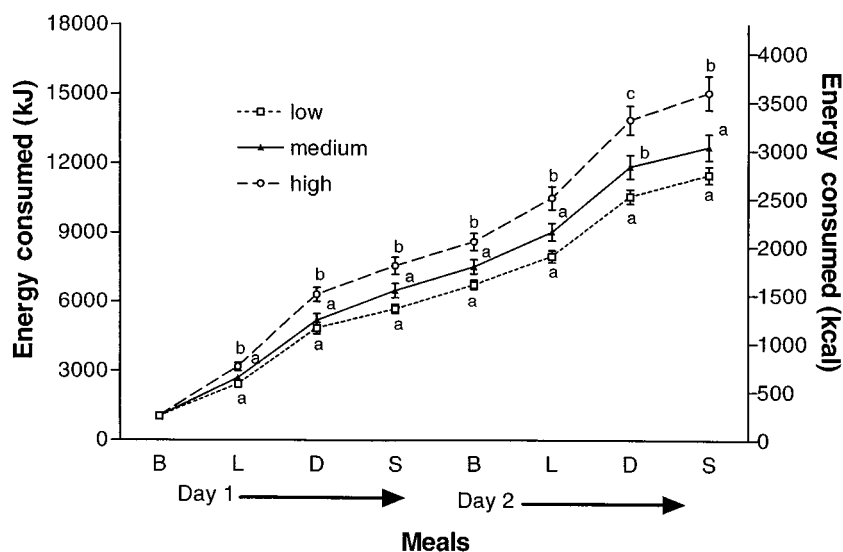


FIGURE 2. Cumulative energy intake by condition. Means with different letters are significantly different, including the meal indicated, at each time point ($P < 0.05$). Energy densities of the diets (main entrees and side dishes): low, 4.3 kJ/g (1.02 kcal/g); medium, 4.9 kJ/g (1.17 kcal/g); and high, 5.6 kJ/g (1.34 kcal/g). B, breakfast; L, lunch; D, dinner; S, evening snack. $\bar{x} \pm$ SEM.

before or after breakfast, lunch, and dinner on either day of the study. Before breakfast, subjects reported a greater degree of fullness on day 2 than on day 1 of the study ($F_{[1,17]} = 7.79$, $P < 0.01$). After breakfast, subjects reported greater feelings of thirst on day 2 ($F_{[1,17]} = 6.12$, $P < 0.02$) than on day 1. Ratings of prospective consumption before lunch were greater on day 1 than on day 2 ($F_{[1,17]} = 15.11$, $P < 0.001$). Results from the questionnaire completed on day 3 showed that, retrospectively, subjects did not experience differences in either hunger between meals (low: 49.2 ± 5.3 mm; medium: 48.8 ± 5.1 mm; and high energy density: 54.0 ± 4.4 mm) or in fullness over the 2 d across conditions (low: 71.3 ± 5.8 mm; medium: 74.3 ± 4.8 mm; and high energy density: 68.1 ± 6.6 mm).

Discharge questionnaire

No subjects correctly reported the purpose of the study or indicated that there were any differences in energy content of the manipulated entrees. Four subjects indicated that they believed we were studying their perceptions of foods before and after eating. Three subjects reported that they believed that the study was related to low-fat diets whereas three other subjects indicated that they believed that the study's purpose was to compare ratings of hunger with amounts of food eaten.

Power analysis

Because the average amount of food consumed daily varied by < 50 g between any two conditions, it is not surprising that we were not able to detect differences in intake (by weight). We did have power ($\alpha = 0.01$; $1 - \beta = 0.80$) to detect hypothetical differences in the amount of food consumed of 13.6% (181 g), 13.9% (188 g), and 18.5% (247 g) between the low and high, low and medium, and medium and high conditions of energy density.

DISCUSSION

The present study is the first to examine the effects of energy density on food and energy intakes while specifically controlling

for the potential effects of both macronutrient composition and palatability. Because individuals did not adjust the amount of food consumed in relation to the energy density of foods, energy intake was driven by the energy density of the meals provided. The results of this study clearly show that energy density can have a significant effect on energy intake independent of either macronutrient composition or palatability.

We successfully controlled for palatability of the manipulated entrees. Subjects rated pleasantness of taste, texture, perceived energy content, and their prospective consumption of three versions of each main entree similarly. Other results from this study also indicate that palatability was held constant. Specifically, subjects consumed a similar amount of each main entree across conditions and ate to similar states of fullness as shown by the lack of difference in ratings of fullness after either lunch or dinner across conditions.

Formulation of foods and diets varying in energy density, but not macronutrient composition (as a percentage of energy), is a challenging task. Results from proximate analysis indicated that we were successful in manipulating energy density of the main entrees. As planned, energy density of the main entrees differed by 20% between conditions. This difference was reduced to $\approx 15\%$ between diets with the inclusion of compulsory foods and by individual variations in the amount consumed of manipulated entrees. Thus, the diet of low energy density contained $\approx 30\%$ less energy per gram than the diet of high energy density. Although the energy density of the diets varied with the inclusion of compulsory food and differences in intake of manipulated entrees, the macronutrient content of the diets was held constant. It is unlikely that the slight variations in macronutrient content were large enough to affect human intake.

One way in which the energy density of foods can be reduced, without changing the macronutrient composition, is by adding foods with a high water content. This is an effective manipulation because water adds weight but not energy to foods. In the present experiment, variations in the energy density of the main entrees were accomplished primarily by altering the proportion

TABLE 3

Lunch and dinner entree visual-analogue-scale ratings¹

Meals and entrees	Low energy density	Medium energy density	High energy density
Lunch			
Pasta salad with Italian dressing			
“How pleasant is the taste of this food right now?” ²	69 ± 4.3	69 ± 4.3	72 ± 3.8
“How pleasant is the texture of this food right now?” ²	58 ± 4.9	69 ± 4.6	66 ± 4.9
“How much of this food do you think you could eat right now?” ³	61 ± 4.4	53 ± 4.8	56 ± 5.4
“How many calories do you think this food has?” ⁴	40 ± 4.2	38 ± 4.1	42 ± 4.4
Pasta salad with yogurt dressing			
“How pleasant is the taste of this food right now?”	66 ± 4.2	68 ± 4.9	64 ± 5.3
“How pleasant is the texture of this food right now?”	70 ± 4.3	72 ± 4.6	66 ± 5.2
“How much of this food do you think you could eat right now?”	60 ± 4.6	49 ± 4.6	60 ± 4.9
“How many calories do you think this food has?”	39 ± 3.5	39 ± 4.3	41 ± 4.2
Dinner			
Italian pasta bake			
“How pleasant is the taste of this food right now?”	73 ± 3.2	79 ± 3.3	78 ± 3.3
“How pleasant is the texture of this food right now?”	68 ± 3.9	71 ± 4.7	75 ± 3.0
“How much of this food do you think you could eat right now?”	65 ± 2.8	55 ± 4.9	68 ± 3.5
“How many calories do you think this food has?”	57 ± 3.7	58 ± 3.3	61 ± 3.7
Chicken noodle casserole			
“How pleasant is the taste of this food right now?”	66 ± 4.5	61 ± 5.8	58 ± 4.9
“How pleasant is the texture of this food right now?”	61 ± 4.5	59 ± 5.1	60 ± 4.2
“How much of this food do you think you could eat right now?”	57 ± 4.6	52 ± 5.2	58 ± 2.5
“How many calories do you think this food has?”	48 ± 3.9	51 ± 4.5	51 ± 3.9

¹ $\bar{x} \pm \text{SEM}$. Values are before-meal ratings. There were no differences in responses to questions across conditions.

² Anchors were “not at all pleasant” and “extremely pleasant”.

³ Anchors were “nothing at all” and “a large amount”.

⁴ Anchors were “no calories at all” and “extremely high in calories”.

of low-fiber vegetables to pasta. Entrees of low energy density contained the greatest amount of vegetables, whereas entrees of high energy density contained the greatest amount of pasta. This manipulation was successful because both of these foods derive most of their energy from carbohydrate while differing primarily in water content. Entrees with low energy density had a higher percentage of moisture than their counterparts with greater energy densities. The small differences in fiber content of the entrees and likewise in fiber intake across conditions reflect the dietary manipulation (ie, proportion of vegetables and pasta) and are most likely not large enough to affect food intake (25).

In the current study, daily intakes of food varied by no more than 50 g between any two conditions. Because the amount of food consumed remained constant, energy intake was driven by the energy density of the diets. These results are consistent with findings from previous studies reporting changes in energy intake, but not in the amount of food consumed when both energy density and fat content of diets varied. For example, in one of the earliest studies on energy density, Duncan et al (14) provided subjects with a low-fat diet or a high-fat diet of twice the energy density (2.9 kJ/g or 0.7 kcal/g compared with 6.3 kJ/g or 1.5 kcal/g) for 5 d. Individuals consumed nearly twice as much energy with the diet of high energy density. Although not reported by the authors, calculations based on the energy consumed and the energy density of the diets show that subjects ate approximately the same amount of food during the two diets. In another study, in which men were fed each of three diets varying in energy density (4.8, 5.6, and 7.0 kJ/g) and fat content (20%, 40%, and 60% of energy) over 14 d, subjects consumed a constant weight of food across dietary treatments with energy intake greatest with the high-fat, high-energy-density diet and lowest on the low-fat,

low-energy-density diet (18). A recent study by Rolls and Miller (26) provides further evidence that individuals tend to consume similar amounts of food, regardless of changes in fat content and energy density, even during discrete eating periods such as snacking. In this study, men and women ate similar amounts of no-fat and regular potato chips and energy intake varied accordingly. Because palatability and macronutrient content were controlled for, our present study confirms that individuals fail to adjust their intakes in response to changes in energy density. Thus, energy density, rather than fat content, might have accounted for differences in energy intake that occurred in previous studies when diets varied in both fat content and energy density.

To consume equal amounts of energy, subjects would had to have eaten $\approx 30\%$ (400 g) more of the diet of low energy density and 12% (160 g) more food with the diet of medium energy density than with the diet of high energy density. Calculations based on results from the present study revealed that we had power to detect differences in the amount of food consumed of 13.6% (181 g) and 18.5% (247 g) between high and low and high and medium conditions of energy density, respectively. Thus, we had adequate power to detect a difference in the amount of food consumed if individuals had adjusted the amount of food consumed in response to changes in energy density.

Average daily energy intakes with the high, medium, and low conditions of energy density were ≈ 7500 kJ (1800 kcal), 6400 kJ (1520 kcal), and 5800 kJ (1375 kcal), respectively. All of these are below the recommended dietary allowance (27) for energy of 9204.8 kJ (2200 kcal) for women 19–50 y of age. Energy needs were also calculated for each subject by using the Harris-Benedict equation (28) with an activity factor of 1.4. The average energy requirement from this computation was 8318 kJ

(1988 kcal). Therefore, in all conditions, subjects failed to consume enough food to maintain appropriate energy intake. This may be partially explained by the low energy density of each of the diets, which in turn is a function of their low fat content. With low-fat, low-energy-density diets, as compared with diets of higher energy density, subjects need to consume greater amounts of food to reach similar energy intakes. For example, in this study, subjects would have needed to eat ≈ 1500 , 1700, and 1960 g of food for the diets of high, medium, and low energy density, respectively, to maintain an energy intake of 8370 kJ (2000 kcal). In comparison, subjects consumed ≈ 1330 g across the three conditions.

Although we cannot be certain of the effect of the laboratory environment or menus on food intake in this study, our results suggest that it may be difficult to maintain adequate food intakes with diets of low energy density. Specifically, gastric distention and other satiety cues may have limited the amount of food able to be consumed. Likewise, knowledge of eating an amount of food that constitutes a culturally acceptable meal (29), or knowledge of portion sizes appropriate for the satisfaction of hunger (30), may have contributed to the termination of eating before consumption of enough food to meet energy needs. It is also possible that food intake might have been limited by sensory-specific satiety (the decline in the pleasantness of a food as it is consumed, whereas other foods remain pleasant). Usually, sensory-specific satiety leads to the termination of intake of a particular food while promoting the selection and consumption of other foods (31). However, in this study, the intake of other foods was limited because side dishes were controlled and the manipulated main entrees were the only foods offered to be consumed ad libitum. Therefore, the large amount of food that must be consumed with diets of low energy density may prevent or hinder adequate energy intakes, thus promoting a reduction in energy intake.


This study provides preliminary evidence that diets of low energy density may be helpful tools for weight loss and control. Across the conditions of energy density, subjects reported no differences in subjective sensations of hunger or fullness before and after meals and no differences in feelings of hunger between meals or fullness over the 2 study days. This is surprising because $\approx 30\%$ less energy was consumed from the diet of low energy density than from the diet of high energy density. Furthermore, as mentioned above, in no diet condition did subjects consume enough food to meet their energy requirements. Thus, diets of low energy density may reduce energy intakes while allowing individuals to consume adequate amounts of food. Also, with diets of low energy density, individuals may not experience adverse feelings, frequently associated with dieting, such as hunger or food deprivation.

Several years ago, the message that fat restriction was the key to weight loss was promoted widely (15) and some researchers concluded that restriction of fat intake would be an effective diet therapy for weight loss (32–34). Nonetheless, when two low-fat diets were compared directly, the diet emphasizing both fat and energy reduction was more effective in reducing body weight than the diet recommending only the reduction of dietary fat (35). Results from the third National Health and Nutrition Examination Survey (2) showing that the proportion of fat in the American diet has decreased while both total energy intake and body weight have increased, imply that reducing fat intake alone may not be effective for weight control. An explanation for these

apparently contradictory findings, as shown by the present study, could be that the overconsumption of energy is related to the energy density and not to the fat content of foods.

Before the advent of modern food technology, the substitution of low-fat foods for high-fat foods often would have led to reductions in not only fat content, but also in energy density. This is because individuals lowered the fat content of their diets primarily through the incorporation of fruits and vegetables. However, the food supply is changing and many commercially available low-fat or fat-free foods are not lower in energy density than their full-fat counterparts. Consumers must be made aware that fat restriction alone will not result in a reduction in energy intake because energy intake is dependent on the energy density, and not just the fat content, of foods.

Although our study provides valuable insight into the potential effectiveness of diets of low energy density for reducing energy intake and weight loss, the results must be interpreted and applied with caution. This study was conducted under a controlled experimental setting. Subjects were not allowed to consume foods in addition to those provided by the laboratory, were not given nutrition information about the foods, and were not aware of the dietary manipulations. The diets, as a function of their low fat content, were all low in energy density. We cannot determine how individuals would respond to higher levels of energy density or if the energy density of more than one food per meal was varied, so that there was a wider range of both foods and energy density levels. Also, it is not known whether subjects would have adjusted their food intakes to compensate for the energy deficits, observed across all conditions, if the same study were conducted over a greater length of time or if subjects were given free access to other foods varying in macronutrient composition and energy density. Furthermore, this study was conducted in normal-weight women and the results cannot be extrapolated to normal-weight men and obese individuals.

In conclusion, this study indicates that energy density influences energy intake independently of macronutrient (fat) content and palatability. Individuals were not sensitive to variations in energy density because they consumed similar amounts of food across conditions. Energy intake was significantly greater from the diets of high energy density than from the diets of lower energy density. Thus, these results imply that the overconsumption of high-fat foods may be due to their high energy density rather than to their fat content, per se. Although energy intake was greatly reduced in the diet of low energy density as compared with the diet of high energy density, individuals reported no differences in feelings of hunger or fullness. This study provides important preliminary information suggesting that diets low in energy density may be helpful for weight loss. 

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