Ad libitum food intake on a "cafeteria diet" in Native American women: relations with body composition and 24-h energy expenditure[1,2]

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ABSTRACT Epidemiologic studies consistently report associations between obesity and dietary fat but not total energy intake. We measured ad libitum food intake in a laboratory setting and evaluated its relation to body weight and composition, energy expenditure, and macronutrient utilization in 28 women of Pima-Papago heritage (aged 27 ± 7 y, 85.3 ± 19.0 kg, 44 ± 6% body fat; $\bar{x}$ ± SD). All women were studied during the follicular phase of the menstrual cycle. After a 4-d weight-maintenance period, the volunteers selected their food for 5 d from computerized vending machines offering a variety of familiar and preferred foods, ie, a "cafeteria diet". Twenty-four–hour energy expenditure and substrate oxidation were measured in a respiratory chamber on the 4th d of weight maintenance and the 5th d of ad libitum intake. Average ad libitum intake was 13 732 ± 4238 kJ/d (11 ± 1% protein, 40 ± 1% fat, 49 ± 4% carbohydrate), ie, moderate overeating by 27 ± 37% above weight maintenance requirements (range: −27% to 124%). Percent body fat correlated with daily energy intake (r = 0.53, P < 0.01), the degree of overeating (r = 0.41, P < 0.05), and the selection of a diet higher in fat and lower in carbohydrate (r = 0.70 and r = −0.63, respectively, P < 0.001). Excess carbohydrate intake caused an increase in carbohydrate oxidation (r = 0.51, P < 0.01), whereas excess fat intake resulted in a decrease in fat oxidation (r = −0.53, P < 0.01) and thus a positive fat balance of 85 ± 65 g/d. The positive relations among degrees of obesity, dietary fat intake and overeating, and the fact that dietary fat does not induce fat oxidation, support the hypothesis that dietary fat promotes obesity in women. *Am J Clin Nutr* 1995;62:911–7.

KEY WORDS Obesity, macronutrient intake and oxidation, respiratory chamber, food-selection system

INTRODUCTION

It is well accepted that energy intake in excess of energy expenditure is the primary cause of obesity. A more recent approach to the study of the etiology of obesity, however, is to consider separately the dietary balances of protein, carbohydrate, and fat (1, 2). Flatt (1), a pioneer in this area, proposed that the difficulty in achieving fat balance on a Western fat-rich diet may be a key factor in promoting body weight gain and obesity. According to Flatt, fluctuations in carbohydrate and protein intakes are compensated for by rapid, parallel fluctuations in carbohydrate and protein oxidation, whereas most excess dietary fat is not oxidized but stored in adipose tissue. The development of obesity, therefore, may be related to excess fat intake, as consistently reported in large-scale studies (3–8), or because of a reduced ability of obesity-prone individuals to oxidize fat (2, 9).

The Pima and Papago Indians of the southwestern United States are members of an obesity-prone population with a prevalence of obesity approaching 80% in women (10). Prospective studies in nondiabetic Pima Indians showed that a low metabolic rate, for a given body size and composition (11), and a low ratio of fat to carbohydrate oxidation are risk factors for body weight gain (9). Little is known, however, about the relations among ad libitum food intake and energy and macronutrient balances in this and other populations.

The objective of this study was to investigate the associations between obesity and both energy and fat intakes in women of Pima-Papago heritage. Recently, we published results on the use of an automated food-selection system to measure ad libitum food intake in male volunteers on a metabolic ward (12, 13). This system allows individuals free access to a wide variety of familiar foods that can be tailored to their preferences. Using this system, we asked whether *1*) ad libitum energy intake is related to body weight or obesity, *2*) ad libitum fat intake is related to obesity, and *3*) changes in ad libitum energy and macronutrient intakes are balanced by parallel changes in energy expenditure and macronutrient oxidation?

SUBJECTS AND METHODS

Subjects

Twenty-eight nondiabetic women of Pima-Papago heritage were admitted for 10 d to the metabolic ward of the Clinical Diabetes and Nutrition Section of the National Institute of Diabetes and Digestive and Kidney Diseases (NIDDK). None of the subjects reported a recent attempt to lose weight. On

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admission, all volunteers were determined to be in good health by medical history, physical examination, electrocardiogram, blood screening, and urine test. According to their medical history, all had regularly occurring menstrual cycles. None were taking oral contraceptives or other medications. Their physical characteristics are presented in **Table 1**. Body composition was determined by hydrostatic weighing with simultaneous measurement of residual lung volume. Percent body fat was estimated from body density by using the equation of Siri (14). Circumferences of the waist (at the level of the umbilicus) and thigh (at the gluteal fold) were measured supine and standing, respectively. The ratio of waist to thigh circumference is an estimate of centrality of body fat. Seventeen volunteers had normal glucose tolerance and 11 had impaired glucose tolerance, according to the criteria of the World Health Organization. None of the volunteers were classified as binge eaters according to the Gormally Binge Eating Scale (15), or were clinically depressed according to their medical history.

Volunteers were restricted to the metabolic ward for the duration of the study. Activity on the metabolic ward was limited to ambulation in the hallways, playing billiards, and playing table games. In addition, volunteers had supervised outings to the hospital courtyard two or three times a week for 30–45 min each. Sixteen of the volunteers were nonsmokers and 12 were occasional smokers. They were allowed to smoke only during scheduled, supervised outings. None of the volunteers complained of difficulties from the restrictive smoking regimen. The experiment was approved by the Institutional Review Board of the NIDDK and written, informed consent was obtained.

Experimental protocol

To avoid any potential influence of menstrual cycle phase on food intake or energy expenditure, volunteers were studied in the follicular phase of the menstrual cycle. They reported to the metabolic ward on the second or third day after the start of menstruation and were studied during the following 9 d. Subjects' nude body weights were measured after they voided each morning at 0530. For the first 4 d, volunteers were placed on a standardized weight maintenance diet (20% protein, 30% fat, and 50% carbohydrate) initially calculated by using a metabolic ward prediction equation based on sex, body weight, and height (unpublished), and subsequently adjusted to maintain body weight within 1% of the weight on the second day of admission. If necessary, adjustments were made to accommodate food dislikes. In our experience, we have determined that 4 d is sufficient for estimating weight maintenance requirements on a metabolic ward. On the 4th d of weight maintenance, 24-h energy expenditure (24-h EE) was measured in a respiratory chamber as previously described (16). After this measurement, volunteers consumed all food ad libitum from an automated food-selection system for 4 d. The 24-h EE measurement was repeated on day 5 of ad libitum intake with the volunteer using a food-selection system placed in the respiratory chamber. Three blood samples were drawn for measurement of estradiol and progesterone: *1*) on admission, *2*) the evening before the first measurement of 24-h EE (weight maintenance period), and *3*) immediately after the last measurement of 24-h EE (ad libitum period). Serum estradiol and progesterone were measured by radioimmunoassay in a 10-mL blood sample drawn from the antecubital vein. Follicular phase was documented by a progesterone concentration < 1.0 μg/L throughout the study and verified by estradiol concentration.

TABLE 1
Physical characteristics of 28 women of Pima-Papago heritage[1]

	Value
Age (y)	27 ± 7 (19–51)
Height (cm)	160 ± 6 (150–173)
Weight (kg)	85.3 ± 19.0 (61.5–131.5)
BMI (kg/m²)	33.1 ± 6.9 (23.0–50.5
Percent body fat (%)	44 ± 6 (29–55)
Fat-free mass (kg)	47.5 ± 7.5 (35.0–64.1)
Fat mass (kg)	38.0 ± 13.0 (19.2–66.7)
Waist-thigh ratio	1.57 ± 0.21 (1.20–2.23)

[1] $\bar{x}$ ± SD; range in parentheses.

Automated food-selection system

The automated food-selection system was described previously (12, 13). Briefly, it includes two vending machines (model 3007; U-Select-It, Des Moines, IA) that together contain 40 trays. For this study, 34 trays were stocked with food items and 6 with beverages. A typical "cafeteria diet" was available including a variety of foods with varying fat, protein, and carbohydrate contents. These included low-, medium-, and high-fat entrees; low- and high-fat meats; cheese; bread; tortillas; pinto beans; fruit; vegetables; cereal; French fries; popcorn; chips; nuts; and low-and high-fat pastry or desserts. The selection included food items typical of the Pima diet (17) and tailored to individual food preferences. The same selection was offered each day but changed slightly with the four daily loads (0600, 1000, 1500 and 1800). In general, ≈20 of the 40 trays at each load contained low-fat items (≤ 30% fat) and 10 contained high-fat items (≥ 50% fat). A selection of low- and high-fat condiments was also available from a small refrigerator and was counted and restocked daily.

During the ad libitum period, volunteers were asked to follow their typical eating pattern and were instructed to return empty wrappers and unconsumed food portions to the vending machines. Weights of all items loaded in and returned to the vending machines were recorded. Daily energy, protein, fat, and carbohydrate intakes were calculated from actual weights of food and condiments consumed. During the 4-d ad libitum period on the ward, volunteers had 24-h access to the vending machines, housed in a separate eating area equipped with a table, chair, television set, microwave oven, and toaster. For simultaneous measurement of food intake and 24-h EE on day 5, the vending machine in the respiratory chamber was loaded before the measurement period with the food items most often selected during the previous 4 d.

Energy expenditure and substrate oxidation

Carbon dioxide production, oxygen consumption, and spontaneous physical activity (SPA) were measured continuously in the respiratory chamber for 23 h from 0800 to 0700 the next day and values were extrapolated to 24 h (16). Carbohydrate, fat, and protein oxidation rates were calculated from 24-h oxygen consumption, carbon dioxide production, and urinary nitrogen excretion (18). Sleeping metabolic rate (SMR) was defined as the average energy expenditure during all 15-min periods between 2300 and 0500 when the activity measured by radar was < 1.5%. During the weight maintenance measurement, volunteers fasted from 2000 the evening before entering the chamber. To account for confinement within the chamber, 80–85% of the weight-maintenance energy was given (19). No restrictions were applied during the ad libitum period. During both measurements in the chamber, volunteers were asked not to exercise in the chamber.

Data analysis

Energy intake is expressed in kJ/d, and as a percentage of weight-maintenance-energy requirements (mean of 3 d). Energy and macronutrient balances were compared between the last day of weight maintenance and the last day of ad libitum intake. To further assess the relation between energy and macronutrient balances and obesity, the data were also divided into tertiles of percent body fat.

Statistical analyses were performed with the programs of the SAS Institute Inc (Cary, NC). All data are expressed as mean ± SD. Comparisons of mean daily energy intake, macronutrient composition, and energy metabolism between the weight maintenance and ad libitum phases were performed by using paired Student's *t* tests. Comparisons between the upper and lower tertiles of body fat were performed by using unpaired Student's *t* tests. During the ad libitum period, an analysis of variance (ANOVA) with repeated measures was used to detect the effect of time on energy or macronutrient consumption. Relations between variables were assessed by Spearman correlation or by linear-regression analyses.

RESULTS

Ad libitum food intake

Mean energy intake required for weight maintenance on our metabolic ward was 9360 ± 1510 kJ/d (4.184 kJ = 1 kcal). During the ad libitum period, energy intake was increased to an average of 13 732 ± 4238 kJ/d ($P < 0.0001$). Compared with weight maintenance, ad libitum intake resulted in moderate overeating for the group by 27 ± 37% ($P < 0.001$) varying from −27% to 124%. On average, the selected diet was composed of 11 ± 1% protein, 40 ± 3% fat, and 49 ± 4% carbohydrate, which is higher in fat and lower in protein than the imposed weight-maintenance diet ($P < 0.0001$). The food quotient of the ad libitum diet or the theoretical ratio of carbon dioxide production to oxygen consumption was 0.846 ± 0.011. By experimental design, the food quotient of the weight-maintenance diet was 0.866. In the ad libitum period, by repeated-measures ANOVA, there was no effect of time (day of study) on energy or macronutrient consumption.

After 5 d of ad libitum intake, body weight increased by 0.4 ± 0.9 kg ($P < 0.05$) over mean baseline body weight. The change in body weight varied widely among individuals, from −1.1 to 2.8 kg, and correlated with energy balance (deficit or excess) over the 5-d period ($r = 0.60$, $P < 0.001$).

The relations between ad libitum energy intake, macronutrient composition, and body weight and composition are reported in **Table 2**. As shown in **Figure 1**, percent body fat was associated with the percentage of fat in the diet ($r = 0.70$, $P < 0.001$) and the degree of overeating above weight maintenance ($r = 0.41$, $P < 0.05$). By multiple-regression analysis, however, percent body fat was no longer associated with the degree of overeating after the percent of fat in the diet was adjusted for. This was due to the fact that percentage fat in the diet and the degree of overeating were correlated ($r = 0.41$, $P < 0.05$). There was no difference in food intake and composition of the diet between the 17 subjects with normal glucose tolerance and the 11 with impaired glucose tolerance.

Energy expenditure and macronutrient oxidation

Intake, oxidation, and balance values on day 4 of the weight-maintenance period and day 5 of the ad libitum period are reported in **Table 3**. Overeating during the ad libitum period was associated with significant increases ($P < 0.001$) in SMR (from 5994 ± 870 to 6464 ± 1126 kJ/d) and spontaneous physical activity (from 6.7 ± 1.8 to 7.6 ± 3.1%/min, $P < 0.05$), but not 24-h EE (NS). The higher respiratory quotient during ad libitum intake reflects increased carbohydrate oxidation and decreased fat oxidation. These changes in intake and oxidation during the ad libitum period resulted in positive balances for each macronutrient (Table 3).

During the ad libitum period, both carbohydrate and protein oxidation correlated with their respective intakes ($r = 0.77$ and $r = 0.71$, respectively, $P < 0.0001$). Fat oxidation, however, was not positively correlated with fat intake, but was positively correlated with the difference or "gap" between 24-h EE and the sum of the energy ingested as carbohydrate and protein ($r = 0.73$, $P < 0.0001$).

As shown in **Figure 2**, the change in 24-h EE between the ad libitum and weight-maintenance periods correlated with change in energy intake ($r = 0.51$, $P < 0.01$). The change in carbohydrate oxidation correlated with the change in carbohydrate intake ($r = 0.51$, $P < 0.01$) whereas the change in fat oxidation correlated negatively with the change in fat intake ($r = -0.53$, $P < 0.01$).

TABLE 2

Spearman rank correlation coefficients (*r* between body weight and body composition, and ad libitum energy intake and macronutrient composition[1]

	Energy (kJ)	Overeating[2] (%)	Protein (%)	Fat (%)	Carbohydrate (%)	Food quotient[3]
Weight	0.41 (0.03)	0.27	0.26	0.30	−0.32	−0.33
Percent body fat	0.53 (0.01)	0.41 (0.03)	0.27	0.70 (0.0001)	−0.63 (0.001)	−0.68 (0.0001)
Waist-thigh ratio	0.52 (0.01)	0.44 (0.02)	−0.15	0.23	−0.09	−0.14

[1] *P* value in parentheses.

[2] Defined as the percent above or below weight-maintenance-energy requirements.

[3] Theoretical respiratory quotient of the diet.

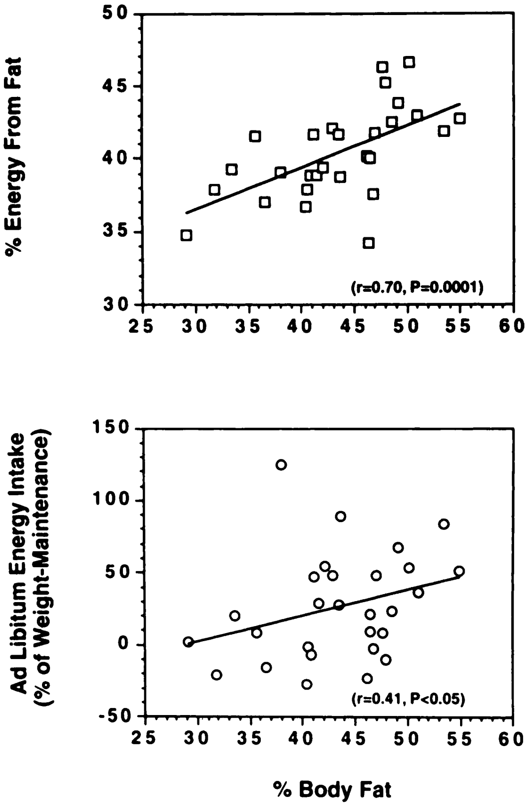

FIGURE 1. The degree of overeating (lower panel) and the selection of a high-fat diet (upper panel) correlated positively with percent body fat (n = 28). (After the exclusion of one outlier, r = 0.51, $P < 0.01$ for the relation between the degree of overeating and percent body fat).

Most compared with least obese volunteers

When individuals in the upper and lower tertiles for obesity were grouped (n = 9 per group), energy intake for the most obese group (101.8 ± 17.6 kg, 50 ± 3% body fat) was 16 117 ± 3845 compared with 11 334 ± 4586 kJ/d ($P < 0.05$) in the least obese group (74.1 ± 11.1 kg, 36 ± 4% body fat). On average, the selected diet was composed of 12 ± 1% protein, 44 ± 2% fat, and 44 ± 2% carbohydrate for the most obese group and 11 ± 1% protein, 38 ± 2% fat, and 51 ± 3% carbohydrate for the least obese group ($P < 0.0001$ for fat and carbohydrate). These differences were associated with a higher 24-h EE in the most obese compared with the least obese group (10376 ± 1502 and 7401 ± 749 kJ/d, respectively) but no difference in 24-h respiratory quotient (0.892 ± 0.033 and 0.881 ± 0.041, respectively). As shown in **Figure 3**, this resulted in a more positive fat balance in the most obese group.

DISCUSSION

Using an automated food-selection system, we investigated whether ad libitum food intake was related to body weight and obesity in women with a genetic predisposition to obesity. When offered unlimited access to a variety of palatable and familiar foods for 5 d, there was a wide range of under- and overeating that for the group averaged ≈27% above weight-maintenance-energy requirements. Obesity was associated with both overeating and the selection of a high-fat diet. Such overeating resulted in an increase in carbohydrate oxidation, related to the increase in carbohydrate intake, but a decrease in fat oxidation. This combination of overeating and decreased fat oxidation led to a more positive fat balance in the most obese individuals.

Little is known about the influence of ad libitum food intake on the pathogenesis of obesity in the Pima, Papago, or other populations. One likely reason is because accurate collection of food intake data and interpretation of its relation to obesity are difficult in free-living conditions. It is well established that obese individuals have higher energy expenditures than do normal-weight individuals (16, 18, 19), yet food intake studies have failed to find higher energy intakes among obese individuals (3–6, 20). The expected associations between reported energy intake and body weight and obesity, however, may be obscured by error in the use of imprecise proxies for estimating food intake and body composition (21) or in systematic underreporting of intake by heavier individuals. Recent studies measuring energy expenditure in free-living conditions (doubly labeled water) simultaneously with estimation of food intake, provide evidence that obese individuals underreport food intake to a greater extent than do nonobese individuals (22, 23). Still, despite this evidence, some investigators continue to question the role of overeating in the pathogenesis of obesity (5, 24). In the present study, we measured food intake on a metabolic ward to avoid the problems associated with recorded or recalled food intake data. In the controlled setting of a metabolic ward, our finding that energy intake was correlated with both body weight and obesity supports the intuitive concept that excess energy intake is required to induce and maintain obesity.

Despite the errors associated with the collection of food intake data, a growing number of studies have found links between obesity and fat intake. Epidemiologic reports from the

TABLE 3
Energy metabolism, macronutrient intakes, oxidation, and balances on day 4 of the weight-maintenance period and day 5 of the ad libitum periods[1]

	Weight maintenance			Ad libitum		
	Intake	Oxidation	Balance	Intake	Oxidation	Balance
Energy (kJ/d)	7912 ± 1372	8569 ± 1443	−649 ± 962	13 949 ± 4247[2]	8832 ± 1753	5117 ± 3623[2,3]
Protein (kJ/d)	1632 ± 268	862 ± 247	770 ± 335[3]	1598 ± 556	787 ± 351	787 ± 351[3]
Fat (KJ/d)	2356 ± 397	3527 ± 1280	−1172 ± 1280[3]	5707 ± 1870[2]	2515 ± 1230[2]	3197 ± 2439[2,3]
Carbohydrate (kJ/d)	4029 ± 774	4117 ± 916	88 ± 623	6720 ± 2092[2]	5473 ± 1527[2]	1247 ± 1435[2,3]

[1] $\bar{x}$ ± SD.
[2] Significantly different from weight-maintenance period, $P < 0.0001$.
[3] Balance significantly different from zero, $P < 0.01$.

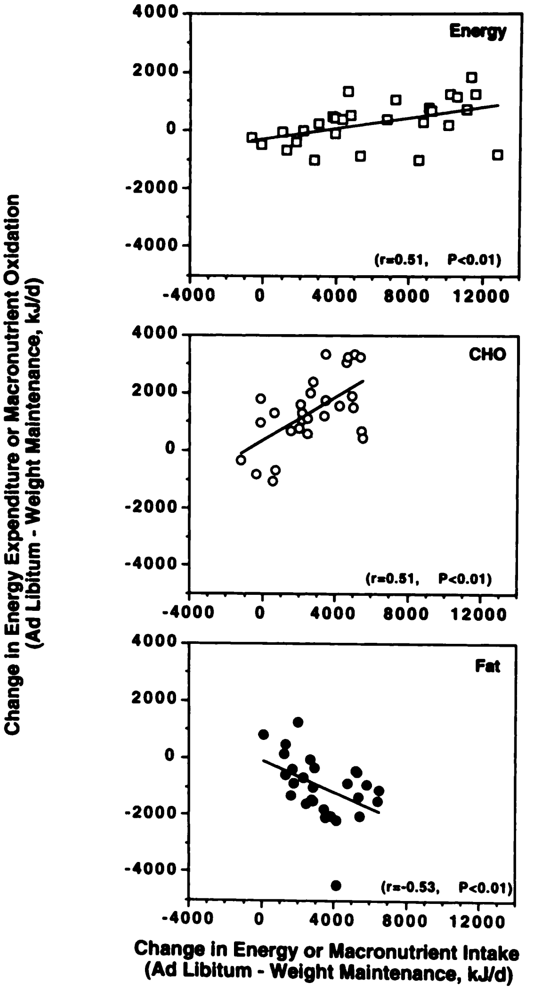

FIGURE 2. Changes in 24-h energy expenditure and carbohydrate (CHO) and fat oxidation compared with the changes in energy, carbohydrate, and fat intakes from the weight maintenance to the ad libitum period. The small increase in 24-h energy expenditure (upper panel) represents the balance between the increase in carbohydrate oxidation (middle panel) and the decrease in fat oxidation (lower panel). (After the exclusion of one outlier, $r = 0.54$, $P < 0.01$ for the relationship between the change in fat intake and the change in fat oxidation).

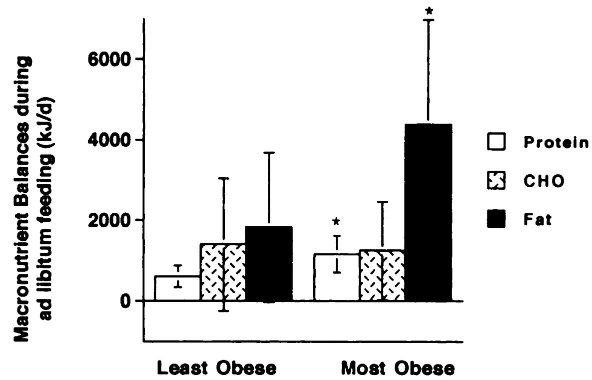

FIGURE 3. Protein, carbohydrate (CHO), and fat balances on day 5 of ad libitum intake for the lower (least obese) and upper (most obese) tertiles of obesity ($n = 9$ in each group). Corresponding energy balances were 3690 ± 3217 in the least obese and 6673 ± 3920 kJ/d in the most obese subjects (NS). Error bars are SD for macronutrient balance. *Significantly different from least obese subjects, $P < 0.05$.

early 1970s suggest that the prevalence of obesity is higher in populations with a diet rich in fat (25). Results from large-scale and population-based studies show that obesity is characterized by consumption of a high-fat, low-carbohydrate diet (3–8, 20). Longitudinal studies have determined that a high fat intake predicts weight gain in both men and women (26), particularly women predisposed to obesity (27). Also, the sensory and hedonic studies of Drewnowski et al (28) and Mela and Sacchetti (29) have demonstrated that obese individuals may have a greater preference for dietary fat than do nonobese individuals. In the present study, women of Pima or Papago heritage selected a diet composed of 11% protein, 40% fat, and 49% carbohydrate, similar to the national average for women, which is 16% protein, 37% fat, and 46% carbohydrate (30). Consistent with previous findings, the most obese individuals selected a diet richer in fat. Interestingly, our correlations between macronutrient intake and obesity are stronger than those reported in large-scale studies, possibly reflecting more precise measurements of food intake on a metabolic ward; better control of other interfering factors such as activity, alcohol consumption, or smoking, or the genetic homogeneity of this obesity-prone population. On the other hand, we recognize that the artificial conditions of the study, ie, free food, restricted habitual activity, and boredom may have influenced food intake in these women.

What are the possible mechanisms responsible for the role of dietary fat in the pathogenesis of obesity? Clinical studies have clearly shown that diets rich in fat induce hyperphagia (7, 31), possibly because fat is more energy dense (32) and less satiating than is carbohydrate (33). Because fats determine the texture, flavor, and odor of many foods (34), it could be argued that fat-rich foods are easy to overeat because of their hedonic appeal and "mouthfeel". Flatt has also proposed that high-fat diets promote hyperphagia to maintain carbohydrate balance (1). In this study, obesity was associated with both overeating and the selection of a high-fat diet. Although we cannot imply cause and effect, our analyses suggest that overeating by many of our volunteers was primarily the result of selecting a high-fat diet.

Another explanation for the role of dietary fat in promoting obesity may be related to differences in the metabolism of the macronutrients (1, 19). It is fairly well established that although the consumption of excess carbohydrate is met with increased carbohydrate oxidation (12, 13), the consumption of excess fat does not increase fat oxidation (35). According to Flatt's studies in mice fed ad libitum, fat oxidation correlates with the "gap" between total energy expenditure and energy ingested as carbohydrate and protein (36). In our female volunteers, fat oxidation correlated with the "gap" described by Flatt, providing further support for the hypothesis that fat oxidation depends on the intakes of carbohydrate and protein, and total energy expenditure (1, 35, 36). In agreement with our studies in white (12) and Pima and Papago men (13), the relation between changes in carbohydrate oxidation and changes in carbohydrate intake support the close regulation of carbohydrate balance, which is likely due to the limited storage capacity for carbohydrate (1, 19). The negative relation between fat oxidation and excess fat intake in the present study most likely reflects the suppression of fat oxidation via the antilipolytic effect of an insulin response to the carbohydrate load.

Of further interest is the possibility that some individuals may be more susceptible to obesity with the consumption of a high-fat diet (2). In Swedish women, high-fat intake was associated with a 6-y increase in BMI only in women defined to be genetically predisposed to obesity (27). In nondiabetic Pima Indians, a low ratio of fat to carbohydrate oxidation, measured under standardized dietary conditions, is associated with subsequent weight gain (11). In whites, Thomas et al (31) found that after 7 d of a high-fat diet, lean men and women were better able to match fat oxidation to fat intake and were therefore in less positive fat balance than were their obese counterparts. In the present study, we found no evidence to support that the most obese women were less able to stimulate fat oxidation in response to fat intake than were the least obese women. Although ad libitum fat balance was significantly more positive among the more obese women, this was largely due to higher fat intake. It is worth noting, however, that the least obese group in our study was "fatter" than the women studied by Thomas et al (37 ± 4% compared with 26 ± 1% body fat) and that our experimental period was 2 d shorter (5 compared with 7 d). A cross-sectional study of a population with a high prevalence of obesity, however, may not be ideal for detecting defects in fat oxidation among individuals.

The findings in this study support the argument that body weight gain occurs through a combination of overeating and the selection of a high-fat diet. Our results, collected in a controlled setting, agree with large-scale studies reporting a link between obesity and dietary fat intake. The moderate overeating induced by exposure to a variety of palatable foods, particularly in more obese women, may be a consequence of a high-fat diet. Such moderate overeating leads to increased carbohydrate oxidation parallel with an increased carbohydrate intake and suppression of fat oxidation, leading to fat deposition. These findings support the growing evidence that excess dietary fat promotes obesity.

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