

A rapidly occurring compensatory decrease in physical activity counteracts diet-induced weight loss in female monkeys

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¹Division of Reproductive Sciences and Neuroscience, Oregon National Primate Center, Beaverton; Departments of ²Physiology and Pharmacology and ³Behavioral Neuroscience, Obstetrics, and Gynecology, Oregon Health and Science University, Portland, Oregon; and ⁴Department of Psychiatry, University of Pittsburgh, Pittsburgh, Pennsylvania

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Sullivan EL, Cameron JL. A rapidly occurring compensatory decrease in physical activity counteracts diet-induced weight loss in female monkeys. *Am J Physiol Regul Integr Comp Physiol* 298: R1068–R1074, 2010. First published January 13, 2010; doi:10.1152/ajpregu.00617.2009.—To study changes in energy balance occurring during the initial phases of dieting, 18 adult ovariectomized female monkeys were placed on a low-fat diet, and available calories were reduced by 30% compared with baseline consumption for 1 mo. Surprisingly, there was not significant weight loss; however, daily activity level (measured by accelerometry) decreased soon after diet initiation and reached statistical significance by the 4th wk of dieting ($18 \pm 5.6\%$ decrease, $P = 0.02$). During a 2nd mo of dieting, available calories were reduced by 60% compared with baseline consumption, leading to $6.4 \pm 1.7\%$ weight loss and further suppression of activity. Metabolic rate decreased by 68 ± 12 kcal/day, with decreased activity accounting for 41 ± 9 kcal/day, and the metabolic activity of the weight lost accounting for 21 ± 5 kcal/day. A second group of three monkeys was trained to run on a treadmill for 1 h/day, 5 days/wk, at 80% maximal capacity, leading to increased calorie expenditure of 69.6 ± 10.7 kcal/day (equivalent to 49 kcal/day for 7 days). We conclude that a diet-induced decrease in physical activity is the primary mechanism the body uses to defend against diet-induced weight loss, and undertaking a level of exercise that is recommended to counteract weight gain and promote weight loss is able to prevent the compensatory decrease in physical activity-associated energy expenditure that slows diet-induced weight loss.

obesity; calorie reduction; activity

MODERATE WEIGHT LOSS IN OBESE and overweight individuals is associated with major health benefits, including reductions in the risk of heart disease (37), stroke (37), type 2 diabetes (35, 42, 70), hypertension (18, 49), hyperlipidemia (21, 60), hypercholesterolemia (22, 60), cardiovascular disease (22, 60), osteoarthritis (60), and depression (22, 60). Thus it is not surprising that, at any time, two-thirds of obese North American adults are attempting to lose weight (58, 61). Currently, American consumers spend \$33 billion annually on weight loss products and services (10). Despite these efforts, the prevalence of overweight and obese adults has escalated over the past several decades, such that 65% of adults in the United States have a body mass index above the healthy range (19). An important contributing factor to the increasing prevalence of obesity is that most of the individuals attempting to lose weight are unsuccessful (60, 63). Dieting is currently the most common weight loss strategy (14, 29, 31, 41, 81). However, the success rates for diet-induced weight loss are very low, ranging from 2 to 20% of individuals actually maintaining weight loss (30, 62, 72, 82). Weight loss in response to a diet is difficult to

accomplish and maintain, as compensatory mechanisms act to prevent weight loss by decreasing energy expenditure (5, 11–13, 26, 43).

The majority of studies examining diet-induced weight loss in humans have not directly measured physical activity or food intake, but rather have relied upon self-report of these measures (28, 50, 71, 83), which has been shown to be unreliable (7, 28, 34, 44, 46, 69). There is clear evidence that dieting leads to a compensatory decrease in total metabolic rate in humans (5, 11–13, 26, 43) and nonhuman primates (38). It has been postulated that a decrease in physical activity contributes to the overall decrease in energy expenditure accompanying calorie reduction, and that this reduction in physical activity is at least partially responsible for the decreased effectiveness of dieting to promote weight loss. Evidence to support this hypothesis comes from several studies that suggest that people decrease physical activity level in response to reduced calorie consumption (13, 33, 43, 55). Also, a single report directly measured physical activity before and after a dietary weight loss intervention in women and found that physical activity decreased after the weight loss intervention (74). However, this study measured activity for short periods of time (5–6 days), and accelerometers were removed during periods of the day when individuals were sleeping or bathing. In contrast, in rodents, detailed measurements of physical activity indicate that activity increases in response to calorie reduction (8, 17, 45, 57). It is hypothesized that the increase in activity in rodent models reflects an increased drive to forage for food, as the elevated activity is decreased when food is made available (36). It is likely that the differential regulation of physical activity in response to calorie reduction in humans vs. rodents is due to species differences in stored energy.

To examine the compensatory decreases in energy expenditure that occur in response to diet-induced weight loss in detail, we have studied a primate species that shows metabolic regulation similar to that of humans (23, 73) (i.e., rhesus monkeys). A group of 18 ovariectomized adult female rhesus monkeys was put on a carefully controlled diet for 2 mo, and food intake, physical activity, total metabolic rate, and body composition were measured before and over the course of 2 mo of dieting: a 1st mo in which available calories were reduced by 30% compared with baseline consumption, and a 2nd mo in which available calories were reduced by 60% compared with baseline consumption.

MATERIALS AND METHODS

Animals

Twenty-one adult female rhesus monkeys (*Macaca mulatta*), 9–13 yr of age, were used in this study.

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For *experiment 1*, 18 monkeys were housed in individual stainless steel cages (32 × 24 × 27 or 32 × 34 × 27 in.) in a temperature-controlled room (24 ± 2°C), with lights on between 0700 and 1900. Two and one-half years before the initiation of this study, these monkeys were ovariectomized and placed on a diet higher in fat than standard monkey chow (35% of calories from fat) to approximate the conditions experienced by many postmenopausal women in the Western world (77). This diet was formulated at the Oregon National Primate Research Center (ONPRC) following a modification of the recipe developed by Clarkson and colleagues to study diet-induced atherosclerosis (59, 77). The diet utilized in this study was modified to prevent loose stool by lowering the percent fat from 43 to 35%, increasing the amount of carbohydrate from 39 to 46%, and reducing the amount of calcium and phosphorus. The diet had a wheat flour base, and 35% of calories were derived from fat, 19% from protein, and 46% from carbohydrate. At the beginning of this study, during a 1-mo baseline period, monkeys continued to receive high-fat diet ad libitum. After the baseline period, monkeys were placed on monkey chow (5% fat), which involved switching their food back to the standard feeding regimen at ONPRC, in which they received high-protein monkey chow biscuits (no. 5047, jumbo biscuits, Ralston Purina, St. Louis, MO; ~16.5 g each, 3.11 metabolizable kcal/g, 616 kcal/meal, 25% protein, 5% fat, 6.5% fiber, 6% ash, and 3% nutrients). During the 1st mo of the diet, the number of available calories was reduced by 30% compared with baseline consumption. During the 2nd mo of the diet, calories available were reduced by 60% compared with baseline calorie consumption. Throughout the study, two meals a day were provided at 0915 and 1515. All aspects of the study were reviewed and approved by the ONPRC Animal Care and Use Committee.

For *experiment 2*, three adult female monkeys, 13–14 yr of age, lived in social groups in pens measuring 14 × 11 × 10 ft, which had perches at various heights and various toys available. Skylights provided natural lighting supplemented with artificial lighting from ~0730 to 1600 each day. Temperature was maintained at 24 ± 3°C. Monkeys were fed Purina high-protein monkey chow (no. 5045; Ralston Purina, St. Louis, MO), supplemented with seeds, fresh fruit, and vegetables. Monkeys were trained to enter transfer cages from their home pen so that they could be transported to a different room for running on treadmills during the experiment. All aspects of the study were reviewed and approved by the University of Pittsburgh Animal Care and Use Committee.

Experimental Design

Experiment 1. The overall goal of this study was to examine the compensatory mechanisms that counteract diet-induced weight loss. During the baseline period (1 mo), initial measurements of body weight, body composition, food intake, activity, total energy expenditure, basal metabolic rate, thermic effect of food, and activity-associated energy expenditure were made. Monkeys were subsequently placed on a diet for 2 mo. In the 1st mo of the study, available calories were reduced by 30% compared with baseline consumption. In the 2nd mo of the study, calorie intake was reduced by 60% compared with baseline consumption. A second measurement of body composition, total energy expenditure, basal metabolic rate, thermic effect of food, and activity-associated energy expenditure was made at the end of the 2nd mo of dieting. Throughout the study, food intake was measured at every meal, body weight was measured weekly, and activity was measured continuously via accelerometry.

Experiment 2. The overall goal of this study was to examine the change in daily activity that occurs when animals participate in an exercise program of 1 h of running a day, 5 days/wk, at levels recommended by the American College of Sports Medicine to prevent weight gain and promote weight loss (15). Monkeys wore collars with a small metal box attached, housing an omnidirectional accelerometer (Actical accelerometer, Respirationics, Phoenix, AZ) throughout the entire study to measure daily level of physical activity. After a baseline period, monkeys

were trained to run on motor-driven treadmills and ran for 1 h/day at 80% maximal capacity for 5 days/wk for 12 wk.

Experimental Measures

Food intake. Total food consumption at each meal was recorded daily throughout the study, by counting the amount of food remaining before the next meal.

Body weight. Body weight measurements were made weekly before consumption of the AM meal, at ~0800.

Dual-energy X-ray absorptiometry measurements. Percent body fat, percent central fat, percent peripheral fat, fat mass in grams, and lean tissue mass in grams were determined using dual-energy X-ray absorptiometry, as previously described (64, 66). Animals were sedated with Telazol (3 mg/kg im, Fort Dodge Animal Health, Fort Dodge, IA), supplemented with ketamine HCl (10–20 mg/kg im; Ketaset, Fort Dodge Animal Health), and were positioned supine on the bed of a Lunar DPX scanner (Lunar, Madison, WI). Total body scans were done in the “Pediatric Medium” scan mode with a voltage of 76 kV. Lunar software version 3.4 was used to calculate body composition. Two or three scans were performed for each monkey at the initiation of the baseline period and after 2 mo of dieting, and averages were calculated for each measure. To delineate central fat mass from peripheral fat mass, fat in the trunk (including both the subcutaneous and visceral compartments) and fat in the extremities were calculated using standard methodology (9, 68).

Metabolic rate. Metabolic rate was measured by placing each monkey in a sealed Lexan metabolic chamber (Columbus Instruments, Columbus, OH) and measuring the amount of carbon dioxide produced and oxygen consumed over a 24-h period using a computer-controlled indirect open-circuit calorimeter (Oxymax System, Columbus Instruments) and previously published methods (66). The metabolic chamber was approximately the same size as the monkey’s home cage (inside dimensions of 30 in. × 24 in. × 24 in.). To prevent social isolation stress during metabolic testing, two familiar monkeys (i.e., two monkeys routinely housed across the room from the experimental monkey) were placed in plain view of the subject. The metabolic rate of each monkey was assessed during the baseline period, when monkeys were consuming high-fat diet, and after 2 mo of dieting. To determine total daily energy expenditure, monkeys were placed in the metabolic chamber at 1000 and remained in the chamber until 0900 the next morning. Before placement in the chamber, monkeys were fed their standard meal at 0915. They were then fed a banana (114 ± 10 g, 108 calories) at 1515, while in the chamber. Water was available ad libitum throughout metabolic testing. BMR was calculated as the average number of kilocalories expended per hour from 2300 to 0300. This time period was selected because this is when monkeys typically sleep, and heart rate (J. Cameron, unpublished observations) and activity are lowest at this time of night (66).

Activity. Activity was measured continuously throughout the experiment using omnidirectional Actical accelerometers (Respirationics, Phoenix, AZ) and previously published methods (66). Each monkey was fitted with a loose-fitting metal collar (Primate Products, Immokalee, FL) that had an activity monitor, housed in a snug protective stainless steel box, mounted on it. The monitor was programmed to store the total number of activity counts per minute. During the study period, monkeys were sedated with ketamine hydrochloride (10–20 mg/kg im; Ketaset, Fort Dodge Animal Health), and the data from each activity monitor were downloaded at least every 45 days (the maximum number of days that the monitor can store data). After the data were downloaded and saved, the activity monitor was reprogrammed and replaced on the collar to resume collection of activity data. The monkeys in this study had been acclimated to wearing collars with activity monitors attached for over 6 mo before the collection of measurements for this study. Average activity during the light and dark cycle was calculated for the baseline period and each week of the diet. Activity-associated energy expenditure was calculated using a previously published calculation of the amount of energy expended (in kcal) per activity count (66). This was calculated by measuring total energy

expenditure at times of day in which there would be little contribution of the thermic effect of food to the total metabolic rate (from 1400 to 1500 and 1800 to 1900), subtracting basal metabolic rate, and dividing the remaining energy expenditure by the number of activity counts occurring during this time period. The number of calories expended per activity count was multiplied by total daily activity counts to determine daily activity-associated energy expenditure.

Exercise training. Monkeys were trained to run on a standard human-sized treadmill (model 910e, Precor, Bothell, WA), using previously published techniques (78–80). Each treadmill was covered by a Plexiglas box that had numerous air holes in the front and back panels for adequate ventilation. Initially, for several days, the monkeys were acclimated to the treadmill by sitting on it and being allowed to explore the treadmill belt and the Plexiglas box. Monkeys then learned to walk on the treadmill, and then speed and duration of each running session were slowly increased to 1.6 mph for 20 min/day. The treadmill adaptation period lasted 3–4 wk. Subsequently, each monkey underwent a “max test”, and their target exercise level was individually determined as 1 h of running, 5 days a wk, at 80% of their maximal capacity. Monkeys were trained by gradually increasing speed and duration of each running session until they reached their individual target speed. Each monkey’s target amount of running was adjusted after a second max test, performed in week 7 of the study, so that they continued to train at 80% maximal capacity.

Maximal heart rate test procedures. After monkeys were trained to walk on the treadmill, and again after 7 wk of running, each monkey had a maximal aerobic power test (max test) performed. Before the max test, monkeys were adapted to wearing nylon jackets that would protect ECG electrodes and leads for several days. For electrode placement, monkeys were sedated with 0.1 mg/kg ketamine hydrochloride (Ketaject, Phoenix Pharmaceuticals, St. Joseph, MO), and standard pediatric heart rate electrodes with self-adhesive pads were adhered to the monkey’s chest. The distal ends of the electrodes were attached to a TM8 telemetry transmitter (Life Sensing Instruments, Tullahoma, TN) that was placed in an inside pocket of a jacket that the monkeys wore to prevent them from manipulating the heart rate electrodes and transmitter. The heart rate signal was received by a HST 220 telemetry receiver (Life Sensing Instruments) and recorded by a computer. Software for the heart rate data collection and storage (Samsedate Heart Rate Variability System) was developed by Autrec (Winston-Salem, NC).

For testing, heart rate was recorded while the monkey sat on the treadmill. Running was then initiated at a speed of 0.8 miles/h (mph; 1.28 km/h), and speed was increased by 0.2 mph every 2 min until the monkey was no longer able to keep pace with the treadmill. Heart rate was recorded for 6 s at the end of each speed interval. Once the monkey reached maximum speed, the treadmill was stopped briefly, and then running was reinitiated at 0.8 mph for a 5-min recovery period. Heart rate was recorded at 1, 3, and 5 min during the recovery period.

Statistical Analyses

For all analyses, normality and homoscedacity were initially tested. If these criteria were met, a repeated-measures ANOVA was utilized to look at differences in variables over time. The assumption of sphericity was examined with Mauchly’s test. The Greenhouse-Geiser correction factor was used in cases where the assumption of sphericity was violated. Least significant difference post hoc tests were used to determine time periods that were significantly different from each other. If the variables were measured twice, then a paired *t*-test was used to look for differences in the variable before and after dieting. Correlations were determined using a Pearson product-moment correlation. If data were not normally distributed and could not be normalized by transformation (using a square root or log transformation), then nonparametric tests were utilized. To look for differences in nonnormally distributed data over time, the Friedman test was used, followed by the Wilcoxon signed ranks test. If variables were measured twice, then a Wilcoxon signed ranks test was utilized. A Spearman’s rho correlation was used to analyze relationships

between parameters that were not normally distributed. Data are presented as means \pm SE. α -Values are considered significant with $P \leq 0.05$. All statistical analyses were conducted using the SPSS software package, version 13.0 (SPSS, Chicago, IL).

RESULTS

During the 1st mo of dieting, available calories were reduced by 30% compared with baseline consumption, and the percentage of calories from fat in the diet was reduced from 35 to 5%. During this 1-mo period, several monkeys ate fewer calories than provided (possibly due to differences in palatability and texture between the diets), so the actual percent decrease in calorie intake was $44 \pm 2.6\%$. At the beginning of the 2nd mo of dieting, available calories were reduced by 60% compared with baseline consumption. A few monkeys continued to eat less food than provided, so that the actual average percent reduction of caloric intake was $68 \pm 0.81\%$.

After 1 mo of dieting, there was no significant weight loss ($P = 0.55$). Body weight was significantly reduced by dieting ($F_{1,85,31.5} = 19.41$, $P < 0.0001$) during the 7th ($P = 0.003$) and 8th wk ($P < 0.0001$) of the dieting (Fig. 1A). The average percentage of weight loss over the 2-mo diet was $6.4 \pm 1.7\%$.

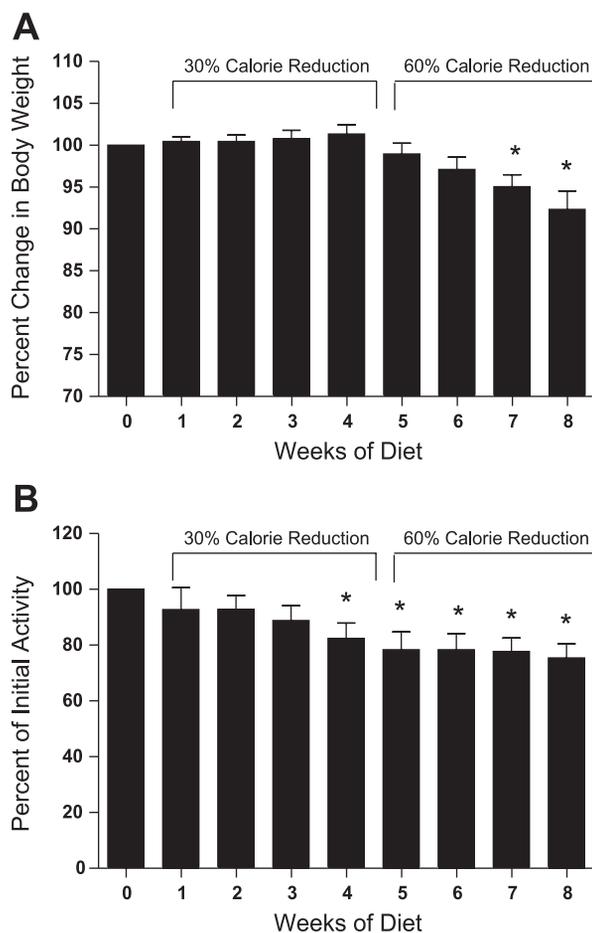


Fig. 1. A: percent change in body weight during 4 wk of 30% calorie restriction and 4 wk of 60% calorie restriction. Weight for each monkey was normalized to its body weight at the beginning of the study (week 0). B: percent change in activity measured by accelerometer during the periods of 30 and 60% calorie restriction, compared with week 0. *Significant change from baseline, $P \leq 0.05$.

Table 1. *Body composition*

	Baseline	After 2-mo Diet
Fat mass, g	1,780 ± 365	1,568 ± 297*
Lean tissue mass, g	5,483 ± 223	5,276 ± 225*
Body fat, %	20.6 ± 3.6	19.6 ± 3.1
Central fat, %	22.7 ± 3.9	22.3 ± 3.5
Peripheral fat, %	57.4 ± 9.8	53.2 ± 8.3
Lean tissue, %	79.4 ± 3.6	80.4 ± 3.1

Values are means ± SE. *Significant difference from baseline measures, $P \leq 0.05$.

Body composition was measured by dual-energy X-ray absorptiometry scan at baseline and at the end of the 2-mo diet period. On average, fat mass decreased from 1,780 ± 365 to 1,568 ± 297 g [$t = 2.3$, degrees of freedom (df) = 15, $P = 0.04$; Table 1] and lean tissue mass from 5,483 ± 223 to 5,276 ± 225 g ($t = 2.4$, df = 15, $P = 0.03$; Table 1) during the 2-mo diet. However, dieting did not change percent body fat ($P = 0.28$; Table 1) or body fat distribution [as the percentage of fat distributed centrally ($P = 0.36$) and peripherally ($P = 0.23$) did not change; Table 1].

In contrast to weight loss, daily activity level began to decrease soon after placement on the diet ($F_{3,4,47.4} = 5.13$, $P = 0.03$; Fig. 1B) and was significantly decreased by the end of the 4th wk of dieting (18 ± 5.6% decrease in activity, $P = 0.02$). During the 2nd mo of dieting, physical activity was further suppressed (26 ± 7.6% decrease in activity, $P < 0.0001$).

In response to the decrease in available calories, total daily energy expenditure decreased by 68 ± 12 kcal/day by the end of 2 mo of dieting ($t = 5.3$, df = 15, $P < 0.0001$; Fig. 2A). Activity-associated energy expenditure significantly decreased by 41 ± 9 kcal/day ($t = -5.5$, df = 16, $P < 0.0001$; Fig. 2B). The loss of metabolically active tissue due to dieting accounted for a decrease in energy expenditure of 21 ± 5 kcal/day. Dieting did not affect the thermic effect of an isocaloric meal ($P = 0.81$; data not shown) or respiratory quotient ($P = 0.20$; data not shown).

To determine whether participating in a regular exercise program that is generally recommended to prevent weight gain and promote weight loss (15) would be able to counteract the diet-induced decrease in physical activity, three additional adult female rhesus monkeys were trained to run on a treadmill at 80% maximal capacity for 1 h/day, 5 days/wk, for 3 mo. Participating in this exercise program was calculated to increase daily calorie expenditure by 69.6 ± 10.7 kcal/day ($t = -5.82$, df = 2, $P = 0.03$, equivalent to 49 kcal/day for a 7-day wk; Fig. 3A). The exercising monkeys experienced an average of a 6.1 ± 1.2% weight loss during the 3-mo exercise period. Exercising for 1 h a day did not significantly change total activity during the other 23 h of the day ($t = -0.39$ df = 2, $P = 0.74$; Fig. 3B).

DISCUSSION

In this study, we characterized the compensatory decreases in activity and metabolic rate that accompany the initial stages of diet-induced weight loss in a nonhuman primate model of postmenopausal women. During the 1st mo of dieting, no significant weight loss occurred; however, daily physical activity level of the monkeys rapidly decreased after diet initiation and was significantly lower during the 4th wk of dieting (18 ± 5.6% decrease). During the 2nd mo of dieting, physical activity was further suppressed (26 ± 7.6% decrease), and, by the end of the 2nd mo of dieting, monkeys had lost a significant amount of weight (6.4 ± 1.7% of initial weight). However, it was minimal considering the substantial diet that they had been on for 2 mo. A compensatory decrease in total energy expenditure (13% decrease) occurred in response to the diet, similar in magnitude to what has been previously reported in humans during dieting (12, 13, 26, 43, 75). Two thirds of the decrease in energy expenditure resulted from the decrease in level of physical activity, and in a second study we showed a similar amount of calories is expended by undertaking a moderate exercise routine of running 5 h/wk, at a level recommended by the American College of Sports Medicine to prevent weight gain and promote weight loss (25). Thus we conclude that diet-induced decreases in the level of physical activity is the primary mechanism the body uses to defend against diet-induced weight loss, and undertaking an exercise program of 5 h of running per week is able to prevent the compensation in physical activity-induced calorie expenditure that slows diet-induced weight loss.

Activity-associated energy expenditure was reduced after 2 mo of dieting due to both the decrease in movement (i.e., amount and intensity of activity), and because it takes less energy to move a reduced body weight (1, 2). This finding supports previous reports in rhesus monkeys (32, 54) and humans (13, 33, 43, 74) that report a decrease in physical activity accompanying reductions in calorie intake. In contrast, rodents show an increase in activity in response to calorie reduction (8, 17, 45, 57). It is hypothesized that rodents increase their activity due to an increased drive to forage for food, as the elevated activity is decreased when food is made available (36). The differential regulation of physical activity in response to calorie reduction has been hypothesized to be dependent on whether an animal has a sufficient amount of stored energy to make it through a time of famine, metabolizing stored energy (slowing activity would protect their energy stores), or whether their stored energy is low, and thus survival would be dependent on finding food, and increasing activity would facilitate foraging (52, 53). A study in emperor penguins provides further support for this hypothesis, as the penguins decrease their activity in response to the first 3 mo of fasting, but, when their energy stores become depleted, their activity begins to increase (56).

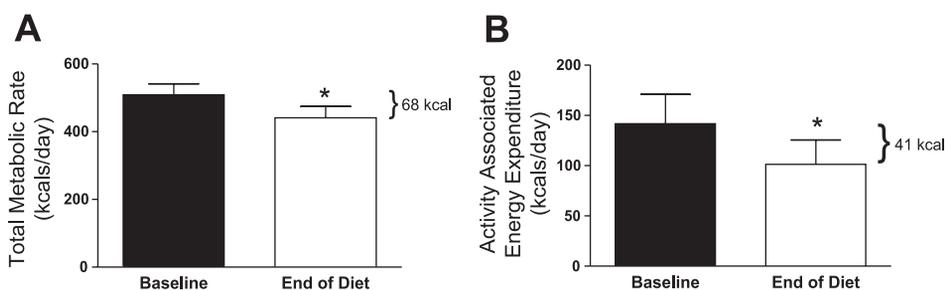
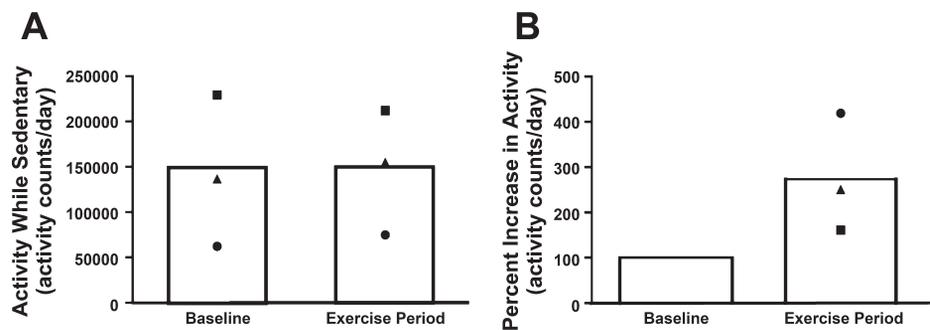


Fig. 2. A: total metabolic rate, measured across a 24-h day in each monkey at baseline (solid bar) and at the end of the 8-wk diet period (open bar). The mean decrease in metabolic rate from the beginning to end of the diet period was 68 kcal. B: activity-associated energy expenditure measured across a 24-h day in each monkey at baseline (solid bar) and at the end of the 8-wk diet period (open bar). The mean decrease in activity-associated energy expenditure was 41 kcal. *Significant difference from baseline, $P \leq 0.05$.

Fig. 3. A: mean activity measured across the 24-h day by accelerometer in 3 monkeys (symbols) at baseline, before monkeys started running on the treadmill 5 days/wk, and mean activity during the 23 h/day when monkeys were not running at the end of 12 wk of running (mean activity shown by bars). B: percent increase in total activity measured across the 24-h day at the end of 12 wk of running compared with the baseline period.



A potential concern of using accelerometers mounted on collars to measure physical activity is the accuracy with which they detect whole body movement. To address this, we conducted a validation study in which we simultaneously measured physical activity by accelerometers mounted on collars and videotaped 16 monkeys (51). Frame-by-frame analysis was used to determine which behaviors generated activity counts, and we found that activity counts were strongly associated with whole body movement, but, not head, neck, or limb movement (51). More recently, we have used accelerometer-derived data to assess sleep, looked at the minute-by-minute data, and found the monkeys sit for longer periods of time than humans and that there are long stretches in the night and day in which zero activity counts are detected. Based on these studies, we believe that collar-worn accelerometers are an excellent way to accurately assess physical activity in nonhuman primates. It is also important to note that the monkeys used in *experiment 1* were individually housed. Interestingly, we find that the activity level of an individual animal is similar in individual cages and group housing (65); thus we feel that the findings in this experiment are also applicable to individuals with access to a larger housing environment.

Two studies have reported that exercise can prevent a diet-induced decrease in energy expenditure (20, 47). In contrast, two other studies comparing weight loss in individuals that either dieted or dieted and exercised report similar weight loss (27), or greater weight loss in the group that only dieted (4). The studies showing an exercise-induced prevention of diet-induced energy expenditure documented participation in an exercise program, but did not directly measure daily level of physical activity, and so did not examine whether participating in purposeful exercise for a part of the day would change physical activity level during the remaining portion of the day. To address this directly, in the present study, a second group of three monkeys ran on a treadmill for 1 h/day, 5 days/wk. We found this led to a $6.1 \pm 1.2\%$ weight loss and a calculated increase in calorie expenditure of 69.6 ± 10.7 kcal/day (equivalent to 49 kcal/day for 7 days) and after a 3-mo period. Importantly, exercising did not change the amount of physical activity during the other 23 h of the day. This finding suggests that combining exercise with dieting will promote weight loss by compensating for the diet-induced decrease in energy expenditure. However, this conclusion is based on a calculation, and it would be worthwhile for future studies to directly test this hypothesis by measuring exercise-associated energy expenditure during dieting. In humans, running 1 h/day, five times a week expends between 700 (for the average woman) and 860 (for the average man) extra calories per day (2). As in monkeys, this expenditure would similarly compensate for the decrease in physical activity in response to dieting [$167 \text{ kcal/day} \times 5 \text{ days/wk} =$

835 kcal (74)] and would thereby enhance diet-induced weight loss. In addition to participating in planned exercise regimens, recent studies indicate that it is possible to effectively increase daily physical activity by making small life-style changes, such as playing activity-promoting video games instead of traditional video games (39), and standing instead of sitting at desks while at school or work (40).

In this study, we found that dieting decreased both fat mass and lean tissue mass, but did not change overall percent body fat. Similar results have been reported in several human studies, which find that caloric restriction reduces both fat and lean tissue mass (48, 76). In contrast, other studies report that the majority of weight loss with a low-calorie diet is fat mass (75%) (3, 6). The loss in lean tissue with dieting is concerning, and dieting has also been reported to decrease muscle tissue mass, strength, and aerobic capacity (76). In contrast, weight loss occurring with exercise has been shown not to decrease lean tissue mass (67) and to actually improve strength and muscle mass (76). Thus combining exercise with dieting is important in maintaining physical fitness and preserving muscle mass, while still reducing body fat mass.

It is important to note that the monkeys in this study were ovariectomized females, an animal model of postmenopausal women. Several studies find that the body weight and fat responses to the initiation of exercise training and to energy deficit are sex dependent (16, 24). Thus the results of this study are most applicable to postmenopausal women, and caution should be used in extending the findings to premenopausal females and to males. Future studies are needed that objectively measure activity in premenopausal females and in males during diet-induced weight loss.

We conclude that decreased physical activity is the primary mechanism the body uses to defend against diet-induced weight loss, and an exercise program of 5 h of running per week is sufficient to prevent the diet-induced decrease in activity. As losing weight and then maintaining weight loss is quite difficult for most people, the findings of this study argue that increased emphasis should be placed on preventing weight gain over adulthood. Our previous studies indicate that the amount of physical activity that an individual undertakes is the best predictor of adult weight gain (66), suggesting that development of obesity in adulthood could be best prevented by maintaining elevated levels of physical activity across the adult years. Thus increased physical activity appears to be the most effective means of both preventing and treating adulthood obesity.

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DISCLOSURES

No conflicts of interest are declared by the author(s).

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