

The NEW ENGLAND JOURNAL of MEDICINE

ESTABLISHED IN 1812

JULY 17, 2008

VOL. 359 NO. 3

Weight Loss with a Low-Carbohydrate, Mediterranean, or Low-Fat Diet

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ABSTRACT

BACKGROUND

Trials comparing the effectiveness and safety of weight-loss diets are frequently limited by short follow-up times and high dropout rates.

METHODS

In this 2-year trial, we randomly assigned 322 moderately obese subjects (mean age, 52 years; mean body-mass index [the weight in kilograms divided by the square of the height in meters], 31; male sex, 86%) to one of three diets: low-fat, restricted-calorie; Mediterranean, restricted-calorie; or low-carbohydrate, non-restricted-calorie.

RESULTS

The rate of adherence to a study diet was 95.4% at 1 year and 84.6% at 2 years. The Mediterranean-diet group consumed the largest amounts of dietary fiber and had the highest ratio of monounsaturated to saturated fat ($P<0.05$ for all comparisons among treatment groups). The low-carbohydrate group consumed the smallest amount of carbohydrates and the largest amounts of fat, protein, and cholesterol and had the highest percentage of participants with detectable urinary ketones ($P<0.05$ for all comparisons among treatment groups). The mean weight loss was 2.9 kg for the low-fat group, 4.4 kg for the Mediterranean-diet group, and 4.7 kg for the low-carbohydrate group ($P<0.001$ for the interaction between diet group and time); among the 272 participants who completed the intervention, the mean weight losses were 3.3 kg, 4.6 kg, and 5.5 kg, respectively. The relative reduction in the ratio of total cholesterol to high-density lipoprotein cholesterol was 20% in the low-carbohydrate group and 12% in the low-fat group ($P=0.01$). Among the 36 subjects with diabetes, changes in fasting plasma glucose and insulin levels were more favorable among those assigned to the Mediterranean diet than among those assigned to the low-fat diet ($P<0.001$ for the interaction among diabetes and Mediterranean diet and time with respect to fasting glucose levels).

CONCLUSIONS

Mediterranean and low-carbohydrate diets may be effective alternatives to low-fat diets. The more favorable effects on lipids (with the low-carbohydrate diet) and on glycemic control (with the Mediterranean diet) suggest that personal preferences and metabolic considerations might inform individualized tailoring of dietary interventions. (ClinicalTrials.gov number, NCT00160108.)

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N Engl J Med 2008;359:229-41
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THE DRAMATIC INCREASE IN OBESITY worldwide remains challenging and underscores the urgent need to test the effectiveness and safety of several widely used weight-loss diets.¹⁻³ Low-carbohydrate, high-protein, high-fat diets (referred to as low-carbohydrate diets) have been compared with low-fat, energy-restricted diets.⁴⁻⁹ A meta-analysis of five trials with 447 participants¹⁰ and a recent 1-year trial involving 311 obese women⁴ suggested that a low-carbohydrate diet is a feasible alternative to a low-fat diet for producing weight loss and may have favorable metabolic effects. However, longer-term studies are lacking.^{4,10} A Mediterranean diet with a moderate amount of fat and a high proportion of monounsaturated fat provides cardiovascular benefits.¹¹ A recent review citing several trials¹² included a few that suggested that the Mediterranean diet was beneficial for weight loss.^{13,14} However, this positive effect has not been conclusively demonstrated.¹⁵

Common limitations of dietary trials include high attrition rates (15 to 50% within a year), small size, short duration, lack of assessment of adherence, and unequal intensity of intervention.^{10,12,15-17} We conducted the 2-year Dietary Intervention Randomized Controlled Trial (DIRECT) to compare the effectiveness and safety of three nutritional protocols: a low-fat, restricted-calorie diet; a Mediterranean, restricted-calorie diet; and a low-carbohydrate, non-restricted-calorie diet.

METHODS

ELIGIBILITY AND STUDY DESIGN

We conducted the trial between July 2005 and June 2007 in Dimona, Israel, in a workplace at a research center with an on-site medical clinic. Recruitment began in December 2004. The criteria for eligibility were an age of 40 to 65 years and a body-mass index (BMI, the weight in kilograms divided by the square of the height in meters) of at least 27, or the presence of type 2 diabetes (according to the American Diabetes Association criteria¹⁸) or coronary heart disease, regardless of age and BMI. Persons were excluded if they were pregnant or lactating, had a serum creatinine level of 2 mg per deciliter (177 μ mol per liter) or more, had liver dysfunction (an increase by a factor of at least 2 above the upper limit of normal in alanine aminotransferase and aspartate aminotransferase levels), had gastro-

intestinal problems that would prevent them from following any of the test diets, had active cancer, or were participating in another diet trial.

The participants were randomly assigned within strata of sex, age (below or above the median), BMI (below or above the median), history of coronary heart disease (yes or no), history of type 2 diabetes (yes or no), and current use of statins (none, <1 year, or \geq 1 year) with the use of Monte Carlo simulations. The participants received no financial compensation or gifts. The study was approved and monitored by the human subjects committee of Soroka Medical Center and Ben-Gurion University. Each participant provided written informed consent.

The members of each of the three diet groups were assigned to subgroups of 17 to 19 participants, with six subgroups for each group. Each diet group was assigned a registered dietitian who led all six subgroups of that group. The dietitians met with their groups in weeks 1, 3, 5, and 7 and thereafter at 6-week intervals, for a total of 18 sessions of 90 minutes each. We adapted the Israeli version (developed by the Maccabi Health Maintenance Organization) of the diabetes-prevention program¹⁹ and developed additional themes for each diet group (see Supplementary Appendix 1, available with the full text of this article at www.nejm.org). In order to maintain equal intensity of treatment, the workshop format and the quality of the materials were similar among the three diet groups, except for instructions and materials specific to each diet strategy. Six times during the 2-year intervention, another dietitian conducted 10-to-15-minute motivational telephone calls with participants who were having difficulty adhering to the diets and gave a summary of each call to the group dietitian. In addition, a group of spouses received education to strengthen their support of the participants (data not shown).

LOW-FAT DIET

The low-fat, restricted-calorie diet was based on American Heart Association²⁰ guidelines. We aimed at an energy intake of 1500 kcal per day for women and 1800 kcal per day for men, with 30% of calories from fat, 10% of calories from saturated fat, and an intake of 300 mg of cholesterol per day. The participants were counseled to consume low-fat grains, vegetables, fruits, and legumes and to limit their consumption of additional fats, sweets, and high-fat snacks.

MEDITERRANEAN DIET

The moderate-fat, restricted-calorie, Mediterranean diet was rich in vegetables and low in red meat, with poultry and fish replacing beef and lamb. We restricted energy intake to 1500 kcal per day for women and 1800 kcal per day for men, with a goal of no more than 35% of calories from fat; the main sources of added fat were 30 to 45 g of olive oil and a handful of nuts (five to seven nuts, <20 g) per day. The diet is based on the recommendations of Willett and Skerrett.²¹

LOW-CARBOHYDRATE DIET

The low-carbohydrate, non-restricted-calorie diet aimed to provide 20 g of carbohydrates per day for the 2-month induction phase and immediately after religious holidays, with a gradual increase to a maximum of 120 g per day to maintain the weight loss. The intakes of total calories, protein, and fat were not limited. However, the participants were counseled to choose vegetarian sources of fat and protein and to avoid trans fat. The diet was based on the Atkins diet (see Supplementary Appendix 2).²²

NUTRITIONAL AND COLOR LABELING OF FOOD IN THE CAFETERIA

Lunch is typically the main meal in Israel. The self-service cafeteria in the workplace provided a varied menu and was the exclusive source of lunch for the participants. A dietitian worked closely with the kitchen staff to adjust specific food items to specific diet groups. Each food item was provided with a label showing the number of calories and the number of grams of carbohydrates, fat, and saturated fat, according to an analysis based on the Israeli nutritional database. Each food item was also labeled with a full circle (indicating "feel free to consume") or a half circle (indicating "consume in moderation"). The labels were color-coded according to diet group and were updated daily (see Supplementary Appendix 2).²³

ELECTRONIC QUESTIONNAIRES AT BASELINE AND FOLLOW-UP

Adherence to the diets was evaluated by a validated food-frequency questionnaire²⁴ that included 127 food items and three portion-size pictures for 17 items.²⁵ A subgroup of participants completed two repeated 24-hour dietary recalls to verify absolute intake (data not shown). We used a validated questionnaire to assess physical activity.²⁶

At baseline and at 6, 12, and 24 months of follow-up, the questionnaires were self-administered electronically through the workplace intranet. The 15% of participants who requested aid in completing the questionnaires were assisted by the study nurse. The electronic questionnaire helped to ensure completeness of the data by prompting the participant when a question was not answered, and it permitted rapid automated reporting by the group dietitians.

OUTCOMES

The participants were weighed without shoes to the nearest 0.1 kg every month. With the use of a wall-mounted stadiometer, height was measured to the nearest millimeter at baseline for determination of BMI. Waist circumference was measured halfway between the last rib and the iliac crest. Blood pressure was measured every 3 months with the use of an automated system (Datascop Acutor 4) after 5 minutes of rest.

Blood samples were obtained by venipuncture at 8 a.m. after a 12-hour fast at baseline and at 6, 12, and 24 months and were stored at -80°C until an assay for lipids, inflammatory biomarkers, and insulin could be performed. Levels of fasting plasma glucose, glycated hemoglobin, and liver enzymes were measured in fresh samples. The level of glycated hemoglobin was determined with the use of Cobas Integra reagents and equipment. Serum levels of total cholesterol, high-density-lipoprotein (HDL) cholesterol, low-density-lipoprotein (LDL) cholesterol, and triglycerides were determined enzymatically with a Wako R-30 automatic analyzer, with coefficients of variation of 1.3% for cholesterol and 2.1% for triglycerides. Plasma insulin levels were measured with the use of an enzyme immunometric assay (Immulite automated analyzer, Diagnostic Products), with a coefficient of variation of 2.5%. Plasma levels of high-molecular-weight adiponectin were measured by an enzyme-linked immunosorbent assay (ELISA) (AdipoGen or Axxora), with a coefficient of variation of 4.8%. Plasma leptin levels were assessed by ELISA (Mediagnost), with a coefficient of variation of 2.4%. Plasma levels of high-sensitivity C-reactive protein were measured by ELISA (DiaMed), with a coefficient of variation of 1.9%. The clinic and laboratory staff members were unaware of the treatment assignments, and the study coordinators were unaware of all outcome data until the end of the intervention.

STATISTICAL ANALYSIS

For weight loss, the prespecified primary aim was the change in weight from baseline to 24 months. We used the Israeli food database²³ in the analysis of the results of the dietary questionnaires. We analyzed the dietary-composition data and biomarkers with the use of raw unadjusted means, without imputation of missing data. We compared the dietary-intake values between groups at each time point with the use of an analysis of variance in which all pairwise comparisons among the three diet groups were performed with the use of Tukey's Studentized range test. We transformed physical-activity scores into metabolic equivalents per week²⁷ according to the amount of time spent in various forms of exercise per week, with each activity weighted in terms of its level of intensity. For intention-to-treat analyses, we included all 322 participants and used the most recent values for weight and blood pressure. To evaluate the repeated measurements over time, we used generalized estimating equations for panel data analysis, also known as cross-sectional time-series analysis, with the use of the Stata software XTGEE command; this allowed us to account for the non-independence of repeated measurements of the same bioindicator in the same participant over time. We used age, sex, time point, and diet group as explanatory variables in our models. To study changes over time and the effects of sex or the presence or absence of diabetes, we added appropriate interaction terms. We assessed the within-person changes from baseline in each diet group with the use of pairwise comparisons. We calculated the homeostasis model assessment of insulin resistance (HOMA-IR) according to the following equation²⁸: $\text{insulin (U/ml)} \times \text{fasting glucose (mmol/liter)} \div 22.5$. For a mean (\pm SD) difference between groups of at least 2 ± 10 kg of weight loss, with 100 participants per group and a type I error of 5%, the power to detect significant differences in weight loss is greater than 90%. We used SPSS software, version 15, and Stata software, version 9, for the statistical analysis.

RESULTS**CHARACTERISTICS OF THE PARTICIPANTS**

The baseline characteristics of the participants are shown in Table 1. The mean age was 52 years and the mean BMI was 31. Most participants (86%) were men. The overall rate of adherence

(Fig. 1) was 95.4% at 12 months and 84.6% at 24 months; the 24-month adherence rates were 90.4% in the low-fat group, 85.3% in the Mediterranean-diet group, and 78.0% in the low-carbohydrate group ($P=0.04$ for the comparison among diet groups). During the study, there was little change in usage of medications, and there were no significant differences among groups in the amount of change; four participants initiated and three stopped cholesterol-lowering therapy. Twenty participants initiated blood-pressure treatment, five initiated medications for glycemic control, and one reduced the dosage of medications for glycemic control.

DIETARY INTAKE, ENERGY EXPENDITURE, AND URINARY KETONES

At baseline, there were no significant differences in the composition of the diets consumed by participants assigned to the low-fat, Mediterranean, and low-carbohydrate diets. Daily energy intake, as assessed by the food-frequency questionnaire, decreased significantly at 6, 12, and 24 months in all diet groups as compared with baseline ($P<0.001$); there were no significant differences among the groups in the amount of decrease (Table 2). The low-carbohydrate group had a lower intake of carbohydrates ($P<0.001$) and higher intakes of protein ($P<0.001$), total fat ($P<0.001$), saturated fat ($P<0.001$), and total cholesterol ($P=0.04$) than the other groups. The Mediterranean-diet group had a higher ratio of mono-unsaturated to saturated fat than the other groups ($P<0.001$) and a higher intake of dietary fiber than the low-carbohydrate group ($P=0.002$). The low-fat group had a lower intake of saturated fat than the low-carbohydrate group ($P=0.02$). The amount of physical activity increased significantly from baseline in all groups, with no significant difference among groups in the amount of increase. The proportion of participants with detectable urinary ketones at 24 months was higher in the low-carbohydrate group (8.3%) than in the low-fat group (4.8%) or the Mediterranean-diet group (2.8%) ($P=0.04$).

WEIGHT LOSS

A phase of maximum weight loss occurred from 1 to 6 months and a maintenance phase from 7 to 24 months. All groups lost weight, but the reductions were greater in the low-carbohydrate and the Mediterranean-diet groups ($P<0.001$ for the inter-

Table 1. Baseline Characteristics of the Study Population.*

Characteristic	Low-Fat Diet (N=104)	Mediterranean Diet (N=109)	Low- Carbohydrate Diet (N=109)	All (N=322)
Age — yr	51±7	53±6	52±7	52±7
Male sex — no. (%)	89 (86)	89 (82)	99 (91)	277 (86)
Current smoker — no. (%)	19 (18)	16 (15)	16 (15)	51 (16)
Weight — kg	91.3±12.3	91.1±13.6	91.8±14.3	91.4±13.4
BMI	30.6±3.2	31.2±4.1	30.8±3.5	30.9±3.6
Blood pressure — mm Hg†				
Systolic	129.6±13.2	133.1±14.1	130.8±15.1	131.3±14.5
Diastolic	79.1±9.1	80.6±9.2	79.4±9.1	79.7±9.2
Waist circumference — cm‡	105.3±9.2	106.2±9.1	106.3±9.1	105.9±9.1
Type 2 diabetes — no. (%)	12 (12)	15 (14)	19 (17)	46 (14)
Coronary heart disease — no. (%)	38 (37)	46 (42)	34 (31)	118 (37)
Blood biomarkers				
Serum LDL cholesterol — mg/dl	117.0±35.6	122.8±34.4	117.2±34.5	119.0±34.8
Serum HDL cholesterol — mg/dl	38.6±9.6	39.4±9.4	37.5±8.7	38.5±9.2
Serum triglycerides — mg/dl	156.5±62.4	173.6±67.7	181.7±116.9	170.8±90.0
Serum non-HDL cholesterol — mg/dl	154.2±37.9	163.3±35.8	161.3±36.0	159.6±36.7
Ratio of total cholesterol to HDL cholesterol	5.2±1.4	5.4±1.6	5.6±1.7	5.4±1.6
Fasting plasma insulin — μU/ml	13.3±6.8	14.6±8.0	14.1±10.2	14.0±8.5
Fasting plasma glucose — mg/dl	86.9±26.0	94.3±38.1	92.6±28.5	91.3±31.5
HOMA-IR	2.9±1.8	3.6±2.9	3.2±2.9	3.2±2.6
Plasma high-sensitivity C-reactive protein — mg/liter	3.6±2.9	4.6±3.4	4.5±3.3	4.2±3.2
Plasma high-molecular-weight adiponectin — mg/dl	7.3±2.6	7.3±2.8	7.3±3.1	7.3±2.8
Plasma leptin — mg/dl	12.0±9.6	14.2±13.2	11.2±8.1	12.5±10.5
Plasma bilirubin — mg/dl	0.74±0.34	0.79±0.35	0.77±0.36	0.77±0.34
Plasma alkaline phosphatase — U/liter	71.4±18.0	74.2±20.1	71.6±17.7	72.4±18.6
Plasma alanine aminotransferase — U/liter	28.2±14.2	27.7±12.6	28.3±11.2	28.1±12.7
Medications in current use				
Lipid-lowering therapy — no. (%)	28 (27)	29 (27)	27 (25)	84 (26)
Antihypertensive therapy — no. (%)	23 (22)	37 (34)	36 (33)	96 (30)
Hormone-replacement therapy — no. (%)	0	3 (3)	4 (4)	7 (2)
Oral glycemic-control medications — no. (%)	6 (6)	7 (6)	13 (12)	26 (8)
Insulin treatment — no. (%)	2 (2)	0	2 (2)	4 (1)

* Plus-minus values are means ±SD. To convert values for cholesterol to millimoles per liter, multiply by 0.02586. To convert values for triglycerides to millimoles per liter, multiply by 0.01129. To convert values for glucose to millimoles per liter, multiply by 0.05551. To convert values for bilirubin to micromoles per liter, multiply by 17.1. BMI denotes body-mass index, HDL high-density lipoprotein, HOMA-IR homeostasis model assessment of insulin resistance, and LDL low-density lipoprotein.

† Data were available from 297 participants.

‡ Data were available from 302 participants.

action between diet group and time) than in the low-fat group (Fig. 2). The overall weight changes among the 322 participants at 24 months were -2.9 ± 4.2 kg for the low-fat group, -4.4 ± 6.0 kg for the Mediterranean-diet group, and -4.7 ± 6.5 kg for the low-carbohydrate group. Among the 277 male participants, the mean 24-month weight changes were -3.4 kg (95% confidence interval [CI], -4.3 to -2.5) for the low-fat group, -4.0 kg (95% CI, -5.1 to -3.0) for the Mediterranean-diet

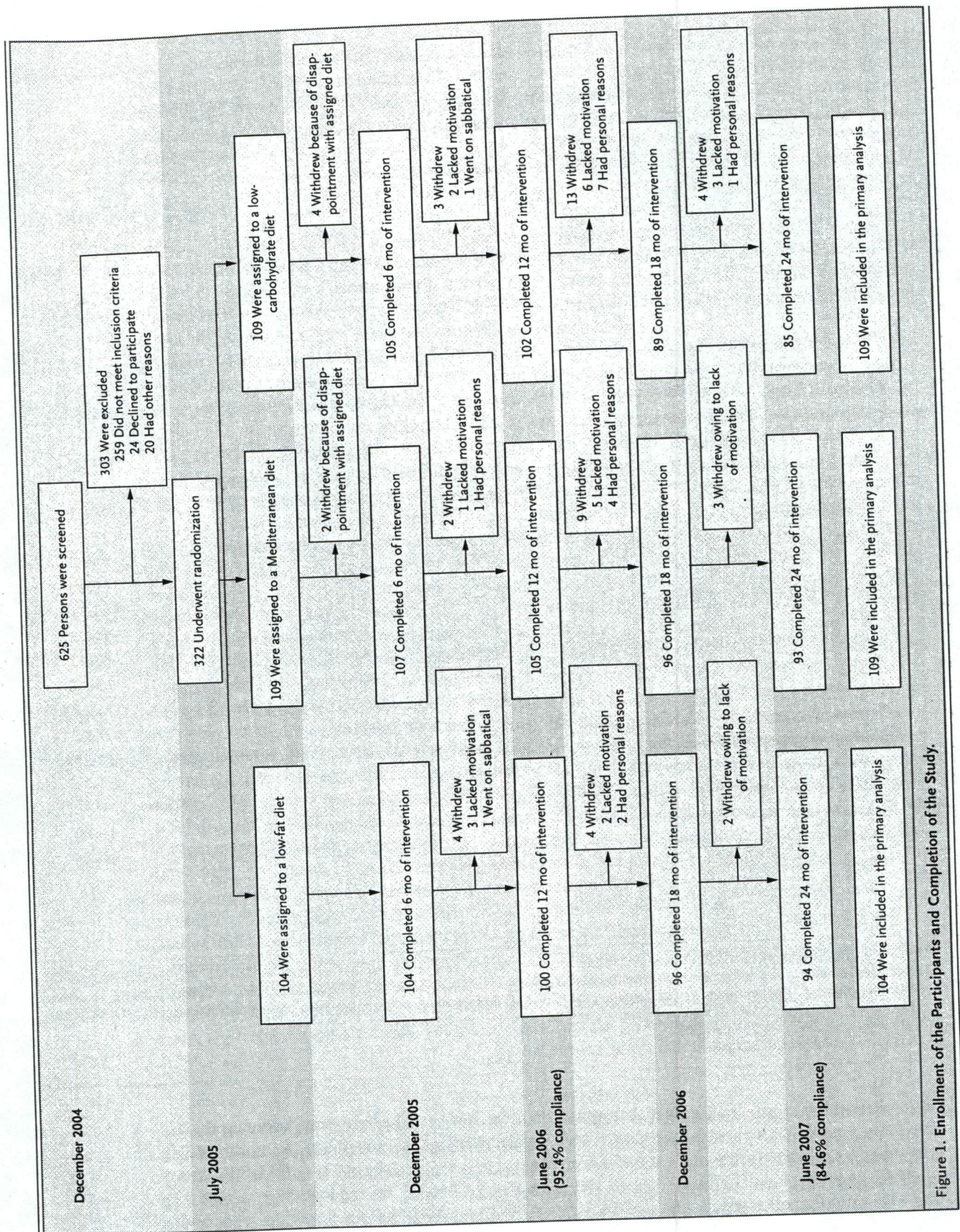


Figure 1. Enrollment of the Participants and Completion of the Study.

group, and -4.9 kg (95% CI, -6.2 to -3.6) for the low-carbohydrate group. Among the 45 women, the mean 24-month weight changes were -0.1 kg (95% CI, -2.2 to 1.9) for the low-fat group, -6.2 kg (95% CI, -10.2 to -1.9) for the Mediterranean-diet group, and -2.4 kg (95% CI, -6.9 to 2.2) for the low-carbohydrate group ($P < 0.001$ for the interaction between diet group and sex). The mean weight changes among the 272 participants who completed 24 months of intervention were -3.3 ± 4.1 kg in the low-fat group, -4.6 ± 6.0 kg in the Mediterranean-diet group, and -5.5 ± 7.0 kg in the low-carbohydrate group ($P = 0.03$ for the comparison between the low-fat and the low-carbohydrate groups at 24 months). The mean (\pm SD) changes in BMI were -1.0 ± 1.4 in the low-fat group, -1.5 ± 2.2 in the Mediterranean-diet group, and -1.5 ± 2.1 in the low-carbohydrate group ($P = 0.05$ for the comparison among groups).

All groups had significant decreases in waist circumference and blood pressure, but the differences among the groups were not significant. The waist circumference decreased by a mean of 2.8 ± 4.3 cm in the low-fat group, 3.5 ± 5.1 cm in the Mediterranean-diet group, and 3.8 ± 5.2 cm in the low-carbohydrate group ($P = 0.33$ for the comparison among groups). Systolic blood pressure fell by 4.3 ± 11.8 mm Hg in the low-fat group, 5.5 ± 14.3 mm Hg in the Mediterranean-diet group, and 3.9 ± 12.8 mm Hg in the low-carbohydrate group ($P = 0.64$ for the comparison among groups). The corresponding decreases in diastolic pressure were 0.9 ± 8.1 , 2.2 ± 9.5 , and 0.8 ± 8.7 mm Hg ($P = 0.43$ for the comparison among groups).

LIPID PROFILES

Changes in lipid profiles during the weight-loss and maintenance phases are shown in Figure 3. HDL cholesterol (Fig. 3A) increased during the weight-loss and maintenance phases in all groups, with the greatest increase in the low-carbohydrate group (8.4 mg per deciliter [0.22 mmol per liter], $P < 0.01$ for the interaction between diet group and time), as compared with the low-fat group (6.3 mg per deciliter [0.16 mmol per liter]). Triglyceride levels (Fig. 3B) decreased significantly in the low-carbohydrate group (23.7 mg per deciliter [0.27 mmol per liter], $P = 0.03$ for the interaction between diet group and time), as compared with the low-fat group (2.7 mg per deciliter [0.03 mmol per liter]). LDL cholesterol levels (Fig. 3C) did not change significantly within groups, and

there were no significant differences between the groups in the amount of change. Overall, the ratio of total cholesterol to HDL cholesterol (Fig. 3D) decreased during both the weight-loss and the maintenance phases. The low-carbohydrate group had the greatest improvement, with a relative decrease of 20% ($P = 0.01$ for the interaction between diet group and time), as compared with a decrease of 12% in the low-fat group.

HIGH-SENSITIVITY C-REACTIVE PROTEIN, HIGH-MOLECULAR-WEIGHT ADIPONECTIN, AND LEPTIN

The level of high-sensitivity C-reactive protein decreased significantly ($P < 0.05$) only in the Mediterranean-diet group (21%) and the low-carbohydrate group (29%), during both the weight-loss and the maintenance phases, with no significant differences among the groups in the amount of decrease (Fig. 4A). During both the weight-loss and the maintenance phases, the level of high-molecular-weight adiponectin (Fig. 4B) increased significantly ($P < 0.05$) in all diet groups, with no significant differences among the groups in the amount of increase. Circulating leptin, which reflects body-fat mass, decreased significantly ($P < 0.05$) in all diet groups, with no significant differences among the groups in the amount of decrease; the decrease in leptin paralleled the decrease in body weight during the two phases (Fig. 4C). The interaction between the effects of low-carbohydrate diet and sex on the reduction of leptin ($P = 0.04$), as compared with the low-fat diet, reflects the greater effect of the low-carbohydrate diet among men.

FASTING PLASMA GLUCOSE, HOMA-1R, AND GLYCATED HEMOGLOBIN

Among the 36 participants with diabetes (Fig. 4D), only those in the Mediterranean-diet group had a decrease in fasting plasma glucose levels (32.8 mg per deciliter); this change was significantly different from the increase in plasma glucose levels among participants with diabetes in the low-fat group ($P < 0.001$ for the interaction between diet group and time). There was no significant change in plasma glucose level among the participants without diabetes ($P < 0.001$ for the interaction among diabetes and Mediterranean diet and time). In contrast, insulin levels (Fig. 4E) decreased significantly in participants with diabetes and in those without diabetes in all diet groups, with no significant differences among groups in the

amount of decrease. Among the participants with diabetes, the decrease in HOMA-IR at 24 months (Fig. 4F) was significantly greater in those assigned to the Mediterranean diet than in those assigned to the low-fat diet (2.3 and 0.3, respectively; $P=0.02$; $P=0.04$ for the interaction among diabetes and Mediterranean diet and time). Among the participants with diabetes, the proportion of glycosylated hemoglobin at 24 months decreased by $0.4\pm 1.3\%$ in the low-fat group, $0.5\pm 1.1\%$ in the Mediterranean-diet group, and $0.9\pm 0.8\%$ in the low-carbohydrate group. The changes were signifi-

Table 2. Changes in Dietary Intake, Energy Expenditure, and Urinary Ketones during 2 Years of Intervention.*

Variable	Low-Fat Diet	Mediterranean Diet	Low-Carbohydrate Diet	P Value†
Energy change from baseline (kcal/day)				
6 mo	-458.3±1412.9	-254.6±740.6	-560.8±1568.3	0.22
12 mo	-559.1±1764.8	-321.7±802.4	-591.1±1472.9	0.33
24 mo	-572.6±1638.0	-371.9±864.2	-550.0±1453.9	0.55
Carbohydrate				
% of energy				
Baseline	51.8±8.1	51.5±8.3	50.8±8.4	0.63
6 mo	50.4±6.9	49.8±8.0	41.4±9.3‡	<0.001
12 mo	50.5±6.8	50.0±7.7	41.6±8.8‡	<0.001
24 mo	50.7±5.7	50.2±8.6	40.4±7.1‡	<0.001
Change from baseline (g/day)				
6 mo	-69.1±191.7	-39.6±98.1	-123.6±223.5‡	0.003
12 mo	-83.4±215.8	-49.0±112.3	-127.7±216.3‡	0.01
24 mo	-82.8±202.0	-50.5±126.1	-129.8±212.6‡	0.02
Protein				
% of energy				
Baseline	18.2±3.3	18.4±3.8	18.7±3.8	0.61
6 mo	19.6±3.7	18.9±3.6	21.6±3.5‡	<0.001
12 mo	19.4±3.4	18.9±3.6	21.5±4.0‡	<0.001
24 mo	19.0±3.2	18.8±3.5	21.8±3.9‡	<0.001
Change from baseline (g/day)				
6 mo	-12.8±58.7	-10.2±47.7	-10.2±69.7	0.99
12 mo	-16.7±84.9	-12.2±47.6	-11.8±69.3	0.86
24 mo	-19.8±75.0	-17.5±48.1	-6.9±66.6	0.38
Total fat				
% of energy				
Baseline	31.4±4.7	31.7±4.9	32.1±5.5	0.65
6 mo	30.7±4.0	33.2±5.1	38.8±6.9‡	<0.001
12 mo	30.8±4.2	32.9±5.1	38.5±6.5‡	<0.001
24 mo	30.0±3.9	33.1±5.5	39.1±5.5‡	<0.001
Change from baseline (g/day)				
6 mo	-14.7±55.6	-5.8±30.8	-3.6±58.2	0.23
12 mo	-18.0±68.1	-8.3±33.1	-4.8±57.7	0.21
24 mo	-18.9±66.4	-10.5±33.2	-1.7±51.2	0.10

Table 2. (Continued.)

Variable	Low-Fat Diet	Mediterranean Diet	Low-Carbohydrate Diet	P Value†
Saturated fat				
% of energy				
Baseline	9.7±2.4	9.7±2.4	9.9±2.3	0.84
6 mo	9.6±1.9	9.7±2.5	12.2±3.9‡	<0.001
12 mo	9.8±2.1	9.6±2.1	12.5±3.8‡	<0.001
24 mo	9.6±1.8	9.6±2.2	12.3±3.2‡	<0.001
Change from baseline (g/day)				
6 mo	-4.8±17.0	-3.0±11.4	0.28±18.7	0.07
12 mo	-5.3±21.3	-3.8±11.5	0.78±19.5‡	0.04
24 mo	-6.2±21.4	-4.6±11.3	0.56±15.7‡	0.02
Change in monounsaturated:saturated fat ratio from baseline				
6 mo	0.00±0.18	0.09±0.21¶	-0.02±0.23	0.001
12 mo	-0.02±0.18	0.08±0.19¶	-0.05±0.22	<0.001
24 mo	0.02±0.21	0.11±0.20¶	-0.01±0.21	<0.001
Change in dietary cholesterol from baseline (mg/day)				
6 mo	-71.8±312.2	-66.7±243.4	11.7±283.2	0.06
12 mo	-87.4±377.0	-78.8±239.8	1.76±325.3	0.09
24 mo	-94.2±373.5	-94.6±254.6	6.51±262.9‡	0.04
Change in dietary fiber from baseline (g/day)				
6 mo	-2.3±17.4	1.2±12.6	-7.4±22.0	0.002
12 mo	-4.3±19.0	0.22±12.9	-8.3±21.6	0.004
24 mo	-4.7±18.8	0.29±13.8	-10.0±21.7	0.002
Level of physical activity (MET/wk)				
Baseline	15.8±22.6	11.3±15.7	14.0±29.4	0.37
6 mo	17.5±23.1	14.2±19.3	18.7±32.0	0.41
12 mo	20.0±23.6	16.1±18.0	18.8±32.5	0.55
24 mo	21.4±26.7	15.6±18.9	16.3±18.9	0.18
Detectable urinary ketone bodies (% of participants)				
Baseline	2.9	1.8	4.6	0.10
24 mo	4.8	2.8	8.3	0.04

* Plus-minus values are means ±SD.

† P values for differences among the three diet groups were calculated by analysis of variance, except for urinary ketone values, for which the chi-square test was used. When the difference among the groups was significant ($P < 0.05$), all pairwise comparisons between groups were tested for significance with the use of Tukey's Studentized range test. The Mediterranean-diet group consumed the largest amounts of dietary fiber and had the highest ratio of monounsaturated to saturated fat ($P < 0.05$ for all comparisons among treatment groups). The low-carbohydrate group consumed the smallest amount of carbohydrates and the largest amounts of fat, protein, and cholesterol; the percentage of participants with detectable urinary ketones was also highest in this group ($P < 0.05$ for all comparisons among treatment groups). The amount of decrease in intake of calories was similar among the diet groups.

‡ The value for the low-carbohydrate group is significantly different from the value for the low-fat group or the Mediterranean-diet group ($P < 0.05$).

§ The value for the low-carbohydrate group is significantly different from the value for the low-fat group ($P < 0.05$).

¶ The value for the Mediterranean-diet group is significantly different from the value for the low-fat group or the low-carbohydrate group ($P < 0.05$).

|| The value for the low-carbohydrate group is significantly different from the value for the Mediterranean-diet group ($P < 0.05$).

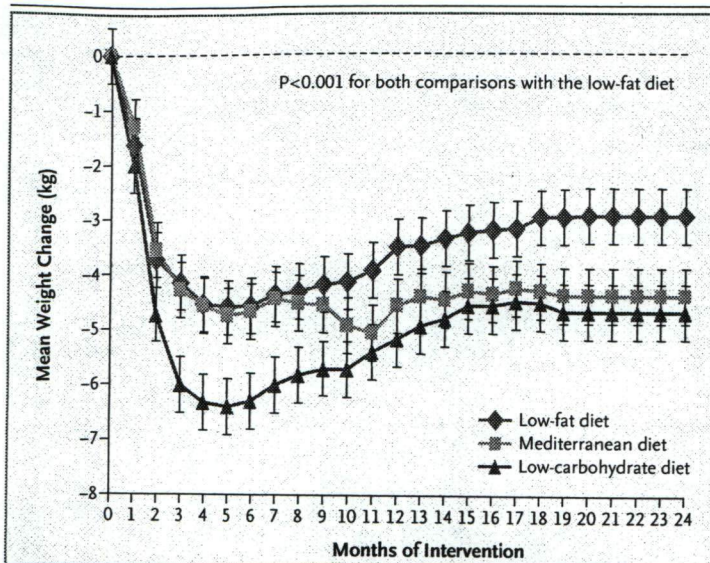


Figure 2. Weight Changes during 2 Years According to Diet Group.

Vertical bars indicate standard errors. To statistically evaluate the changes in weight measurements over time, generalized estimating equations were used, with the low-fat group as the reference group. The explanatory variables were age, sex, time point, and diet group.

cant ($P < 0.05$) only in the low-carbohydrate group ($P = 0.45$ for the comparison among groups).

LIVER-FUNCTION TESTS

Changes in bilirubin, alkaline phosphatase, and alanine aminotransferase levels were similar among the diet groups. Alanine aminotransferase levels were significantly reduced from baseline to 24 months in the Mediterranean-diet and the low-carbohydrate groups (reductions of 3.4 ± 11.0 and 2.6 ± 8.6 units per liter, respectively; $P < 0.05$ for the comparison with baseline in both groups).

DISCUSSION

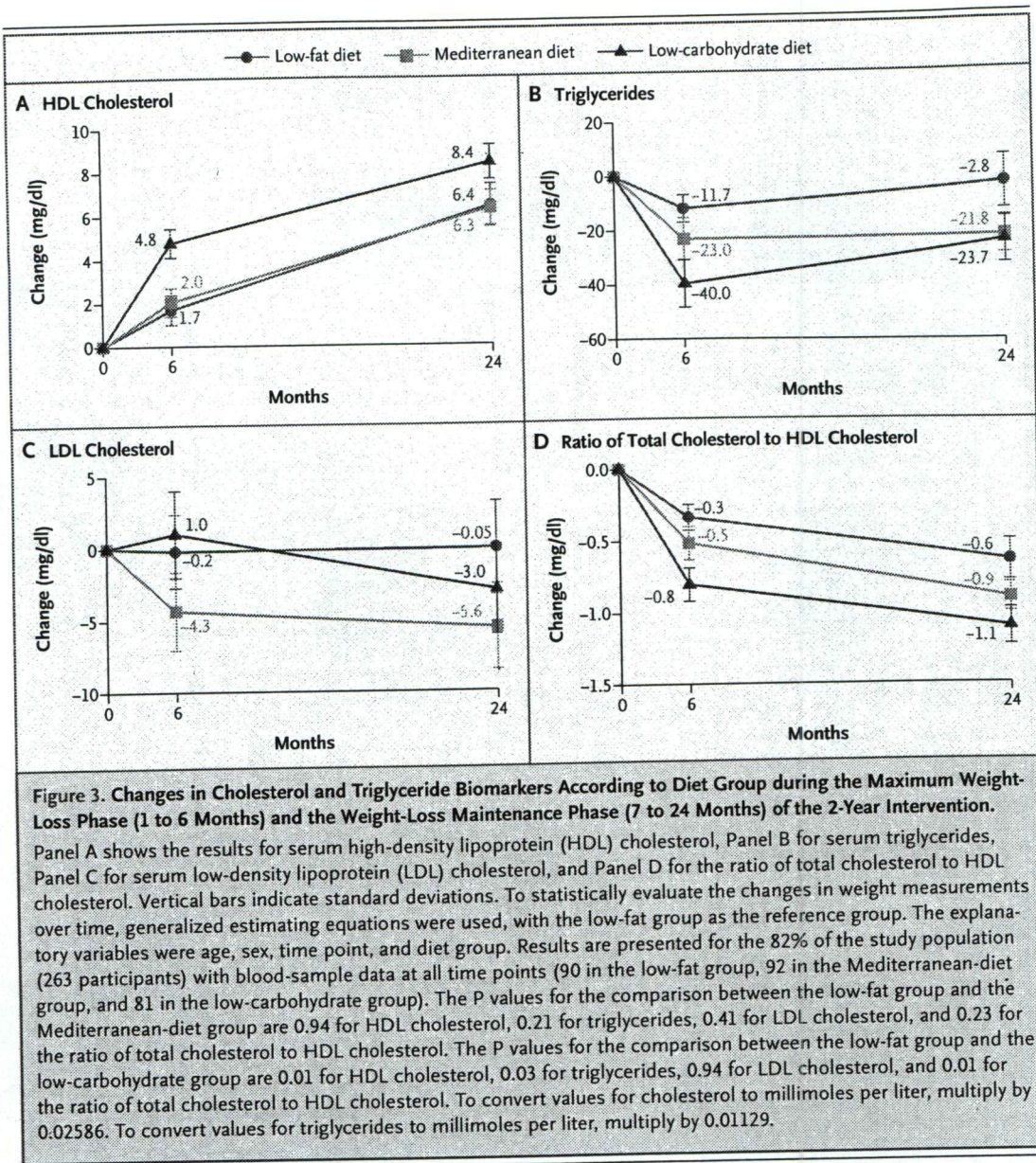
In this 2-year dietary-intervention study, we found that the Mediterranean and low-carbohydrate diets are effective alternatives to the low-fat diet for weight loss and appear to be just as safe as the low-fat diet. In addition to producing weight loss in this moderately obese group of participants, the low-carbohydrate and Mediterranean diets had some beneficial metabolic effects, a result suggesting that these dietary strategies might be considered in clinical practice and that diets might be individualized according to personal preferences and metabolic needs. The similar caloric deficit achieved in all diet groups suggests that a low-car-

bohydrate, non-restricted-calorie diet may be optimal for those who will not follow a restricted-calorie dietary regimen. The increasing improvement in levels of some biomarkers over time up to the 24-month point, despite the achievement of maximum weight loss by 6 months, suggests that a diet with a healthful composition has benefits beyond weight reduction.

The present study has several limitations. We enrolled few women; however, we observed a significant interaction between the effects of diet group and sex on weight loss (women tended to lose more weight on the Mediterranean diet), and this difference between men and women was also reflected in the changes in leptin levels. This possible sex-specific difference should be explored in further studies. The data from the few participants with diabetes are of interest, but we recognize that measurement of HOMA-IR is not an optimal method to assess insulin resistance among persons with diabetes. We relied on self-reported dietary intake, but we validated the dietary assessment in two different dietary-assessment tools and used electronic questionnaires to minimize the amount of missing data. Finally, one might argue that the unique nature of the workplace in this study, which permitted a closely monitored dietary intervention for a period of 2 years, makes it difficult to generalize the results to other free-living populations. However, we believe that similar strategies to maintain adherence could be applied elsewhere.

The strengths of the study include the one-phase design, in which all participants started simultaneously; the relatively long duration of the study; the large study-group size; and the high rate of adherence. The monthly measurements of weight permitted a better understanding of the weight-loss trajectory than was the case in previous studies.

We observed two phases of weight change: initial weight loss and weight maintenance. The maximum weight reduction was achieved during the first 6 months; this period was followed by the maintenance phase of partial rebound and a plateau. Among all diet groups, weight loss was greater for those who completed the 24-month study than for those who did not. Even moderate weight loss has health benefits, and our findings suggest benefits of behavioral approaches that yield weight losses similar to those obtained with pharmacotherapy.²⁹



We distinguished between changes in levels of biomarkers (leptin, adiponectin, and high-sensitivity C-reactive protein) that are apparently related to loss of adipose tissue and changes in biomarkers (triglycerides, HDL cholesterol, glucose, and insulin) that apparently reflect, in part, the effects of specific diet composition. The changes we observed in levels of adiponectin and leptin,³⁰ which were consistent in all groups, reflect loss of weight. Consumption of monounsaturated fats is thought to improve insulin sensitivity,^{14,31,32} an effect that may explain the favorable effect of the Mediterranean diet on glucose and insulin levels. The

results imply that dietary composition modifies metabolic biomarkers in addition to leading to weight loss. Our results suggest that health care professionals might consider more than one dietary approach, according to individual preferences and metabolic needs, as long as the effort is sustained.

This trial also suggests a model that might be applied more broadly in the workplace. As Okie recently suggested,³³ using the employer as a health coach could be a cost-effective way to improve health. The model of intervention with the use of dietary group sessions, spousal sup-

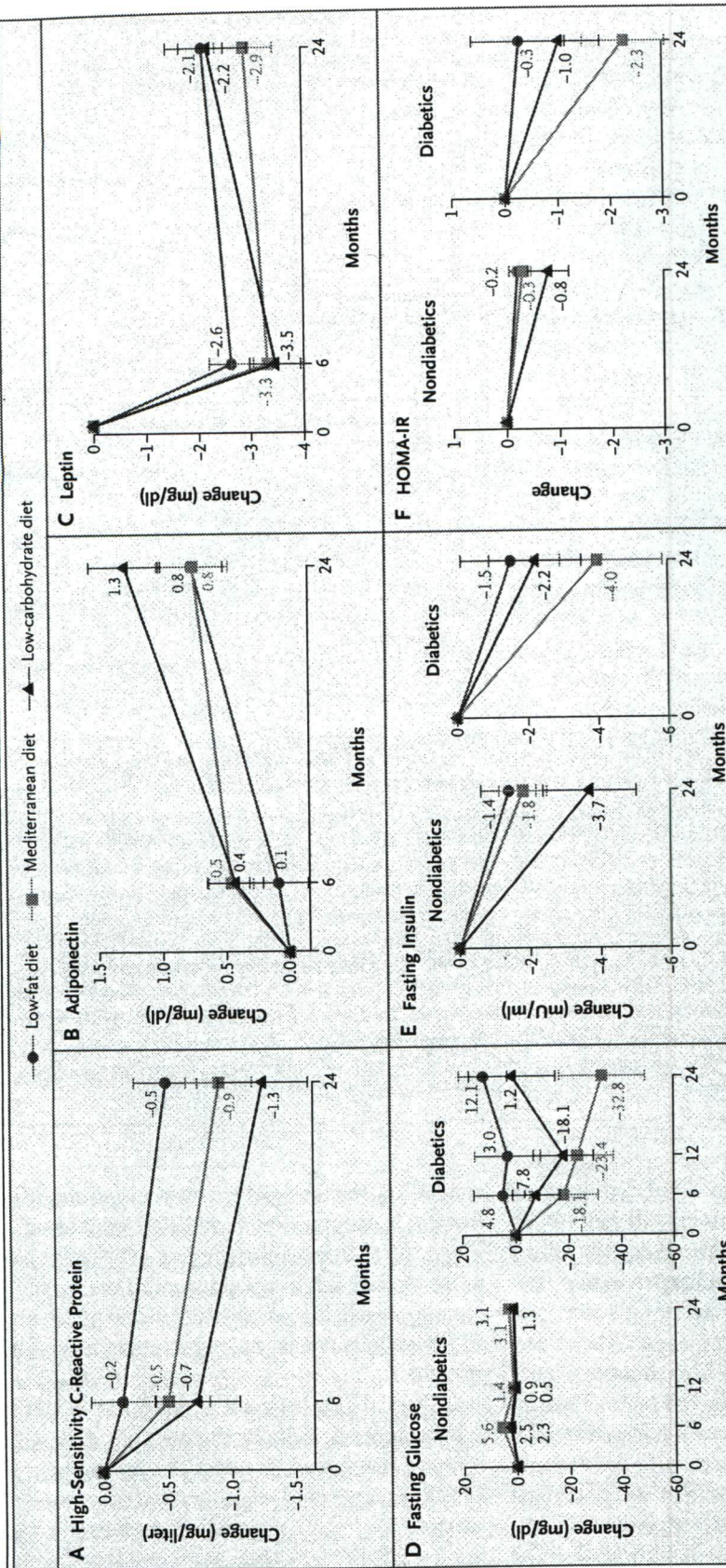


Figure 4. Changes in Biomarkers According to Diet Group and Presence or Absence of Type 2 Diabetes.

Panel A shows the results for plasma high-sensitivity C-reactive protein, Panel B for plasma adiponectin, Panel C for plasma leptin, Panel D for fasting plasma glucose, Panel E for fasting plasma insulin, and Panel F for the homeostasis model assessment of insulin resistance (HOMA-IR). Vertical bars indicate standard deviations. To statistically evaluate the response of weight measurements over time, generalized estimating equations were used, with the low-fat group as the reference group. The explanatory variables were age, sex, time point, and diet group. Data were available for 36 participants with type 2 diabetes: 11 in the low-fat group, 13 in the Mediterranean-diet group, and 12 in the low-carbohydrate group. The P values for the comparison between the low-fat group and the Mediterranean-diet group are 0.49 for high-sensitivity C-reactive protein, 0.50 for adiponectin, 0.54 for leptin, <0.001 for fasting glucose, 0.78 for fasting insulin, and 0.04 for HOMA-IR. The P values for the comparison between the low-fat group and the low-carbohydrate group are 0.12 for high-sensitivity C-reactive protein, 0.32 for adiponectin, 0.47 for leptin, 0.12 for fasting glucose, 0.20 for fasting insulin, and 0.27 for HOMA-IR. The P values for the interaction among diabetes and Mediterranean diet and time are <0.001 for fasting glucose and 0.04 for HOMA-IR. To convert values for glucose to millimoles per liter, multiply by 0.05551.

port, food labels, and monthly weighing in the workplace within the framework of a health promotion campaign might yield weight reduction and long-term health benefits.

Supported by the Nuclear Research Center Negev (NRCN), the Dr. Robert C. and Veronica Atkins Research Foundation, and the S. Daniel Abraham International Center for Health and Nutrition, Ben-Gurion University, Israel.

No potential conflict of interest relevant to this article was reported.

We thank the 322 participants in the Dietary Intervention Randomized Controlled Trial (DIRECT) for their consistent cooperation, as well as the consultants and health care providers (Yitzhak Gurevitz, Hassia Krakauer, Meir Yoseffi, Meyer Aviv, Ilanit Asulin, Zvi Zur, Sapir Medikar, Haim Strasler, Avraham Shlonsky, Dr. Abby Bloch, and Dr. Ayala Canfi), the workplace cafeteria managers (Naftali Tal, Yitzhak Chen, Yair Tubul, and the Norcate Company), the adviser researchers (Drs. Ofra Paz-Tal, Assaf Rudich, Amir Tirosh, Ilana Harman-Bohem, and Ronit Andvelt), and the members of the DIRECT steering committee (Prof. Shimon Weitzman, Prof. Uri Goldbourt, and Prof. Eran Leitersdorf) for their invaluable contributions.

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CORRECTION

Weight Loss with a Low-Carbohydrate, Mediterranean, or Low-Fat Diet

To the Editor: How do Shai et al. (July 17 issue)¹ explain why the subjects in their study regained weight between month 6 and month 24, despite a reported reduction of 300 to 600 calories per day? Contributing possibilities may include the notion that a food-frequency questionnaire cannot precisely determine energy or macronutrient intake but, rather, ascertains general dietary patterns. Certain populations may underreport intake^{2,3} and have a decreased metabolic rate. The authors did not measure body composition, which is critical for documenting weight-loss components.

In addition, the titles of the diets that are described in the article are misleading. Labeling the "low-carbohydrate" diet as such is questionable, since 40 to 42% of calories were from carbohydrates from month 6 to month 24, and data regarding ketosis support this view. Participants in the low-fat and Mediterranean-diet groups consumed between 30% and 33% of calories from fat and did not increase fiber consumption, highlighting the importance of diet quality. Furthermore, the authors should have provided baseline values and P values for within-group changes from baseline (see Table 2 of the article).

Contrary to the authors' assertion, it is not surprising that the effects on many biomarkers were minimal, since the dietary changes were minimal. The absence of biologically significant weight loss (2 to 4% after 2 years) highlights the fact that energy restriction and weight loss in themselves may minimally affect metabolic outcomes and that lifestyle changes must incorporate physical activity to optimize the reduction in the risk of chronic disease.^{4,5}

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To the Editor: Shai and colleagues found that a low-fat diet was less effective than either a Mediterranean diet or a low-carbohydrate diet in achieving weight loss. However, the "low-fat" group was actually not instructed to follow a low-fat diet, because the diet composition (i.e., calories from fat) did not change during the intervention. So, in reality, since the members of this group consumed the same diet as they did habitually, it should have been called the control group. Weight loss is known to occur as a consequence of reducing the proportion of calories from fat,¹ so the design of the study was not really fair to the low-fat diet. Moreover, the dropout rate was 15% in the Mediterranean group, 22% in the low-carbohydrate group, and only 10% in the low-fat group (P=0.04). In a study involving Danish subjects,² my colleagues and I also observed that there was a significantly higher dropout rate among participants on a Mediterranean diet (28%) than among those on a (real) low-fat diet (16%), after both 6 months and 18 months. Retention is an end point that deserves comment.

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Dr. Astrup reports receiving consulting fees from Weight Watchers and Global Dairy Platform and reports that his department at the University of Copenhagen has received research funding from many food companies. No other potential conflict of interest relevant to this letter was reported.

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To the Editor: Shai et al. report that either a Mediterranean diet or a low-carbohydrate diet was an effective alternative to a low-fat diet in terms of weight loss. Absolute values for the energy intake before and after the intervention are not given for any of the groups. However, the data provided in the article suggest that the weight loss in the low-carbohydrate group may have been simply a hypocaloric effect, even though the authors state that the energy intake in this group was not restricted. Thus, if the daily intake of carbohydrates was no more than 120 g (equal to 500 kcal), as stated in the Methods section, and if the

fraction of the energy intake provided by carbohydrates was around 40%, as stated in Table 2, then the total daily energy intake in the low-carbohydrate group must have been no more than approximately 1250 kcal, which is significantly less than the daily intake targeted for the two other groups.

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To the Editor: In the study by Shai et al., participants who were on the low-fat diet decreased their total fat intake from 31.4% to 30.0% — in other words, hardly at all. It is important to measure disease end points, not just risk factors. Greater increases in high-density lipoprotein (HDL) cholesterol among patients on the Atkins diet may not necessarily be beneficial, as the torcetrapib study indicated.¹ Very-low-fat diets may reverse coronary heart disease² and prostate cancer³ and also improve gene expression,⁴ despite reductions in HDL cholesterol, whereas flow-mediated vasodilatation, a measure of endothelial function and a predictor of cardiovascular events, worsened among subjects on the Atkins diet.⁵

In the "Atkins diet" that was tested by Shai et al., the authors state that they counseled the study participants to choose vegetarian sources of fat and protein and to avoid trans fat. However, such a diet is not representative of the Atkins diet, which recommends bacon, butter, and brie, not fruits and vegetables. Why were the participants counseled to do this?

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Dr. Ornish reports writing general-interest books on health and wellness (including diet) for which he receives royalties. He also reports receiving lecture fees from the Harry Walker speaker's bureau and consulting fees from PepsiCo, Mars, and Safeway. No other potential conflict of interest relevant to this letter was reported.

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To the Editor: Shai et al. report very low attrition rates among study participants, and this is surely a good point, given the 2-year length of the study. The authors properly recognize that this finding is probably due to a closely monitored intervention, but they do not report anything about the costs of their face-to-face, dietitian-based approach. As noted by Glasgow and Emmons,¹ among factors that impede the translation of research into widespread practice, important obstacles are the high cost and large time demands on both staff and participants. Even if the authors' strategies for maintaining adherence could be applied outside the workplace, we are not as optimistic as they are, considering the low cost-effectiveness that usually characterizes face-to-face approaches targeting eating habits.

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1. Glasgow RE, Emmons KM. How can we increase translation of research to practice? Types of evidence needed. *Annu Rev Public Health* 2007;28:413-433.

The authors reply: Roberts and colleagues correctly note that a food-frequency questionnaire cannot precisely assess exact caloric intake. In our study, we used identical nutritional values for each of the 137 questionnaire items, irrespective of the specific dietary intervention. For example, "vegetable soups" were not specially analyzed within the low-fat group as "no fat added" or in the low-carbohydrate group as "creamed" or "no starch added." Thus, although the questionnaire data revealed three distinct dietary regimens throughout the intervention, these data might have underestimated the true differences among the groups. Correlations between data from food-frequency questionnaires and those from 24-hour dietary recalls, which were used in a subgroup of participants, were more than 0.8 for most nutrients.

In response to the letters from Astrup and Moller and Krogh-Madsen: the diet-recall data confirm that the total caloric deficit was simi-

lar among the groups and that the low-fat group maintained a relatively low intake of fat (Table 1). Obviously, with a substantial total caloric deficit, the absolute consumption of fiber was decreased; however, the decrease in the low-fat group was half of that in the low-carbohydrate group.

We agree with Roberts et al. on the importance of physical activity, but our study specifically focused on diet composition. Roberts et al. are incorrect in characterizing the weight loss as biologically not meaningful, since it yielded clinically important changes in risk factors. Intriguingly, the weight reduction achieved among the moderately obese subjects in our study was identical to that reported in a recent meta-analysis on long-term pharmacotherapy for obesity.²

In response to Ornish's letter: the low-carbohydrate diet was based on Atkins's book, although we encouraged the study participants to consume a variety of protein and fat sources to maintain successful long-term adherence. We specifically reported on retention in detail and noted that adherence was higher in this trial than in any other trial of a similar length that we know of. The setting and methods we used to maximize adherence rates permitted a robust test of the three dietary strategies, as assessed by weight loss and established measurements of lipids, glycemic control, and hepatic and inflammatory biomarkers. As noted by Manzoni and colleagues, we did not assess cost-effectiveness. However, we believe that cost-effective interventions can be implemented in the workplace, with the use of group meetings and by working with food-service providers.

Several readers have informed us that our online Supplementary Appendix was incomplete. We have updated the appendix to provide more complete information.

Table 1. Dietary Intake from 24-Hour Dietary Recall among Participants in the Dietary Intervention Randomized Controlled Trial (DIRECT).

Variable	Low-Fat Diet	Mediterranean Diet	Low-Carbohydrate Diet
Energy (kcal)	1347±239	1356±258	1281±380
Fat			
Total (g)	38.7±13.9	49.8±19.8	54.8±23.7†
% of energy	23.9±8.0	31.7±9.1‡	40.3±10.0‡
Protein			
Total (g)	94.2±24.4	83.2±22.5	109.9±36.0
% of energy	28.3±6.1	25.2±8.0	33.9±7.6‡
Carbohydrates			
Total (g)	135.8±44.1	152.9±8.3	87.6±37.5‡
% of energy	48.2±9.7	45.0±11.7	28.3±11.7‡
Dietary cholesterol (mg)	274±82	281±93	358±62‡

^a Plus-minus values are means ±SD. During the first 6 months of the study, 24-hour dietary recalls were obtained from 27 participants on the low-fat diet, 22 on the Mediterranean diet, and 18 on the low-carbohydrate diet; the results were analyzed with the use of the Israeli nutritional database.
[†] P<0.05 for the comparison with the low-fat diet.
[‡] P<0.05 for the comparison with the low-fat diet.

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