

Consumption of diacylglycerol oil as part of a reduced-energy diet enhances loss of body weight and fat in comparison with consumption of a triacylglycerol control oil¹⁻³

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ABSTRACT

Background: Diacylglycerol is a natural component of edible oils that has metabolic characteristics that are distinct from those of triacylglycerol.

Objective: We assessed the efficacy of an oil containing mainly 1,3-diacylglycerol in reducing body weight and fat mass when incorporated into a reduced-energy diet.

Design: The study was a randomized, double-blind, parallel intervention trial that was conducted at an outpatient clinical research center. The subjects ($n = 131$) were overweight or obese men (waist circumference ≥ 90 cm) and women (waist circumference ≥ 87 cm). Food products (muffins, crackers, soup, cookies, and granola bars) containing diacylglycerol or triacylglycerol oil and having the same fatty acid composition were incorporated into a reduced-energy diet (2100–3350-kJ/d deficit) for 24 wk. Percentages of change in body weight, fat mass, and intraabdominal fat area were assessed.

Results: In an intention-to-treat analysis, body weight and fat mass decreased significantly more in the diacylglycerol group than in the triacylglycerol group ($P = 0.025$ and 0.037 , respectively). By the end of the trial, mean body weight had decreased 3.6% and 2.5% in the diacylglycerol and triacylglycerol groups, respectively. Fat mass decreased 8.3% and 5.6% in the diacylglycerol and triacylglycerol groups, respectively.

Conclusion: Foods containing diacylglycerol oil promoted weight loss and body fat reduction and may be useful as an adjunct to diet therapy in the management of obesity. *Am J Clin Nutr* 2002;76:1230–6.

KEY WORDS Diacylglycerol, body weight, body composition, visceral fat, intraabdominal fat, fat mass, triacylglycerol, obesity, overweight

INTRODUCTION

Fifty-five percent of adults in the United States are overweight or obese (1). Obesity is a growing problem in many countries worldwide and is associated with many health risks such as heart disease, diabetes mellitus, hypertension, gallbladder disease, and some types of cancer (2–4). Both the total amount of fat and the distribution of fat in the body are important determinants of the complications associated with obesity (2).

Diacylglycerol is a natural component of various edible oils (5, 6) and is currently used in small quantities in foods as an emulsifier.

Recent studies suggested that when diacylglycerol is consumed in large amounts, it has metabolic characteristics that are distinct from those of triacylglycerol and that these characteristics may be beneficial in preventing and managing obesity. Experimental studies in animals and humans showed that diacylglycerol (mainly 1,3-diacylglycerol) decreases postprandial triglyceridemia in comparison with a triacylglycerol control (7, 8). In controlled feeding studies, diacylglycerol prevented the accumulation of body weight and fat associated with a high-fat and high-sucrose diet in obesity-prone mice (9) and decreased body weight and abdominal fat stores in Japanese men (10). These effects do not appear to be due to the poor digestibility or reduced energy content of diacylglycerol. The apparent digestibilities of diacylglycerol and triacylglycerol oils were identical (96.3%) in rats, and the energy contents measured in a bomb calorimeter were similar (38.9 and 39.6 kJ/g for diacylglycerol and triacylglycerol, respectively) (11). Thus, the putative influence of diacylglycerol oil consumption on body weight and fat mass appears to be related to its influence on energy expenditure, regulation of food intake, or both. Investigations currently under way may further elucidate the mechanisms responsible for these effects.

In a randomized, double-blind, clinical trial, we investigated the efficacy and safety of substituting $\approx 15\%$ of dietary energy either with an oil composed primarily of diacylglycerol or with a triacylglycerol oil with a similar fatty acid composition. We compared the effects of the 2 oils in enhancing reductions in body weight, fat mass, and intraabdominal fat (IAF) area in response to a reduced-energy diet.

SUBJECTS AND METHODS

Study design

This was a randomized, double-blind, controlled, parallel trial conducted at the Chicago Center for Clinical Research, Chicago.

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The protocol was approved by an institutional review board (Schulman Associates IRB, Inc, Cincinnati). The conditions and procedures of the investigation were reviewed with all subjects before they signed an informed consent form.

Subject selection

Potential subjects were screened at the first clinic visit (2–4 wk before randomization). Eligible subjects were aged ≥ 18 y and had a waist circumference of ≥ 87 cm (women) or ≥ 90 cm (men). These circumferences were chosen because they correspond to an IAF area of ≈ 100 cm² on the basis of regression equations published by Lemieux and colleagues (12). The subjects also had to have a normal activity level and be judged to be in good health on the basis of a medical history, a physical examination, an electrocardiogram, and routine laboratory tests. Women with childbearing potential had to be willing to practice a medically approved form of contraception.

Subjects were excluded if they had lost >4.5 kg body weight in the 2 mo before screening, had had gastrointestinal surgery for weight-reducing purposes, or had a body mass index (in kg/m²) >40 . Subjects with a history of diabetes mellitus or a fasting glucose concentration >6.94 mmol/L were also excluded, as were subjects who took any medications known to influence lipid or carbohydrate metabolism or had a blood triacylglycerol concentration >3.96 mmol/L or a total cholesterol concentration >7.77 mmol/L.

Randomization

After the screening, subjects who met the entrance criteria were contacted and asked to return to the clinic within 1–4 wk. At the second clinic visit, vital signs, body weight, and anthropometric measurements were assessed. Participants also underwent a brief physical examination and had an electrocardiogram. Dual-energy X-ray absorptiometry and computed tomography (CT) scans were performed for assessment of body composition and IAF, respectively. After baseline measurements, the subjects were randomly assigned to either the diacylglycerol oil group or the triacylglycerol oil group, and study products were dispensed to them.

Treatment period

During the 24-wk treatment period, subjects returned to the clinic for 8 visits (weeks 2, 4, 6, 8, 12, 16, 20, and 24). At each visit, vital signs, body weight, and anthropometric measurements were assessed, and any adverse events experienced by the subjects were reported. Three-day diet records and study-product diaries were collected and reviewed, and new diet records were dispensed; remaining, unused study products were collected, and new study products were provided.

Fasting serum samples were collected at visit 10 (week 24) for serum chemistry and hematology analyses. At weeks 12 and 24, samples were collected for urinalysis and a urine pregnancy test for women with childbearing potential. Additionally, at weeks 12 and 24, dual-energy X-ray absorptiometry and CT scans were repeated. Each subject completed a 7-d physical activity recall questionnaire at weeks 4, 12, and 24. At the final clinic visit (week 24) each subject underwent a brief physical examination and had an electrocardiogram.

Anthropometric and body-composition measurements

Circumference measurements at each clinic visit throughout the study were made by using a nonstretch anthropometric tape on the upper arm, waist, and thigh. Midupper arm circumference was

measured on the right arm at the midpoint between the tip of the acromion and the tip of the olecranon, waist circumference was measured at the narrowest part of the torso located between the lower rib and the iliac crest, and midthigh circumference was measured on the right thigh, midway between the inguinal crease and the proximal border of the patella (13).

Whole-body dual-energy X-ray absorptiometry scans were performed with a QDR 4500 A fan beam X-ray bone densitometer (class 1, type B; Hologic Inc, Waltham, MA) at baseline and at weeks 12 and 24. Measurements of fat mass and fat-free mass were made with the use of Hologic Systems Software version 9.02b (Hologic Inc) according to the procedures outlined in the *Hologic QDR 4500 User's Guide*.

CT scans were performed with a Siemens Somatom Plus 4 scanner (Siemens Medical Solutions USA, Inc, Malvern, PA) at baseline and at weeks 12 and 24. The following radiographic factors were used: 120 peak kV, 200 mA, an exposure time of 0.75 s, and a slice thickness of 8 mm. Scans were taken at the level of the liver and spleen and at the L4–L5 region while the subject was supine on the CT table. All CT scans were quantified by using FatScan version 2.0 software (N2 System Co, Osaka, Japan) to evaluate IAF area and subcutaneous fat area. The liver-spleen attenuation ratio was determined by using the CT scanner software.

Laboratory measurements

Samples collected for serum chemistry, hematology, lipid, and urinalysis testing were analyzed by Covance Laboratory Services, Indianapolis, in accordance with the requirements of the Clinical Laboratory Improvement Act by using appropriate standards. Serum chemistry testing was conducted on the Hitachi 747-200 high-throughput, random-access chemistry analyzer (Roche Diagnostics, Indianapolis), and serum hematology testing was performed by using the Advia 120 (Bayer, Dublin). Urinalysis testing was performed by using the Model 500 IRIS (International Remote Imaging Systems, Inc, Chatsworth, CA).

Serum lipids (total, LDL, HDL, and non-HDL cholesterol and triacylglycerol) were analyzed according to the Standardization Program of the US Centers for Disease Control and Prevention and the National Heart, Lung, and Blood Institute by using Hitachi analyzers (Roche Diagnostics). LDL-cholesterol concentrations were calculated in mg/dL according to the Friedewald equation (LDL cholesterol = total cholesterol – HDL cholesterol – triacylglycerol/5) and were then converted to mmol/L. Because this equation is not valid when the triacylglycerol concentration is >4.52 mmol/L, no LDL cholesterol value was calculated under these circumstances. There were 15 instances (for 9 subjects) throughout the study in which LDL-cholesterol concentrations were not calculated because of high triacylglycerol concentrations.

Test articles and dosing

The diacylglycerol oil (Econa Oil; Kao Corporation, Biological Science Laboratories, Tochigi, Japan) used in this study was prepared from rapeseed oil under the presence of lipase and was $\approx 90\%$ diacylglycerol (by wt). The ratio of 1,2-diacylglycerol to 1,3-diacylglycerol was 3:7. Triacylglycerol oil was prepared from a mixture of rapeseed, soybean, and safflower oils. This mixture was used to match the major fatty acid composition of the diacylglycerol and triacylglycerol oils as closely as possible (**Table 1**). The intended use of the diacylglycerol oil product is as a substitute for other oils in cooking.

TABLE 1
Fatty acid composition of the test oils

Fatty acid	% by wt	
	Diacylglycerol oil	Triacylglycerol oil
16:0	2.87	6.12
18:0	1.17	2.61
18:1	28.42	30.05
18:2	58.49	55.51
18:3	6.76	3.29
20:0	0.16	0.5
20:1	0.27	0.61
22:1	0.25	0.43
Others	1.61	0.78

Subjects incorporated various food products containing either diacylglycerol or triacylglycerol oil into their diets during the trial. The food products included muffins (blueberry, apple, and banana flavors), crackers, instant soup mix (vegetable, chicken, and mushroom flavors), sugar cookies, and granola bars. ABIC International Consultants, Inc (Fairfield, NJ) prepared the instant soup mixes and directed the manufacturing process of the other food products at a local New Jersey bakery according to Good Manufacturing Practices. Study food products were packaged and labeled by the manufacturing plants according to a coding system so that both the subjects and the study personnel were blinded to the oil content (ie, either diacylglycerol or triacylglycerol) of the food products.

The diacylglycerol oil and triacylglycerol oil products were designed to be equal in energy, to provide equal quantities of test or control oil, and to be similar to each other in taste and appearance. Diacylglycerol oil or triacylglycerol oil was the only major fat source in the products, and each serving of study product contained ≈ 8 –9 g of either oil.

Study products were dispensed at clinic visits on weeks 0, 2, 4, 6, 8, 12, 16, and 20. Participants also picked up study products at 2-wk intervals when there was no clinic visit scheduled (ie, at weeks 10, 14, 18, and 22). Subjects were allowed to select various study foods, within the guidelines of appropriate dosing, by completing an order form.

Doses of study products for each subject were determined individually on the basis of calculated energy requirements. Substitution of the study food products for other foods in the diet was done with the goal of achieving $\approx 15\%$ of the total energy in the diet from either diacylglycerol or triacylglycerol oil. On the basis of the energy-requirement calculations, the number of study food products incorporated into the diet ranged from 2 to 5 servings/d.

At clinic visits, subjects brought their entire study-product supply (including empty and full packages) to the site. A staff member counted the number of servings consumed and calculated the subjects' compliance. Additionally, subjects recorded their use of study products in daily diaries that were dispensed at the baseline visit and reviewed by the coordinator at each subsequent clinic visit.

Diet counseling and physical activity

At the screening visit, a dietitian instructed all subjects on how to complete their 3-d diet records. Dietary intakes were recorded on 3 consecutive days: 2 weekdays (Monday–Friday) and 1 weekend day (Saturday or Sunday). The dietary instruction that was

provided to the participants at baseline (week 0) and reinforced at each visit thereafter emphasized a reduced-energy diet containing ≈ 30 –35% of energy as fat, 45–50% of energy as carbohydrate, and 15–20% of energy as protein. Alcohol intake was limited to < 150 g/wk. The desired energy intake was based on an estimate of the subject's initial maintenance energy needs. First, age and body weight (measured at the screening visit) were used to estimate the basal metabolic rate on the basis of the World Health Organization's revised equation (13). The basal metabolic rate was then multiplied by a factor to correct for the activity level (1.3 for mild daily activity and 1.5 for strenuous daily activity) determined from the 7-d physical activity recall questionnaire administered at the screening. Finally, based on this estimate of initial energy needs, a diet was prescribed that was intended to induce an energy deficit of ≈ 2100 –3350 kJ/d.

Diet records were dispensed at each clinic visit with instructions to complete them during the week before the next clinic visit. Completed diet records were collected from subjects at each clinic visit and reviewed with the subjects by the study coordinator to monitor adherence to the required diet. Energy consumption (in kJ/d) and the percentage of energy from fat were used as the principal indicators of dietary adherence and stability. Three-day food records collected at baseline (week 0), week 12, and week 24 were analyzed by using Nutrition Data System for Research software (version 4.01_30; University of Minnesota, Minneapolis). Seven-day physical activity recall questionnaires were completed by each subject at visits 1, 2, 4, 7, and 10 (screening, baseline, and weeks 4, 12, and 24).

Statistical analysis

Analyses were performed for intention-to-treat and per-protocol samples with SAS version 8.0 software (SAS Institute Inc, Cary, NC). Analysis of variance (ANOVA) models were generated using the PROC MIXED procedure. The intention-to-treat sample included data from all subjects who had at least one clinic visit after receiving at least one dose of study product. In the intention-to-treat analyses, for those subjects who did not have efficacy measurements at the planned analysis time points, the most recent available value was carried forward to the rest of the analysis time points. The per-protocol sample included data from all subjects who completed ≥ 12 wk of the study and complied with the study protocol by consuming $\geq 75\%$ of the study products. The per-protocol analyses used efficacy measurements only for the time points for which the efficacy variables were available.

Repeated-measures ANOVA was used to assess the effects of treatment and time (week) and treatment-by-time interactions on percentages of change from baseline in body weight, fat mass, and IAF area. The initial model was reduced in a step-wise manner until only significant ($P < 0.05$) factors remained or until treatment was the only factor left in the model. ANOVA models were also used to compare the percentages of change from baseline at subsequent visits in the secondary efficacy variables (anthropometric measurements, liver-spleen ratio, subcutaneous abdominal fat area, fat-free mass, and lipids). Possible differences between the treatment groups in dietary intakes and physical activity (metabolic equivalent \cdot h) at baseline and at weeks 12 and 24 and changes from baseline at weeks 12 and 24 were assessed by using ANOVA. One metabolic equivalent approximates the amount of energy consumed while seated in a chair. The incidence of adverse events and any abnormal laboratory shifts were assessed with Fisher's exact test (two-tailed). For all analyses, transformations

TABLE 2Baseline and demographic characteristics of the subjects in intention-to-treat analyses¹

Variable	Diacylglycerol oil group (n = 65)	Triacylglycerol oil group (n = 62)
Age (y)	45.9 ± 11.4 ²	48.1 ± 11.2
Sex (%)		
Male	38.5	40.3
Female	61.5	59.7
Race (%)		
Non-Hispanic white	55.4	62.9
Black	32.3	37.1
Other	12.3	0.0
BMI (kg/m ²)	34.5 ± 3.7	33.9 ± 3.7
Circumference (cm)		
Abdominal at umbilicus	106.1 ± 10.4	107.0 ± 12.2
Midupper arm	37.3 ± 3.0	36.4 ± 3.5
Midhigh	60.1 ± 4.9	59.9 ± 5.6
Lipids (mmol/L)		
Total cholesterol	5.47 ± 0.95	5.67 ± 0.97
LDL cholesterol	3.57 ± 0.83	3.66 ± 0.77
HDL cholesterol	1.19 ± 0.28	1.27 ± 0.28
Non-HDL cholesterol	4.28 ± 0.93	4.40 ± 0.93
Triacylglycerol ³	1.37 (0.36, 4.83)	1.47 (0.43, 4.38)

¹There were no significant differences between the groups.² $\bar{x} \pm SD$.³Median; minimum and maximum in parentheses.

were applied when necessary before running ANOVA to improve kurtosis or skew.

RESULTS

Subjects and demographics

Of the 230 persons who underwent screening, 131 were randomly assigned to 1 of the 2 treatment groups. Of those 131 subjects, 65 received diacylglycerol oil products and 66 received triacylglycerol oil products. In the diacylglycerol oil group, 22 subjects did not complete the study. Five subjects withdrew their consent, 1 was withdrawn from the study for noncompliance (<75% of the study products were consumed), 1 withdrew because of an adverse event, and 15 were discontinued for other reasons. In the triacylglycerol oil group, 30 subjects did not complete the study. Eleven subjects withdrew their consent, 4 withdrew because of adverse events, and 15 were discontinued for other reasons. Thus, 43 subjects who consumed diacylglycerol oil and 36 subjects who consumed triacylglycerol oil completed the study.

The diacylglycerol oil and triacylglycerol oil groups did not differ significantly in demographic and baseline variables (Table 2). The subjects ranged in age from 19 to 71 y and had a mean body mass index of ≈ 34 . Both groups were predominantly female ($\approx 60\%$) and white ($\approx 59\%$) and had a mean abdominal circumference of ≈ 106 cm.

Intention-to-treat analyses

Body weight

Mean percentages of change in body weight during treatment are shown in Figure 1. Body weight decreased in both treatment groups. Beginning at week 2, decreases in body weight were greater in the diacylglycerol oil group than in the triacylglycerol

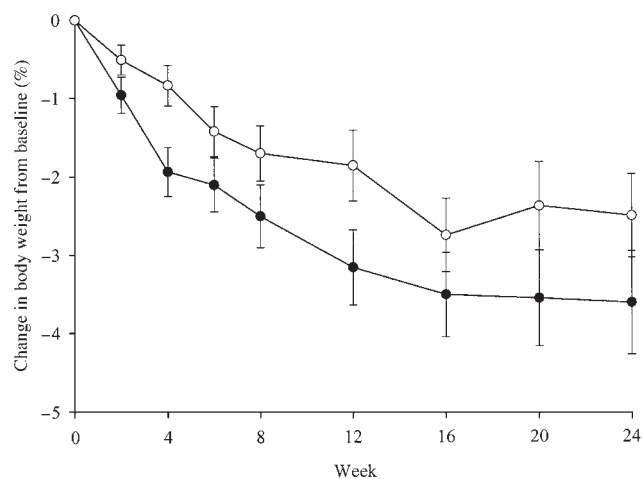


FIGURE 1. Mean (\pm SEM) percentages of change in body weight from baseline to weeks 2, 4, 6, 8, 12, 16, 20, and 24 among subjects in the intention-to-treat sample who were assigned to the diacylglycerol oil (\bullet ; $n = 63$ at week 2; $n = 65$ at all other times) or triacylglycerol oil (\circ ; $n = 62$) treatment groups. Repeated-measures ANOVA showed significant treatment ($P = 0.025$) and time ($P < 0.001$) effects but no significant treatment-by-time (week) interaction ($P = 0.123$). Body weights at baseline were 98.0 ± 1.6 and 97.6 ± 1.8 kg in the diacylglycerol and triacylglycerol oil groups, respectively.

oil group. Repeated-measures ANOVA showed significant treatment ($P = 0.025$) and time ($P < 0.001$) effects but no significant treatment-by-time interaction.

Fat mass

Mean percentages of change in fat mass during treatment are shown in Figure 2. Fat mass decreased from baseline to weeks 12

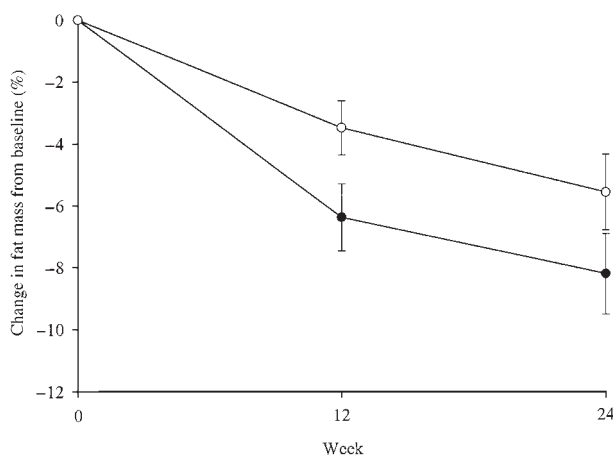


FIGURE 2. Mean (\pm SEM) percentages of change in fat mass from baseline to weeks 12 and 24 among subjects in the intention-to-treat sample who were assigned to the diacylglycerol oil (\bullet ; $n = 49$ at week 12 and $n = 50$ at week 24) or triacylglycerol oil (\circ ; $n = 45$ at week 12 and $n = 46$ at week 24) treatment groups. Repeated-measures ANOVA showed significant treatment ($P = 0.037$) and time ($P < 0.001$) effects but no significant treatment-by-time (week) interaction ($P = 0.853$). Fat mass values at baseline were 35.4 ± 0.9 and 34.7 ± 0.9 kg in the diacylglycerol and triacylglycerol oil groups, respectively.

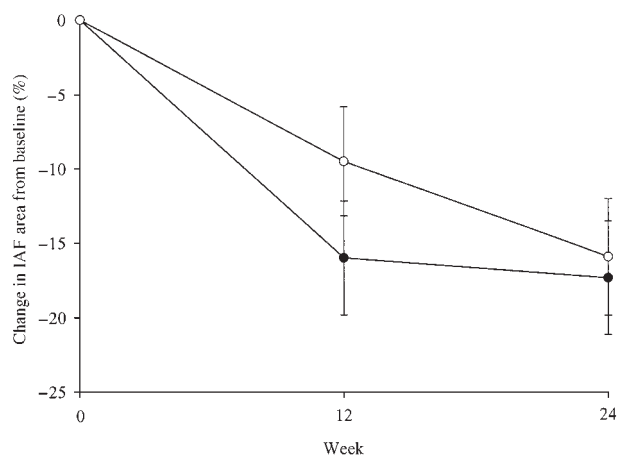


FIGURE 3. Mean (\pm SEM) percentages of change in intraabdominal fat (IAF) area from baseline to weeks 12 and 24 among subjects in the intention-to-treat sample who were assigned to the diacylglycerol oil (\bullet ; $n = 46$) or triacylglycerol oil (\circ ; $n = 42$) treatment groups. Repeated-measures ANOVA showed no significant treatment ($P = 0.395$) or time ($P = 0.064$) effects and no significant treatment-by-time (week) interaction ($P = 0.215$). IAF areas at baseline were 150.4 ± 10.7 and 160.6 ± 9.9 cm² in the diacylglycerol and triacylglycerol oil groups, respectively.

and 24 in both treatment groups. Repeated-measures ANOVA showed significant treatment ($P = 0.037$) and time ($P < 0.001$) effects but no significant treatment-by-time interaction.

Intraabdominal fat area

Mean percentages of change in IAF area during treatment are shown in **Figure 3**. Repeated-measures ANOVA indicated no significant effects, although there was a trend for both groups to show decreases from baseline ($P = 0.064$ for time effect).

Per-protocol analyses

Responses to treatment within the per-protocol sample were not significantly different from those noted in the intention-to-treat analyses (data not shown).

Secondary body-composition variables

Anthropometric measurements at baseline were not significantly different between the diacylglycerol and triacylglycerol oil groups. Total abdominal fat decreased from baseline to week 24 in both groups. Repeated-measures ANOVA indicated a significant time effect ($P < 0.001$) but no significant treatment effect.

Subcutaneous fat area decreased in both treatment groups from baseline to week 24. Repeated-measures ANOVA indicated a significant time effect ($P < 0.001$) but no significant treatment effect.

Lipids

The diacylglycerol and triacylglycerol oil groups did not differ significantly in the change from baseline to week 24 in serum concentrations of total, LDL, HDL, and non-HDL cholesterol and triacylglycerol (data not shown).

Safety

Adverse events were generally few, and the most common adverse events were upper respiratory infections ($n = 29$),

headaches ($n = 22$), and gastrointestinal complaints ($n = 54$). There were no significant differences between the groups in any adverse events reported. Most events were considered mild or moderate. Although most adverse events were thought to be unrelated to the study product, some gastrointestinal system complaints ($n = 26$) and one instance each of headache, upper respiratory infection, acne, and rash were judged by the investigator to be possibly related; one subject in the triacylglycerol oil group experienced taste perversion, which was judged by the investigator to be related to the study product. Only 2 subjects reported serious adverse events during the trial. One subject had a cholecystectomy and dropped out of the study. The other subject had a urinary tract infection, which was treated at a hospital, but remained in the study.

In general, the incidence of abnormal laboratory values was similar between the groups, with the exception of lactate dehydrogenase. Five subjects in the triacylglycerol oil group had abnormal lactate dehydrogenase concentrations at both weeks 12 and 24, whereas no subjects in the diacylglycerol oil group had abnormal concentrations ($P = 0.023$). In general, vital signs (blood pressure and pulse) were not significantly different between the groups at baseline and throughout the study. The median liver-spleen attenuation ratio increased in both treatment groups from baseline to week 24 (3.9% and 1.5% in the diacylglycerol and triacylglycerol oil groups, respectively), indicating that neither group had an increased hepatic fat content.

Diet

The diacylglycerol and triacylglycerol oil groups did not differ significantly at baseline in dietary variables as determined by analysis of 3-d diet records. During the trial changes from baseline in energy and percentage of energy from carbohydrate were not significantly different between the diacylglycerol and triacylglycerol oil groups, but the percentage of energy from fat decreased more in the triacylglycerol oil group (-4.4%) than in the diacylglycerol oil group (-1.0% ; $P = 0.043$).

Physical activity

Physical activity, which was assessed by the 7-d physical activity recall questionnaire, did not differ significantly between the diacylglycerol and triacylglycerol oil groups but did change significantly over time within each group ($P < 0.01$ for time). From baseline to the end of the study, physical activity increased 10.6% and 12.8% in the diacylglycerol and triacylglycerol oil groups, respectively.

DISCUSSION

The primary objective of this clinical trial was to evaluate the efficacy of diacylglycerol oil compared with that of control oil (triacylglycerol oil with a similar fatty acid composition) in enhancing reductions in body weight and fat as part of a reduced-energy diet in overweight or obese men and women. At each time point after randomization, the mean body weight loss was greater in the group who received diacylglycerol oil than in the group who received triacylglycerol oil. In addition, mean fat loss was greater in the diacylglycerol oil group than in the triacylglycerol oil group, confirming results from previous studies in animals and humans.

The results of the present trial extend those recently published by Nagao et al (10), who studied 38 healthy, nonobese

men (mean body mass index: ≈ 24) for 16 wk. In that investigation, mean (\pm SEM) reductions in body weight were greater in the group who received diacylglycerol oil (2.6 ± 0.3 kg) than in the triacylglycerol oil control group (1.1 ± 0.4 kg; $P < 0.001$). In addition, abdominal fat decreased more with the diacylglycerol oil treatment (-38 ± 3 cm²) than with the triacylglycerol oil control (-17 ± 8 cm²; $P < 0.05$). The present trial expanded the sample under examination to include men and women and participants who were older and heavier than those studied by Nagao et al (10).

The mechanisms responsible for the enhanced reductions in body weight and fat associated with diacylglycerol consumption remain to be elucidated. Postprandial elevations in triacylglycerol and chylomicron concentrations are markedly smaller after diacylglycerol consumption than after consumption of triacylglycerol with a similar fatty acid composition (7, 8). The main digestive product of diacylglycerol is 1-monoglyceride, which is poorly reesterified into triacylglycerol in the small intestinal mucosa (14); thus, greater amounts of fatty acids are released into the portal circulation than after triacylglycerol ingestion (15). In contrast, the main product of triacylglycerol digestion is 2-monoglyceride, which is esterified to form triacylglycerol and incorporated into chylomicra (16).

A similar example of metabolic discrimination of dietary fats occurs in the utilization of medium- and long-chain fatty acids. Medium-chain fatty acids are transported in the portal blood directly to the liver (17). Long-chain fatty acids are incorporated into chylomicra and transported through lymph (17). Data from studies in animals and humans show increased postprandial energy expenditure after short-term feeding with medium-chain fatty acids and attenuation of weight gain after long-term feeding with medium-chain fatty acids (17, 18).

To explain the difference in the effect that diacylglycerol oil and triacylglycerol oil appear to have on body fat stores, it must be inferred that these 2 types of oil differ in their effect on energy expenditure and energy intake. Studies in experimental animals provide some evidence of increased energy usage (9, 15).

Murase et al (9) compared the effects of a standard chow control diet (5% triacylglycerol), a triacylglycerol diet (30% triacylglycerol + 13% sucrose), and a diacylglycerol diet (30% diacylglycerol + 13% sucrose) in C57BL/6J mice. After 5 mo of ad libitum feeding, body weight and fat were significantly higher in the triacylglycerol diet group than in the diacylglycerol diet group and the control group. Hepatic acyl-coenzyme A oxidase activity and messenger RNA for acyl-coenzyme A synthase increased in the diacylglycerol diet group, suggesting a higher capacity for hepatic lipid oxidation. Insulin and leptin concentrations in the diacylglycerol diet group were similar to those in the control group but were significantly lower than those in the triacylglycerol diet group. The triacylglycerol diet group had more leptin messenger RNA than did the control group, whereas the diacylglycerol diet group did not. Thus, substituting diacylglycerol for triacylglycerol prevented the increases in body fat, insulin, and leptin associated with a high-fat and high-sucrose diet in mice that were prone to obesity and diabetes. Both the diacylglycerol (270 kJ/d) and triacylglycerol (286 kJ/d) diets resulted in higher total daily energy intake than did the control diet (242 kJ/d), and fecal fat loss did not differ significantly between the 2 high-fat treatments. Therefore, the mice that consumed the diacylglycerol diet were able to maintain smaller fat stores while having a higher energy intake than


that of controls, suggesting that diacylglycerol consumption increased energy expenditure.

Watanabe et al (15) found that in comparison with a triacylglycerol control, oxygen consumption in rats increased ≈ 1 ml \cdot kg⁻¹ \cdot min⁻¹ during the 90 min after diacylglycerol administration, suggesting a short-term increase in energy expenditure. This result is similar to the effect observed after consumption of medium-chain triacylglycerol (17).

Flatt (19–21) postulated that fat stores expand when the respiratory quotient is higher than the food quotient of the diet, ie, when fat oxidation is lower than fat intake. Enlarged fat stores result in a greater release of fatty acids, which elevate fat oxidation, thus reestablishing an equilibrium between fat intake and oxidation. Increased carbohydrate intake rapidly promotes higher carbohydrate oxidation, whereas short-term increases in triacylglycerol intake do not elevate fat oxidation (19, 20, 22). Because greater amounts of fatty acids from digested diacylglycerol are released into the portal circulation than are incorporated into chylomicra, hepatic exposure to fatty acids increases after diacylglycerol intake, leading to greater β -oxidation by the liver than that after triacylglycerol intake (9, 15, 23). Thus, unlike triacylglycerol consumption, diacylglycerol consumption promotes a short-term increase in fat oxidation (15), which may allow a balance between fat oxidation and fat intake to occur at a higher level of fat consumption.

Data from mice indicate that a smaller fat mass is associated with smaller liver glycogen stores (21, 24, 25). Increased hepatic fat oxidation, which occurs with diacylglycerol consumption (9, 23), down-regulates liver glycogen stores (26). The depletion of liver glycogen has been hypothesized to enhance the drive to feed until the glycogen stores are replete (21). Thus, if the hepatic glycogen “set-point” is reduced so that glycogen stores are maintained at a lower level, a smaller quantity of carbohydrate and energy would need to be consumed to achieve repletion (19, 27). This hypothesis is consistent with the view that regulation of food intake is more closely linked to the maintenance of carbohydrate than to fat balance (21, 26) and may provide an explanation for the apparent lack of compensatory increase in the drive to feed when body fat stores decrease during chronic diacylglycerol consumption (10).

Weight loss in both treatment groups was modest and approximately one-half of the amount anticipated. In part, this may have been a consequence of the suboptimal characteristics of the study food products, which were relatively high in energy and sucrose. Subjects reported that they had a difficult time consuming the number of servings of study products required while maintaining a reduced-energy diet, and the authors feel that this was a major limitation in the design of the present trial. Future trials will ideally use more concentrated sources of diacylglycerol such as margarine or mayonnaise.

Obesity is a difficult condition to treat. Energy restriction and increased physical activity are the first lines of therapy. Unfortunately, these interventions have shown limited success for long-term maintenance of weight and fat loss. Replacing a portion of dietary triacylglycerol with diacylglycerol as part of a lifestyle intervention program shows promise as a means by which losses of body weight and fat may be enhanced during consumption of an energy-restricted diet. 

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