Dietary Fat and Carbohydrates Differentially Alter Insulin Sensitivity During Caloric Restriction

ERIK KIRK, DOMINIC N. REEDS, BRIAN N. FINCK, MITRA S. MAYURRANJAN, BRUCE W. PATTERSON, and SAMUEL KLEIN

Center for Human Nutrition and Division of Geriatrics and Nutritional Science, Washington University School of Medicine, St Louis, Missouri

See editorial on page 1490.

Background & Aims: **We determined the effects of acute and chronic calorie restriction with either a low-fat, high-carbohydrate (HC) diet or a low-carbohydrate (LC) diet on hepatic and skeletal muscle insulin sensitivity.** ***Methods:*** **Twenty-two obese subjects (body mass index, 36.5 ± 0.8 kg/m^2) were randomized to an HC (>180 g/day) or LC (<50 g/day) energy-deficit diet. A euglycemic-hyperinsulinemic clamp, muscle biopsy specimens, and magnetic resonance spectroscopy were used to determine insulin action, cellular insulin signaling, and intrahepatic triglyceride (IHTG) content before, after 48 hours, and after ~11 weeks (7% weight loss) of diet therapy.** ***Results:*** **At 48 hours, IHTG content decreased more in the LC than the HC diet group (29.6% ± 4.8% vs 8.9% ± 1.4%; $P < .05$) but was similar in both groups after 7% weight loss (LC diet, 38.0% ± 4.5%; HC diet, 44.5% ± 13.5%). Basal glucose production rate decreased more in the LC than the HC diet group at 48 hours (23.4% ± 2.2% vs 7.2% ± 1.4%; $P < .05$) and after 7% weight loss (20.0% ± 2.4% vs 7.9% ± 1.2%; $P < .05$). Insulin-mediated glucose uptake did not change at 48 hours but increased similarly in both groups after 7% weight loss (48.4% ± 14.3%; $P < .05$). In both groups, insulin-stimulated phosphorylation of c-Jun-N-terminal kinase decreased by 29% ± 13% and phosphorylation of Akt and insulin receptor substrate 1 increased by 35% ± 9% and 36% ± 9%, respectively, after 7% weight loss (all $P < .05$).** ***Conclusions:*** **Moderate calorie restriction causes temporal changes in liver and skeletal muscle metabolism; 48 hours of calorie restriction affects the liver (IHTG content, hepatic insulin sensitivity, and glucose production), whereas moderate weight loss affects muscle (insulin-mediated glucose uptake and insulin signaling).**

Insulin resistance is the most common metabolic complication associated with obesity and is associated with an increased risk of developing nonalcoholic fatty liver disease and type 2 diabetes mellitus.[1,2] A reduced calorie diet is a primary therapy for insulin-resistant obese persons, because even moderate diet-induced weight loss (5%–10% of body weight) decreases intrahepatic triglyceride (IHTG) content and improves hepatic and skeletal muscle insulin sensitivity.[3–9] However, the effect of brief calorie restriction (CR) (≤3 days) is confusing because short-term therapy with a very low calorie diet (≤800 kcal/day) improves insulin action,[10,11] whereas short-term fasting induces insulin resistance.[12,13]

The mechanism responsible for the apparent discrepancy between severe and complete CR on insulin action is not clear, but it is possible that differences in total carbohydrate intake could be responsible. Data from studies that used the hyperinsulinemic-euglycemic clamp technique to assess insulin action found that short-term CR with low-carbohydrate (LC) intake (0–50 g/day) is associated with a decline in hepatic and skeletal muscle insulin sensitivity,[14,15] whereas short-term CR with adequate carbohydrate intake (100 g/day) is associated with an increase in both hepatic and skeletal muscle insulin sensitivity.[4] We previously found that carbohydrate restriction, not total energy restriction, is responsible for initiating the lipolytic response to fasting; providing daily energy requirements by infusing a lipid emulsion (carbohydrate restriction) resulted in the same increase in lipolytic rate that occurred after complete fasting.[16] The summation of these data suggests that short-term CR with an LC diet could have adverse effects on insulin sensitivity because of increased free fatty acid release into the circulation, which can cause both hepatic[17,18] and skeletal muscle[19] insulin resistance.

The current recommended dietary guidelines for treating obesity are to reduce daily energy intake by 500–1000 kcal.[20] Although both LC and high-carbohydrate (HC), low-fat diets are frequently used to lose weight, it is not known whether the short-term and long-term effects of CR on IHTG content and insulin action in liver and

Abbreviations used in this paper: CR, calorie restriction; GCRC, General Clinical Research Center; HC, high-carbohydrate; HOMA-IR, homeostasis model assessment of insulin resistance; IHTG, intrahepatic triglyceride; JNK, c-Jun-N-terminal kinase; LC, low-carbohydrate; PKB, protein kinase B; Ra, rate of appearance; Rd, rate of disappearance.

© 2009 by the AGA Institute

0016-5085/09/$36.00
doi:10.1053/j.gastro.2009.01.048

muscle differ between diets. Therefore, the purpose of the present study was to evaluate the short-term and long-term metabolic effects of a 1000-kcal/day deficit HC (≥180 g/day) or LC (≤50 g/day) diet in obese insulin-resistant subjects. A euglycemic-hyperinsulinemic clamp procedure, in conjunction with stable isotope tracer infusion, was performed to assess hepatic and muscle insulin sensitivity, vastus lateralis muscle samples were obtained to determine the concentration of key factors that regulate skeletal muscle insulin sensitivity, and magnetic resonance spectroscopy was used to determine IHTG content after short-term CR (48 hours) and moderate (7%) weight loss. We hypothesized that, compared with an energy-deficit HC diet, consuming an energy-deficit LC diet has adverse effects on insulin action.

Subjects and Methods

Subjects

Twenty-two obese subjects (4 men and 18 women; 43.6 ± 2.5 years of age; body mass index, 36.5 ± 0.8 kg/m^2) participated in this study. All subjects completed a medical evaluation, which included a history and physical examination, standard blood and urine tests, an electrocardiogram, and a 2-hour oral glucose tolerance test. All subjects were considered insulin resistant, defined as a homeostasis model assessment of insulin resistance (HOMA-IR) value >3.0.[21] In addition, 63% of subjects had impaired glucose tolerance based on a plasma glucose concentration between 140 and 199 mg/dL at 2 hours after a 75-g oral glucose load.[22] Subjects who had diabetes, a history of excessive alcohol consumption, liver disease, or evidence of other serious illnesses or organ dysfunction as well as subjects who smoked tobacco products or took medications that are known to alter glucose metabolism were excluded from the study. All subjects were weight stable (≤2% change in body weight) and had been sedentary (<1 hour of exercise per week) for at least 3 months before being enrolled in the study.

The study was approved by the Human Studies Committee of Washington University School of Medicine (St Louis, MO). Written informed consent was obtained from each subject before participation in this study.

Experimental Design

Body composition assessments. Total body fat mass and fat-free mass were determined by using dual-energy x-ray absorptiometry (QDR 4500; Hologic, Waltham, MA).[23] Total abdominal, subcutaneous abdominal, and intra-abdominal fat volumes were quantified by using magnetic resonance imaging (Siemens Vision 1.5 Tesla imager; Siemens, Erlanger, Germany). IHTG content was determined by using proton magnetic resonance spectroscopy with a 1.5T scanner (Magneton Vision Scanner; Siemens)[24]; three 2 × 2 × 2 voxels were analyzed for each subject, and the values were averaged for data analyses. These body composition assessments were made at baseline (before diet intervention), after 48 hours of CR with either an HC or LC diet, and after subjects lost 7% of their initial body weight and were weight stable for 4 weeks.

Euglycemic-hyperinsulinemic clamp procedure. Subjects were admitted to the inpatient unit of the General Clinical Research Center (GCRC) on 2 separate occasions. A euglycemic-hyperinsulinemic clamp procedure, in conjunction with stable isotopically labeled tracer infusion, was performed at baseline (before diet intervention), after 48 hours of CR with either an HC or LC diet, and after subjects lost 7% of their initial body weight and were weight stable for 4 weeks. Subjects were instructed to abstain from exercise and to maintain their regular diet for at least 3 days and to abstain from consumption of caffeine and alcohol for at least 24 hours before each admission. Female subjects were studied during the follicular phase of their menstrual cycle.

During the first GCRC admission, subjects were admitted for 4 days. In the evening on the day of admission, subjects consumed a standard meal containing 15 kcal/kg fat-free mass and 55% of total energy as carbohydrates, 30% as fat, and 15% as protein at ~6:00 PM and then fasted (except for water) and rested in bed until completion of the clamp procedure the next day. The following morning, at 6:00 AM, a catheter was inserted into an antecubital vein of one arm to infuse stable isotopically labeled glucose, insulin, and dextrose; another catheter was inserted in a contralateral hand vein, which was placed in a thermostatically controlled (65°C) box to obtain arterialized blood.[25] At 6:30 AM, resting energy expenditure was determined by using a metabolic measuring cart (Delta Trac; SensorMedics, Yorba Linda, CA). At ~7:00 AM, after a blood sample was obtained to determine the background glucose enrichment, a primed, continuous infusion of [6,6-$^2H_2$]glucose was started and maintained for 7 hours. At 210 minutes after starting the tracer infusion, insulin was infused at a rate of 40 mU · m^2 body surface area^{-1} · min^{-1} for 210 minutes (initiated with a 2-step priming dose of 160 mU · m^2 body surface area^{-1} · min^{-1} for 5 minutes followed by 80 mU · m^2 body surface area^{-1} · min^{-1} for 5 minutes). Dextrose (20%), enriched with [6,6-$^2H_2$]glucose to ~2.5% to minimize changes in plasma glucose enrichment,[26] was infused at a variable rate to maintain euglycemia (plasma glucose concentration of 5.6 mmol/L). The infusion rate of [6,6-$^2H_2$]glucose was decreased by 75% during the clamp procedure to account for the expected decline in hepatic glucose production. Blood samples were taken every 10 minutes during the last 30 minutes of the basal period and the clamp procedure to determine plasma glucose tracer-to-tracee ratio and concentration and plasma insulin concentration during basal conditions and insulin infusion. A muscle biopsy specimen from the vastus lateralis was taken at 240 minutes (ie, 30 minutes after

starting the insulin infusion) to assess specific cellular factors involved in insulin sensitivity. The tissue was immediately frozen in liquid nitrogen and then stored at −80°C until final analyses.

Diet intervention. After completing the first insulin clamp procedure, subjects were randomized to treatment with either a low-calorie HC diet or an LC diet. The energy content of the HC and LC diets was designed to provide a 1000-kcal daily energy deficit, based on an estimated daily energy requirement (calculated as 1.3 times measured resting energy expenditure); the average total daily energy intake was ~1100 kcal. The HC diet provided ≥180 g carbohydrates per day and ~65% of total daily energy intake as carbohydrates, 20% as fat, and 15% as protein; the LC diet provided ≤50 g carbohydrates per day and ~10% of daily energy intake as carbohydrates, 75% as fat, and 15% as protein.

Subjects remained in the GCRC until the second insulin clamp procedure and body composition assessment were completed. All food was provided by the GCRC metabolic kitchen, and subjects' food intake was monitored. On the first day of the diet intervention (ie, the day of the first clamp procedure), the calorie and carbohydrate contents of the diet were adjusted to account for the glucose calories infused during the clamp procedure. On the third morning in the GCRC, the insulin clamp procedure was repeated after 48 hours of consuming either a low-calorie HC or low-calorie LC diet. After completing the second insulin clamp procedure, the calorie and carbohydrate contents of the diet were again adjusted to account for the glucose calories infused during the clamp procedure. The following morning (day 4 in the GCRC), IHTG content and body composition were evaluated and subjects were then discharged from the GCRC.

All subjects received detailed dietary instructions by a registered dietician and were instructed to follow the HC and LC diet until they lost 7% of their total body weight. Subjects received weekly individual or group behavior therapy and diet education with a registered dietician and an experienced behavior counselor to enhance dietary compliance. Once subjects achieved a 7% body weight loss (on average after 6 ± 1 weeks), total calorie intake was adjusted to maintain a constant body weight and prevent further weight loss. After being weight stable at their new body weight for at least 4 weeks, subjects were readmitted to the GCRC and the insulin clamp procedure and body composition analyses were repeated.

Sample Analyses

Plasma substrate and hormone concentrations. Plasma glucose concentration was determined using an automated glucose analyzer (YSI 2300 STAT Plus; Yellow Spring Instrument Co, Yellow Springs, OH). Plasma insulin and leptin concentrations were measured using radioimmunoassay, and enzyme-linked immunosorbent assay kits were used to measure plasma adiponectin concentrations (Linco Research, St Louis, MO). The relative changes in plasma 3-hydroxybutyrate concentrations at 48 hours and ~11 weeks of CR compared with baseline values were determined using a gas chromatography/mass spectrometry platform as described previously.[27]

Plasma glucose isotopic enrichment. Plasma glucose tracer-to-tracee ratio was determined using gas chromatography/mass spectrometry (Agilent Technologies/HP 6890 Series GC System – 5973 Mass Selective Detector; Hewlett-Packard, Palo Alto, CA) after preparing the heptafluorobutyryl derivative of glucose and selectively monitoring ions at m/z 519 and 521.[28]

Muscle Akt/protein kinase B (PKB), IRS-1, and c-Jun-N-terminal kinase (JNK)-1 phosphorylation were determined using Western blotting analyses (muscle Akt/PKB and JNK-1 phosphorylation) and immunoprecipitation (IRS-1 phosphorylation). Muscle samples were homogenized in lysis buffer (50 mmol/L Tris, 150 mmol/L NaCl, and 1% Nonidet P40) containing a cocktail of protease and phosphatase (NaF and $NaVO_4$) inhibitors.[29] Protein content was quantified and then 60 μg protein was electrophoresed by sodium dodecyl sulfate/polyacrylamide gel electrophoresis and transferred to nitrocellulose membranes. Blots were probed with polyclonal antibodies directed against total Akt/PKB (Amersham Biosciences, Pittsburgh, PA), Akt/PKB phosphorylated at serine 473 (Amersham Biosciences), total JNK (EMD Biosciences, San Diego, CA), and JNK phosphorylated at threonine 183 (EMD Biosciences). To evaluate IRS-1 tyrosine phosphorylation, IRS-1 was immunoprecipitated from 500 μg of protein using a polyclonal antibody against IRS-1 (gift of Mike Mueckler) before sodium dodecyl sulfate/polyacrylamide gel electrophoresis and immunoblotting with an antibody directed against phosphotyrosine (Cell Signaling, Danvers, MA) or IRS-1 (gift of Mike Mueckler). The intensity of bands obtained by Western blotting analyses was quantified by digitizing the autoradiographic images and using Image Processing and Analysis in Java Program (ImageJ, National Institutes of Health, version 1.36b). The intensity of the phosphorylated forms of the proteins was corrected for total content of that protein and normalized to the baseline value (ie, before intervention); therefore, values are expressed as percentage change from baseline.

Calculations. Total (endogenous and exogenous) glucose rate of appearance (Ra) in plasma during basal conditions and the clamp procedure was calculated by dividing the glucose tracer infusion rate by the average plasma glucose tracer-to-tracee ratio between 180 and 210 minutes (basal) and 390 and 420 minutes (clamp).[30] Endogenous glucose Ra was calculated by subtracting the unlabeled glucose tracer infusion rate from total glucose Ra. It was assumed that glucose rate of disappearance (Rd) was equal to total glucose Ra.

The HOMA-IR was determined by dividing the product of plasma glucose concentration (in mmol/L) and plasma insulin concentration (in mU/L) by 22.5.[21] Hepatic insulin sensitivity index was assessed as the reciprocal of the hepatic insulin resistance index, which is calculated as the product of the basal hepatic glucose production rate (in μmol · kg fat-free mass^{-1} · min^{-1}) and fasting plasma insulin concentration (in mU/L).[31,32] Skeletal muscle insulin sensitivity was determined by evaluating the ability of insulin to stimulate skeletal muscle glucose uptake, assessed as the relative increase in whole body glucose Rd during insulin infusion compared with baseline values.

Statistical Analysis

A 2-way analysis of variance with repeated measures was used to compare between- and within-group differences in the changes in outcome measures from baseline to 48 hours and from baseline to 7% weight loss. Tukey's post hoc procedure was used to locate differences if a significant main effect was found. The relationship between the percent change in intra-abdominal fat volume and the percent change in IHTG content and hepatic insulin sensitivity index were assessed by using linear regression analysis. A P value of $\leq$.05 was considered statistically significant. Data are expressed as means ± SEM. All data were analyzed using SAS (version 8.2; SAS Institute Inc, Cary, NC).

Results

Study Subject Characteristics

Baseline metabolic variables and body composition measurements were not different between subjects randomized to the HC and LC diet groups (Table 1). Fifty percent of subjects in the HC diet group and 58% of subjects in the LC diet group had nonalcoholic fatty liver disease, defined as IHTG content >5.6%.[33]

Dietary Compliance

Changes in plasma 3-hydroxybutyrate concentrations during CR suggest that study subjects in both the HC and LC diet groups were compliant with their dietary assignment. In subjects randomized to CR with an HC diet, plasma β-hydroxybutyrate values increased ~2-fold at 48 hours of CR (P = .02) and returned to baseline values at 11 weeks of CR. In subjects randomized to CR with an LC diet, plasma 3-hydroxybutyrate increased ~10-fold at 48 hours of CR (P < .0001) and remained 10-fold greater than baseline at 11 weeks of CR (P = .002).

Body Weight and Body Composition

Short-term CR caused a similar decrease in body weight at 48 hours with either diet (Table 2) (mean weight loss for both groups combined, 2.0% ± 0.2%; P < .0001). Long-term weight loss after completing the diet intervention was also similar in both groups (Table 2) (mean weight loss for both groups combined at ~11 weeks of dieting, 7.5% ± 0.4%; P < .0001). The time to achieve 7% weight loss was not different between the HC diet group (6.2 ± 1.0 weeks) and the LC diet group (5.9 ± 1.0 weeks).

Changes in body fat mass and fat-free mass at ~11 weeks of dieting and 7% weight loss were not different between the HC and LC groups (the average decreases in fat mass, fat-free mass, and intra-abdominal fat volume in all subjects were 11.3% ± 0.9%, 3.8% ± 0.6%, and 12.0% ± 2.8%, respectively; all P < .001) (Figure 1). CR with either the HC or LC diet caused a progressive decrease in IHTG content. The relative decrease in IHTG was ~3 times greater in the LC group than in the HC group at 48 hours of CR but was not different between groups after ~11 weeks of CR (~7% weight loss) (Figure 1). There was not a significant relationship between percent change in intra-abdominal fat

Table 1. Baseline Body Composition and Metabolic Characteristics of the Study Subjects

	HC diet group (n = 11)	LC diet group (n = 11)	All subjects (n = 22)
Age (*y*)	45.4 ± 4.0	41.8 ± 3.1	43.6 ± 2.5
Body weight (*kg*)	101.0 ± 4.1	101.9 ± 4.0	101.5 ± 2.8
Body mass index (*kg/m^2*)	36.9 ± 1.2	36.1 ± 1.0	36.5 ± 0.8
Fat-free mass (*kg*)	57.2 ± 3.1	57.9 ± 3.2	57.6 ± 2.2
Fat mass (*kg*)	41.7 ± 2.4	42.1 ± 1.7	41.9 ± 1.4
Fat mass (*% body wt*)	42.3 ± 1.9	42.3 ± 1.4	42.3 ± 1.1
Total abdominal fat volume (*cm^3*)	5625 ± 233	5753 ± 321	5686 ± 191
Subcutaneous abdominal fat volume (*cm^3*)	4010 ± 243	4208 ± 385	4105 ± 219
Intra-abdominal fat volume (*cm^3*)	1556 ± 234	1544 ± 221	1550 ± 158
IHTG content (*%*)	11.2 ± 2.9	12.4 ± 2.9	11.8 ± 2.0
Plasma glucose level (*mg/dL*)	96.8 ± 2.7	101.5 ± 4.5	99.1 ± 2.6
Plasma insulin level (μ*U/mL*)	15.5 ± 2.8	18.7 ± 2.4	17.1 ± 1.8
Plasma triglyceride level (*mg/dL*)	138.9 ± 17	147.7 ± 21.0	143.5 ± 13
High-density lipoprotein cholesterol level (*mg/dL*)	45.2 ± 2.7	44.1 ± 3.7	44.6 ± 2.2
Low-density lipoprotein cholesterol level (*mg/dL*)	93.3 ± 5.5	96.7 ± 7.3	95.0 ± 4.5

NOTE. Values are expressed as means ± SEM.

Table 2. Percent Change From Baseline in Body Weight and Metabolic Variables After 48 Hours and 11 Weeks (7% Weight Loss) of CR in Subjects Consuming an HC or LC Diet

	Percent change after 48-hour CR		Percent change after ~11-week CR	
	HC	LC	HC	LC
Body wt	−1.6 ± 0.2[a]	−2.2 ± −0.2[a]	−7.3 ± 0.6[a]	−7.6 ± 0.5[a]
Plasma glucose level	−2.6 ± 2.3	−9.8 ± 2.4[b,c]	−6.2 ± 1.6[b]	−8.9 ± 3.0[b]
Plasma insulin level	−22.0 ± 5.1[b]	−33.9 ± 6.4[a]	−22.0 ± 5.7[b]	−38.4 ± 5.2[a,c]
C-peptide level	−14.4 ± 3.5[b]	−26.3 ± 4.5[a]	−12.0 ± 3.1[b]	−25.3 ± 3.6[a]
Free fatty acid level	13.9 ± 6.2[b]	32.1 ± 8.0[b]	−1.5 ± 9.9	−1.5 ± 7.5
HOMA-IR	−23.8 ± 5.9[b]	−40.3 ± 6.1[a,c]	−27.1 ± 5.1[a]	−44.0 ± 4.7[a,c]

NOTE. Values are means ± SEM.
Value significantly different from baseline value: [a]$P < .001$, [b]$P < .05$; value significantly different from value in HC group: [c]$P < .05$.

volume and percent change in IHTG ($R^2 = 0.001$; $P > .05$).

Plasma Adipokine and Hepatic Enzyme Concentrations

Plasma leptin concentration decreased similarly in both groups after 48 hours (10.8% ± 3.6% decrease from baseline in combined groups, $P < .01$) and ~11 weeks (19.4% ± 6.8% decrease from baseline in combined groups, $P < .01$) of CR. Plasma adiponectin concentrations decreased in both groups after 48 hours (8.8% ± 3.5% decrease from baseline in combined groups, $P < .05$) and tended to increase after ~11 weeks (12.1% ± 7.2% increase from baseline in combined groups, $P > .05$) of CR.

Plasma alanine aminotransferase and aspartate aminotransferase concentrations did not change after 48 hours and ~11 weeks of CR in either the HC or LC diet groups. In the combined groups, plasma alanine aminotransferase concentrations were 29.2 ± 2.4, 31.1 ± 3.4, and 33.4 ± 5.2 IU/L and plasma aspartate aminotransferase concentrations were 25.5 ± 2.0, 28.0 ± 2.9, and 26.2 ± 2.8 IU/L at baseline, 48 hours, and 11 weeks of CR, respectively.

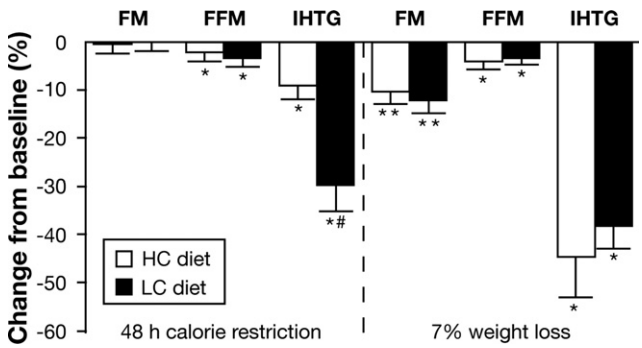

Figure 1. Changes in body composition and IHTG content after 48 hours (2% weight loss) and ~11 weeks (7% weight loss) of CR in obese subjects consuming either an HC or LC 1000-kcal/day deficit diet. Values are means ± SEM. Value significantly different from baseline value: *$P < .05$, **$P < .001$; Value significantly different from corresponding high-carbohydrate diet group, #$P < .05$. FM, fat mass; FFM, fat-free mass.

In Vivo Measures of Insulin Sensitivity and Glucose Homeostasis

Plasma glucose, c-peptide, and insulin concentrations. CR caused a decline in plasma glucose, c-peptide, and insulin concentrations both after 48 hours and ~11 weeks (~7% weight loss) of dieting in the HC and LC groups (Table 2). There was a trend toward a greater decrease in both plasma glucose, c-peptide, and insulin concentrations in the LC group than the HC group after both short-term and long-term dieting. However, only the decrease in plasma glucose concentration after 48 hours of CR and the decrease in plasma insulin concentration after 7% weight loss were significantly different between groups.

HOMA-IR. HOMA-IR improved in both groups after 48 hours of CR and did not change further after ~11 weeks of dieting (~7% weight loss) (Table 2). However, the decrease in HOMA-IR was greater in the LC than the HC diet group after both 48 hours of CR and 7% weight loss (Table 2).

Hepatic insulin sensitivity index. Hepatic insulin sensitivity increased after 48 hours of CR in both the HC and LC groups but did not improve further after 11 weeks of CR (7% weight loss) (Figure 2*A*). However, the improvement in hepatic insulin sensitivity was greater in the LC than the HC group after both 48-hour CR and 7% weight loss (Figure 2*A*). There was not a significant correlation between percent changes in IHTG content and hepatic insulin sensitivity index value ($R^2 = 0.083$, $P > .05$).

Basal glucose kinetics. Basal glucose Ra decreased after 48 hours of CR in both the HC and LC groups but was not different between groups and did not change further with more prolonged CR and 7% weight loss. Glucose Ra in the combined groups were 13.8 ± 0.4, 12.0 ± 0.4, and 12.2 ± 0.3 μmol · kg fat-free mass^{-1} · min^{-1} at baseline and at 48 hours and 11 weeks of CR, respectively ($P < .001$ for each CR value compared with baseline value). The decline in basal glucose Ra was greater in the LC than the HC group after both short-term (48 hours) and long-term (~11 weeks, 7% weight loss) CR (Figure 3).

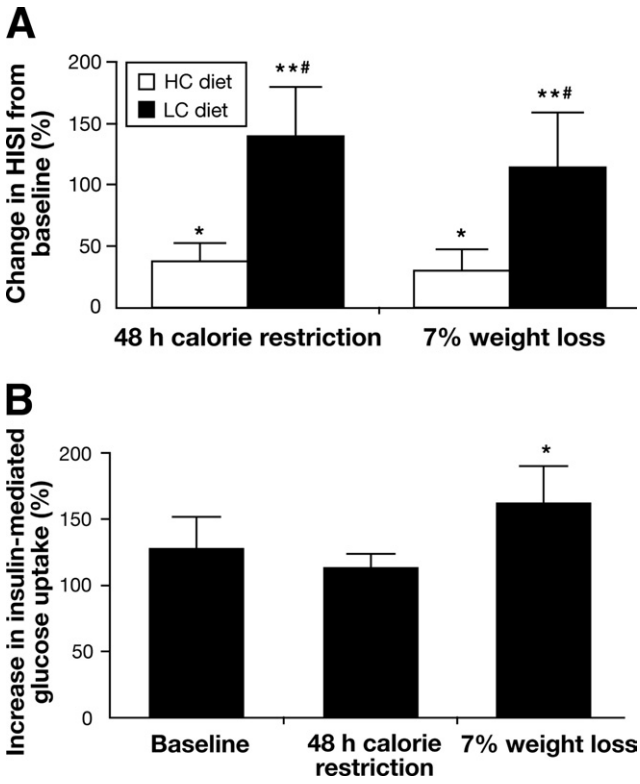

Figure 2. (*A*) Hepatic insulin sensitivity index (HISI) in subjects consuming either an HC or LC diet and (*B*) changes in insulin-mediated glucose uptake, an index of skeletal muscle insulin sensitivity, in both groups combined after 48 hours and ~11 weeks (7% weight loss) of CR. Value significantly different from baseline value: $^{*}P < .05$, $^{**}P < .001$. Value significantly different from value in HC group: $^{\#}P < .05$.

Insulin-mediated glucose uptake. Plasma insulin concentrations during the clamp procedure were not different between the HC and LC groups at any time point during the study. However, plasma insulin concentrations after 48 hours (84.3 ± 3.4 μU/mL) and 11 weeks (84.5 ± 0.2 μU/mL) of CR were ~10% lower than values at baseline (95.4 ± 3.3 μU/mL; $P < .0001$). Glucose Rd values during insulin infusion were similar in both groups: 30.0 ± 2.6, 25.0 ± 1.4, and 31.1 ± 2.5 μmol · kg fat-free mass^{-1} · min^{-1} at baseline and at 48 hours and 11 weeks of CR for the combined groups, respectively. The relative increase in glucose Rd during insulin infusion was not greater at 48 hours of CR than at baseline before CR in either diet group. However, the relative increase in glucose Rd during insulin infusion was greater after 7% weight loss than at baseline in both diet groups. Both short-term (48 hours) and long-term (11 weeks, 7% weight loss) CR caused similar changes in insulin-mediated increases in glucose Rd in the HC and LC groups, so the data from both groups are combined (Figure 2*B*).

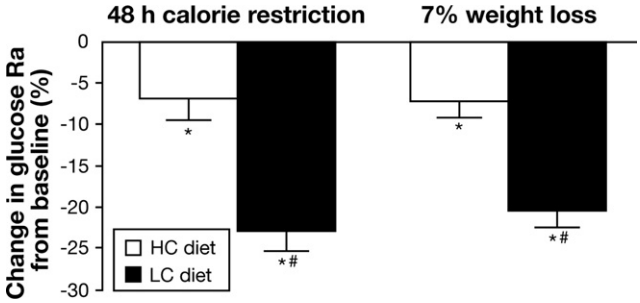

Figure 3. Relative changes in basal glucose Ra in plasma after 48 hours of CR and 7% weight loss. Values are means ± SEM. Value significantly different from baseline value: $^{*}P < .001$. Value significantly different from value in HC group: $^{\#}P < .001$.

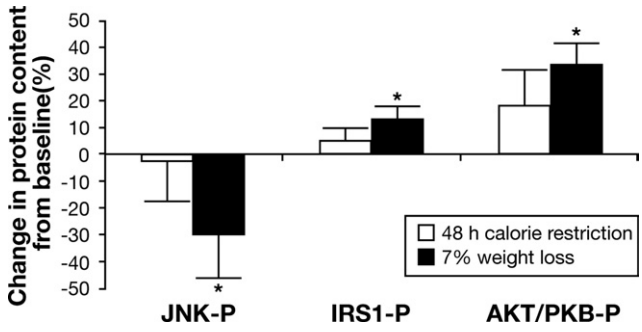

Figure 4. Changes in phosphoTyr183 JNK, phosphoTyr IRS, and phosphoSer473 Akt/PKB protein levels in vastus lateralis muscle biopsy specimens obtained after 30 minutes of insulin infusion during a euglycemic-hyperinsulinemic clamp procedure after 48 hours and ~11 weeks (7% weight loss) of CR. Values are corrected for total JNK, IRS1, and Akt/PKB protein content and normalized (=0) to values from baseline samples (day 0). Values are expressed as means ± SEM. Value significantly different from corresponding baseline value: $^{*}P < .05$.

Cellular Insulin Signaling in Skeletal Muscle

At 48 hours of CR, skeletal muscle phosphorylation of Tyr183 JNK, Tyr IRS1, and Ser473 Akt/PKB content assessed after insulin stimulation (30 minutes of insulin infusion) was not significantly different than baseline (before CR) in either diet group (Figure 4). However, at 11 weeks of CR (7% weight loss), insulin-stimulated skeletal muscle phosphoTyr IRS1 and phosphoSer473 Akt/PKB content increased whereas phosphoTyr183 JNK content decreased compared with baseline in both diet groups. Changes in phosphorylation status of Tyr183 JNK, Tyr IRS1, and Ser473 Akt/PKB were similar in the HC and LC groups, so the data from both groups are combined in Figure 4.

Discussion

An energy-deficit diet is the cornerstone of therapy for obesity. However, the most appropriate macronutrient composition of diet therapy needed to improve metabolic health remains controversial. In the present study, we carefully evaluated the longitudinal metabolic effects of short-term (48 hours; 2% weight loss) and longer-term (11 weeks; 7% weight loss) CR (1000-kcal/day energy deficit) with either an HC or LC diet in obese and insulin-resistant but nondiabetic adults. Our data show that short-term CR caused a rapid decrease in IHTG

content, increase in hepatic insulin sensitivity, and decrease in endogenous glucose production rate, whereas longer-term CR and moderate 7% weight loss improved skeletal muscle insulin sensitivity, in conjunction with an increase in cellular insulin signaling. In addition, short-term CR with an LC diet caused a greater change in liver fat content and metabolic function than short-term CR with an HC diet. These data underscore the complexity of the metabolic effects of CR with diets that differ in macronutrient composition and show temporal differences among organ systems in the adaptive response to CR itself and subsequent weight loss.

Our results refute our original hypothesis that an LC diet will cause insulin resistance because of increased adipose tissue lipolytic rates and excessive free fatty acid release into the bloodstream. In fact, we found that LC intake rapidly caused a greater reduction in IHTG content, improvement in hepatic insulin sensitivity, and decrease in endogenous glucose production rate than consumption of an isocaloric low-fat diet. The mechanism responsible for the early beneficial effects on liver metabolism is not known but is probably related to the greater decrease in plasma insulin concentrations in subjects consuming the LC diet. The decline in circulating insulin levels likely decreased IHTG because of enhanced lipolysis of IHTG and hepatic fatty acid oxidation[14] and decreased hepatic glucose production because of hepatic glycogen depletion[17] and decreased glycogenolysis.[4,34] These metabolic alterations are similar to the physiologic adaptations that occur during the early response to starvation, which are also triggered by a reduction in carbohydrate intake.[16] However, in contrast to data obtained from studies evaluating the metabolic effects of brief fasting,[12–14] we did not detect a significant decline in skeletal muscle insulin sensitivity after 48 hours of CR with an LC diet.

Weight loss, but not short-term CR, was necessary to increase skeletal muscle insulin-mediated glucose disposal. The improvement in muscle insulin sensitivity we observed in vivo is explained by enhanced cellular insulin signaling (increased insulin-stimulated IRS-1 tyrosine and Akt/PKB serine phosphorylation) detected after 7% weight loss but not after 48 hours of CR. These results are consistent with data from a study conducted in subjects with type 2 diabetes mellitus that found insulin-stimulated Akt/PKB did not change after 2 days of CR.[35] In addition, our data suggest that the mechanism responsible for the increase in insulin signaling involves down-regulation of JNK, which inhibits IRS-1 serine phosphorylation and the proximal component of the insulin signaling cascade.[36] Therefore, these findings show that the increase in JNK associated with obesity and type 2 diabetes mellitus is responsive to nutritional manipulation and can be normalized by weight loss.

Nonalcoholic fatty liver disease is associated with insulin resistance[37,38] and is an important risk factor for diabetes.[39] We previously found a linear inverse correlation between IHTG content and insulin sensitivity in both liver and skeletal muscle.[38] In the present study, dietary manipulation of IHTG content allowed us to dissociate the interrelationships among IHTG and insulin sensitivity in liver and skeletal muscle. After 48 hours of CR, IHTG content decreased by ~20%, which was associated with a decrease in basal glucose production rate and an increase in hepatic insulin sensitivity, whereas skeletal muscle insulin sensitivity did not change. Continued CR until subjects lost 7% of initial body weight caused a further decrease in IHTG content, without a further decrease in basal glucose production or improvement in hepatic insulin sensitivity. However, 7% weight loss up-regulated skeletal muscle insulin signaling and increased muscle insulin sensitivity. These data support the notion of a causal link between steatosis and hepatic insulin resistance. The mechanism responsible for the link between IHTG content and hepatic insulin sensitivity is unknown but could be related to an accumulation of intracellular fatty acid metabolites, which can antagonize the effects of insulin signaling on endogenous glucose production.[40]

Our data provide new insights into the potential mechanism responsible for the marked improvement in glycemic control observed within days after Roux-en-y gastric bypass surgery in obese patients with type 2 diabetes mellitus.[41] For example, in one study, 90% of patients were able to discontinue all diabetes medications and maintain normal glycemia at discharge from the hospital 6 days after Roux-en-y gastric bypass surgery, before much weight loss occurred.[42] These observations have led to the hypothesis that diversion of ingested nutrients from the upper gastrointestinal tract has beneficial effects on glucose homeostasis, possibly because of an altered incretin response to meals.[43] However, our results suggest that the rapid decrease in liver fat and improvement in hepatic insulin sensitivity that occur after brief CR can completely explain the early improvement in glucose homeostasis observed after bariatric surgery. Food intake is limited after Roux-en-y gastric bypass surgery, and patients usually consume less than 250 kcal/day for several days after the operation.[41] Therefore, the marked postoperative reduction in calorie intake itself likely has profound effects on hepatic fat content and metabolism.[40] Moreover, the decrease in calorie intake makes it unlikely that diversion of ingested nutrients from the upper gastrointestinal tract has an important effect on glucose metabolism.

In summary, the data from this study show that the effect of moderate CR in obese subjects with either a low-fat or LC diet on metabolic function is a continuum, with differential effects on specific organ systems. Brief (48-hour) CR and minimal weight loss (~2% of initial body weight) primarily affects the liver, manifested by a decrease in IHTG content, an increase in hepatic insulin

sensitivity, and a decrease in endogenous glucose production, whereas longer (~11 weeks) CR and moderate weight loss (~7% of initial body weight) primarily affects skeletal muscle, manifested by an increase in muscle insulin-mediated glucose uptake and enhanced cellular insulin signaling. These findings help explain the rapid improvement in glucose homeostasis observed after low-calorie diet therapy and bariatric surgery.

References

1. Bray GA, Bellanger T. Epidemiology, trends, and morbidities of obesity and the metabolic syndrome. Endocrine 2006;29: 109–117.
2. Adams LA, Lymp JF, St Sauver J, et al. The natural history of nonalcoholic fatty liver disease: a population-based cohort study. Gastroenterology 2005;129:113–121.
3. Goldstein DJ. Beneficial health effects of modest weight loss. Int J Obes Relat Metab Disord 1992;16:397–415.
4. Kelley DE, Wing R, Buonocore C, et al. Relative effects of calorie restriction and weight loss in noninsulin-dependent diabetes mellitus. J Clin Endocrinol Metab 1993;77:1287–1293.
5. Petersen KF, Dufour S, Befroy D, et al. Reversal of nonalcoholic hepatic steatosis, hepatic insulin resistance, and hyperglycemia by moderate weight reduction in patients with type 2 diabetes. Diabetes 2005;54:603–608.
6. Tiikkainen M, Bergholm R, Vehkavaara S, et al. Effects of identical weight loss on body composition and features of insulin resistance in obese women with high and low liver fat content. Diabetes 2003;52:701–707.
7. Wing RR, Blair EH, Bononi P, et al. Caloric restriction per se is a significant factor in improvements in glycemic control and insulin sensitivity during weight loss in obese NIDDM patients. Diabetes Care 1994;17:30–36.
8. Markovic TP, Jenkins AB, Campbell LV, et al. The determinants of glycemic responses to diet restriction and weight loss in obesity and NIDDM. Diabetes Care 1998;21:687–694.
9. Lara-Castro C, Newcomer BR, Rowell J, et al. Effects of short-term very low-calorie diet on intramyocellular lipid and insulin sensitivity in nondiabetic and type 2 diabetic subjects. Metabolism 2008; 57:1–8.
10. Henry RR, Gumbiner B. Benefits and limitations of very-low-calorie diet therapy in obese NIDDM. Diabetes Care 1991;14:802–823.
11. Jazet IM, Pijl H, Frolich M, et al. Two days of a very low calorie diet reduces endogenous glucose production in obese type 2 diabetic patients despite the withdrawal of blood glucose-lowering therapies including insulin. Metabolism 2005;54:705–712.
12. Bergman BC, Cornier MA, Horton TJ, et al. Effects of fasting on insulin action and glucose kinetics in lean and obese men and women. Am J Physiol Endocrinol Metab 2007;293:E1103–E1111.
13. Duska F, Andel M, Kubena A, et al. Effects of acute starvation on insulin resistance in obese patients with and without type 2 diabetes mellitus. Clin Nutr 2005;24:1056–1064.
14. Jensen MD, Haymond MW, Gerich JE, et al. Lipolysis during fasting. Decreased suppression by insulin and increased stimulation by epinephrine. J Clin Invest 1987;79:207–213.
15. Svanfeldt M, Thorell A, Brismar K, et al. Effects of 3 days of "postoperative" low caloric feeding with or without bed rest on insulin sensitivity in healthy subjects. Clin Nutr 2003;22:31–38.
16. Klein S, Wolfe RR. Carbohydrate restriction regulates the adaptive response to fasting. Am J Physiol 1992;262:E631–E636.
17. Boden G, Cheung P, Stein TP, et al. FFA cause hepatic insulin resistance by inhibiting insulin suppression of glycogenolysis. Am J Physiol Endocrinol Metab 2002;283:E12–E19.
18. Mittelman SD, Bergman RN. Inhibition of lipolysis causes suppression of endogenous glucose production independent of changes in insulin. Am J Physiol Endocrinol Metab 2000;279: E630–E637.
19. Roden M, Price TB, Perseghin G, et al. Mechanism of free fatty acid-induced insulin resistance in humans. J Clin Invest 1996; 97:2859–2865.
20. National Institutes of Health, National Heart, Lung, and Blood Institute. Clinical guidelines on the identification, evaluation, and treatment of overweight and obesity in adults—the evidence report. Obesity Res 1998;6:51S–209S.
21. Mathews DR, Hosker JP, Redenski AS, et al. Homeostasis model assessment: insulin resistance and Beta-cell function from fasting plasma glucose and insulin concentrations in man. Diabetologia 1985;28:412–419.
22. American Diabetes Association. Diagnosis and classification of diabetes mellitus. Diabetes Care 2005;28:S37–S42.
23. Genton L, Hans D, Kyle UG, et al. Dual-energy X-ray absorptiometry and body composition: differences between devices and comparison with reference methods. Nutrition 2002;18: 66–70.
24. Selzer ML. The Michigan Alcoholism Screening Test: the quest for a new diagnostic instrument. Am J Psychiatry 1971;127: 89–94.
25. Jensen MD, Heiling VJ. Heated hand vein blood is satisfactory for measurements during free fatty acid kinetic studies. Metabolism 1991;40:406–409.
26. Finegood DT, Bergman RN, Vranic M. Estimation of endogenous glucose production during hyperinsulinemic-euglycemic glucose clamps. Comparison of unlabeled and labeled exogenous glucose infusates. Diabetes 1987;36:914–924.
27. Lawton KA, Berger A, Mitchell M, et al. Analysis of the adult human plasma metabolome. Pharmacogenomics 2008;9:383–397.
28. Patterson BW. Use of stable isotopically labeled tracers for studies of metabolic kinetics: an overview. Metabolism 1997;46: 322–329.
29. Cresci S, Wright LD, Spratt JA, et al. Activation of a novel metabolic gene regulatory pathway by chronic stimulation of skeletal muscle. Am J Physiol 1996;270:C1413–C1420.
30. Steele R. Influences of glucose loading and of injected insulin on hepatic glucose output. Ann N Y Acad Sci 1959;82:420–430.
31. Gastaldelli A, Miyazaki Y, Pettiti M, et al. Separate contribution of diabetes, total fat mass, and fat topography to glucose production, gluconeogenesis, and glycogenolysis. J Clin Endocrinol Metab 2004;89:3914–3921.
32. Groop LC, Bonadonna RC, DelPrato S, et al. Glucose and free fatty acid metabolism in non-insulin-dependent diabetes mellitus. Evidence for multiple sites of insulin resistance. J Clin Invest 1989;84:205–213.
33. Szczepaniak LS, Nurenberg P, Leonard D, et al. Magnetic resonance spectroscopy to measure hepatic triglyceride content: prevalence of hepatic steatosis in the general population. Am J Physiol Endocrinol Metab 2005;288:E462–E468.
34. Christiansen MP, Linfoot PA, Neese RA, et al. Effect of dietary energy restriction on glucose production and substrate utilization in type 2 diabetes. Diabetes 2000;49:1691–1699.
35. Jazet IM, Ouwens DM, Schaart G, et al. Effect of a 2-day very low-energy diet on skeletal muscle insulin sensitivity in obese type 2 diabetic patients on insulin therapy. Metabolism 2005; 54:1669–1678.
36. Aguirre V, Uchida T, Yenush L, et al. The c-Jun NH(2)-terminal kinase promotes insulin resistance during association with insulin receptor substrate-1 and phosphorylation of Ser(307). J Biol Chem 2000;275:9047–9054.

37. Deivanayagam S, Mohammed BS, Vitola BE, et al. Nonalcoholic fatty liver disease is associated with hepatic and skeletal muscle insulin resistance in overweight adolescents. Am J Clin Nutr 2008;88:257–262.
38. Korenblat KM, Fabbrini E, Mohammed BS, et al. Liver, muscle, and adipose tissue insulin action is directly related to intrahepatic triglyceride content in obese subjects. Gastroenterology 2008;134:1369–1375.
39. Fracanzani AL, Valenti L, Bugianesi E, et al. Risk of severe liver disease in nonalcoholic fatty liver disease with normal aminotransferase levels: a role for insulin resistance and diabetes. Hepatology 2008;48:792–798.
40. Boden G, Shulman GI. Free fatty acids in obesity and type 2 diabetes: defining their role in the development of insulin resistance and beta-cell dysfunction. Eur J Clin Invest 2002;32(Suppl 3): 14–23.
41. Pories WJ, Swanson MS, MacDonald KG, et al. Who would have thought it? An operation proves to be the most effective therapy for adult-onset diabetes mellitus. Ann Surg 1995;222:339–350; discussion 350–352.
42. Wickremesekera K, Miller G, Naotunne TD, et al. Loss of insulin resistance after Roux-en-Y gastric bypass surgery: a time course study. Obes Surg 2005;15:474–481.
43. Rubino F, Forgione A, Cummings DE, et al. The mechanism of diabetes control after gastrointestinal bypass surgery reveals a role of the proximal small intestine in the pathophysiology of type 2 diabetes. Ann Surg 2006;244:741–749.

Received September 30, 2008. Accepted January 22, 2009.

Reprint requests

Address requests for reprints to: Samuel Klein, MD, Center for Human Nutrition, Washington University School of Medicine, 660 South Euclid Avenue, Campus Box 8031, St Louis, Missouri 63110. e-mail: sklein@wustl.edu; fax: (314) 362-8230.

Acknowledgments

The authors thank Joan Heins for providing dietary and behavioral therapy, Adewole Okunade, Jennifer Shew, and Freida Custodio for their technical assistance, the staff of our General Clinical Research Center and Intensive Research Unit for their help in performing the studies, and the study subjects for their participation.

Conflicts of interest

The authors disclose no conflicts.

Funding

Supported by grant UL1 RR024992 from the National Center for Research Resources, a component of the National Institutes of Health, and National Institutes of Health grants DK 37948, DK 56341 (Clinical Nutrition Research Unit), RR-00036 (General Clinical Research Center), and RR-00954 (Biomedical Mass Spectrometry Resource).