Saturated, but not n-6 polyunsaturated, fatty acids induce insulin resistance: role of intramuscular accumulation of lipid metabolites

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Saturated, but not n-6 polyunsaturated, fatty acids induce insulin resistance: role of intramuscular accumulation of lipid metabolites


Saturated, but not n-6 polyunsaturated, fatty acids induce insulin resistance: role of intramuscular accumulation of lipid metabolites. J Appl Physiol 100: 1467–1474, 2006. First published December 15, 2005; doi:10.1152/japplphysiol.01438.2005.—Consumption of a Western diet rich in saturated fats is associated with obesity and insulin resistance. In some insulin-resistant phenotypes this is associated with accumulation of skeletal muscle fatty acids. We examined the effects of diets high in saturated fatty acids (Sat) or n-6 polyunsaturated fatty acids (PUFA) on skeletal muscle fatty acid metabolite accumulation and whole-body insulin sensitivity. Male Sprague-Dawley rats were fed a chow diet (16% calories from fat, Con) or a diet high (53%) in Sat or PUFA for 8 wk. Insulin sensitivity was assessed by fasting plasma glucose and insulin and glucose tolerance via an oral glucose tolerance test. Muscle ceramide and diacylglycerol (DAG) levels and triacylglycerol (TAG) fatty acids were also measured. Both high-fat diets increased plasma free fatty acid levels by 30%. Compared with Con, Sat-fed rats were insulin resistant, whereas PUFA-treated rats showed improved insulin sensitivity. Sat caused a 125% increase in muscle DAG and a small increase in TAG. Although PUFA also resulted in a small increase in DAG, the excess fatty acids were primarily directed toward TAG storage (105% above Con). Ceramide content was unaffected by either high-fat diet. To examine the effects of fatty acids on cellular lipid storage and glucose uptake in vitro, rat L6 myotubes were incubated for 5 h with saturated and polyunsaturated fatty acids. After treatment of L6 myotubes with palmitate (C16:0), the ceramide and DAG content were increased by two- and fivefold, respectively, concomitant with reduced insulin-stimulated glucose uptake. In contrast, treatment of these cells with linoleate (C18:2) did not alter DAG, ceramide levels, and glucose uptake compared with controls (no added fatty acids). Both 16:0 and 18:2 treatments increased myotube TAG levels (C18:2 vs. C16:0, P < 0.05). These results indicate that increasing dietary Sat induces insulin resistance with concomitant increases in muscle DAG. Diets rich in n-6 PUFA appear to prevent insulin resistance by directing fat into TAG, rather than other lipid metabolites.

Diacylglycerol; ceramide; L6 myotube; stearoyl CoA desaturase 1

THE EXCESSIVE ACCUMULATION of triacylglycerol (TAG) in obesity is associated with the development of insulin resistance and Type 2 diabetes. Skeletal muscle is a major site for insulin-stimulated glucose disposal (4), and the accumulation of TAG within lipid droplets in skeletal muscle is positively correlated to the severity of insulin resistance (13, 22, 32). However, insulin sensitivity and intramyocellular TAG (IMTG) increase after endurance exercise training (6, 15, 18), and TAG storage protects Chinese hamster ovary cells from lipotoxicity (25), indicating that IMTG per se does not cause insulin resistance but may be a proxy for other lipid metabolites that directly interfere with insulin signaling. Indeed, skeletal muscle insulin resistance is mediated by intramyocellular accumulation of fatty acyl-CoA metabolites, such as diacylglycerols (DAG) and ceramides, which are elevated in insulin-resistant states (1, 23, 36, 51) and directly interfere with insulin signal transduction (8, 21, 41, 45, 51).

Whereas increased availability of fatty acids has been linked to skeletal muscle insulin resistance (3, 5), it appears that the type of fatty acid is also critical. Epidemiological evidence suggests that the consumption of a Western diet that is high in saturated fats closely correlates with the development of insulin resistance in humans (26, 33). Direct examination in muscle cells in vitro indicates that saturated fatty acids cause insulin resistance whereas unsaturated fatty acids exert a protective effect or even improve insulin sensitivity (9, 29). Saturated fats are less readily oxidized (14, 24) and accumulate as DAG and ceramide in vitro, whereas mono- and polyunsaturated fats accumulate as IMTG or free fatty acids (FFA) (14, 29, 41), thus providing a link between fatty acid subtype and insulin resistance. Numerous dietary studies in rodents and humans indicate that saturated fat significantly worsens insulin resistance, whereas unsaturated fatty acids exert a protective effect or even improve insulin sensitivity (for review, see Ref. 37).

The biochemical and molecular processes linking saturated fats to insulin resistance remain unresolved but may relate to altered membrane phospholipid fatty acid composition and membrane fluidity and stability (43), changes in lipogenic gene transcription (10), the type of fatty acids within TAG (2, 28), and direct interference with insulin signaling (8, 21, 41, 45, 51). Lipid metabolites that interfere with insulin signal transduction accumulate in tissues of insulin-resistant animals (23, 36, 40, 47, 51); however, the effects of markedly altering the types of dietary fatty acids on the accumulation of these lipid metabolites in whole animals are unknown. The primary aim of the present study was to examine the role of diets rich in either saturated, stearoyl CoA desaturase 1.

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saturated or polyunsaturated fatty acids on skeletal muscle fatty acid metabolite accumulation and whole-body insulin sensitivity. We hypothesized that a diet high in saturated fatty acids would induce insulin resistance and increase the contents of skeletal muscle DAG and ceramide, whereas a diet high in polyunsaturated fatty acids would not affect DAG and ceramide contents or impact on insulin sensitivity. To confirm the biochemical responses to fatty acids, independent of potential changes in metabolic or hormonal fluxes, we also incubated rat L6 myotubes, an in vitro skeletal muscle model, with saturated and unsaturated fatty acids and hypothesized that the in vivo effects would persist in vitro.

Stearyl CoA desaturase 1 (SCD1) is an endoplasmic reticulum-bound enzyme that converts saturated fatty acids (primarily 16:0; 18:0) to monounsaturated fatty acids. Global SCD1 deficiency produces a lean, obesity-resistant, insulin-sensitive phenotype (31); however, preventing the ability to desaturate fatty acids should lead to insulin resistance because saturated fats accumulate as DAG and ceramide. Although polyunsaturated fatty acids reduce and saturated fatty acids increase SCD1 expression in liver (30), the role of dietary fatty acids on SCD1 expression and activity in skeletal muscle is unknown, despite the importance of skeletal muscle in fuel metabolism and insulin resistance. Accordingly, the second aim of this study was to investigate the role of dietary fatty acids on skeletal muscle SCD1 gene and protein expression in vivo.

METHODS

Animal Experiments

Twenty-four male Sprague-Dawley rats (initial body mass 95–110 g) were obtained from Samtako, Bio Korea (Kyong-Ki, Korea) and housed four per cage in an environmentally controlled laboratory (temperature 22 ± 1°C and relative humidity 55 ± 2%) with a 12:12-h light-dark cycle (light, 0700 to 1900). In the week before any experimental intervention, animals were given ad libitum access to standard rodent chow (Samtako, Bio Korea). Food intake was not determined in this study because the polyunsaturated fatty acid diet was too “liquid” to obtain accurate measures of the food remaining in cages. The Animal Ethics Committee of Korea National Sport University approved all procedures performed in this study.

After 1 wk, rats were divided into one of three experimental diet groups. Control rats (Con; n = 8) were fed standard rat chow (61.8% carbohydrate, 15.7% fat, 22.5% protein expressed as percentage of total caloric intake) purchased from Samtako (Bio Korea). The other groups consumed high-fat diets (23.4% carbohydrate; 52.8% fat; 22.9% protein) that consisted primarily of saturated fatty acids (Sat; n = 8) derived from lard and coconut oil or polyunsaturated fatty acids (PUFA; n = 8) derived from safflower oil (ICN Biomedicals). The main fatty acid in the PUFA diet was linoleic acid (18:2, n-6). Animals were provided with food and water ad libitum throughout the experimental period. Animals were maintained on their diets for 8 wk before testing.

Oral Glucose Tolerance Test

After the 8-wk experimental period, rats were overnight fasted and weighed and underwent an oral glucose tolerance test (OGTT). Glucose (20% wt/vol solution) was administered by oral gavage at a dose of 2.0 g/kg body mass, and blood was obtained from a tail vein in unrestrained conscious rats before glucose administration and at 15, 30, 60, and 120 min thereafter. At least 2 days after OGTT and after an overnight fast (10 h), rats were anesthetized by intraperitoneal injection of pentobarbital sodium (60 mg/kg body mass) and the vastus lateralis muscle was rapidly dissected out, immediately frozen in liquid nitrogen, and stored at −80°C until analyses. A blood sample was drawn from the femoral artery, and rats were killed by heart removal.

Analyses

Measurement of skeletal muscle lipid metabolites. IMTG content was analyzed as previously described (49). Freeze-dried muscle was powdered and cleaned of all visible connective tissue and blood under magnification. Lipid was extracted by a Folch extraction, the TAG was saponified in an ethanol-KOH solution at 60°C, and glycerol content was determined fluorometrically. DAG and ceramide were extracted and quantified according to the methods of Preiss et al. (35) with minor modifications. Briefly, lipids were extracted from freeze-dried, powdered muscle by using chloroform-methanol-PBS+0.2% SDS (1:2:0.8 vol/vol/vol). DAG kinase and 32P-ATP (15 mCi/mmol cold ATP) were added to extracts, and the reaction was stopped with chloroform-methanol (2:1). Samples were spotted onto thin-layer chromatography (TLC) plates and developed to two-thirds of the total plate length in a solvent consisting of chloroform-acetone-methanol-acetic acid-water (100:40:20:20:10). Bands corresponding to DAG and ceramide were identified against standards after phospho-imaging, dried, scraped from the TLC plate, and counted in a liquid scintillation analyzer (Tri-Carb 2500TR, Packard, Canberra, Australia).

Determination of TAG fatty acid composition. Freeze-dried muscle (~100 mg) was extracted with chloroform-methanol (2:1 by volume) containing 10 mg/l of butylated hydroxytoluene. After storage of the samples overnight at 4°C, each sample was filtered, rinsed with an additional volume of extracting solvent, and partitioned against 0.9% NaCl. This was evaporated under nitrogen gas, and the lipids were reconstituted in chloroform. Samples were spotted onto TLC plates and developed in a solvent consisting of petroleum ether-diethyl ether-acetic acid-water (85:15:3 vol/vol/vol), and the TAG fraction was identified against standards (Nuchek, 18 5A) and scraped into a vial. Methyl esters of fatty acids of the TAG extract were prepared by transmethylation using 5% H2SO4 in methanol. The fatty acid methyl esters were separated by capillary gas liquid chromatography using a 50 m × 0.32 mm (ID) fused silica, bonded-phase column (BPX70, SGE, Melbourne, Australia) with helium as carrier gas at a flow rate of 43 cm/s. The column oven was maintained at 125°C for 3 min and increased at a rate of 8°C/min to 220°C and this temperature was maintained for the duration of the run. Fatty acids were identified by comparison with standard mixtures of fatty acid methyl esters and the results are expressed as percent of the total TAG fraction.

Evaluation of mRNA content by RT-PCR. Approximately 20 mg of muscle were extracted for total RNA by a modification of the acid guanidium thiocyanate-phenol chloroform extraction method. The total RNA was quantified by spectrophotometry (Hitachi U 2000 spectrophotometer), and 100 ng of each total RNA sample were reverse transcribed. Control samples were also analyzed where all the above reagents are added to RNA samples except the MultiScribe reverse transcriptase. The reverse transcription reactions were performed by use a GeneAmp PCR system 2400 (Perkin-Elmer, Wellesley, MA) with conditions at 25°C for 10 min, 48°C for 30 min, and 95°C for 5 min. Two milliliters of 0.5 mmol/l EDTA (pH 8.0) were added to each sample and stored at −20°C until further analysis. Real-time PCR was employed to quantify rat SCD1 mRNA. Rat probe and primers were designed (Primer Express version 1.0 Applied Biosystems) from the rat gene sequence accessed from Gen-Bank/EMBL (NM_139192). The sequences of the primers and probe were as follows: forward primer, 5'-CAC GCC GAC CTT CAC AA-3'; reverse primer, 5'-TTC TTG ACA GCC GGG TTG TT-3'; Taqman probe, 5'-TTC TTC TCT CAC GTG GTT TGG CTG CTG-3'. Ribosomal 18S was used as a constitutive housekeeping control.
Dietary Fats, Muscle Lipids, and Insulin Resistance

(Applied Biosystems, Foster City, CA). The concentrations of forward primer, reverse primer, probe, and cDNA were 300 nM, 300 nM, 100 nM, and 10 ng, respectively. Gene expression was quantified by a multiplex comparative critical threshold method (Bio-Rad i Cycler IQTM, Hercules, CA).

Determination of protein content and activity. Muscle was homogenized (Polytron; Brinkman Instruments, Westbury, NY) in ice-cold buffer containing 20 mM HEPES, 1 mM DTT, 1 mM Na3PO4·2H2O, 2 mM EDTA, 1% Triton X-100, 10% glycerol (vol/vol), 3 mM benzamidine, 1 mM phenylmethylsulfonyl fluoride, 5 μM phosphatase inhibitor cocktail 2 (Sigma), and 5 μg/ml protease inhibitor cocktail (Sigma) and rotated for 40 min at 4°C. Homogenates were centrifuged at 16,000 g for 45 min, and the supernatant was removed and rapidly frozen in liquid nitrogen. Protein concentration of the muscle lysates was subsequently determined according to the bicinchoninic acid method (Pierce Kit, Progen Industries, Darra, QLD, Australia). Muscle lysates were solubilized in Laemmli sample buffer and boiled for 5 min, resolved by SDS-PAGE on 12% polyacrylamide gels, transferred to a nitrocellulose membrane, blocked with 5% milk, and immunoblotted with the primary antibody overnight. The SCD1 antibody was obtained from Santa Cruz Biotechnology (Santa Cruz, CA). After incubation with horseradish peroxidase-conjugated secondary antibody (Amersham Biosciences, Castle Hill, NSW, Australia), the immunoreactive proteins were detected with enhanced chemiluminescence (Amersham BioSciences) and quantified by densitometry (Chemidoc XRS, Bio-Rad Laboratories, Regents Park, NSW, Australia).

Blood metabolite and hormone analysis. Whole blood was obtained from the tail vein and used for blood glucose (Glucocard II, KDK) determination before anesthesia. Whole blood was transferred to an EDTA-administered tube and centrifuged (5,000 rpm for 15 min), and plasma was collected. FFA concentration was determined by an enzymatic colorimetric method (NEFA C test kit, Wako), and insulin levels were measured before anesthesia. Whole blood was transferred to an EDTA-administered tube and centrifuged (5,000 rpm for 15 min), and the plasma was collected. FFA concentration was determined by an enzymatic colorimetric method (NEFA C test kit, Wako), and insulin levels were measured before anesthesia. Whole blood was transferred to an EDTA-administered tube and centrifuged (5,000 rpm for 15 min), and the plasma was collected. FFA concentration was determined by an enzymatic colorimetric method (NEFA C test kit, Wako), and insulin levels were measured before anesthesia.

L6 myoblasts were maintained at 37°C in 5% CO2-95% O2 humidified air in α modified essential medium + 10% FBS. Differentiation was induced by switching to medium containing 2% FBS when the myoblasts were ~70% confluent. Experimental treatments were started after 2 days, by which time nearly all of the myoblasts had fused to form myotubes. Cells were incubated with 0.5 mM fatty acids or BSA for 5 h. Cells were washed with warm PBS and incubated in MEM without (basal) or with 100 mM insulin for 30 min. The medium was removed and 2-deoxy-d-[14C]glucose uptake (0.5 μCi/ml, 10 μM insulin/cold 2-DG) was added. The assay was stopped after 20 min by the addition of ice-cold PBS, and cells were lysed in 0.3 M NaOH. Radioactivity was determined by liquid scintillation counting.

Statistics

Data are expressed as means ± SE. Statistical analysis was performed by a one-way analysis of variance with a Student-Newman-Keuls post hoc test. Statistical significance was set at P < 0.05.

RESULTS

Glucose Tolerance Is Reduced in Rats Fed Diets High in Saturated, but not n-6 Polyunsaturated, Fatty Acids

Animal weights were not different between groups after 8 wk diet (Con, 391 ± 9; Sat, 409 ± 7; PUFA 380 ± 4 g). Both high-fat diets increased plasma FFA by ~30% but were without effect on fasting blood glucose (Table 1). Fasting plasma insulin was increased in animals fed saturated fat compared with chow-fed animals and reduced in animals fed polyunsaturated fat (Table 1). The homeostasis model assessment of insulin resistance (HOMA-IR) index was increased in Sat and decreased in PUFA compared with Con (Fig. 1A). These data indicate that Sat rats were insulin resistant and that insulin sensitivity was improved in PUFA rats. An OGTT was also performed, and blood glucose and insulin levels were measured. The glucose area under the curve was not different between groups (Fig. 1B); however, plasma insulin levels were elevated in Sat compared with Con, indicating insulin resistance in these animals (Fig. 1B). Conversely, plasma insulin levels were decreased in PUFA compared with Con, indicating improved insulin sensitivity (Fig. 1C).

Table 1. Fasting plasma metabolites in rats fed a chow diet or high-fat diet consisting of either saturated or polyunsaturated fatty acids

<table>
<thead>
<tr>
<th></th>
<th>Con</th>
<th>Sat</th>
<th>PUFA</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFA, μmol/l</td>
<td>354 ± 29</td>
<td>460 ± 23*</td>
<td>448 ± 25*</td>
</tr>
<tr>
<td>Glucose, mmol/l</td>
<td>3.99 ± 0.16</td>
<td>4.61 ± 0.15</td>
<td>4.26 ± 0.10</td>
</tr>
<tr>
<td>Insulin, pmol/l</td>
<td>27 ± 5</td>
<td>76 ± 24*</td>
<td>13 ± 3*†</td>
</tr>
</tbody>
</table>

Values are means ± SE; n = 8. Con, chow diet; Sat, saturated fatty acid high-fat diet; PUFA, polyunsaturated fatty acid high-fat diet. *Different from Con, †different from Sat, P < 0.05.

Skeletal Muscle Lipid Content Is Influenced by Dietary Content

Lipids were assessed in skeletal muscle after an 8-h fast. Skeletal muscle TAG was increased in Sat and PUFA compared with Con, and PUFA TAG content tended (P = 0.08) to be greater than Sat (Fig. 2A). Skeletal muscle DAG content was increased in Sat and PUFA compared with Con (Fig. 2B). DAG content was greater in Sat vs. PUFA. Ceramide content in rodent muscles was variable and was not affected by dietary content (Fig. 2C). Dietary fatty acid composition exerted a profound effect on the fatty acid profile in skeletal muscle TAG. Sat increased the proportion of saturated fatty acids and decreased unsaturated fatty acids within TAG compared with Con (Fig. 3A). The elevation in saturated fats with Sat is attributed to increases in 12:0, 14:0, and 18:0 (Fig. 3A). The elevation in saturated fats with Sat is attributed to increases in 12:0, 14:0, and 18:0 (Fig. 3A). The elevation in saturated fats with Sat is attributed to increases in 12:0, 14:0, and 18:0 (Fig. 3A). The elevation in saturated fats with Sat is attributed to increases in 12:0, 14:0, and 18:0 (Fig. 3A). The elevation in saturated fats with Sat is attributed to increases in 12:0, 14:0, and 18:0 (Fig. 3A).

Interestingly, 18:1 was markedly elevated and 18:2 decreased in Sat vs. Con. PUFA increased the percentage of unsaturated fats in TAG, which was largely due to increased 18:2. PUFA also decreased the proportion of all saturated fatty acids in TAG compared with Con and Sat (Fig. 3B). The proportion of saturated fatty acids was 32, 42, and 17% for Con, Sat, and PUFA, respectively.

SCD1 Is Increased by a Saturated Fatty Acid Diet

SCD1 mRNA was unaffected by a diet high in polyunsaturated fatty acids and tended (P = 0.11) to increase with saturated fatty acid feeding (Fig. 4A). We examined SCD1 protein expression by Western blot and report increased SCD1 in Sat compared with Con and PUFA (Fig. 4B). An index of SCD1 enzyme activity, which was calculated as the relative amount of product (16:1) to the corresponding substrate (16:0), was increased in Sat vs. PUFA. DAG content was greater in Sat vs. PUFA. Ceramide content in rodent muscles was variable and was not affected by dietary content (Fig. 2C). Dietary fatty acid composition exerted a profound effect on the fatty acid profile in skeletal muscle TAG. Sat increased the proportion of saturated fatty acids and decreased unsaturated fatty acids within TAG compared with Con (Fig. 3A). The elevation in saturated fats with Sat is attributed to increases in 12:0, 14:0, and 18:0 (Fig. 3A). The elevation in saturated fats with Sat is attributed to increases in 12:0, 14:0, and 18:0 (Fig. 3A). The elevation in saturated fats with Sat is attributed to increases in 12:0, 14:0, and 18:0 (Fig. 3A). The elevation in saturated fats with Sat is attributed to increases in 12:0, 14:0, and 18:0 (Fig. 3A). The elevation in saturated fats with Sat is attributed to increases in 12:0, 14:0, and 18:0 (Fig. 3A). The elevation in saturated fats with Sat is attributed to increases in 12:0, 14:0, and 18:0 (Fig. 3A). The elevation in saturated fats with Sat is attributed to increases in 12:0, 14:0, and 18:0 (Fig. 3A). The elevation in saturated fats with Sat is attributed to increases in 12:0, 14:0, and 18:0 (Fig. 3A).
was increased ($P < 0.05$) in Sat compared with Con and reduced ($P < 0.05$) in PUFA (Fig. 4D).

**Effect of Palmitate and Linoleate on Fatty Acid Metabolite Content and Glucose Uptake in L6 Myotubes**

To enable biochemical studies to be conducted in the absence of possible confounding factors, such as alterations in circulating metabolites and hormones, we performed experiments in L6 myotubes. Although the metabolic action of these cells to insulin is blunted and direct comparisons with in vivo studies should be interpreted with caution, L6 myotubes nevertheless possess the proteins required for fatty acid and glucose uptake and metabolism. Glucose uptake was determined in L6 myotubes after 5 h treatment with 0.5 mM palmitate (saturated) or linoleate (polyunsaturated) fatty acids. Palmitate decreased insulin-stimulated glucose uptake, whereas linoleate pretreatment did not affect glucose uptake (Fig. 5A). The addition of palmitate to culture media resulted in significant DAG (5-fold) and ceramide (2-fold) accumulation (Fig. 5, C and D). TAG content determined by fluorometric analysis after 5-h incubation revealed a small increase with palmitate (Fig. 5B). TAG was increased by linoleate treatment (Fig. 5B), whereas DAG and ceramide content were unchanged (Fig. 5, C and D). These data indicate that palmitate-induced ceramide and DAG accumulation are associated with insulin resistance in skeletal muscle cell culture (8, 29, 41). They also indicate that linoleate promotes synthesis of TAG and does not affect insulin-stimulated glucose uptake.

**DISCUSSION**

The present study demonstrates that a diet high in saturated fat induces muscle DAG accumulation and saturation of the TAG pool and is associated with whole-body insulin resistance. Conversely, animals fed a diet high in n-6 polyunsaturated fat retained insulin sensitivity despite small increases in muscle DAG, which may result from enhanced TAG storage. Thus fatty acid oversupply per se is not the major determinant of fat-induced insulin resistance, but rather dietary fat composition (42, 43).

An important caveat of the present study relates to the interpretation of insulin resistance. The OGTT and HOMA-IR assessments do not allow for assessment of tissue-specific
effects on insulin-stimulated glucose uptake. Although skeletal muscle accounts for $\geq 80\%$ of insulin-mediated glucose disposal (4) and is likely to represent events occurring at the whole-body level, we cannot definitively conclude that the observed whole-body changes are due to altered skeletal muscle function. In this regard, it appears that glucose intolerance may only become apparent when insulin resistance occurs in numerous tissues (50). Thus the present data relating to insulin resistance should be interpreted with these considerations in mind.

DAGs and ceramides antagonize insulin signaling in vitro, and this is the first study to directly examine the effects of dietary fatty acid composition on the accumulation of these lipid metabolites in vivo. DAGs are increased in fatty acid-induced insulin resistance (19, 51) and are proposed to interfere with insulin signaling via novel PKC activation (51). In the present study, DAG was elevated in SAT and occurred concomitantly with insulin resistance, observations that are consistent with the present and previous studies in muscle cell culture that ascribe a direct role for saturated, but not unsaturated, fatty acids in this process (7, 9, 14, 29). However, our in vivo finding that DAGs were moderately elevated in PUFA rats, where insulin action was improved, indicates that total DAG accumulation may not be essential for insulin resistance and that other factors such as a critical threshold of intracellular DAG, cellular localization of DAG, or the molecular DAG species may be important mediators of insulin resistance. Collectively, these data indicate that an abundance of dietary saturated fatty acids induce insulin resistance, possibly via a marked increase in DAG content, whereas smaller increases in DAG were not associated with insulin resistance in animals fed an isocaloric diet rich in polyunsaturated fatty acids.

Ceramide is a second messenger in the sphingomyelin signaling pathway and is produced via the hydrolysis of sphingomyelin and from de novo synthesis (palmitoyl-CoA and serine). Ceramides antagonize insulin signaling (8, 41, 45), and ceramide accumulation correlates with the development of skeletal muscle insulin resistance in vivo (1, 16, 44, 47). In contrast with our hypothesis, dietary fatty acid composition did not affect muscle ceramide content. This was unexpected because long-chain saturated fatty acids are thought to exclusively act as the substrate for ceramide de novo synthesis (46); however, a recent study that infused a lipid emulsion primarily composed of linoleate (18:2) induced ceramide generation and insulin resistance in humans (44). A dissociation between ceramide content and insulin sensitivity has been observed previously (19, 23, 51) and, consistent with the present findings, indicates that ceramides may not induce insulin resistance in vivo.

IMTG content positively correlates with insulin resistance (13, 22, 32), which has led to the assumption that excess IMTG storage is undesirable. However, in some circumstances, such...
as after endurance exercise training, increased TAG is associated with enhanced insulin sensitivity (6, 15, 18, 44). In the present study, IMTG was increased in rats fed a Sat diet and, to a greater extent, in rats on the PUFA diet. These data are consistent with our studies in L6 myotubes demonstrating marked increases in IMTG with linoleate compared with palmitate treatment. Unsaturated fats promote TAG accumulation in various cell types (e.g., cardiac, pancreatic, Chinese hamster ovary cells) (see Ref. 25), and this and previous studies in skeletal muscle culture (29) have demonstrated increased TAG storage after incubation with unsaturated fats. Thus unsaturated fatty acids may protect cells from “lipotoxicity” by promoting uptake of fatty acids into an inert triglyceride lipid pool, rather than bioactive lipids such as DAGs and ceramides (25). The observations in PUFA rats of elevated muscle TAG and reduced DAG content, lower basal plasma insulin, and enhanced insulin sensitivity compared with Sat supports this possibility. The reason(s) for IMTG accumulation was not addressed in this study but may relate to the preference of DAG acyltransferase (converts DAG to TAG) for unsaturated rather than saturated fatty acids (12, 39).

The fatty acid profile of different body tissues at least partially reflects the fatty acid composition of the diet. In this study we compared the fatty acid profile of TAG between groups. The 8-wk Sat diet increased the degree of saturation within skeletal muscle TAG, which was due to increases in short (12:0, 14:0)- and long (18:0)-chain fatty acids. Whether an increase in TAG saturation contributes to insulin resistance in muscle is unknown. It is possible that the excess stearate (18:0) within this pool is hydrolyzed and provides a substrate for DAG and ceramide production, thereby affecting insulin signaling. In contrast with Sat, PUFA increased the degree of unsaturation within IMTG, which was primarily due to increased linoleate (18:2). Increased unsaturation of the muscle membrane fatty acids is associated with improved insulin sensitivity (43), and the lipid-lowering agent bezafibrate reduces the saturation in muscle TAGs and improves insulin sensitivity (28). Here, we show that a greater degree of desaturation in TAG is associated with improved insulin sensitivity, and, conversely, an increase in saturation correlates with insulin resistance.

SCD1 converts SATs to monounsaturated fatty acids and impacts on metabolic function. Our current understanding of the biological role of SCD1 derives from studies in liver and others conducted in SCD1-null (ab/ab, SCD-1+/−) mice (11, 31) that demonstrate SCD1 deficiency to induce a leaner phenotype and resistance to diet-induced obesity (11, 31). There are very limited data describing SCD1 regulation in skeletal muscle, a tissue that displays marked structural, functional, and metabolic differences than liver. We show that SCD1 gene and protein expression is not different between chow-fed and polyunsaturated fat-fed rats, which is not consistent with the findings in liver that polyunsaturated fatty acids oppose the induction of sterol regulatory-element binding protein 1c and inhibit SCD1 gene expression (10, 48). In contrast, SCD1 protein expression was elevated in insulin-resistant Sat rats. Regarding the known function of SCD1, these data indicate that rather than being a causative factor in obesity and insulin resistance, increasing skeletal muscle SCD1 may act as a protective mechanism intended to reduce the incorporation of saturated fatty acids into bioactive lipid species such as DAGs and ceramides. Studies that directly test this hypothesis warrant further investigation.

Chronic high-fat feeding induces insulin resistance in rodents; however, the role of specific dietary fats is not well characterized. Previous reports indicate that insulin resistance (20, 43) or glucose intolerance (27) occurs in rats fed a diet high in n-6 PUFAs, whereas rats fed diets high in n-3 and with low n-6–to–n-3 ratios maintain normal insulin sensitivity. In this study, we observed an ~20% improvement in HOMA-IR in rats fed a PUFA diet consisting mainly of n-6 fatty acids.
(n-6:n-3 PUFA of >75:1), an effect observed previously in Type 2 diabetes patients (17). The discrepancies between ours and previous rodent studies (20, 27, 43), although difficult to pinpoint, may be due to the duration of treatment (8 wk in the present study vs. 3–4 wk). With respect to the time-course effects, PUFAs upregulate genes involved in fat oxidation and decrease genes involved in lipid synthesis and storage (38). Although the transcriptional response is rapid, the time required for a phenotype change may take weeks to manifest and thus explain the observed differences between studies. A more likely explanation is that the chow-fed animals were mildly insulin resistant. These animals gained weight at a similar rate to the PUFAs, suggesting increased food intake. It is also possible that the small amount of saturated fats in the chow diet (~10% of total calories) resulted in slight insulin resistance in the controls. These possibilities remain to be determined. Despite these differences, it appears that an n-6 PUFA diet is more desirable than a Sat diet, but that n-3 PUFA substitution for n-6 is advantageous for insulin action. Thus although a diet supplemented with n-3 PUFAs enhances insulin action (34, 42, 43), our data suggest that a diet rich in n-6 PUFAs is not detrimental to insulin action as previously described and may even result in modest improvements in insulin action.

In conclusion, the results of the present study demonstrate that a diet high in saturated fatty acids induces insulin resistance whereas polyunsaturated fatty acids modestly enhance insulin sensitivity. The insulin resistance in the Sat rich diet was associated with elevated DAG content and increased saturation of muscle TAG. These effects were partially ameliorated with polyunsaturated fatty acids, possibly via increased incorporation into TAG.

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