A modified high-fat diet induces insulin resistance in rat skeletal muscle but not adipocytes

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Wilkes, Jason J., Arend Bonen, and Rhonda C. Bell. A modified high-fat diet induces insulin resistance in rat skeletal muscle but not adipocytes. Am. J. Physiol. 275 (Endocrinol. Metab. 38): E679–E686, 1998.—We hypothesized that variation in dietary fatty acid composition in rats fed a high-fat diet had tissue-specific effects on glucose uptake sufficient to maintain normal glucose tolerance. Rats were fed one of three diets for 3 wk. The isocaloric high-fat-mixed oil (HF-mixed) diet and the high-fat-safflower oil (HF-saff) diet both provided 60% kcal fat, but fat composition differed [HF-mixed = saturated, polyunsaturated (n-3 and n-6), and monounsaturated fatty acids; HF-saff = polyunsaturated fatty acids (mainly n-6)]. The control diet was high carbohydrate (HCHO, 10% kcal fat). Insulin-stimulated 3-O-methyl-D-glucose uptake into perfused hindlimb muscles was reduced in rats fed HF-saff and HF-mixed diets compared with those fed HCHO diet (P < 0.02). Basal uptake increased in HF-saff and HF-mixed-fed rats vs. HCHO-fed rats (P < 0.04). In adipocytes, HF-saff feeding decreased 2-deoxyglucose uptake vs. HF-mixed feeding and HCHO feeding (P < 0.05), but 2-deoxyglucose uptake in HF-mixed-fed rats did not differ from that in HCHO-fed rats (P > 0.05). Glucose tolerance was significantly reduced in HF-saff-fed rats but was unaffected by the HF-mixed diet. Therefore, in skeletal muscle of rats, 1) feeding a diet high in fat induces a reduction in insulin-stimulated glucose uptake but 2) provides an increase in basal glucose uptake. In contrast, 3) in adipocytes, insulin-stimulated glucose transport is reduced only when the high-fat diet is high in n-6 polyunsaturated fatty acids but not when fat comes from these mixed sources. Glucose intolerance becomes evident when insulin resistance is seen in multiple tissues.

High-fat feeding; fatty acids; rats

In rodents and humans, dietary intake of high amounts of fat has been shown to have adverse effects on insulin sensitivity and to contribute to the development of glucose intolerance and overt diabetes [recently reviewed by Storlien et al. (32)]. Much of the work reported in the literature has used a model in which the absolute amount of dietary fat is considered to be the central variable affecting insulin sensitivity. Fat intakes ranging from ~40 to 75% of total kilocalories, usually in the form of saturated fat, safflower oil, or corn oil (both high in n-6 polyunsaturated fatty acids), have been reported to reduce whole body insulin-stimulated glucose uptake (6, 10, 14, 15, 17, 19, 23, 27, 34, 35). This is accompanied by reductions in insulin-stimulated glucose uptake in individual skeletal muscles (6, 11, 14, 15, 17, 19, 23, 33, 35) and adipose tissue (6, 8, 35) along with enhanced hepatic glucose production (10, 14, 34). Thus high dietary fat intake will alter the regulation of glucose transport in insulin-sensitive tissues, leading to changes in the whole body.

In addition to the amount of dietary fat being an important determinant of insulin sensitivity, there is also evidence that variation in fatty acid composition may independently affect insulin action and alter insulin sensitivity. Storlien et al. (34) demonstrated that when a portion of the fat from a high polyunsaturated fat diet (60% total kcal as fat) was replaced with fish oil (6% kcal of total kcal) containing long-chain n-3 fatty acids, glucose uptake in skeletal muscle and hepatic glucose output were restored to levels observed in chow-fed rats. Saturated fat combined with these large amounts of linolenic acid (C18:3, n-3) similarly alleviated insulin resistance in muscle and in the whole body (33). Monounsaturated fatty acids, when fed at high levels, may not lead to the reductions in insulin sensitivity observed with the high polyunsaturated fat diets (4, 26) and may improve indexes of glucose tolerance in non-insulin-dependent diabetes mellitus patients (18). Thus different dietary fatty acids appear to have varying effects on insulin-sensitive tissues, and this may affect the expression of glucose tolerance.

The purpose of this study was to examine direct measures of insulin resistance in several insulin-dependent tissues in high-fat-fed rats consuming diets of 60% kcal from fat but with different fatty acid combinations and to relate these measures to whole body glucose tolerance. Initial studies in our laboratory used a modified high-fat version (60% kcal fat) of the American Institute of Nutrition 1993 (high-fat-mixed oil, HF-mixed) diet as a model of insulin resistance. We predicted that 3 wk of feeding this diet would produce a similar degree of insulin resistance and glucose intolerance as had been observed with a safflower oil-based high-fat diet (33, 34) because the HF-mixed diet contained a high degree of polyunsaturated and saturated fatty acids and a relatively low amount of n-3 fatty acids, in addition to a large proportion of calories as fat. In fact, in preliminary studies, we observed no difference in glucose tolerance in rats fed the HF-mixed diet vs. those fed a control, 60% carbohydrate diet (1). This prompted us to consider the possibility that this combination of fatty acids in the HF-mixed diet may lead to tissue-specific changes in glucose uptake. We hypothesized that normal glucose tolerance observed after feeding the HF-mixed diet may reflect reciprocal changes in either the presence or degree of insulin resistance in insulin-sensitive tissues.
MATERIALS AND METHODS

Animals and diets. Male Sprague-Dawley rats weighing ~200 g were individually housed, with a 12:12-h light-dark cycle, and were randomly assigned to one of three dietary groups (Dyets, Bethlehem, PA): high carbohydrate (HCHO: 20% kcal protein, 10% fat, 70% carbohydrate), high fat-safflower oil (HF-saff, 20% kcal protein, 59% fat, 20% carbohydrate), or HF-mixed (20% kcal protein, 59% fat, 20% carbohydrate). The source of fat in the HCHO and HF-saff diets was safflower oil, whereas the HF-mixed diet contained a mixture of soybean oil (12% of kcal), hydrogenated coconut oil (24% of kcal), and high-oleic sunflower oil (24% of kcal). Diets used in this study are outlined in Table 1.

Before the start of the experimental diets, food intake (g/day) on standard rat chow (lab chow, PMI Feeds, St. Louis, MO) was determined for 3 days. Rats were fed their respective experimental diets at 96% of ad libitum chow energy intake daily; access to water was unlimited at all times. Food was generally consumed in its entirety by all animals each day. Rats were weighed a minimum of three times weekly to ensure that growth rates in all dietary groups were similar. After 3 wk of feeding, rats underwent an intravenous glucose tolerance test (details below). Rats recovered from this procedure for 5 days before glucose tolerance was directly assessed in skeletal muscle and adipose tissue. All procedures used in this study were approved by the Animal Care Committee at the University of Waterloo and followed the Guidelines of the Canadian Council on Animal Care.

Intravenous glucose tolerance tests. One subgroup of rats (n = 10 rats/dietary group) underwent the intravenous glucose tolerance test (IVGTTs) in the anesthetized state, whereas a second subgroup of rats (n = 5 rats/dietary group) were conscious during their IVGTTs. All rats were fasted overnight before the IVGTT. For the anesthetized group, rats were anesthetized with a tail vein injection of pentobarbital sodium (65 mg/kg body wt, less 10%), and buprenorphine (Temgesic, 0.003 mg/100 g body wt) was administered subcutaneously as an analgesic. Animals were kept on a heating blanket during both the surgery and experiment to prevent hypothermia during anesthesia (16). The jugular vein was fitted with a catheter, and animals were allowed to rest for 30 min. Two basal blood samples were drawn at 5-min intervals, and then a bolus of glucose (300 mg/kg, 10% solution) was injected into the catheter and immediately rinsed with heparinized saline (16 units/ml) to prevent clotting. Blood samples (~0.2 ml) were collected into NaF/heparinized microcentrifuge tubes at 1, 2.5, 3.5, 5, 6.5, 8, 12, and 18 min post-glucose dose and placed on ice. Samples were centrifuged (Eppendorf microcentrifuge, 12,000 rpm, 4 min), and plasma was separated from red cells. Plasma for glucose and insulin determinations was stored frozen at −20°C until use. Glucose was determined by a spectrophotometric method (glucose Trinder method, no. 315; Sigma, St. Louis, MO), and insulin was determined by RIA using a rat-specific antibody (Linco, St. Charles, MO). After the IVGTT, the jugular catheters were tied off, and rats were allowed to recover under a heating lamp and were returned to their cages later the same day. Rats ate normal quantities of food 24–48 h after surgery, and body weights were back to preoperative levels by 2–3 days after surgery.

For the conscious group, rats were anesthetized under halothane, given buprenorphine, fitted with the jugular catheter, and then allowed to regain consciousness. Rats rested quietly in the experimental cage for 30 min before the basal blood samples were drawn. Glucose administration, timing of samples after the glucose bolus, sample separation and storage, and animal recovery were identical to those in the protocol outlined for the anesthetized rats.

Glucose tolerance (Kg) was determined as the slope of the log of blood glucose vs. time, using the samples obtained from the 2.5- to 12-min period after glucose injection. In both the conscious and anesthetized groups, Kg showed significant effects of diet treatment (P < 0.001), but the effects of anesthesia were not statistically different (P > 0.05); therefore, values from the anesthetized and conscious groups were combined. The acute insulin response to glucose was calculated as the area under the insulin curve from 1 to 6.5 min after glucose injection and was corrected for the prestimulus baseline levels. Plasma from basal (fasting) samples was also used for determination of triglycerides (Sigma, no. 339) and free fatty acids (Waco Chemicals, Richmond, VA).

3-O-methylglucose uptake into perfused hindlimbs. Rats were anesthetized by intraperitoneal injection of pentobarbital sodium (65 mg/kg body wt), and the epididymal fat pads were quickly removed for assessment of glucose uptake into isolated adipocytes. Rats were surgically prepared for hindlimb perfusion as described by Ruderman et al. (29), with modifications previously made in our lab (7, 20, 21). Briefly, the gastrointestinal tract was removed, and all major blood vessels within the abdominal cavity were tightly sutured. Heparin (500 mU/ml) was injected into the vena cava of each rat (0.5 ml) before cannulation to inhibit clotting. The descending aorta was cannulated (20-gauge angiocath) to deliver perfusate to the hindlimb, and the inferior vena cava was cannulated (14-gauge angiocath) to remove the effluent to complete a one-pass perfusion system. A cell-free perfusate containing Krebs-Henseleit buffer with 4% BSA (Sigma) under constant gassing (95% O2-5% CO2) was connected to the indwelling cannulas via Tygon tubing, which was connected to a pump while the rat was layed in a warm chamber (30°C). Over the first 20 min of the perfusion protocol, the flow rate was gradually increased to 20 ml/min once flow back pressure stabilized between −80 and −100 mmHg. This flow

Table 1. Compositions of diets used in this study
Fatty acid composition of adipose tissue. Fatty acid composition was determined in samples of epididymal fat pads from rats in the other two groups (P<0.005). Fasting plasma levels of glucose, insulin, triglycerides, and free fatty acids did not differ significantly among experimental treatment groups. $K_g$, calculated as the slope of the log of blood glucose concentrations over time for 2.5–12 min after the bolus glucose injection, showed a significant main effect of dietary group as well as an interaction of dietary group with time (P<0.001). Mean blood glucose concentration was lower in the HCHO group than in any other group at 2.5 min. See Fig. 1 for mean body weight and fat pad weight over the course of the experiment. The mean blood glucose concentration was similar among dietary groups at 2.5 min and continued to increase over time. The mean body weight and fat pad weight were similar among dietary groups at the start of the experiment and continued to increase over time.

RESULTS

Body weights of rats fed the HF-mixed, HF-saff, and HCHO diets are presented in Table 2. Final body weights measured on the day of the hindlimb perfusions did not differ significantly among the experimental treatment groups.

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Determination of fatty acid composition of adipose tissue. Fatty acid composition was determined in samples of epididymal adipose tissue from a subset of rats (n=5 rats/group) with the use of the method described by Wainwright et al. (36). Homogenized adipose tissue was extracted using chloroform-methanol (1:1, vol/vol) in the presence of 0.02% butylated hydroxytoluene (wt/vol). After separation, samples were dried under nitrogen, and the total lipids were fractionated by TLC with the use of silica gel plates (Analtech GF) and a chloroform-methanol-acetic acid-water (50:30:4:2) solvent system. The fatty acids of the resulting phospholipid fractions were methylated with 14% boron trifluoride in methanol and analyzed by gas chromatography (Perkin-Elmer 8420, Norwalk, CT). Fatty acids were identified by comparison of their retention times with those of authentic standards.

Statistical analysis. Body weight, food intake, fat pad weight, and $K_g$ data were assessed for differences among dietary groups using a one-way ANOVA (Statview, Abacus Concepts, Berkeley, CA). Differences in glucose uptake among different muscles and in adipocytes at the various concentrations of insulin were assessed using a repeated-measures one-way ANOVA, with muscle type and insulin concentration, respectively, as the repeated factors. Significant effects were further analyzed using Tukey’s t-test; for all analyses, P<0.05 was accepted as statistically significant.
Table 2. Final body weights; fat pad weights; fasting plasma triglyceride, free fatty acid, and glucose concentrations; characteristics of glucose tolerance; and acute insulin response to glucose in rats after 3–4 wk of experimental diets

<table>
<thead>
<tr>
<th>Measurement</th>
<th>HCHO Diet</th>
<th>HF-Saff Diet</th>
<th>HF-Mixed Diet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final body wt, g</td>
<td>309 ± 4</td>
<td>317 ± 5</td>
<td>321 ± 4</td>
</tr>
<tr>
<td>Fat pad wt, g</td>
<td>3.49 ± 0.19*</td>
<td>3.56 ± 0.11*</td>
<td>4.65 ± 0.25†</td>
</tr>
<tr>
<td>Glucose, mM</td>
<td>7.1 ± 1</td>
<td>6.7 ± 0.2</td>
<td>6.5 ± 0.2</td>
</tr>
<tr>
<td>Insulin, mg/ml</td>
<td>0.68 ± 0.08</td>
<td>0.54 ± 0.12</td>
<td>0.55 ± 0.08</td>
</tr>
<tr>
<td>Triglycerides, mg/dl</td>
<td>17.1 ± 5.2</td>
<td>13.4 ± 3.9</td>
<td>16.0 ± 4.4</td>
</tr>
<tr>
<td>Free fatty acids, mmol/l</td>
<td>0.94 ± 0.6</td>
<td>0.37 ± 0.28</td>
<td>0.75 ± 0.17</td>
</tr>
<tr>
<td>K₉, %/min</td>
<td>3.70 ± 0.4*</td>
<td>2.70 ± 0.04</td>
<td>3.90 ± 0.02*</td>
</tr>
<tr>
<td>Acute insulin response to glucose (AUC – basal)</td>
<td>11.5 ± 1.7</td>
<td>13.7 ± 2.6</td>
<td>17.8 ± 2.3</td>
</tr>
</tbody>
</table>

Values are means ± SE. AUC, area under the curve; K₉, glucose tolerance. For glucose, there was a significant main effect of anesthesia, P < 0.001. For K₉, there was a significant main effect of diet (P < 0.02) but no significant main effect of anesthesia and no significant interaction (P > 0.05). Values within a row with different symbols differ significantly (P < 0.05).

Table 3. Fatty acid composition of adipose tissue from rats fed experimental diets for 3–4 wk

<table>
<thead>
<tr>
<th>Fatty Acid</th>
<th>HCHO Diet</th>
<th>HF-Saff Diet</th>
<th>HF-Mixed Diet</th>
</tr>
</thead>
<tbody>
<tr>
<td>C10</td>
<td>1.7 ± 0.10*</td>
<td>2.0 ± 0.30*</td>
<td>2.2 ± 0.17*</td>
</tr>
<tr>
<td>C12</td>
<td>2.2 ± 0.05*</td>
<td>1.7 ± 0.80*</td>
<td>5.1 ± 0.5†</td>
</tr>
<tr>
<td>C18:1 (n-9)</td>
<td>26.5 ± 9.9*</td>
<td>22.7 ± 5.0*</td>
<td>40.4 ± 1.7†</td>
</tr>
<tr>
<td>C18:2 (n-6)</td>
<td>31.8 ± 4.0*</td>
<td>51.0 ± 7.4†</td>
<td>18.0 ± 1.8#</td>
</tr>
<tr>
<td>C20:4 (n-6)</td>
<td>0.6 ± 0.10</td>
<td>0.7 ± 0.12</td>
<td>0.31 ± 0.06</td>
</tr>
<tr>
<td>C18:3 (n-3)</td>
<td>0.8 ± 0.10*</td>
<td>0.7 ± 0.14*</td>
<td>1.8 ± 0.2‡</td>
</tr>
<tr>
<td>C22:6 (n-3)</td>
<td>0.1 ± 0.01*</td>
<td>0.11*</td>
<td>0.2 ± 0.03†</td>
</tr>
<tr>
<td>Ratio of n-6 to n-3</td>
<td>36.8*</td>
<td>72.8†</td>
<td>9.1‡</td>
</tr>
</tbody>
</table>

Values are means ± SE. Fatty acid composition from epididymal fat pad is expressed as a relative percentage. Ratio of n-6 to n-3 was determined from fatty acids reported here. Values with different symbols are significantly different from each other (P < 0.05).
fatty acids plays a significant role in affecting this measure. Varying the fatty acid composition of a high-fat diet from a single source of predominantly n-6 polyunsaturated fatty acids to include a large portion of oleic acid and short-chain saturated fatty acids and to improve the n-6-to-n-3 ratio allowed normal glucose tolerance to be maintained in the presence of insulin resistance in skeletal muscle. This supports the hypothesis that the HF-mixed diet has differential effects on insulin resistance in the insulin-sensitive tissues, skeletal muscle and adipose tissue. Varying the fatty acid composition in this way had a tissue-specific effect on insulin-stimulated glucose uptake in muscle and fat cells, with insulin resistance being observed only in muscle but not in adipocytes. Moreover, basal glucose uptake in skeletal muscle increased. This suggests that in certain tissues, insulin resistance may be accompanied by compensatory changes in an attempt to offset diminished glucose uptake. Together, these observations suggest that in the rat, high-fat feeding induces changes in both skeletal muscle and adipose tissues but that the variation in dietary fat composition contributes significantly to the overall ability of the animal to maintain glucose homeostasis.

A large proportion of a glucose load is disposed of in insulin-sensitive tissues, with muscle accounting for >80% of the insulin-mediated glucose disposal in healthy chow-fed rodents (2). It is not known whether the different dietary interventions may affect the relative contribution of muscle, fat, and other insulin-sensitive tissues to insulin-mediated glucose disposal.

Our data provide some insight into how diet may affect the partitioning of glucose uptake and the physiological significance of these changes. In our study, glucose intolerance was observed only when insulin resistance was present in both skeletal muscle and adipose tissue (after HF-saff feeding) but not when insulin resistance was observed in only skeletal muscle (i.e., after HF-mixed feeding). Thus glucose tolerance was preserved in rats with uncompromised glucose uptake into adipose...
cytes. The epididymal fat pad mass was increased in the HF-mixed group relative to the other two dietary groups; thus the larger fat mass in these animals may account for an absolute increase in the amount of glucose disposed and may help to preserve glucose tolerance. Because adipocyte cell size and the absolute number of adipocytes per fat pad were not assessed in this study, it is not clear whether the increased fat pad mass reflects an increased cell number, cell size, or both. Results from this study suggest that glucose uptake per adipocyte was increased in the cells from rats fed the HF-mixed diet relative to those fed the HF-saff diet, although, in the absence of cell volume measurements, this cannot be confirmed in this study. Other investigators have reported that the rate of glucose uptake into isolated adipocytes is similar regardless of whether results are expressed per cell or per unit cell volume (3).

The recent suggestion that particular fatty acids may act as natural ligands for peroxisome proliferator-activated receptor-\( \gamma \) (PPAR-\( \gamma \)) (13, 30) points to another possible mechanism through which different dietary fats may contribute to maintenance of normal glucose tolerance. PPAR-\( \gamma \), when activated, induces adipogenesis and also improves insulin sensitivity (30). It is unclear whether PPAR-\( \gamma \) activation is able to reverse insulin resistance induced by high-fat feeding (10, 31), although newly formed, smaller adipocytes are more sensitive to the effects of insulin (5). Thus it is conceivable that if PPAR-\( \gamma \) were differentially activated by the two high-fat diets used in this study because of differing proportions of available fatty acids, then glucose tolerance may be preserved in the face of increased fat mass. This may be an area for future research.

Another alternative may be that insulin sensitivity must be reduced in all or some critical number of insulin-sensitive tissues before glucose tolerance is disturbed. Others have shown that with high-fat feeding, hepatic insulin resistance develops more rapidly than insulin resistance in skeletal muscle (14); therefore, we assume that this is also present in our study. Hepatic insulin sensitivity was not assessed in this study, and, therefore, the effects of the HF-mixed diet on the liver remain unknown.

Feeding of either high-fat diet (HF-mixed or HF-saff) to rats resulted in a reduction in insulin-stimulated glucose uptake in all muscle groups relative to HCHO-fed rats. This effect is well documented in animals consuming diets with a fat content >50% of total calories (6, 10, 14, 15, 17, 19, 23, 27, 33, 34) and may be related to the large amount of stored lipids that accumulates within the muscle cells (24, 25, 33). In fact, both the high polyunsaturated fat diet (HF-saff) and the monounsaturated/short-chain fatty acid soybean oil-based diet (HF-mixed) similarly reduced insulin sensitivity in skeletal muscle in these rats. Using a clamp technique, Storlien et al. (33) observed reversal of insulin resistance in skeletal muscle after including 6% of kilocalories from long-chain n-3 fatty acids in a high polyunsaturated fat diet or after including 6% of kilocalories from short-chain n-3 fatty acids along with a high saturated fat diet. The HF-mixed-based diet used in this study contained ~10 times less (0.8% kcal) n-3 fatty acid (linolenic acid) than the high fish oil diet used by Storlien et al. (33). This suggests that the level of n-3 fatty acids in the HF-mixed diet was not sufficient to alleviate insulin resistance in muscle when found in combination with the high saturated short-chain and monounsaturated fatty acids.

It is unknown whether changes in the muscle cell membrane fluidity and/or composition under these varied dietary conditions could have modulated insulin-stimulated glucose transport through changes in cell content of phospholipid signaling molecules. It is evident from studies by others that high-fat feeding changes insulin-signaling patterns. Feeding a high-fat beef tallow-based diet with ratio of saturated to monounsaturated fat similar to that in the HF-mixed diet results in a reduction in the gene expression of the insulin receptor substrate-1 and PI 3-kinase in rat skeletal muscle compared with muscle from rats fed a high safflower oil diet (similar to the HF-saff diet) (12), contributing to glucose intolerance in these animals. Furthermore, both the expression of the insulin-regulatable glucose transporter GLUT-4 (mRNA and protein) and the ability of insulin-stimulated PI 3-kinase activity to increase GLUT-4 translocation are dramatically reduced in skeletal muscle after feeding a high-lard-based diet to mice (9, 38). These studies may suggest that our findings of reduced insulin sensitivity in muscle of high-fat-fed groups could in part be due to changes in insulin signaling, which may ultimately produce a lower glucose uptake.

In skeletal muscle, when insulin was not present in the perfusate, an increased glucose uptake was observed in all the muscle groups (oxidative, mixed fiber, and glycolytic muscles) from HF-saff-fed rats and in two muscle groups (oxidative and mixed muscle) from HF-mixed-fed rats relative to HCHO-fed rats. In both high-fat groups, the elevation in basal glucose uptake was most apparent in oxidative muscle. Thus both groups of high-fat-fed rats were able to achieve a higher glucose uptake during the 5-min perfusion period than would have been possible with a normal basal uptake component coupled with the compromised insulin-stimulated uptake. This could be an adaptive response to the development of insulin resistance in this tissue, since oxidative muscles as a group have the highest insulin sensitivity in normal, healthy rats (22). The upregulation of basal uptake in oxidative muscle may result from alteration of the diet fatty acid composition, since Storlien et al. (35) saw elevated basal uptake in oxidative muscle after supplementing a high saturated fat diet with n-3 fatty acids. The weak positive relationship observed between non-insulin-stimulated glucose uptake and oxidative capacity in muscle from HCHO-fed rats is also present in muscle from rats fed the HF-mixed diet, albeit the level of basal uptake is higher in this latter group. In contrast, the HF-saff-fed rats showed a fairly constant increased basal level of uptake, and this was irrespective of the fiber composition of these muscles. Subtle differences between the effects...
of the HF-saff and HF-mixed diet may be due to the
nature of the cellular mechanisms responsible for up-
regulating basal glucose transport. Kahn and Pedersen
(9) observed reduced muscle GLUT-1 mRNA after 7 wk
of feeding an 80% fat diet to rats, whereas, in rats fed a
high safflower oil diet (60% kcal) for 4 wk, Stevenson et
al. (31) reported no change in the amount of GLUT-1. In
a different model of insulin resistance, the denervated
rat, we have observed that increases in basal glucose
uptake are accompanied by increases in GLUT-1 expres-
sion (7). The cellular mechanisms and/or transporter
proteins involved in the upregulation of basal transport
remain to be determined in this particular high-fat
feeding model. Interestingly, as in the denervated rat
model, the increase in basal uptake after high-fat
feeding does not fully restore the muscle's total capacity
for glucose transport when insulin is available. This
suggests that the basal compensatory mechanisms are
only partially capable of offsetting the reduction in
glucose uptake when insulin is present. This may help
account for the normal fasting glucose concentrations
in the same animals that expressed glucose intolerance
after a glucose challenge.

In contrast to its effects in skeletal muscle, the
HF-mixed diet had no adverse effect on insulin-
stimulated glucose uptake into isolated adipocytes,
whereas HF-saff feeding reduced insulin-stimulated
glucose transport in isolated adipocytes relative to
HCHO-fed rats. The absolute multiple of increase in
glucose uptake after insulin stimulation compared with
basal levels of uptake was approximately twofold and
most likely reflects the combination of the specific
incubation conditions used in this study along with
properties inherent to cells from animals of this particu-
lar size and age fed purified diets. Still, the relative
impairment in glucose uptake by adipocytes after HF-
saff feeding but not HF-mixed feeding suggests that in
adipose tissue, unlike skeletal muscle, the total amount
of dietary fat was not the important factor affecting
glucose uptake, but the fatty acid composition of the
diet had an important impact on this process. Our
results suggest that, in the presence of large amounts
of dietary fat, glucose uptake can proceed normally in
adipocytes if fatty acid profiles allow and points to an
interactive effect between fatty acid classes and amount
of dietary fatty acid as determinants of glucose uptake
in fat cells.

Membrane fatty acid composition of adipocytes re-
lected dietary fatty acid intake after feeding of the
experimental diets. Whether changes in fatty acid
profiles in adipocytes from rats fed the HF-mixed diet
containing the mixture of saturated, n-6 and n-3 poly-
saturated, and monounsaturated fatty acids lead to
changes in numbers of glucose transporters or restore
some aspect of the insulin signal transduction-glucose
transporter translocation pathway (8) is not known. If
the proportion of membrane n-3 fatty acids is impor-
tant in determining glucose uptake in adipocytes, then
this study suggests that in adipocytes, unlike muscle,
only a small amount of dietary n-3 fatty acid is required
to remedy the impaired glucose uptake induced by a
high-fat diet. Understanding these observations as well
as their application to humans will require more de-
tailed understanding of the relationships among di-
etary availability of particular fatty acids, responsive-
ness of membrane composition to diet, and biochemical
or molecular mechanisms controlling incorporation of
specific fatty acids into membranes.

In summary, this study demonstrates that dietary
fatty acid composition of a high-fat diet is critical in
determining the effects on tissue-specific insulin resis-
tance and whole body glucose tolerance in rats. When
the fatty acid composition of a high-fat diet is changed
from a single source of predominately n-6 polyunsatures-
ted fatty acids to include a large portion of oleic acid
and short-chain saturated fatty acids and an increased
n-3-to-n-6 ratio, normal glucose tolerance is main-
tained despite the presence of insulin resistance in
skeletal muscle. It is conceivable then that overall
glucose tolerance in rats may be sustained when one of
the compartments mediating glucose homeostasis be-
comes less responsive to insulin. Varying the fatty acid
composition to the HF-mixed diet appears to have
tissue-specific effects on glucose uptake such that al-
though hormonally regulated glucose uptake in skel-
etal muscle is adversely affected, basal glucose uptake
in skeletal muscle is increased and glucose uptake into
adipose tissue is apparently spared. These results
underline the importance of examining dietary effects
in multiple tissues and at both the cellular and whole
body levels to gain insight into how diet affects the
interaction among tissues to achieve glucose homeosta-
sis. The extent to which our observations are specifi-
cally related to a small amount of n-3 fatty acids or
other fatty acids such as monounsaturates or some
combination remains to be determined but may be
important for understanding the development and re-
versal of insulin resistance, glucose intolerance, and
impairment of glucose homeostasis in animal models
and in humans.

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