Diets enriched in sucrose or fat increase gluconeogenesis and G-6-Pase but not basal glucose production in rats

S. RENEE COMMERFORD,1 JENNIFER B. FERNIZA,1 MICHAEL E. BIZEAU1,2 JEFFREY S. THRESHER,1 WAYNE T. WILLIS,1 AND MICHAEL J. PAGLIASSOTTI1,2
1Exercise Science Research Institute, Arizona State University, Tempe, Arizona 85287; and 2University of Colorado Health Sciences Center, Department of Medicine, Denver, Colorado 80262

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Commerford, S. Renee, Jennifer B. Ferniza, Michael E. Bizeau, Jeffrey S. Thresher, Wayne T. Willis, and Michael J. Pagliassotti. Diets enriched in sucrose or fat increase gluconeogenesis and G-6-Pase but not basal glucose production in rats. Am J Physiol Endocrinol Metab 283: E545–E555, 2002. First published May 21, 2002; 10.1152/ajpendo.00120.2002.—High-fat (HFD) and high-sucrose diets (HSD) reduce insulin suppression of glucose production in vivo, increase the capacity for gluconeogenesis in vitro, and increase glucose-6-phosphatase (G-6-Pase) activity in whole cell homogenates. The present study examined the effects of HSD and HFD on in vivo gluconeogenesis, the catalytic and glucose-6-phosphate translocase subunits of G-6-Pase, glucokinase (GK) translocation, and glucose cycling. Rats were fed a high-starch control diet (STD; 68% cornstarch), HSD (68% sucrose), or HFD (45% fat) for 7–13 days. The ratio of 3H in C6:C2 of glucose after 3H2O injection into 6- to 8-h-fasted rats was significantly increased in HSD (0.68 ± 0.07) and HFD (0.71 ± 0.08) vs. STD (0.40 ± 0.10). G-6-Pase activity was significantly higher in HSD and HFD vs. STD in both intact and disrupted liver microsomes. HSD and HFD significantly increased the amount of the p36 catalytic subunit protein, whereas the p46 glucose-6-phosphate translocase protein was increased in HSD only. Despite increased nonglycerol gluconeogenesis and increased G-6-Pase, basal glucose and insulin levels as well as glucose production were not significantly different among groups. Hepatocyte cell suspensions were used to ascertain whether diet-induced adaptations in glucose phosphorylation and GK might serve to compensate for upregulation of G-6-Pase. Tracer-estimated glucose phosphorylation and glucose cycling (glucose ↔ glucose 6-phosphate) were significantly higher in cells isolated from HSD. After incubation with either 5 or 20 mM glucose and no insulin, GK activity (nmol·mg protein−1·min−1) in digitonin-treated eluates (translocated GK) was significantly higher in HSD (32 ± 4 and 146 ± 6) vs. HFD (4 ± 1 and 83 ± 10) and STD (9 ± 2 and 87 ± 9). Thus short-term, chronic exposure to HSD and HFD increase in vivo gluconeogenesis and the G-6-Pase catalytic subunit. Exposure to HSD diet also leads to adaptations in glucose phosphorylation and GK translocation.
account for the removal of 25–30% of an oral glucose load (19, 27, 39, 46). In addition, the liver avidly consumes dietary lipid and protein (46), and the presence of either or both of these nutrients influences the contribution of the liver to glucose removal (46). Carbohydrate composition also influences hepatic carbohydrate metabolism. For example, fructose extraction by the liver appears to be remarkably high (estimated at 50–75%), and both glucose phosphorylation and glycolysis synthesis are stimulated by fructose (16, 51, 68). Thus the liver can be considered a dietary nutrient buffer with the extent of nutrient uptake by the liver determined, in large part, by the composition of nutrients presented to it. Because the development of obesity and type 2 diabetes results from both genetic and environmental factors, it would appear likely that diet composition might significantly influence hepatic glucose metabolism and thus the hepatic adaptations that characterize these disease states.

We have examined the impact of chronic changes in diet composition on hepatic glucose metabolism in rats to determine the ability of dietary nutrients to induce adaptations that characterize prediabetic states and type 2 diabetes. In rats, diets enriched in fat or sucrose reduce the ability of insulin to suppress glucose production in vivo, reduce the ability of insulin to suppress gluconeogenesis in perfused liver, and increase the capacity for gluconeogenesis from a number of precursors in both perfused livers and isolated hepatocytes (10, 28, 45, 48, 49, 62). These diet-induced adaptations occur rapidly and independently of changes in body composition, are accompanied by increased hepatic lipids, and do not result in the overproduction of glucose in vivo (28, 49). Recent studies performed in humans also suggest that diets enriched in fat or protein can reduce insulin suppression of glucose production and/or increase gluconeogenesis (9, 33). One aim of the present study was to determine whether diets enriched in fat or sucrose increase gluconeogenesis in vivo and to critically examine whether any diet-induced changes involve the circulating milieu.

G-6-Pase is a multicomponent enzyme that is tightly associated with the endoplasmic reticular membrane and catalyzes the dephosphorylation of glucose 6-phosphate, the terminal step of glycolysis and gluconeogenesis (21, 41, 67). Nutrients and hormones influence the expression of hepatic G-6-Pase mRNA and G-6-Pase protein levels (4, 36, 37). For example, infusions of glucose, lipid, or xylitol increased G-6-Pase mRNA and protein in rats in vivo in the presence of basal insulin levels (36–38). Exposure of primary hepatocytes to glucose, xylitol, or fructose increased G-6-Pase mRNA in the absence of insulin (4, 11, 35). The extent to which nutrients can influence this protein when ingested, and thus in the presence of hyperinsulinemia, has not been critically examined. This information is essential for our understanding of the regulation of this protein complex, because it appears that the repressive effects of insulin on its transcription are dominant (63). Thus a second purpose of the present study was to determine the effects of diets enriched in fat or sucrose on the catalytic subunit and glucose-6-phosphate translocase subunits of G-6-Pase.

The presence of GLUT2 in the liver allows rapid equilibration between the extracellular and intracellular glucose levels; thus net glucose release represents the balance between G-6-Pase and glucokinase. Although diets enriched in fat or sucrose produce many adaptations in the liver, when provided for 1 wk they do not increase total basal glucose production or result in basal hyperinsulinemia (28, 49, 53, 62). Thus diet manipulation in rats provides a useful model to investigate intrahepatic adaptations that may be linked to the preservation of normal rates of glucose production. The third aim of the present study was to examine the effects of high-fat and high-sucrose diets on glucokinase activity. Acute regulation of glucokinase activity is complex, involving interaction with a glucokinase-regulatory protein (GKRP) and translocation from the nucleus to the cytoplasm in response to nutrients and insulin (1, 43, 66). Given the complexity of the glucokinase system in the liver, we examined diet-induced effects on both glucose phosphorylation and glucokinase translocation using isolated hepatocytes.

**METHODS**

**Experimental Animals**

Male Sprague-Dawley rats bred at the Arizona State University Animal Care Facility were used for this study. Rats weighed 170–210 g upon entering the study. Rats were individually caged under controlled conditions (12:12-h light-dark cycle; 50–60% relative humidity; 25°C) with free access to water. All procedures for animal use were approved by the Institutional Animal Care and Use Committee at Arizona State University.

**Diet Protocol**

Rats were provided ad libitum access to a semipurified starch diet (STD; Research Diets, New Brunswick, NJ) for 2 wk (baseline period) (Table 1). The baseline period was followed by an experimental diet period when rats either remained on the STD or were switched to either a high-fat diet (HFD; Table 1) or a high-sucrose diet (HSD; Table 1). To ensure equivalent energy intake, body weight gain, and body composition, rats were provided 95% of the calories consumed during the 2nd wk of ad libitum baseline feeding throughout the experimental diet period (49). Rats were studied after 7–13 days on the experimental diet. We have previously demonstrated that this duration of time results in reduced insulin suppression of glucose production in vivo (49), reduced insulin suppression of hepatic gluconeogenesis in vitro (48), and increased capacity for gluconeogenesis in vitro (10, 48) in animals fed either the HSD or HFD. Throughout the protocol, food intake was measured daily, and body weight was recorded once per week.

**Experiments**

**In vivo gluconeogenesis.** After 7–9 days of experimental diet, catheters (PE-50, Clay-Adams Intramedic) were implanted in anesthetized rats (im injection of 5 mg/kg acepromazine, 10 mg/kg xylazine, and 50 mg/kg ketamine) in the left carotid artery and right jugular vein (54). Animals were allowed ≥4 days to recover and were required to be at...
Table 1. Composition of experimental diets

<table>
<thead>
<tr>
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<th>HFD</th>
<th>HSD</th>
<th>STD</th>
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<tr>
<td>Casein</td>
<td>246</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>DL-Methionine</td>
<td>3.7</td>
<td>3</td>
<td>3</td>
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<tr>
<td>Corn starch</td>
<td>220</td>
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<td>500</td>
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<tr>
<td>Maltodextrin 10</td>
<td>184.6</td>
<td>0</td>
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</tr>
<tr>
<td>Sucrose</td>
<td>0</td>
<td>650</td>
<td>0</td>
</tr>
<tr>
<td>Cellulose</td>
<td>50</td>
<td>50</td>
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<tr>
<td>Corn Oil</td>
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</tr>
<tr>
<td>Salt mix</td>
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<td>35</td>
<td>35</td>
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<tr>
<td>Vitamin mix</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Choline bitartrate</td>
<td>2</td>
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</table>

% energy

- Protein: 20 20 20
- Fat: 45 12 12
- Carbohydrate: 35 68 68

Diets were formulated by Research Diets (New Brunswick, NJ). STD, high-starch diet; HSD, high-sucrose diet; HFD, high-fat diet. Maltodextrin 10 is enzyme-converted cornstarch with a dextrose equivalence of 10%. Salt and vitamin mix were prepared according to guidelines from the American Institute of Nutrition (57).

>95% of their presurgical body weight in order to be studied. Animals (n = 9–10/group) were provided their respective diets during the recovery period. On the day of study, a baseline blood sample was taken from 6- to 8-h-fasted rats, and an intravenous bolus of 3H2O was delivered (0.5 mCi/100 g body wt). Blood samples were taken at 30-min intervals for 4 h.

G-6-Pase activity. After 7–9 days of experimental diet, a separate group of 6- to 8-h-fasted rats (n = 6–7/group) was anesthetized. Once the absence of pedal and corneal reflexes was established, the abdomen was incised, and a portion of the liver was removed and immediately homogenized on ice in 10 mM HEPES plus 0.25 M sucrose, pH 7.4. Microsomes were extracted by the procedures of Daniele et al. (17). Briefly, the homogenate was centrifuged at 30,000 g for 10 min at 4°C. The resulting supernatant was then centrifuged for 30 min at 100,000 g at 4°C. The pelleted microsomes were resuspended in 10 mM HEPES plus 0.25 M sucrose (pH 7.4). G-6-Pase activity was assessed on intact microsomes and on microsomes wherein the membrane was disrupted with 0.5% sodium cholate. G-6-Pase activity was measured at 0.25, 0.5, 1, 2, 10, and 15 mM as previously described (12). Total protein was determined by the Bradford method. Integrity of the microsomal membrane was assessed using mannose 6-phosphate (1 mM) as substrate in the G-6-Pase assay, since this substrate is neither bound nor transported by the glucose 6-phosphate transporter but has equivalent reactivity with the catalytic subunit (5). In addition, enrichment of the microsomal preparation was assessed using the ratio of NADPH-cytochrome c reductase activity in intact microsomes relative to total liver homogenates (6).

Western blotting. A second portion of liver was homogenized on ice in a buffer containing 20 mM HEPES, pH 7.4, 1% Triton X-100, 10% glycerol, 2 mM EGTA, 1 mM sodium vanadate, 2 mM dithiothreitol, 1 mM phenylmethylsulfonyl fluoride, 50 mM β-glycerophosphate, 3 mM benzamidine, 10 μM leupeptin, 5 μM pepstatin, and 10 μg/ml aprotinin. Samples were rotated for 30 min at 4°C and centrifuged at 14,500 rpm for 1 h at 4°C. Total protein concentration was determined by the Bradford method.

Equivalent amounts of protein from either total cell lysates (glucokinase) or microsomal fractions (p36 catalytic subunit, p46 glucose-6-phosphate translocase) were resolved by SDS-PAGE. After electrophoresis of proteins from gels to Hybond-P membranes (Amersham Pharmacia Biotech, Piscataway, NJ), membranes were incubated with antibodies against the p36 catalytic subunit of G-6-Pase (gift from Dr. Gilles Mithieux, Lyon, France), the p46 glucose-6-phosphate translocase (gift from Dr. Gerald van de Werve, Montreal, Canada), or glucokinase (gift from Dr. Mark Magnuson, Nashville, TN). Detection was performed using enhanced chemiluminescence reagents (Amersham Pharmacia) and band intensity determined by optical density.

Basal and euglycemic hyperinsulinemic clamps. Basal and hyperinsulinemic euglycemic clamps were performed on 6- to 8-h-fasted conscious rats (n = 5–6/group) as previously described (49). The basal period consisted of a primed continuous (12 μCi, 0.1 μCi/min) intravenous infusion of [3-3H]glucose (HPLC purified, New England Nuclear Laboratory) and arterial blood sampling at 100, 110, and 120 min. After the 120-min blood sample, a primed continuous infusion of insulin was initiated to rapidly increase the insulin concentration approximately fourfold over basal (4 mU·kg⁻¹·min⁻¹). A variable glucose infusion was also initiated (20% glucose) to maintain basal plasma glucose concentrations. The glucose infused contained [3-3H]glucose to minimize changes in glucose specific activity (20). Arterial blood samples were taken at 5- to 10-min intervals (125–240 min), and larger arterial samples were taken at 220, 230, and 240 min.

Hepatocyte isolation. After 7–9 days of experimental diet, overnight-fasted rats (n = 5–6/group) were anesthetized, and the abdominal cavity was opened to expose the portal vein, into which a catheter (20 G Angiocath, Becton-Dickinson) was introduced and sutured in place. The liver was perfused using standard methods previously described (8). Trypan blue exclusion averaged 90.1 ± 1.0% and exceeded 90% for all animals except one (87%). Results were the same regardless of whether that animal was included in the analysis; thus reported data include that animal.

Initial time course studies for glucose phosphorylation and cycling. Isolated cells were suspended (30 mg/ml) in Krebs-Henseleit buffer containing 1% gelatin and incubated at 37°C (2 ml/vial, in triplicate) for 10, 20, 30, 40, 50, or 60 min in the presence of 15 mM glucose and 0.2 mM fructose with 1.5 μCi of either [2-3H]glucose (n = 3) or [6-3H]glucose (n = 3). Glucose specific activity and accumulation of 3H2O were determined for each rat at each time point by means of ion exchange chromatography. These studies demonstrated that accumulation of 3H2O was linear and that glucose specific activity remained constant over the 60-min time period for incubations with [2-3H]glucose (Fig. 1) and [6-3H]glucose (data not shown). Fructose levels were not significantly different from zero by 30–40 min of incubations. Therefore, higher fructose levels were used in subsequent studies.

Glucose phosphorylation and cycling. Isolated cells were suspended (30 mg/ml) in Krebs-Henseleit buffer containing 1% gelatin and incubated at 37°C (2 ml/vial, in triplicate) for 1 h at either 20 mM glucose or 20 mM glucose and 0.5 mM fructose. Incubations included 1.5 μCi of either [2-3H]glucose (n = 5) or [6-3H]glucose (n = 5). After 1 h, 1.0 ml of cells was added to an equal volume of perchloric acid, a portion of which was neutralized with potassium carbonate for glucose and fructose analyses and the remainder adjusted to a pH of 3 for ion exchange chromatography (9). Another portion (0.5 ml) of cells was centrifuged, the resulting supernatant was removed, and the packed cells were immediately frozen in liquid N2. All samples were stored at −80°C for subsequent analysis.
Glucokinase activity and translocation. Two milliliters of suspended hepatocytes (60 mg) were incubated at 37°C for 30 min under the following conditions: 5 mM glucose, 5 mM glucose with 5 nM insulin, 20 mM glucose, 20 mM glucose with 5 nM insulin, 0.5 mM fructose, 0.5 mM fructose with 5 mM glucose, and 0.5 mM fructose with 20 mM glucose. At 30 min, hepatocytes were permeabilized in 300 mM sucrose, 3 mM HEPES, 2 mM dithiothreitol, 5 mM MgCl₂, and 0.05 mg/ml digitonin (pH 7.2), as previously described (1). After 6 min in permeabilization medium, the digitonin-treated eluate was transferred to tubes with dithiothreitol (4 mM) and 5 mM digitonin treated either glycolytically or into glycogen (24). Net glycolysis represents phosphorylated glucose not further metabolized either glycolytically or into glycogen (24). Net glycogen synthesis was estimated from the incorporation of [6-³H]glucose into glycogen. Assumptions regarding these techniques have been discussed in detail previously (24, 26).

Hormones and metabolites. Plasma glucose was determined using a kit (Sigma). Glycogen content and radioactivity were determined on frozen packed cells according to the method of Chan and Exton (14). Protein determinations were made using the Bradford method.

Ion exchange chromatography on samples from suspended hepatocytes. Samples (0.5 ml) were placed onto a series of two columns (hydrogen resin, Bio-Rad AG 50W-X8 and acetate resin, Bio-Rad AG1-X8). Glucose was eluted from the initial water rinse. Amino acids were eluted off the hydrogen column with 4 M NH₄. Lactate and pyruvate were eluted off the acetate column with 2 M formic acid and 2 M acetic acid, respectively. ³H₂O accumulation was determined from aliquots of the glucose fraction that were counted directly or evaporated to dryness. Lactate, pyruvate, and amino acid standards were used to assess recovery.

Calculations

In vivo studies. Tracer-estimated glucose appearance was calculated by isotope dilution with adjustment for the labeled exogenous infusion (20, 60). Gluconeogenesis was estimated from the ratio of tritium bound to C6 of glucose relative to that bound to C2 of glucose (58). This method takes advantage of the binding of ³H from ³H₂O to C3 of pyruvate that becomes C6 of glucose in the gluconeogenic process (29, 58). Because the ³H bound to C2 of glucose arises from both gluconeogenesis and glycogenolysis, the amount of ³H bound to C6 relative to that bound to C2 provides an estimate of glucose formed via non-glycerol gluconeogenesis (29). Total gluconeogenesis was estimated using the ratio of tritium bound to C5 of glucose relative to that bound to C2 (30).

In vitro studies. Rates of glucose phosphorylation were calculated from the sum of accumulated ³H₂O and tritiated glycogen from vials containing [2-³H]glucose (24). Estimation of tritiated glycogen served to decrease the error resulting from incomplete equilibration between glucose 6-phosphate and fructose 6-phosphate (26). Glycolysis was calculated as the sum of tritiated pyruvate, lactate, amino acids, and tritiated water in vials containing [6-³H]glucose (24). Glucose cycling was calculated as the difference between glucose phosphorylation and total glucose metabolism (glycolysis + [6-³H]glucose incorporation into glycogen) (24). Thus glucose cycling represents phosphorylated glucose not further metabolized either glycolytically or into glycogen (24). Net glycogen synthesis was estimated from the incorporation of [6-³H]glucose into glycogen. Assumptions regarding these techniques have been discussed in detail previously (24, 26).

Enzymes. Total glucokinase activity from isolated cells was calculated as the sum of glucokinase activity in the digitonin eluate and that in the residual cell matrix (1). Microsomal membrane integrity is presented as “percent latency of mannose-6-phosphatase,” calculated as: 100 – [100 × (mannose-6-phosphatase activity in intact microsomes)/mannose-6-phosphatase activity in disrupted microsomes)] (5). Thus 100% latency would represent zero activity in intact microsomes and, therefore, an inability of mannose-6-phosphatase to gain access to the catalytic subunit.

Data Analysis

Data were analyzed both as a one-way analysis of variance (ANOVA) using Bonferroni’s multiple comparison test to determine where significant differences lie and by the non-parametric analysis of Kruskal-Wallis. The two analyses gave identical interpretations. Student’s unpaired t-test was used to compare within-diet responses to different experimental conditions. Significance was set at P < 0.05. All data are reported as means ± SE.
RESULTS

Energy Intake and Weight Gain

During the experimental diet feeding period, energy intake (~100 kcal/day) and body weight gain (~40 g/wk) were not significantly different among diet groups.

In Vivo Gluconeogenesis

Because we had previously demonstrated that both the HSD and HFD increased the capacity for gluconeogenesis in perfused liver and isolated hepatocytes from a number of precursors (10, 48), this first experiment sought to determine whether this adaptation occurred in vivo.

There were no significant differences among diet groups in any of the metabolites or hormones measured (Table 2). Nonglycerol gluconeogenesis, as assessed by the C6: C2 ratio of glucose, was significantly increased in HSD and HFD (Table 2). In addition, total gluconeogenesis, as assessed by the C5: C2 ratio, was also increased in HSD and HFD (Table 2). The tritiated water pool appeared to reach steady state between 30 and 60 min after injection (data not shown).

G-6-Pase Activity and Protein Levels

In a previous study, short-term (1 wk) exposure to the HSD increased G-6-Pase activity in whole cell homogenates isolated from perportal or perivenous regions of the liver (11). In this experiment, we sought to determine whether diet-induced changes in G-6-Pase activity involved the microsomal membrane and the extent to which HSD and HFD influenced the catalytic subunit and glucose-6-phosphate translocase protein.

G-6-Pase activity was significantly increased in both intact and disrupted microsomes from HSD and HFD rats (Fig. 2). Consistent with the observed diet-induced increase in G-6-Pase activity, Western blot analysis demonstrated that both the HSD and HFD increased (P < 0.05) the amount of the p46 catalytic subunit (Fig. 3). In contrast, only the HSD produced a significant increase in the amount of the p36 glucose-6-phosphate translocase (Fig. 3). Insulin and glucose concentrations were not significantly different among diet groups (Table 3). Neither percent latency nor the enrichment of NADPH-cytochrome c reductase (microsomal marker) was significantly different among groups (Table 3).

In Vivo Glucose Appearance Under Basal and Hyperinsulimemic Conditions

We investigated basal and insulin-stimulated glucose metabolism in the three dietary groups to demonstrate that these diets, when provided for 1 wk, do not increase basal glucose production but do lead to insulin resistance on glucose production.

Insulin, glucose, and NEFA concentrations were not significantly different among diet groups (Table 4). Basal rates of glucose appearance were not significantly different among diet groups (Table 4). Insulin suppression of NEFA concentrations was not significantly different among groups (Table 4). However, insulin suppression of endogenous glucose appearance was significantly reduced in HSD and HFD (Table 4).

Table 2. Plasma metabolites, hormones, and gluconeogenesis in fasted rats

<table>
<thead>
<tr>
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<th>STD (n = 9)</th>
<th>HSD (n = 9)</th>
<th>HFD (n = 10)</th>
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<tr>
<td>Insulin, µU/ml</td>
<td>30 ± 4</td>
<td>35 ± 5</td>
<td>34 ± 5</td>
</tr>
<tr>
<td>Glucagon, pg/ml</td>
<td>97 ± 11</td>
<td>103 ± 12</td>
<td>91 ± 10</td>
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<tr>
<td>Corticosterone, ng/ml</td>
<td>132 ± 21</td>
<td>152 ± 24</td>
<td>115 ± 19</td>
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<tr>
<td>Glucose, mM</td>
<td>6.1 ± 0.4</td>
<td>6.3 ± 0.5</td>
<td>6.2 ± 0.4</td>
</tr>
<tr>
<td>Lactate, mM</td>
<td>0.9 ± 0.1</td>
<td>0.7 ± 0.2</td>
<td>0.7 ± 0.1</td>
</tr>
<tr>
<td>Glycerol, mM</td>
<td>0.15 ± 0.02</td>
<td>0.18 ± 0.01</td>
<td>0.16 ± 0.02</td>
</tr>
<tr>
<td>NEFA, mM</td>
<td>0.7 ± 0.1</td>
<td>0.8 ± 0.2</td>
<td>0.8 ± 0.1</td>
</tr>
<tr>
<td>C6:C2</td>
<td>0.40 ± 0.10</td>
<td>0.68 ± 0.07*</td>
<td>0.71 ± 0.08*</td>
</tr>
<tr>
<td>C5:C2</td>
<td>0.49 ± 0.06</td>
<td>0.79 ± 0.08*</td>
<td>0.81 ± 0.07*</td>
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</table>

Values are means ± SE. NEFA, nonesterified fatty acids. C6:C2, tritium incorporation from 3H2O into the 6th carbon of glucose relative to that in the 2nd carbon of glucose; C5:C2, tritium incorporation from 3H2O into the 5th carbon of glucose relative to that in the 2nd carbon of glucose. Higher ratio indicates a greater contribution of nonglycerol gluconeogenesis to glucose production or total gluconeogenesis to glucose production, respectively. *Significantly different from STD.

Fig. 2. Glucose-6-phosphatase activity with different diets in intact (A) and disrupted (B) microsomes. Values are means ± SE; n = 6–7/diet group. Units are nmol Pi·mg microsomal protein⁻¹·min⁻¹. STD, high-starch diet; HSD, high-sucrose diet; HFD, high-fat diet. HSD and HFD were significantly greater than STD at all concentrations of glucose 6-phosphate (P ≤ 0.03) in both intact and disrupted microsomes.
Low concentrations of fructose are known to stimulate glucose phosphorylation (41). Because we did not observe fructose stimulation of glucose phosphorylation at 20 mM glucose, we estimated glucose phosphorylation in a subset of rats (n = 3–4/diet) at lower glucose concentrations in the presence and absence of fructose. Under these conditions, glucose phosphorylation was increased by fructose (HSD, 38%; HFD, 42%; STD, 46%; Fig. 4).

**Glucokinase Translocation**

Glucokinase activity in digitonin eluates was significantly higher in HSD-fed rats after incubations with either 5 or 20 mM glucose (Fig. 5). This was the case whether the data were reported as an absolute rate (Fig. 5) or as a percentage of the total activity (data not shown). The glucose-induced increment (from 5 to 20 mM glucose) in glucokinase activity in digitonin eluates was not significantly different among diets (Fig. 5). Glucokinase activity in digitonin eluates was not significantly different among diet groups with fructose alone, and the increment in glucokinase activity resulting from fructose addition to either low or high glucose was significantly less in HSD-fed rats vs. HFD- and STD-fed rats (Table 6). Glucokinase activity in digitonin eluates after incubations with insulin was significantly reduced in HSD at both 5 and 20 mM glucose and in HFD at 20 mM glucose vs. STD (Fig. 6).

Within each diet group, total glucokinase activity (sum of digitonin eluate and residual cell matrix) was not significantly different across substrate conditions and averaged 12% higher in HSD compared with STD and HFD. Western blot analysis of total cell lysates from livers of 6- to 8-h-fasted rats demonstrated that glucokinase protein levels were not significantly different among diet groups (data not shown).

**DISCUSSION**

The present study examined the effects of short-term (~1 wk) exposure to diets enriched with sucrose or fat on in vivo gluconeogenesis, the catalytic and glucose-6-phosphate translocase subunits of G-6-Pase, and glucokinase. The results demonstrate that short-term exposure to either the high-sucrose or the high-fat diet increased the contribution of gluconeogenesis to glucose production in vivo without apparent effects on the circulating environment. These diets also increased microsomal G-6-Pase activity via changes in the

<table>
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<th>Table 3. Integrity of microsomal preparations</th>
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<td>Plasma glucose, mM</td>
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<td>Plasma insulin, µU/ml</td>
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<tr>
<td>NADPH-cytochrome c reductase ratio</td>
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<td>Percent latency</td>
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Values are means ± SE; for n = 6-7/group. Glucose and insulin samples from cardiac puncture. See METHODS for definitions of cytochrome c reductase ratio and percent latency.
Glucose phosphorylation in isolated hepatocytes

Tracer-estimated glucose metabolism in rats revealed that the C6:C2 ratio and total gluconeogenesis (C5:C2 ratio) were increased in response to dietary changes. Elevated glucose phosphorylation and increased gluconeogenesis were assessed using tritiated water incorporation into glucose. The results showed that sucrose- or fat-enriched diets (10) and perfused livers (48) increased the capacity for gluconeogenesis and glycogenolysis in the liver, as reflected in the increased G-6-Pase activity. The capacity for gluconeogenesis in both isolated hepatocytes (10) and perfused livers (48) was retained in vivo. Toward this end, we set the diet-induced increase in G-6-Pase were significantly different among diet groups. Thus intrahepatic adaptations to high-sucrose and high-fat diets can lead to increased reliance on gluconeogenesis in vivo.

The intrahepatic sites that appear to contribute to these diet-induced increases in gluconeogenesis include pyruvate carboxylase, phosphoenolpyruvate carboxykinase (PEPCK), and fructose-1,6-bisphosphatase (10, 59). Our previous data suggested that the increased capacity for flux through pyruvate carboxylase and PEPCK was, in part, the result of increased intrahepatic lipid oxidation (10). The terminal enzyme of both gluconeogenesis and glycogenolysis in the liver, G-6-Pase, appears to respond to changes in nutrient composition/delivery (4, 11, 35–38). However, previous studies were all performed in the absence of insulin (in vitro) or in the presence of basal insulin concentrations (in vivo). The repressive effects of insulin on G-6-Pase transcription and mRNA have been shown to be dominant over the stimulatory affects of cAMP and dexamethasone and high-fat diets compared with the high-starch diet. Thus diets enriched in sucrose or fat increase both the capacity for gluconeogenesis in vitro and the contribution of gluconeogenesis to glucose production in vivo. Importantly, in vivo changes in gluconeogenesis occurred under conditions in which circulating substrate and hormone concentrations were not significantly different among groups. Thus intrahepatic adaptations to high-sucrose and high-fat diets can lead to increased reliance on gluconeogenesis in vivo.

Table 4. Basal and euglycemic hyperinsulinemic clamp results

<table>
<thead>
<tr>
<th></th>
<th>STD (n = 5)</th>
<th>HSD (n = 6)</th>
<th>HFD (n = 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal conditions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma glucose, mM</td>
<td>6.3 ± 0.5</td>
<td>6.5 ± 0.4</td>
<td>6.5 ± 0.5</td>
</tr>
<tr>
<td>Plasma insulin, µU/ml</td>
<td>35 ± 6</td>
<td>39 ± 5</td>
<td>41 ± 6</td>
</tr>
<tr>
<td>Plasma NEFA, mM</td>
<td>0.6 ± 0.1</td>
<td>0.6 ± 0.1</td>
<td>0.7 ± 0.1</td>
</tr>
<tr>
<td>Glucose appearance, mg·kg⁻¹·min⁻¹</td>
<td>12.8 ± 1.2</td>
<td>12.5 ± 1.0</td>
<td>12.9 ± 0.9</td>
</tr>
<tr>
<td>Hyperinsulinemic, euglycemic conditions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma glucose, mM</td>
<td>6.5 ± 0.6</td>
<td>6.4 ± 0.4</td>
<td>6.6 ± 0.5</td>
</tr>
<tr>
<td>Plasma insulin, µU/ml</td>
<td>146 ± 11</td>
<td>155 ± 15</td>
<td>143 ± 12</td>
</tr>
<tr>
<td>Plasma NEFA, mM</td>
<td>0.51 ± 0.04</td>
<td>0.29 ± 0.04</td>
<td>0.26 ± 0.03</td>
</tr>
<tr>
<td>Glucose infusion rate, mg·kg⁻¹·min⁻¹</td>
<td>15.4 ± 1.2</td>
<td>10.4 ± 1.0*</td>
<td>9.4 ± 0.9*</td>
</tr>
<tr>
<td>Endogenous glucose appearance, mg·kg⁻¹·min⁻¹</td>
<td>4.1 ± 0.5</td>
<td>9.4 ± 0.7*</td>
<td>9.1 ± 0.8*</td>
</tr>
<tr>
<td>Total glucose disappearance, mg·kg⁻¹·min⁻¹</td>
<td>19.5 ± 1.3</td>
<td>19.8 ± 1.1</td>
<td>18.5 ± 1.1</td>
</tr>
</tbody>
</table>

Values are means ± SE. Basal conditions represent the average of 3 samples taken between 100 and 120 min. Hyperinsulinemic euglycemic conditions represent the average of 3 samples taken between 220 and 240 min. *Significantly different from STD.

Table 5. Tracer-estimated glucose metabolism in isolated hepatocytes

<table>
<thead>
<tr>
<th></th>
<th>STD</th>
<th>HSD</th>
<th>HFD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucose phosphorylation</td>
<td>1.3 ± 0.3</td>
<td>2.2 ± 0.2*</td>
<td>1.8 ± 0.3</td>
</tr>
<tr>
<td>Glucose, 20 mM + fructose, 0.5 mM</td>
<td>1.8 ± 0.2</td>
<td>2.2 ± 0.4</td>
<td>1.9 ± 0.4</td>
</tr>
<tr>
<td>Glucose cycling</td>
<td>-0.2 ± 0.3</td>
<td>0.9 ± 0.2*</td>
<td>0.6 ± 0.3</td>
</tr>
<tr>
<td>Glucose, 20 mM + fructose, 0.5 mM</td>
<td>-0.2 ± 0.2</td>
<td>0.7 ± 0.4</td>
<td>0.4 ± 0.5</td>
</tr>
</tbody>
</table>

Values are means ± SE in nmol·mg cell⁻¹·min⁻¹; n = 5/group. *Significantly different from STD.

Fig. 4. Glucose phosphorylation at low glucose (GLC) concentrations with or without fructose (FRU). Values are means ± SE; n = 3–4/diet group. *Significantly greater than 5.5 mM glucose alone.
In the present study, the consumption of diets enriched in sucrose or fat for ~1 wk increased the amount of the p36 catalytic subunit of G-6-Pase. Because the delivery of nutrients was accomplished by ingestion, their presentation to the liver occurred in the context of hyperinsulinemia. Thus, if the diet-induced increase in G-6-Pase catalytic subunit protein requires increased gene expression, it suggests that these dietary nutrients or specific aspects of their metabolism overcome the dominant effects of insulin, that the regulation of G-6-Pase by chronic nutrient delivery is distinct from that which occurs acutely, and/or that increased protein expression results from nutrient-induced adaptations in posttranscriptional events.

Although streptozotocin-induced diabetes has been shown to increase both the catalytic subunit and the glucose-6-phosphate translocase (32), the latter appears to be less responsive to hypoinsulinemia in vivo, hyperinsulinemia in H4IIE cells, and cAMP stimulation in both H4IIE cells and primary hepatocytes (25). In the present study, exposure to the sucrose-enriched diet increased protein levels for both the catalytic subunit and the glucose-6-phosphate translocase, whereas the high-fat diet increased the amount of the catalytic subunit protein only. Importantly, upregulation of the glucose-6-phosphate translocase after sucrose exposure did not result in increased microsomal G-6-Pase activity relative to the high-fat diet group. These data suggest that compensatory upregulation of the translocase, to match changes in the catalytic subunit, is not required to achieve adequate delivery of glucose 6-phosphate to the catalytic subunit in intact microsomes.

G-6-Pase catalytic subunit mRNA, protein, and activity are subject to regulation by hormones and nutrients (4, 25, 35–38, 63, 67). In particular, incubation of liver microsomes with polyunsaturated fatty acyl-CoA esters decreased G-6-Pase activity, whereas G-6-Pase activity was increased when microsomes were incubated with saturated fatty acyl-CoA esters (41, 42). In the present study, continuous provision of a high-polyunsaturated fatty acid diet for ~1 wk increased the amount of the catalytic subunit and the activity of G-6-Pase in both intact and disrupted microsomes. Two previous studies have reported that high-polyunsaturated fatty acid diets provided for periods up to or exceeding 3 wk resulted in decreased microsomal G-6-Pase activity (22, 40). The reasons for this discrepancy are not obvious but may include the duration of dietary treatment, differences in overall nutrient composition of the diets, and the type of polyunsaturated fatty acid used. We have previously demonstrated that high-sucrose diets increase the saturated fatty acid content of plasma and microsomal membranes in the liver (52). Thus it is possible that the sucrose diet-mediated induction of the catalytic and/or translocase subunits involves changes to the membrane lipid environment required to achieve adequate delivery of glucose 6-phosphate to the catalytic subunit in intact microsomes.

Table 6. Glucokinase activity in digitonin eluates

<table>
<thead>
<tr>
<th>Treatment</th>
<th>STD</th>
<th>HSD</th>
<th>HFD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low glucose, 5 mM</td>
<td>9 ± 2</td>
<td>32 ± 4*</td>
<td>4 ± 1</td>
</tr>
<tr>
<td>High glucose, 20 mM</td>
<td>87 ± 9</td>
<td>146 ± 6*</td>
<td>83 ± 10</td>
</tr>
<tr>
<td>Fructose, 0.5 mM</td>
<td>52 ± 4</td>
<td>59 ± 2</td>
<td>47 ± 5</td>
</tr>
<tr>
<td>Low glucose, 5 mM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ fructose, 0.5 mM</td>
<td>95 ± 9</td>
<td>90 ± 10†</td>
<td>83 ± 5</td>
</tr>
<tr>
<td>High glucose, 20 mM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ fructose, 0.5 mM</td>
<td>136 ± 8</td>
<td>144 ± 4‡</td>
<td>114 ± 5</td>
</tr>
</tbody>
</table>

Values are means ± SE in nmol/mg protein·min⁻¹; n = 5-6/group. *Significantly different from STD and HFD; †increment from low glucose significantly different from STD; ‡increment from high glucose significantly different from STD.
between G-6-Pase and glucokinase activities. Thus diets appear to increase the amount of p85 associated with insulin receptor substrate (IRS)-1 in the basal state 

The overexpression of G-6-Pase produces glucose intolerance but not fasting hyperglycemia (65). The explanation for such an observation may involve the low control strength exerted by G-6-Pase on glucose production (2). In the present study, the high-sucrose and high-fat diets not only increased G-6-Pase but also gluconeogenesis, yet normal rates of basal glucose production and concentrations of glucose and insulin were maintained. The maintenance of normal rates of glucose production in these dietary models likely results from appropriate adjustments in glycogenolysis. However, it is interesting that basal phosphatidylinositol (PI) 3-kinase activity in the liver was increased after exposure to the high-sucrose diet (47), whereas high-fat diets appear to increase the amount of p85 associated with insulin receptor substrate (IRS)-1 in the basal state (3).

The net release of glucose represents the balance between G-6-Pase and glucokinase activities. Thus diet-induced adaptations in glucokinase might serve to offset upregulation of G-6-Pase. The regulation of glucokinase is complex, involving a regulatory protein and translocation from the nucleus to the cytoplasm in response to various stimuli (1, 43, 66). The digitonin release assay measures the distribution of glucokinase between free and bound states (1). The latter most likely represents glucokinase bound to GKR (43). Recent work comparing this assay with glucokinase translocation determined by immunofluorescence demonstrated comparable results (43). In the present study, glucokinase activity in digitonin eluates was increased in hepatocytes isolated from sucrose-fed rats at both low (5 mM) and high (20 mM) glucose concentrations. In addition, glucose phosphorylation and glucose cycling were significantly increased in hepatocytes from sucrose-fed rats. These data support the notion that translocation of glucokinase out of the cell nucleus was promoted and/or import back into the nucleus was restricted in hepatocytes isolated from rats fed the high-sucrose diet. The result of this sucrose-induced adaptation is increased glucose phosphorylation and cycling. The lack of effect of the high-fat diet on glucokinase and glucose phosphorylation may relate to the low potential activity of fructose to regulate this protein (66, 68). In a recent study, the infusion of small amounts of fructose corrected the regulation of glucose production by hyperglycemia in type 2 diabetic subjects, suggesting that impaired regulation of glucokinase may contribute to the dysregulation of glucose production in this disease (23).

Glucokinase activity in digitonin-treated eluates was increased in high-sucrose diet-fed rats in the absence of insulin. Addition of insulin resulted in glucokinase activities in digitonin-treated eluates that were not significantly different from the high-starch diet-fed rats. Thus it is possible that glucokinase translocation approached a maximum in the high-sucrose diet group in the absence of insulin. Alternatively, the adaptation leading to increased glucokinase translocation in high-sucrose diet-fed rats may involve steps that are also used by insulin. However, the first possibility does not explain the lack of insulin stimulation of glucokinase translocation at low glucose concentrations, where adequate room should be available to expand glucokinase activity in digitonin-treated eluates. The second possibility requires further study.

The ability of insulin to suppress glucose production in vivo and stimulate glucokinase translocation in vitro was reduced in both high-sucrose and high-fat diets. It appears that sucrose-induced hepatic insulin resistance involves impairments in insulin-stimulated tyrosine phosphorylation of IRS proteins and activation of PI 3-kinase, whereas impairments downstream of PI 3-kinase characterize high-fat diet-induced hepatic insulin resistance (3, 47). It is worth noting that both of these diets produced hepatic insulin resistance without affecting insulin-stimulated glucose disappearance or suppression of NEFA levels. In fact, the development of peripheral insulin resistance requires ~2–3 wk of diet exposure and is accompanied by fasting hyperinsulinemia (28, 49).

The present study examined the effects of diets enriched with sucrose or fat on in vivo gluconeogenesis, glucose-6-phosphatase, and glucokinase translocation. The data demonstrate that relatively short-term chronic exposure to these diets increased in vivo gluconeogenesis, the expression of the catalytic subunit of G-6-Pase, and G-6-Pase activity in both intact and disrupted microsomes. Diets enriched with sucrose also increased the expression of the p46 glucose-6-phosphate translocase. However, this additional adaptation did not result in a further increase in microsomal G-6-Pase activity. Sucrose exposure also led to increased cytosolic availability of glucokinase and an increased capacity for glucose phosphorylation. These latter adaptations may serve to compensate for upregulation of G-6-Pase after sucrose exposure.

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REFERENCES


