Decreased visceral adiposity accounts for leptin effect on hepatic but not peripheral insulin action

Barzilai, Nir, Li She, Lisen Liu, Jiali Wang, Meizu Hu, Patricia Vuguiin, and Luciano Rossetti. Decreased visceral adiposity accounts for leptin effect on hepatic but not peripheral insulin action. Am. J. Physiol. 277 (Endocrinol. Metab. 40): E291–E298, 1999.—Leptin decreases visceral fat (VF) and increases peripheral and hepatic insulin action. Here, we generated similar decreases in VF using leptin (Lep), β3-adrenoreceptor agonism (β3), or food restriction (FR) and asked whether insulin action would be equally improved. For 8 days before the in vivo study, Sprague-Dawley rats (n = 24) were either fed ad libitum [control (Con)], treated with Lep or β3 (CL-316,243) by implanted osmotic mini-pumps, or treated with FR. Total VF was similarly decreased in the latter three groups (Lep, 3.11 ± 0.96 g; β3, 2.87 ± 0.48 g; and FR, 3.54 ± 0.77 g compared with 6.91 ± 1.41 g in Con; P < 0.001) independent of total fat mass (by 17 kcal/day). Decreased VF resulted in similar and independent metabolic effects of leptin on energy expenditure, substrate partitioning, insulin action, and storage of body fat have also emerged.

In fact, whereas chronic administration of leptin improves insulin action in animal models (7, 19, 34), recent studies have also shown acute modulation of insulin action by leptin in vivo (22, 39, 43) and in vitro (11). Thus insulin action may be improved before and independently of the leptin-induced decrease in VF.

To delineate the contribution of the leptin-induced changes in VF to the potent effects of leptin on in vivo insulin action, in the current study we generated similar decreases in VF by alternative means and compared their impact on hepatic and peripheral insulin action. We utilized the β3-adrenoreceptor agonist CL-316,243, which caused decreased VF (by 60%) with no changes in food intake and modest decline in total fat mass (~10%) (20), and caloric restriction designed to achieve a similar decrease in VF.

We hypothesize that if decreased VF is solely responsible for the leptin-induced improvement in insulin action, the latter will be independent of the modality by which VF is decreased. Alternatively, leptin may play a direct role in the modulation of peripheral or hepatic insulin action.

Materials and Methods

Experimental animals. Four groups of male Sprague-Dawley rats (Charles River Laboratories, Wilmington, MA) received the following treatment by osmotic minipumps for 8 days: 1) Con (n = 6), saline; 2) Lep (n = 6), recombinant mouse leptin at the rate of ~0.5 mg·kg⁻¹·day⁻¹ (Amgen, Thousand Oaks, CA; 95% pure by SDS-PAGE); 3) β3 (n = 6), a β3-adrenoreceptor agonist, at the rate of ~0.1 mg·kg⁻¹·day⁻¹ (CL-316,243 provided by Wyeth-Ayerst Research); and 4) FR (n = 6), saline and food restriction at the physiological level of 17 kcal/day. Data obtained from four of the six Lep rats were included in a previous publication (7) and are reported here solely to facilitate comparison with β3 and FR. These rats were selected on the basis of their VF to

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match that obtained with the alternative interventions. Food intake and body weights were measured every 24 h during the 8-day infusion period. Rats were housed in individual cages and subjected to a standard light (6 AM to 6 PM)-dark (6 PM to 6 AM) cycle. Eight days before the in vivo study, rats were anesthetized with an intraperitoneal injection of pentobarbital sodium (50 mg/kg body wt), the osmotic minipumps were placed in the subcutaneous interscapular area, and indwelling catheters were inserted in the right internal jugular vein and in the left carotid artery (4, 5, 7, 38). The venous catheter was extended to the level of the right atrium, and the arterial catheter was advanced to the level of the aortic arch.

Body composition. Body composition was assessed as in Refs. 3, 5, and 7. Briefly, rats received an intra-arterial bolus injection of 20 µCi of tritiated-labeled water ([3H]O; New England Nuclear, Boston, MA), and plasma samples were obtained at 30-min intervals for 3 h. Steady-state conditions for plasma [3H]O specific activity were achieved within 45 min in all studies. Five plasma samples obtained between 1 and 3 h were used in the calculation of the whole body distribution space of water. Vf (i.e., epididymal, perinephric, and mesenteric fat depots) was dissected and weighed at the end of each experiment.

Measurements of in vivo glucose kinetics. Measurements were performed as in Refs. 7 and 39. Briefly, a primed-continuous infusion of HPLC-purified [3-3H]glucose (New England Nuclear; 40 µCi bolus, 0.4 µCi/min) was administered for the duration of the study. Two hours after the basal period, a primed-continuous infusion of somatostatin (1.5 µg·kg⁻¹·min⁻¹) and regular insulin (3 mU·kg⁻¹·min⁻¹) were administered, and a variable infusion of a 25% glucose solution was started at time 0 and periodically adjusted to clamp the plasma glucose concentration at ~7.5 mM for the rest of the studies. Samples for determination of [3H]glucose specific activity were obtained every 10 min, and plasma samples for determination of plasma insulin, glycerol, and free fatty acid (FFA) concentrations were obtained every 30 min during the study. At the end of the infusions, rats were anesthetized (pentobarbital, 60 mg/kg iv), the abdomen was quickly opened, portal vein blood was obtained, and muscle and liver were freeze-clamped in situ with aluminum tongs preceded in liquid nitrogen.

Rates of glycolysis and glycogen synthesis were estimated as in Refs. 37 and 39. Rates of hepatic glucose fluxes were determined as in Refs. 36, 37, and 39. Gene expression of phosphoenolpyruvate carboxykinase (PEPCK) and glucose-6-phosphatase (G-6-Pase) by RT-PCR were determined as in Refs. 7, 36, and 38. Gene expression of β3-adrenoceptor agonist (Mese) fat pads obtained after the study from control rats (Con) and from rats treated for 8 days with leptin (Lep), β3-adrenoceptor agonist (Mese), or caloric restriction (FR). *P < 0.01 vs. all other groups.

### RESULTS

Caloric intake, body weight, and fat distribution. Because our design required matching VF by various experimental means, rats had to be preselected for assignment to each study group according to their body weights. Marked decreases in body weight were anticipated after 8 days of Lep and FR; thus rats were weighed before initiation of treatment. Con and β3 rats weighed 303 ± 19 and 288 ± 18 g, whereas Lep and FR rats weighed 351 ± 3 and 338 ± 6 g. As expected, administration of exogenous leptin decreased food intake by ~50%, and administration of CL-316,243 (β3) resulted in similar food intake as Con (Table 1). Because we had previously shown that pair-feeding to Lep was not sufficient to reproduce the effect of Lep on total abdominal fat (7), in this study FR rats received approximately one-half the caloric consumption of Lep. After these protocols, similar body weight and lean body mass (LBM) were achieved in all groups (Table 1, Fig. 1A), and epididymal, perinephric, and mesenteric fat depots were similarly decreased by all interventions (Table 1, Fig. 1C). Thus the remaining differences in body composition among the groups were due to variations in the amount of total fat mass (Fig. 1B). However, the latter was significantly lower in Lep (34 ± 8 g), β3 (28 ± 9 g), and FR (17 ± 8 g) compared with Con (54 ± 4 g).

Decreasing VF per se markedly enhances hepatic insulin sensitivity. Plasma leptin levels were markedly increased in Lep (39 ± 8 ng/ml) compared with β3, FR, and Con (2 ± 1, 3 ± 1, and 4 ± 1 ng/ml, respectively). During the insulin clamp studies, the plasma glucagon (116 ± 11, 96 ± 18, 125 ± 12, and 102 ± 9 pg/ml) and corticosterone (154 ± 22, 126 ± 28, 168 ± 21, and 186 ± 25 nmol/l in Con, Lep, β3, and FR, respectively) concentrations were similar in all groups. Table 2 displays the basal biochemical parameters in all experimental groups. Postabsorptive (6 h of fasting) plasma glucose concentrations were similar in all groups. However, plasma insulin levels were markedly decreased by interventions and were significantly lower in Lep compared with all other groups. Basal plasma FFA and glycerol levels were similar at basal in all groups. At basal, glucose production (GP, Fig. 2A) was similar in all groups (11.2 ± 0.9, 12.2 ± 1.0, 11.5 ± 0.9, and 12.4 ± 1.3 mg·kg⁻¹·min⁻¹ in Con, Lep, β3, and FR, respectively). During the insulin clamp, plasma insulin levels were higher in Con (0.39 ± 0.09 μU/ml) than in Lep (0.21 ± 0.06 μU/ml, 0.18 ± 0.06 μU/ml, and 0.16 ± 0.06 μU/ml in Lep, β3, and FR, respectively). During the insulin clamp, plasma insulin levels were higher in Con (0.39 ± 0.09 μU/ml) than in Lep (0.21 ± 0.06 μU/ml, 0.18 ± 0.06 μU/ml, and 0.16 ± 0.06 μU/ml in Lep, β3, and FR, respectively).

### Table 1. Caloric intake and body composition

<table>
<thead>
<tr>
<th></th>
<th>Con (n = 6)</th>
<th>Lep (n = 6)</th>
<th>β3 (n = 6)</th>
<th>FR (n = 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calories, kcal/day</td>
<td>69 ± 4</td>
<td>29 ± 3*</td>
<td>61 ± 4</td>
<td>17 ± 0*</td>
</tr>
<tr>
<td>Body wt, g</td>
<td>322 ± 15</td>
<td>315 ± 0*</td>
<td>290 ± 13</td>
<td>291 ± 16</td>
</tr>
<tr>
<td>Epi, g</td>
<td>3.50 ± 0.54*</td>
<td>1.98 ± 0.18</td>
<td>1.90 ± 0.21</td>
<td>1.94 ± 0.23</td>
</tr>
<tr>
<td>Peri, g</td>
<td>1.22 ± 0.27*</td>
<td>0.49 ± 0.07</td>
<td>0.59 ± 0.06</td>
<td>0.69 ± 0.16</td>
</tr>
<tr>
<td>Mese, g</td>
<td>2.12 ± 0.39*</td>
<td>0.74 ± 0.23</td>
<td>0.66 ± 0.09</td>
<td>0.71 ± 0.09</td>
</tr>
</tbody>
</table>

Values are means ± SE. Caloric intake, body weight (BW), epididymal (Epi), perinephric (Peri), and mesenteric (Mese) fat pads obtained after the study from control rats (Con) and from rats treated for 8 days with leptin (Lep), β3-adrenoceptor agonist (β3), or caloric restriction (FR). *P < 0.01 vs. all other groups.
METHODS. Total VF was similar for all intervention groups vs. Con.

Effect of decreasing VF with Lep, β3, or FR on gluconeogenesis and glycogenolysis. The direct contribution of plasma glucose to the hepatic glucose 6-phosphate (G-6-P) pool was calculated from the specific activities of UDP-glucose and plasma glucose (Table 3), and it was similar in all groups. Thus decreased VF resulted in similar decreases (to <30% of Con) in the rates of GP, flux through G-6-Pase or total glucose output (TGO), and glucose cycling (GC) in response to physiological hyperinsulinemia. Lep and FR increased the percentage of hepatic G-6-P pool that is derived from PEP-gluconeogenesis (GN), but the rate of GN was similar in all intervention groups (Table 4). In a net sense, the major contribution to the decreased GP in all intervention groups was due to a marked decrease in glycogenolysis (to <20% of Con).

DISCUSSION

In this study we attempted to delineate whether the potent effects of leptin on in vivo insulin action are secondary to the associated changes in body composition. Decreasing VF led to a striking improvement in hepatic insulin sensitivity that was independent of increased to similar levels, and plasma FFA and glycerol levels decreased similarly in all groups (Table 2). Although GP (Fig. 2B) was decreased from basal in all groups, it was about threefold lower (and similar) in all intervention groups (6.1 ± 0.7, 1.2 ± 0.5, 1.5 ± 0.7, and 2.3 ± 0.7 mg·kg⁻¹·min⁻¹ in Con, Lep, β3, and FR, respectively).

Table 2. Metabolic characteristics

<table>
<thead>
<tr>
<th></th>
<th>Con (n = 6)</th>
<th>Lep (n = 6)</th>
<th>β3 (n = 6)</th>
<th>FR (n = 6)</th>
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<tbody>
<tr>
<td>Glucose, mM</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Basal</td>
<td>7.4 ± 0.3</td>
<td>7.3 ± 0.2</td>
<td>7.6 ± 0.2</td>
<td>7.1 ± 0.3</td>
</tr>
<tr>
<td>Clamp</td>
<td>7.5 ± 0.3</td>
<td>7.2 ± 0.2</td>
<td>7.3 ± 0.3</td>
<td>7.2 ± 0.3</td>
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<tr>
<td>Insulin, pM</td>
<td></td>
<td></td>
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<tr>
<td>Basal</td>
<td>150 ± 9†</td>
<td>66 ± 7†</td>
<td>98 ± 8</td>
<td>91 ± 8</td>
</tr>
<tr>
<td>Clamp</td>
<td>370 ± 23*</td>
<td>347 ± 27*</td>
<td>326 ± 24*</td>
<td>354 ± 28*</td>
</tr>
<tr>
<td>FFA, mM</td>
<td></td>
<td></td>
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<tr>
<td>Basal</td>
<td>1.10 ± 0.18</td>
<td>0.93 ± 0.08</td>
<td>1.07 ± 0.23</td>
<td>1.13 ± 0.14</td>
</tr>
<tr>
<td>Clamp</td>
<td>0.43 ± 0.12*</td>
<td>0.32 ± 0.06*</td>
<td>0.54 ± 0.18*</td>
<td>0.37 ± 0.10*</td>
</tr>
<tr>
<td>Glycerol, µM</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Basal</td>
<td>129 ± 11</td>
<td>105 ± 13</td>
<td>119 ± 14</td>
<td>111 ± 12</td>
</tr>
<tr>
<td>Clamp</td>
<td>44 ± 5*</td>
<td>35 ± 6*</td>
<td>50 ± 14*</td>
<td>47 ± 12*</td>
</tr>
</tbody>
</table>

Values are means ± SE. Plasma glucose, insulin, free fatty acids (FFA), and glycerol levels at basal and during insulin somatostatin clamp from control and treated rats. *P < 0.01 vs. basal; †P < 0.01 vs. all other groups.
The latter finding indicates that, at least within the time frame of the present study, the effects of leptin on peripheral insulin action are not likely to be solely mediated via decreased VF and/or activation of the β3-adrenoreceptor system. Furthermore, rapid changes in VF modulate hepatic much more than peripheral insulin action.

"Manipulating" body composition. It is well established that weight loss is commonly associated with decreased plasma insulin concentrations and increased insulin sensitivity (8, 13, 15, 16, 27). Early studies in obese mice reported marked improvements in glucose tolerance after leptin treatment (19, 34). However, whereas some reports suggested that the improvement in glucose tolerance may precede the decline in body weight and total fat mass (34, 41), it has been difficult to discern the relative contribution of the associated changes in body composition to the improved glucose tolerance observed with leptin treatment (19, 34). Furthermore, although pair-feeding vehicle-treated rats to the level of leptin-treated rats resulted in similar decreases in body weight and FM, leptin caused a selective and marked decrease in visceral adiposity (7). The latter observation further complicates the interpretation of potential effects of leptin treatment on in vivo insulin action.

Administration of β3-adrenoreceptor agonists causes marked decreases in circulating leptin concentrations (18, 28, 30); however, consistent with previous reports (20), in the present study food intake was not decreased compared with Con (Table 1). Despite similar caloric total fat mass (FM) and of the modalities used to achieve the "target" VF. This observation provides support for a cause-effect relationship between intra-abdominal deposition of fat and hepatic insulin resistance. Conversely, the marked stimulation of insulin-mediated glucose uptake, glycolysis, and glycogen synthesis induced by leptin treatment could not be reproduced by decreasing VF by alternative means. The latter finding indicates that, at least within the time frame of the present study, the effects of leptin on

![Table 3. Hepatic glucose fluxes during insulin clamp](Image)

<table>
<thead>
<tr>
<th></th>
<th>Con</th>
<th>Lep</th>
<th>β3</th>
<th>FR</th>
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<tbody>
<tr>
<td>[3H]glucose, dpm/nmol</td>
<td>41.7 ± 3.4</td>
<td>21.4 ± 2.2</td>
<td>37.1 ± 6.3</td>
<td>37.1 ± 2.4</td>
</tr>
<tr>
<td>[3H]UDP-Glucose, dpm/nmol</td>
<td>12.8 ± 2.3</td>
<td>7.8 ± 0.9</td>
<td>10.1 ± 1.8</td>
<td>12.3 ± 1.0</td>
</tr>
<tr>
<td>Direct, %</td>
<td>34 ± 6</td>
<td>38 ± 3</td>
<td>27 ± 4</td>
<td>33 ± 3</td>
</tr>
<tr>
<td>TGO, mg·kg⁻¹·min⁻¹</td>
<td>9.1 ± 0.4*</td>
<td>1.7 ± 0.5</td>
<td>2.4 ± 0.6</td>
<td>2.9 ± 1.0</td>
</tr>
<tr>
<td>GC, mg·kg⁻³·min⁻¹</td>
<td>3.1 ± 0.3*</td>
<td>0.7 ± 0.3</td>
<td>0.7 ± 0.4</td>
<td>1.0 ± 0.5</td>
</tr>
</tbody>
</table>

Values are means ± SE of 6 rats/group. After [3-3H]glucose infusion, ratio of specific activities of hepatic [3H]UDP-glucose and plasma [3H]glucose represents the % of hepatic glucose 6-phosphate (G-6-P) pool derived from plasma glucose (Direct). Total glucose output (TGO) is total in vivo flux through G-6-phosphatase (G-6-Pase). Glucose cycling (GC) is input of extracellular glucose into G-6-P pool followed by exit of plasma-derived G-6-P back into extracellular pool. *P < 0.01 vs. all others.

![Table 4. Hepatic glucose fluxes during insulin clamp](Image)

<table>
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<th>Con</th>
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<th>FR</th>
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<tbody>
<tr>
<td>[14C]UDP-glucose, dpm/nmol</td>
<td>12.0 ± 1.1</td>
<td>16.8 ± 2.8</td>
<td>10.1 ± 2.3</td>
<td>20.8 ± 5.0</td>
</tr>
<tr>
<td>[14C]PEP, dpm/nmol</td>
<td>25.8 ± 3.0</td>
<td>12.2 ± 3.2</td>
<td>15.4 ± 3.3</td>
<td>18.3 ± 1.4</td>
</tr>
<tr>
<td>Indirect, %</td>
<td>24 ± 3*</td>
<td>65 ± 8</td>
<td>34 ± 5*</td>
<td>56 ± 6</td>
</tr>
<tr>
<td>GN, mg·kg⁻¹·min⁻¹</td>
<td>2.2 ± 0.2*</td>
<td>1.1 ± 0.2</td>
<td>0.8 ± 0.3</td>
<td>1.6 ± 0.4</td>
</tr>
<tr>
<td>GlycoCO, mg·kg⁻¹·min⁻¹</td>
<td>3.9 ± 0.4*</td>
<td>0.1 ± 0.1*</td>
<td>0.9 ± 0.3</td>
<td>0.4 ± 0.3</td>
</tr>
</tbody>
</table>

Values are means ± SE. After [14C]lactate infusion, ratio of specific activities of hepatic [14C]UDP-glucose and [14C]PEP × 2 represents % of hepatic G-6-P pool derived from PEP-glucose (Indirect). Glucoseogenesis (GN) is calculated from indirect portion × TGO; glycogenolysis (GLYCO) is derived from GN subtracted from hepatic glucose production (HGP). *P < 0.01 vs. all others.
intake, β3 rats gained less weight and their FM was significantly lower than Con rats. This may be due to increased energy expenditure and thermogenesis in this group (20).

To generate similar VF with FR it was necessary to further decrease the caloric intake by ~50%; this intervention resulted in much lower FM than in the other groups. This finding is a dramatic confirmation of the selective effects of Lep and β3 on intra-abdominal adiposity. This model is also different from the administration of leptin and β3-adrenoreceptor agonists, because energy expenditure is expected to be markedly decreased. Thus similar declines and final mass of VF were obtained in the three intervention groups despite differences in food consumption, weight gain, energy expenditure, food intake, and whole body adiposity.

VF and hepatic insulin sensitivity. All interventions that decreased VF resulted in similar fasting plasma glucose levels despite lower plasma insulin levels compared with Con rats, suggesting an improvement in postabsorptive hepatic insulin sensitivity. To directly test whether hepatic insulin sensitivity was improved by decreasing VF, we performed low-dose insulin clamp studies in combination with somatostatin infusions. The plasma glucose, FFA, glycerol, and insulin concentrations during the insulin clamp studies were similar in all groups (Table 2). This procedure also erased the portal-venous insulin gradient, matching peripheral and hepatic insulin levels in all groups. Decreasing VF resulted in a marked decrease in GP during the insulin infusion, indicating heightened hepatic insulin sensitivity (Fig. 2B). This improvement in insulin action was independent of the modalities by which decreased VF was achieved, and it is consistent with other animal models, such as the calorie-restricted "old" rats (2) and rats with surgical removal of VF (6). Although the mechanism(s) whereby VF regulates insulin sensitivity remain to be delineated, it is evident that the impacts of changes in VF on hepatic glucose fluxes are remarkable. It has been suggested that the unique metabolic characteristics of the intra-abdominal fat depots that concern the turnover of glycerol, FFA, and lactate play a role through a "portal effect" (9), i.e., the hepatic load of FFA, lactate, and glycerol can modulate liver glucose metabolism (31, 35). However, it should be noted that, in this experimental model, the peripheral concentrations of these substrates were unchanged during the basal and insulin clamp periods. Although potential effects of long-term differences in plasma FFA, lactate, or glycerol levels on hepatic enzymes cannot be excluded, alternative hypotheses should also be considered for the "cross-talk" between intra-abdominal fat depots and the liver. For example, a fat-derived and secreted peptide, tumor necrosis factor-α (TNF-α), causes peripheral and hepatic insulin resistance via its antagonism of early insulin signaling (14, 21).

Consistent with the lower GP, the rates of TGO and GC were also markedly decreased in parallel with the changes in VF. This suggests a marked decrease in the in vivo flux through G-6-Pase. In a net sense, the decreased GP in the intervention groups was mainly the result of a marked suppression of hepatic glycogenolysis, which was most pronounced in the group treated with leptin (Table 2). Overall, whereas hepatic insulin sensitivity improved similarly with all interventions designed to decrease VF, there were some changes in the intrahepatic distribution of hepatic glucose flux and in the gene expression of key hepatic enzymes that appear to be treatment specific. For example, the percent contribution of GN to TGO was increased by Lep → FR → β3 (Fig. 2C). This is supported by the increased expression of hepatic PEPCK in Lep and FR. Although leptin has similar effects on PEPCK mRNA when administered acutely via a peripheral vein (39) or in a cerebral ventricle (29), it should be pointed out that the decline in plasma insulin concentrations might also contribute to the upregulation of this gene. By contrast, it is noteworthy that acute and chronic stimulation of the β3-adrenergic systems has frequently divergent effects. We have previously shown that the acute (6-h) administration of the same β3-adrenoreceptor agonist increased the gene expression of G-6-Pase and PEPCK, perhaps via activation of hypothalamic efferent pathway(s) (29). The waning of this effect after more prolonged exposure to the agonist may be due to either the associated marked decline in leptin levels and/or central or peripheral downregulation of the β3-adrenoreceptor system. This also suggests that the stimulation of the β3-adrenergic system is not likely to mediate
intervention groups. This improvement in peripheral insulin action was accounted for by about a twofold increase in the rate of glycogen synthesis and by an ~25% increase in the rate of whole body glycolysis. On the basis of epidemiological evidence correlating insulin resistance and hyperinsulinemia with intra-abdominal adiposity (9, 25), it has been suggested that decreasing VF should lead to a marked improvement in the action of insulin on peripheral glucose disposal. Indeed, modest increases in the rates of insulin-mediated glucose uptake and glycogen synthesis were detected when VF was markedly decreased using caloric restriction or β3-adrenergic agonism. However, this improvement could only account for a small fraction (up to 30%) of the effects of leptin on glucose uptake. Thus 8-day leptin administration exerts potent effects on peripheral insulin action, which are largely independent of the associated decrease in VF. Several mechanism(s) may be invoked to account for the enhanced muscle insulin sensitivity in rats treated with leptin. Leptin has been shown to increase skeletal muscle glucose uptake quite rapidly in some rodent studies (22, 43), and activation of early insulin signaling by leptin has been demonstrated in a muscle cell line (23) and in a preliminary report in rats (24). However, acute exposure of skeletal muscle and adipose cells to leptin, with and without insulin, failed to alter the glucose transport system in some studies (46). Thus leptin may augment muscle insulin signaling via a direct action on local receptors or via hypothalamic efferent pathways. An additional explanation may be found in the "lipopenic" effects of leptin (32) and in the close correlation between intramyocellular lipid levels and insulin sensitivity (33). In fact, leptin enhances lipid oxidation and depletes triglyceride stores in preadipocytes, pancreatic β-cells, and muscle (1, 32, 45). The latter effects may be mediated in part via decreased gene expression of acetyl-CoA carboxylase.

Taken together with the hepatic actions of leptin, the above data suggest that a prolonged elevation in circulating leptin favors the storage of energy into glycogen rather than into lipid stores. The latter metabolic adaptation may represent a response to signals generated by leptin in the hypothalamic "lipostat" and/or the results of peripheral actions of the hormone.

In conclusion, decreasing intra-abdominal adiposity by ~60% via three different means results in a dramatic increase in hepatic insulin sensitivity. Conversely, the potent effect of leptin administration on peripheral insulin action cannot be solely explained on the basis of the associated decrease in VF mass. Understanding the biochemical mechanism(s) that are responsible for the specific action of leptin on skeletal muscle glucose disposal should help to clarify the link between nutrient excess, weight gain, and insulin resistance.

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REFERENCES


