Amylin improves the effect of leptin on insulin sensitivity in leptin-resistant diet-induced obese mice

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Evidence indicating that leptin can stimulate insulin sensitivity independently of food intake and body weight reduction via central mechanisms has accumulated (9, 14, 17, 27). Amylin also activates multiple central nervous system regions to regulate both energy and glucose homeostasis (19, 21, 22). Therefore, it is possible that leptin and amylin interact with each other in the regulation of glucose metabolism. However, whether amylin improves the effect of leptin on insulin sensitivity is unclear. Diet-induced obesity; diabetes; adenosine 5′-monophosphate-activated protein kinase (AMPK)

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sible clinical usefulness of leptin/amylin coadministration as a new antidiabetic treatment in obesity-associated diabetes.

MATERIALS AND METHODS

Experimental animals. Eight-week-old male C57BL/6J mice were purchased from Japan SLC, Shizuoka, Japan. The mice were caged individually and kept under a 12:12-h light-dark cycle (lights on at 0900). The mice were fed a high-fat diet (D12451, 45% of energy as fat; Research Diets, New Brunswick, NJ) for 5 wk, with free access to water (termed DIO mice), before experiments. Body weight of DIO mice before experiments was significantly heavier than that of control mice fed a standard diet (NMF, 13% of energy as fat; Oriental Yeast, Tokyo, Japan) (32.6 ± 0.5 vs. 26.9 ± 0.4 g; P < 0.01). Metabolic characteristics of control and DIO mice are summarized in Table 1. The result of an insulin tolerance test (ITT) showed that DIO mice were insulin resistant compared with control mice. Animal care and all experiments were conducted in accordance with the Guidelines for Animal Experiments of Kyoto University and were approved by the Animal Research Committee, Graduate School of Medicine, Kyoto University.

Leptin and/or amylin infusion experiments. DIO mice were divided into four treatment groups [saline (S), leptin (L), amylin (A), and leptin plus amylin (L/A)] to be counterbalanced for starting body weight and blood glucose level. On day 0, all mice were implanted subcutaneously in the midscapular region with two osmotic minipumps (Alzet model 2002; Alza, Palo Alto, CA) containing either saline, leptin (500 μg·kg−1·day−1); Amgen, Thousand Oaks, CA), or amylin (100 μg·kg−1·day−1; Bachem, Torrance, CA). High-fat diet feeding was continued during the experiment.

Body weight and food intake. Body weight was measured on days 0, 5, and 10. Daily food intake was measured before and during the leptin and/or amylin infusion experiment.

Indirect calorimetry. Measurement of oxygen consumption (V O2) and carbon dioxide production (VCO2) was performed over a period of 48 h, after ≥72 h of acclimation, using an Oxymax indirect calorimeter (Columbus Instruments, Columbus, OH) on days 4 and 5 (n = 4/group) for S, L, A, and L/A-treated mice. Respiratory exchange ratio (ratio of CO2 production to O2 [VCO2/VO2]), which indicates the relative contribution of fat and carbohydrate oxidation to overall metabolism, was calculated and averaged across the 48-h measurement session.

Metabolic variables. Blood was obtained from nonfasted mice between 1500 and 1700 at the end of the experiment. Blood glucose levels were measured by the glucose oxidase method using a reflectance glucometer (MS-GR102; Terumo, Tokyo, Japan). Plasma insulin levels were measured by enzyme immunoassay using an Insulin-EIA kit (Morinaga, Tokyo, Japan). Plasma glucagon levels were measured by enzyme immunoassay with a Glucagon-EIA kit (Yanaihara, Shizuoka, Japan). Plasma leptin levels were measured by an ELISA kit for mouse leptin (Millipore, Billerica, MA). Plasma amylin levels were measured by enzyme immunoassay using a mouse Amylin-EIA kit (Phoenix Pharmaceuticals, Burlingame, CA).

ITT. An ITT was performed on day 10. For the ITT, after a 4-h fast, mice were injected with 0.8 μl/g ip human insulin (Humulin R; Eli Lilly Japan, Kobe, Japan). Blood was sampled from the tail vein before and 30, 60, and 120 min after the insulin injection. Blood glucose levels were determined as described above. The area under the curve (AUC) during the ITT was calculated in each mouse.

Liver weight and tissue triglyceride content. Liver weight was measured at the end of the experiment. Liver and skeletal muscle triglyceride content were measured as described previously (18). Liver and gastrocnemius muscle were isolated at the end of the experiment and immediately frozen in liquid nitrogen, and lipids were extracted with isopropyl alcohol-heptane (1:1, vol/vol). After the solvent was evaporated, the lipids were resuspended in 99.5% (vol/vol) ethanol, and the triglyceride content was measured using the Triglyceride E-test Wako kit (Wako Pure Chemicals, Osaka, Japan).

Isoform-specific AMPK activity. AMPK activity was determined as described previously (18). Soleus muscles were isolated at the end of the experiment and immediately frozen in liquid nitrogen. To measure isoform-specific AMPKα1 and -α2 activity in soleus muscle, AMPK was immunoprecipitated from muscle lysates (200 μg of protein) with specific antibodies against the α1- and α2-subunits (Upstate Cell Signaling Solutions, Lake Placid, NY) bound to Protein A-Sepharose beads, and the kinase activity of the immunoprecipitates was measured using “SAMS” peptide and [γ-32P]ATP.

Pair-feeding and weight-matched calorie restriction experiments. Pair-feeding experiments were performed to assess the influence of food intake reduction. In this experiment, DIO mice (mean body weight 31.2 ± 0.4 g) were divided into three treatment groups [S, saline + pair-fed L/A-treated mice (PF), and L/A] to be counterbalanced for starting body weight and blood glucose level. Saline, leptin, and amylin were infused using two osmotic minipumps, as described above. Pair-fed mice were fed the same amount of food consumed by L/A-treated mice on the previous day at the end of light phase once for 14 days. Body weight was measured on days 0 and 10. Weight-matched calorie restriction experiments were performed to assess the influence of body weight reduction. In this experiment, the food consumption of DIO mice (mean body weight 31.7 ± 0.5 g) was restricted to match their body weight to those of L/A-treated mice (weight-matched DIO mice, termed CR mice). CR mice were fed ∼70% of the amount of food consumed by S-treated mice on the previous day at the end of light phase at once for 14 days. An ITT was performed on day 10 of these experiments. Liver and gastrocnemius muscle were obtained for triglyceride content measurements at the end of these experiments.

Statistical analyses. Data are expressed as means ± SE. Comparisons between or among groups was by Student’s t-test or ANOVA with Fisher’s protected least significant difference test. P < 0.05 was considered statistically significant.

RESULTS

Effect of leptin and/or amylin on food intake, body weight, and energy expenditure in DIO mice. Leptin and amylin were administered for 14 days in DIO mice, using osmotic minipumps. Plasma leptin and amylin levels at the end of the experiment were shown in Table 2. Administration of leptin (500 μg·g−1·day−1) was adequately effective in control mice fed a standard diet, as shown in our previous report (18), but it had no significant effect on food intake or body weight in DIO mice (Fig. 1, A and B), indicating that these DIO mice were in the leptin-resistant state. Administration of amylin (100 μg·g−1·day−1) had no effect on food intake or body weight in mice fed a standard diet (data not shown) or DIO mice (Fig. 1, A and B). However, L/A coadminis-

Table 1. Metabolic characteristics of control and DIO mice

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control (n = 6)</th>
<th>DIO (n = 9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood glucose, mg/dl</td>
<td>142.4 ± 5.4</td>
<td>160.4 ± 6.6</td>
</tr>
<tr>
<td>Plasma insulin, pg/ml</td>
<td>466.9 ± 99.1</td>
<td>535.0 ± 87.6</td>
</tr>
<tr>
<td>AUC in ITT, %/min × 100</td>
<td>77.3 ± 10.5</td>
<td>102.5 ± 5.5*</td>
</tr>
<tr>
<td>Liver TG content, mg/g tissue</td>
<td>9.8 ± 0.8</td>
<td>23.6 ± 2.4**</td>
</tr>
<tr>
<td>Skeletal muscle TG content, mg/g tissue</td>
<td>5.2 ± 0.7</td>
<td>5.6 ± 1.1</td>
</tr>
</tbody>
</table>

Values are means ± SE. DIO, diet-induced obese; AUC, area under the curve; ITT, insulin tolerance test; TG, triglyceride. Blood glucose, plasma insulin, liver TG content, and skeletal muscle TG content were measured in saline-treated control and DIO mice at the end of the experiment. Blood samples were obtained during ad libitum feeding. AUC in ITT was measured on day 10. *P < 0.05 and **P < 0.01 vs. control mice.
tration significantly reduced cumulative food intake for 10 days by 15.3% in DIO mice compared with saline administration (Fig. 1A). Body weight was decreased by 9.2% for 10 days of L/A coadministration (Fig. 1B).

To assess the effect of leptin and/or amylin on energy expenditure, indirect calorimetry was performed. L/A coadministration significantly increased \( \dot{V}O_2 \), a marker of energy expenditure, in both the light and dark phases (Fig. 1C). In addition, L/A coadministration significantly decreased respiratory exchange ratio in the dark phase, indicating increased utilization of fat as the fuel source (Fig. 1D).

**Effect of leptin and/or amylin on glucose metabolism in DIO mice.** On day 14, there was no difference in blood glucose levels under ad libitum feeding among groups (Fig. 2A). On the other hand, L/A coadministration decreased plasma insulin levels significantly, whereas administration of L or A alone did not change plasma insulin levels, compared with saline administration (282.8 ± 69.6 vs. 535.0 ± 87.6 pg/ml, \( P < 0.01 \)), indicating the improvement of insulin sensitivity in L/A-treated mice (Fig. 2B). Plasma glucagon levels of DIO mice were significantly higher than that of control mice (106.9 ± 26.0 vs. 45.0 ± 8.0 pg/ml, \( P < 0.01 \)). L/A coadministration tended to suppress plasma glucagon levels, but not significantly (Fig. 2C).

To evaluate insulin sensitivity, we performed ITTs. The ITT actually showed greater decrease in glucose levels after insulin injection in L/A-treated mice than in L- or A-treated mice (Fig. 2D). Consistent with these findings, the glucose AUC after insulin injection was decreased only in L/A-treated mice (Fig. 2E).

**Effect of leptin and/or amylin on liver weight, tissue triglyceride content, and AMPK activity in skeletal muscle in DIO mice.** Because fat accumulation in insulin target tissues is considered to be one of the reasons for insulin resistance (36, 41), we examined liver and gastrocnemius muscle triglyceride

### Table 2. Plasma leptin and amylin levels in mice administered leptin and/or amylin

<table>
<thead>
<tr>
<th>Variable, ng/ml</th>
<th>S</th>
<th>L</th>
<th>A</th>
<th>L/A</th>
</tr>
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<tbody>
<tr>
<td>L</td>
<td>28.5 ± 5.6</td>
<td>53.0 ± 5.3*</td>
<td>19.7 ± 4.8</td>
<td>45.1 ± 6.6†</td>
</tr>
<tr>
<td>A</td>
<td>1.7 ± 0.1</td>
<td>1.8 ± 0.2</td>
<td>2.7 ± 0.2**</td>
<td>2.9 ± 0.2**†</td>
</tr>
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</table>

Values are means ± SE for 8–9 mice in each group. S, saline; L, leptin; A, amylin; L/A, leptin + amylin. Plasma L and A levels were measured at the end of the experiment. Blood samples were obtained during ad libitum feeding. *\( P < 0.05 \) and **\( P < 0.01 \) vs. S-treated mice; †\( P < 0.05 \) vs. A-treated mice in L/A-treated mice.
Liver weight was significantly decreased (by 16%) in L/A-treated mice compared with that in S-treated mice (Fig. 3A). In addition, L/A coadministration significantly decreased triglyceride contents in liver (by 42%) and skeletal muscle (by 46%), whereas administration of L or A alone did not decrease tissue triglyceride contents compared with saline administration (Fig. 3, B and C).

Leptin has been shown to decrease skeletal muscle triglyceride content in part by increasing fatty acid β-oxidation through AMPKα2 activation in skeletal muscle (24). Therefore, we measured AMPK activity in soleus muscle, where the effect of leptin on AMPK activity was pronounced (24). AMPKα1 activity in soleus muscle was not changed significantly in any group of mice compared with S-treated mice (Fig. 3D). On the other hand, AMPKα2 activity in soleus muscle was increased significantly only in L/A-treated mice (by 71%) compared with those in S-treated mice (Fig. 3E), consistent with the results of tissue triglyceride contents.

Pair-feeding and weight-matched calorie restriction experiments. We performed pair-feeding experiments to assess whether the body weight reduction and the enhancement of insulin sensitivity by L/A coadministration was associated with food intake reduction. Pair-feeding to L/A-treated mice reduced body weight in DIO mice significantly, but the change was apparently smaller than in L/A-treated mice (Fig. 4A). In addition, PF mice showed neither the improvement in insulin sensitivity (Fig. 4, B and C) nor the decrease in triglyceride contents of liver and skeletal muscle (Fig. 4, D and E), in contrast to L/A-treated mice.

Then, we performed weight-matched calorie restriction experiments to assess whether the enhancement of insulin sensitivity by L/A coadministration was associated with body weight reduction. To match the body weight to L/A-treated mice, the food intake was restricted to 70% of S-treated mice in CR mice (Fig. 4A). In this condition, CR mice showed neither the improvement of insulin sensitivity (Fig. 4, B and C) nor the decrease in triglyceride contents of liver and skeletal muscle (Fig. 4, D and E), in contrast to L/A-treated mice.

**DISCUSSION**

Leptin could be an ideal drug for obesity-associated diabetes because it has both a weight-reducing effect and an antidiabetic effect. However, even high pharmacological doses of leptin elicit only marginal weight loss in non-leptin-deficient DIO rodents and humans (8, 15), whereas leptin replacement ther-
apy induces profound weight loss in leptin-deficient mice and humans (10, 13). The obese state is thus thought to be associated with leptin resistance, wherein overweight/obese individuals become insensitive to high circulating leptin levels. Sensitizing agents of leptin’s effects are expected to treat obesity-associated diabetes comprehensively. In this study, we demonstrated that L/A coadministration not only reduced food intake and body weight but also enhanced insulin sensitivity accompanied by an increase of AMPK activity in skeletal muscle and decrease of tissue triglyceride contents in leptin-resistant DIO mice. Our results indicate the possible clinical usefulness of L/A coadministration as a new antidiabetic treatment in obesity-associated diabetes.

Recently, coadministration of L (500 μg·kg⁻¹·day⁻¹) and A (100 μg·kg⁻¹·day⁻¹) was shown to result in a synergistic fat-specific body weight reduction in DIO rats (34). The synergistic antiosesity effect of leptin and amylin was established by the response surface methodology analysis using lower dose ranges of L (0–125 μg·kg⁻¹·day⁻¹) and A (0–50 μg·kg⁻¹·day⁻¹) in DIO rats (39). However, because the study of L/A coadministration was not fully examined in mice, the adequate doses of L and A were unclear in DIO mice. Therefore, we chose L (500 μg·kg⁻¹·day⁻¹) and A (100 μg·kg⁻¹·day⁻¹) in the present study according to the first report (34). Administration of L (500 μg·g⁻¹·day⁻¹) had no significant effect on food intake or body weight in DIO mice (Fig. 1, A and B). Although amylin itself has been shown to dose-dependently reduce food intake and body weight (20, 26), administration of A (100 μg·kg⁻¹·day⁻¹) was not effective in our DIO mice (Fig. 1, A and B). Under these conditions, L/A coadmindistration reduced food intake and body weight in DIO mice in a greater than mathematically additive manner (Fig. 1, A and B). Our data support that L/A coadministration is a useful treatment for obesity beyond species difference. With the dose of leptin used in the present study, the plasma leptin level in DIO mice increased to 45.1–53.0 ng/ml (Table 2), which can be seen in human obese subjects. In addition, higher leptin levels were obtained in the obese human clinical trial without any clinically significant adverse effects on major organ systems (15). Therefore, the leptin level achieved with the dose used in the present study could be clinically applied in humans.

In general, amylin is considered not to affect insulin secretion and insulin sensitivity but rather to complement the effects of insulin on circulating glucose levels through two main mechanisms (43). First, amylin suppresses postprandial glucagon secretion, thereby decreasing glucagon-stimulated hepatic glucose output following nutrient ingestion (12). Second, amylin also slows the rate of gastric emptying and thus the rate at which nutrients are delivered from the stomach to the small intestine for absorption (44, 45). On the other hand, leptin is
considered to increase insulin sensitivity with augmentation of insulin receptor signaling in insulin target organs such as the liver and skeletal muscle (30) and suppress secretion of glucagon (28, 42). In this study, the tendency toward a decrease, but not a significant one, in plasma glucagon levels was observed in L/A-treated mice (Fig. 2C). Further studies are needed to evaluate the effect of leptin on plasma glucagon in DIO mice. Administration of L or A alone did not affect insulin sensitivity in DIO mice (Fig. 2A–D). However, L/A coadministration effectively enhanced insulin sensitivity in DIO mice (Fig. 2A–D). Taken together, our results indicate that amylin improved the insulin-sensitizing action of leptin in DIO mice.

One of the mechanisms by which leptin enhances insulin sensitivity is the reduction of fat accumulation in insulin target organs by activation of the AMPK/H2 in skeletal muscle (24, 37, 38). In this study, we demonstrated that only L/A coadministration effectively reduced liver and skeletal muscle triglyceride contents accompanied by AMPK activation in the skeletal muscle (Fig. 3A–E). Previously, we demonstrated that AMPK in skeletal muscle was activated and insulin sensitivity enhanced in LepTg mice. High-fat diet feeding diminished both the activation of AMPK and the enhancement of insulin sensitivity, and diet substitution to standard diet restored them in LepTg mice, indicating that AMPK activity in skeletal muscle closely parallels insulin sensitivity (37). Based on the results of LepTg mice, we proposed that the AMPK activity in peripheral tissues could be a novel biochemical marker of leptin sensitivity in vivo (37). Therefore, the increase of AMPK activity in L/A-treated mice suggests that amylin improved leptin sensitivity in leptin-resistant DIO mice.

For the treatment of obesity-associated diabetes, it is universally accepted that dietary management is used initially with specific emphasis on weight reduction, because weight reduction leads to improvement in deteriorated glucose metabolism (1, 3). Therefore, to assess the influence of food intake and body weight reduction, we compared insulin sensitivity and tissue triglyceride contents among PF, CR, and L/A-treated mice. In this study, PF mice did not show reduced body weight compared with L/A-treated mice (Fig. 4A). Because amylin-induced weight loss was attributable primarily to reduced food intake (20, 33, 35), weight loss in L/A-treated mice suggests additional mechanisms such as restoration of leptin’s effect on energy expenditure. In previous analyses of calorie restriction effects on metabolism, calorie restriction was accompanied by an expected counterregulatory decline in energy expenditure in rodents (39). However, in this study, we showed that L/A coadministration increased energy expenditure significantly,
whereas it reduced food intake (Fig. 1C). In addition, CR mice, whose food consumption was restricted to match their body weight to those of the L/A-treated mice, showed neither the improvement of insulin sensitivity (Fig. 4, B and C) nor the decrease in liver and skeletal muscle triglyceride contents (Fig. 4, D and E). These results showed that the improvement of insulin sensitivity and the decrease in tissue triglyceride contents by L/A coadministration were achieved by other mechanisms besides calorie restriction.

In conclusion, we demonstrated that L/A coadministration effectively improves insulin sensitivity in addition to reducing food intake and body weight in DIO mice. Our data indicate that L/A coadministration could be a new antidiabetic treatment in obesity-associated diabetes.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

T.K., K.E., and K.N. did the conception and design of the research; T.K., T.S., and L.M. analyzed the data; T.K., K.E., T.S., L.M., D.A., Y.Y., S.Y.-K., M.A.-A., J.F., K.H., and T.S., and L.M. performed the experiments; T.K., T.S., and L.M. prepared the figures; T.K., T.S., and L.M. drafted the manuscript; T.K. and K.E. edited and revised the manuscript; T.K., K.E., and K.N. interpreted the results of the experiments; T.K., prepared the figures; T.K. drafted the manuscript; T.K. drafted the manuscript. All authors have approved the final version of the manuscript.

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