Exenatide improves hepatic steatosis by enhancing lipid use in adipose tissue in nondiabetic rats

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AIM: To investigate the metabolic changes in skeletal muscle and/or adipose tissue in glucagon-like peptide-1-induced improvement of nonalcoholic fatty liver disease (NAFLD).

METHODS: Male Wistar rats were fed either a control diet (control group) or a high-fat diet (HFD). After 4 wk, the HFD-fed rats were subdivided into two groups; one group was injected with exenatide [HFD-Ex(+) group] and the other with saline [HFD-Ex(-) group] every day for 12 wk. The control group received saline and were fed a control diet. Changes in weight gain, energy intake, and oxygen consumption were analyzed. Glucose tolerance tests were performed after 8 wk of treatment. Histological assessments were performed in liver and adipose tissue. RNA expression levels of lipid metabolism-related genes were evaluated in liver, skeletal muscle, and adipose tissue.

RESULTS: Exenatide attenuated weight gain [HFD-Ex(-) vs HFD-Ex(+)] and reduced energy intake, which was accompanied by an increase in oxygen consumption and a decrease in the respiratory exchange ratio [HFD-Ex(-) vs HFD-Ex(+)]. However, exenatide did not affect glucose tolerance. Exenatide reduced lipid content in the liver and adipose tissue. Exenatide did not affect the expression of lipid metabolism-related genes in the liver or skeletal muscle. In adipose tissue, exenatide significantly upregulated lipolytic genes, including hormone-sensitive lipase, carnitine palmitoyltransferase-1, long-chain acyl-CoA dehydrogenase, and acyl-CoA oxidase 1 [HFD-Ex(-) vs HFD-Ex(+)]. Exenatide also upregulated catalase and superoxide dismutase 2 [HFD-Ex(-) vs HFD-Ex(+)].

CONCLUSION: In addition to reducing appetite, enhanced lipid use by exenatide in adipose tissue may reduce hepatic lipid content in NAFLD, most likely by decreasing lipid influx into the liver.

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Key words: Adipose tissue; Energy expenditure; Exenatide; Glucagon-like peptide-1; Hepatic steatosis; Lipolysis; Nonalcoholic fatty liver disease

Core tip: Glucagon-like peptide-1 (GLP-1) is reported to improve nonalcoholic fatty liver disease (NAFLD), mainly via direct action on the liver. However, organs other than the liver may also be involved in regulation of hepatic lipid contents. In this study, we found significant upregulation of lipolytic genes in adipose tissue in exenatide-treated NAFLD rats. Up-regulation
of catalase, superoxide dismutase and mitochondrial morphological regulators was observed in adipose tissue. These metabolic changes were accompanied by increased oxygen consumption and decreased respiratory exchange ratio. Taken together, enhanced lipid use by GLP-1 in adipose tissue may play an important role in the improvement of NAFLD.

INTRODUCTION

Nonalcoholic fatty liver disease (NAFLD) is considered a hepatic manifestation of metabolic syndrome. The significant increase in the prevalence of NAFLD in the general population indicates that NAFLD is a burgeoning problem\(^4\). NAFLD is a chronic liver disease that is characterized by steatosis that is histologically similar to that in alcoholic liver injury, without excessive alcoholic intake or hepatitis viral infection\(^2\). Nonalcoholic steatohepatitis, a severe stage of NAFLD, frequently progresses into liver cirrhosis and hepatocellular carcinoma\(^4-8\). Body weight reduction and control of complicated diabetes are essential to improve NAFLD\(^7,8\). However, the attempts to restrict food intake and increase physical exercise are often insufficient to treat NAFLD\(^9\).

Glucagon-like peptide-1 (GLP-1), an incretin hormone produced by intestinal L cells, is an effective therapeutic agent for type 2 diabetes mellitus\(^10,11\). GLP-1 regulates plasma glucose levels by promoting insulin secretion and inhibiting glucagon secretion in a glucose-dependent manner\(^12,13\). Exenatide is a GLP-1 receptor agonist, sharing 53% sequence homology with GLP-1\(^14,15\). Exenatide has a longer half-life and enhanced potency compared with GLP-1 because it is less susceptible to degradation by dipeptidyl peptidase-4\(^16\).

GLP-1 may also be able to treat obesity by controlling gastrointestinal motility, which may suppress appetite and promote satiety\(^17,18\). GLP-1 was also reported to reduce hepatic steatosis in animal models of NAFLD\(^19-22\). Although the mechanism underlying this effect of GLP-1 is not completely understood, earlier studies suggested that GLP-1 had direct effects on the liver by improving hepatic insulin sensitivity\(^19,20\) and enhancing lipid hydrolysis and oxidation\(^21-23\). Because the GLP-1 receptor is expressed in many organs, including the brain, heart, kidney, stomach, liver, muscle, and adipose tissue\(^12,24\), GLP-1 may reduce hepatic lipid accumulation via extrahepatic pathways. In particular, skeletal muscle and adipose tissue are potential targets for GLP-1. Fatty acid influx into the liver is affected by the extent of fatty acid oxidation in skeletal muscle, as well as triglyceride storage and hydrolysis in adipose tissue. Therefore, changes in lipid metabolic activities in these tissues should reduce hepatic lipid content.

We hypothesized that GLP-1 would affect lipid metabolism in skeletal muscle and/or adipose tissue, leading to the reduction of lipid influx into the liver, resulting in the suppression of hepatic lipid accumulation. In the present study, we show that exenatide enhanced triglyceride hydrolysis and fatty acid oxidation in adipose tissue during the improvement of hepatic steatosis in a high-fat diet (HFD)-induced rat model of NAFLD. Additionally, upregulation of mitochondrial morphologic regulators was observed in adipose tissue. Exenatide increased the systemic energy expenditure and decreased the respiratory exchange ratio (RER). Collectively, the enhancing effects of exenatide (and hence GLP-1) on lipid use in adipose tissue may play a role in the improvement of hepatic steatosis in NAFLD.

MATERIALS AND METHODS

Animals

Four-week-old male Wistar rats weighing 80 g were purchased from Japan SLC (Hamamatsu, Japan). Rats were maintained under standard conditions with a 12-h light/dark cycle. All studies were performed in accordance with the Guide for the Care and Use of Laboratory Animals (National Institutes of Health) and were approved by the Animal Care Committee of Kyushu University. The rats were divided into two groups and fed a control diet \((n = 8; \text{control group})\) or an HFD diet \((n = 16)\). The control diet \((3.73 \text{ kcal/g})\) comprised 20.8% protein, 48.6% fat, and 58.2% carbohydrate. The HFD \((5.06 \text{ kcal/g})\) comprised 18.2% protein, 62.2% fat, and 19.6% carbohydrate. After 4 wk of feeding, HFD-fed rats were subdivided into two groups \((n = 8 \text{ per group})\) and intra-peritoneally injected with either 10 μg/kg body weight exenatide \([\text{Eli Lilly, Indianapolis, IN, United States; HFD-Ex(+) group}]\) or saline \([\text{HFD-Ex(-) group}]\) every day for 12 wk. Rats in the control group were injected with saline and fed a control diet. Body weight was measured every 4 wk. Starting from week 6 of feeding (week 2 of exenatide/saline injection), daily food consumption in each cage (2 rats) was measured every 2 wk for 6 wk and averaged levels of energy intakes were calculated. At week 16 of feeding (week 12 of injections), rats were sacrificed after an overnight fast, and the liver, gastrocnemius muscle, and epididymal white adipose tissues were removed.

Indirect calorimetry

At week 12 of feeding (week 8 of injections), oxygen consumption \((\text{VO}_2, \text{mL/kg/h})\) and RER were determined in the HFD-Ex(-) group and HFD-Ex(+) group \((n = 4 \text{ per group})\) using an Oxymax indirect calorimeter \((\text{Columbus Instrument, Columbus, OH, United States})\). After 3 d of acclimation, \(\text{VO}_2\) and RER were measured...
Table 1 Primer sequences

| Gene        | Forward          | Reverse           |
|-------------|------------------|-------------------|
| SREBP1c     | GGAGCCATGGATTGCACATT | AGGAAGGCTTCCACAGAAGA |
| FAS         | CTTAGGTCGCTTGGCTGGA | CGAAGGCTTGGCTGCTGA  |
| ACC1        | GTTCGCTGAGACAAGCCTCA  | GTGCCAGAAAGCAGCTTAC |
| LPL         | GTGCCAAGGACCATGCTTGGTGCT | CGTTAATCTGGTGGTGGACTA  |
| HSL         | TTTGCGCTGAGGGTGTC | GACACGGTCATGCAAGAGTC |
| ApoB        | TAGCTAGATGGTGATCAACT | ATGGGCTGCGAGGGGATTAC |
| CPT-1       | CGTGGAGCTCTTAAAGGCAACA | CAGGTCAGTACCTTGGACTA  |
| LCAT        | AAGGCTCGTTGCTGCTCAAAC | CAGCCCTGTGCAATTGGAGTA  |
| ACOX1       | GCCGCTGATAGTGGAAATGA | GGGTCTAAGTGGTGGTGAAT |
| Catalase    | GAAAATACACCAACACCTCAGAAG | GTAGCTAGGGTGGACCTGAGAA  |
| SOD2        | GACTAGGCGCAACGGGACATC | ACTCGAGAAACCCCTTGGCCTCAC |
| TGF         | TGCGCGCTGAGGAGGAAATGA | CTCTCGTTGATGAAATGGCAAAC |
| MCP4        | TCACACAGAGGAGGCAATACCAACA | ACAGAAGTGGCTGATTGTTG |
| Mn1         | CTTGTGATCGCTGAGGATGTACCTGTTTGC | CTCGGCTGATTTGCTGGTG |
| Mn2         | TCAGCCGCGTACCTGACTGACAGGA | TCGAGCCGCAAATGGCGAGCA |
| Opal        | ATGCTGCCGATCTGGTGGTACAC | CGTTGCGGCAATGGCAATTTAACC |
| Dnmt1       | ATGGTGTTGCTGCGTATTGAAACAA | GTCCTCGGATACAGGCGGAGG |
| GAPDH       | GCCACACGCAAGGCTGAGAATG | ATGGTGGTGAAGACGCCAGTA |

SREBP1c: Sterol regulatory-element-binding protein-1; FAS: Fatty acid synthase; ACC1: Acetyl-CoA carboxylase 1; LPL: Lipoprotein lipase; HSL: Hormone-sensitive lipase; ApoB: Apolipoprotein B; CPT-1: Carnitine palmitoyltransferase-1; LCAT: Long-chain acyl-CoA dehydrogenase; ACOX1: Acyl-CoA oxidase-1; SOD2: Superoxide dismutase 2; TGF: Tumor necrosis factor; MCP4: Monocyte chemotactic protein-1; Mn1: Mitofusin 1; Mn2: Mitofusin 2; Opal: Optic atrophy-1; Dnmt1: Dynamin-1; GAPDH: Glyceraldehyde 3-phosphate dehydrogenase.

every 4 min for 24 h. The rats were kept in a stable environment with a temperature of 25 °C, 12-h light/dark cycle, and airflow of 2 L/min. RER was calculated as the ratio of the volume of CO2 produced to O2 consumed.

Histological analysis

The liver and epididymal adipose tissue samples were fixed in 10% formalin and embedded in paraffin. Serial sections (5 μm thick) were cut from each block. Histological features were evaluated after staining sections with hematoxylin and eosin. The numbers of lipid droplets in liver tissue sections and the diameters of adipocytes in adipose tissue sections were determined using BIOREVO BZ9000 and BZ-9000 microscopes (Keyence, Osaka, Japan). The numbers of hepatic lipid droplets per unit area (μm2) and the diameters in 100 adipocytes were evaluated in five animals from each group.

Reverse transcription-polymerase chain reaction

Total RNA was prepared from all tissues using TRIzol reagent (Invitrogen, Carlsbad, CA, United States) and cDNA was synthesized from 1.0 μg of RNA by GeneAmp RNA polymerase chain reaction (PCR) (Applied Biosystems, Hammonton, NJ, United States) with random hexamers. Real-time PCR was performed using LightCycler FastStart DNA Master SYBR Green I (Roche, Basel, Switzerland). The reaction mixture (20 μL) contained Master SYBR Green I, 4 mmol/L MgCl2, 0.5 μmol/L of the upstream and downstream PCR primers, and 2 μL of first-strand cDNA as a template. To control for variations in reactions, all PCR data were normalized against glyceraldehyde 3-phosphate dehydrogenase expression. The primer sequences used in this study are listed in Table 1.

Glucose tolerance test

At week 12 of feeding (week 8 of injections), intraperitoneal glucose tolerance tests (IPGTTs) were performed in the HFD-Ex(-) group and HFD-Ex(+) group. After a 14-h fast, the rats were injected with glucose solution (2 g/kg body weight) and serum glucose levels were measured before (0 min) and at 15, 30, 60, 90, and 120 min after glucose injection using a portable glucometer (Lifescan, Bucks, United Kingdom).

Immunoblotting

Adipose tissue samples (250 mg) were homogenized in 1 mL of lysis buffer (25 mmol/L Tris-HCl pH 7.6, 150 mmol/L NaCl, 1% NP-40, 1% sodium deoxycholate, 0.1% sodium dodecyl sulfate). The lysates were centrifuged at 8050 g for 20 min. The upper lipid phase was discarded and the lower aqueous phase was re-centrifuged under the same conditions. The supernatant was collected and loaded onto Mini-Protean TGX gels (Bio-Rad, Hercules, CA, United States) and transferred onto polyvinylidene difluoride membranes. After blocking the membranes with 5% albumin, immunoblotting analyses were performed using antibodies raised against AMP-activated protein kinase (AMPK), phosphorylated AMPK (P-AMPK; Cell Signaling Technology, Beverly, MA, United States), and β-actin (Santa Cruz Biotechnology, Dallas, TX, United States).

Statistical analysis

All results are expressed as the means ± SD. Statistical analyses were performed using JMP v. 8.01 (SAS Institute, Cary, NC, United States). The differences of means were tested by Tukey-Kramer test (among 3 groups) or Kruskal-Wallis test (between 2 groups) to identify signifi-
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Figure 1 Changes in body weight and energy intake. A: Time-course of body weight. Four-week-old rats were fed a control diet (control group; n = 8) or a high-fat diet (HFD) (n = 16). After 4 wk of feeding, HFD-fed rats were subdivided into two groups (n = 8 per group) and intraperitoneally injected with either 10 μg/kg body weight exenatide [HFD-Ex(+)] group or saline [HFD-Ex(-)] group every day for 12 wk. Rats in the control group were injected with saline. At week 16 of feeding, the body weight was significantly lower in the HFD-Ex(+)] group than in the control and HFD-Ex(-) groups. n = 8. *P < 0.05 vs other groups; B: Daily energy during the treatment period. Energy intake was lower in the HFD-Ex(+)] group than in the control or HFD-Ex(-) group.

cance. Values of P < 0.05 were considered statistically significant.

RESULTS
Exenatide attenuated weight gain and increased oxygen consumption
No apparent differences in weight gain were observed among the three groups after 4 wk of feeding the experimental diets. After this time, body weight gain was generally suppressed in rats treated with exenatide, whereas the body weight of rats in the control and HFD-Ex(-) groups continued to increase. At 16 wk, the body weight of rats in the HFD-Ex(+) group was significantly lower than that of the control and HFD-Ex(-) group (376 ± 36 g vs 655 ± 81 g, respectively, P < 0.05) (Figure 1A). To assess the effects of exenatide on food intake, we measured energy intake (kcal/day per body) between weeks 6 and 12 of the feeding protocol. Energy intake was lower in the HFD-Ex(+) group than in the other groups throughout this time (Figure 1B). Using indirect calorimetry, we determined systemic energy consumption and RER in the HFD-Ex(-) and HFD-Ex(+) groups at week 12 of feeding. Indirect calorimetry revealed that oxygen consumption was significantly greater in the HFD-Ex(+) group than in the HFD-Ex(-) group (1269 ± 67 mL/kg/h vs 1114 ± 97 mL/kg/h, P < 0.05), and this increase was predominant during the dark cycle (Figure 2A). RER was significantly lower in the HFD-Ex(+) group than in the HFD-Ex(-) group (0.748 ± 0.02 vs 0.791 ± 0.01, P < 0.05) (Figure 2B). These findings indicate that exenatide enhanced systemic energy consumption by increasing lipid oxidation.

Exenatide reduced lipid accumulation in the liver and adipose tissue
Lipid accumulation in the liver and epididymal white adipose tissue was histologically analyzed at week 16 of feeding. Although marked accumulation of lipid droplets was observed in the livers of the HFD-Ex(-) group, the number of hepatic lipid droplets was significantly decreased in the HFD-Ex(+) group compared with the HFD-Ex(-) group (Figure 3A, C). In adipose tissue, the adipocytes were frequently enlarged in the HFD-Ex(-) group, reflecting lipid accumulation. However, enlarged adipocytes were not observed in the HFD-Ex(+) or control groups (Figure 3B). Furthermore, the mean diameter of adipocytes in the HFD-Ex(+) group was similar to that in the control group and was significantly smaller in both groups than in the HFD-Ex(-) group (Figure 3D).

Effects of exenatide on the expressions of genes involved in lipid metabolism in the liver and skeletal muscle
Because exenatide increased oxygen consumption, decreased RER, and decreased lipid accumulation in the liver and adipose tissue, we hypothesized that exenatide altered lipid metabolic activities, including triglyceride hydrolysis and lipid oxidation. To confirm this hypothesis, we determined the expression of lipid metabolism-associated genes in the liver, skeletal muscle, and adipose tissue. In liver, we found that the expression levels of sterol regulatory element-binding protein-1c (SREBP1c), fatty acid synthase (FAS), acetyl-CoA carboxylase-1 (ACO1), hormone-sensitive lipase (HSL), and apolipoprotein B (ApoB) were not significantly different among the three groups [HFD-Ex(-) vs HFD-Ex(+); 2.20 ± 1.29 vs 1.07 ± 0.57, 1.37 ± 0.51 vs 1.15 ± 0.68, 1.03 ± 0.29 vs 1.03 ± 0.29, 1.61 ± 0.69 vs 1.27 ± 0.21, and 0.99 ± 0.29 vs 0.89 ± 0.15, respectively, P > 0.05] (Figure 4A). Additionally, exenatide did not affect the expression of carnitine palmitoyltransferase-1 (CPT1), long-chain acyl-CoA dehydrogenase (LCAD), or acyl-CoA oxidase 1 (ACOX1) [HFD-Ex(-) vs HFD-Ex(+); 1.06 ± 0.50 vs 0.95 ± 0.39, 1.11 ± 0.41 vs 0.83 ± 0.21, and 0.85 ± 0.14 vs 0.74 ± 0.25, respectively, P > 0.05]. In skeletal muscle, the expression of lipoprotein lipase (LPL) was significantly increased in the HFD-Ex(+)] group compared with the control group [control vs HFD-Ex(+); 1. ± 0.60 vs 5.48 ± 4.47, P < 0.05] but not compared with the HFD-Ex(-) group [HFD-Ex(-) vs HFD-Ex(+); 3.24 ± 2.19 vs 5.48 ± 4.47, P > 0.05]. As in the liver, exenatide did not affect the
expression of HSL, CPT1, LCAD, or ACOX1 in skeletal muscle [HFD-Ex(-) vs HFD-Ex(+); 1.44 ± 0.65 vs 1.87 ± 0.88, 1.26 ± 0.51 vs 1.53 ± 0.63, 2.15 ± 0.78 vs 1.88 ± 0.77, and 1.40 ± 0.33 vs 1.32 ± 0.61, respectively, \( P > 0.05 \)].

Exenatide upregulated genes involved in triglyceride hydrolysis and fatty acid oxidation in adipose tissue

In adipose tissue, exenatide significantly increased the expression of HSL in the HFD-Ex(+) group compared with the control and HFD-Ex(-) groups [HFD-Ex(-) vs HFD-Ex(+); 0.98 ± 0.37 vs 1.61 ± 0.42, \( P < 0.05 \)] (Figure 5A). The expression of LPL was also increased in the HFD-Ex(+) group, albeit not significantly. In terms of genes involved in mitochondrial \( \beta \)-oxidation of fatty acids, the expression levels of CPT1, LCAD, and ACOX1 were significantly increased in the HFD-Ex(+) group compared with the control and HFD-Ex(-) groups [HFD-Ex(-) vs HFD-Ex(+); 1.04 ± 0.27 vs 1.88 ± 0.97, 1.26 ± 0.23 vs 2.52 ± 1.00, and 1.58 ± 0.45 vs 2.41 ± 0.85, respectively, \( P < 0.05 \)], suggesting that exenatide enhanced lipid oxidation in adipose tissue.

Enhanced lipid oxidation results in the accumulation of intracellular reactive oxygen species (ROS), which induces the cellular response to eliminate this harmful by-product\(^{25-27}\). Therefore, we determined the adipose tissue expression levels of catalase and superoxide dismutase (SOD)2 and found that they were significantly greater in the HFD-Ex(+) group than in the control and HFD-Ex(-) groups [HFD-Ex(-) vs HFD-Ex(+); 1.12 ± 0.29 vs 2.37 ± 0.66 and 0.99 ± 0.21 vs 1.49 ± 0.23, respectively, \( P < 0.05 \)] (Figure 5B).

Because macrophage infiltration into adipose tissue plays an important role in the development of insulin resistance\(^{28-30}\), we determined the expression levels of tumor necrosis factor and monocyte chemotactic protein 1. However, the expression levels of these genes were not significantly different among the three groups [HFD-Ex(-) vs HFD-Ex(+); 1.01 ± 0.40 vs 1.27 ± 0.30 and 0.90 ± 0.41 vs 0.76 ± 0.49, respectively, \( P > 0.05 \)], which suggests that the metabolic changes in adipose tissues induced by exenatide did not involve macrophage activation (Figure 5B).

Effects of exenatide on mitochondrial morphologic regulators in adipose tissue

In response to changes in the nutritional environment, mitochondria can change their morphology through two coordinated processes, fusion and fission, which are transcriptionally regulated by a group of genes\(^{31,32}\). In this group, mitofusin-1 (Mfn1) and mitofusin-2 (Mfn2) regulate mitochondrial fusion of the outer membrane and are believed to play a role in intracellular lipid con-
In addition, optic atrophy-1 (Opa1) regulates the fusion of the inner membrane while dynamin-1 (Dnm1) regulates mitochondrial fission and is involved in intracellular lipid accumulation. Therefore, to determine whether the induction of lipid oxidation in adipose tissue is accompanied by changes in mitochondrial morphologic regulation, we determined the expression levels of these regulators. Notably, the expression levels of Mfn1, Mfn2, and Opa1 were significantly greater in the HFD-Ex(+) group than in the control and HFD-Ex(-) group [HFD-Ex(-) vs HFD-Ex(+); 1.13 ± 0.17 vs 2.08 ± 0.40, 0.99 ± 0.28 vs 1.76 ± 0.50, and 1.08 ± 0.19 vs 1.76 ± 0.30, respectively, \( P < 0.05 \)] (Figure 6). Additionally, the expression of Dnm1 was significantly greater in the HFD-Ex(+) group than in the control group [control vs HFD-Ex(+); 1 ± 0.50 vs 1.58 ± 0.27, \( P < 0.05 \)], but was not significantly greater than that in the HFD-Ex(-) group [HFD-Ex(-) vs HFD-Ex(+); 1.28 ± 0.23 vs 1.58 ± 0.27, \( P > 0.05 \)]. These findings indicate that exenatide not only induces lipid consumption or accumulation, but also that it might regulate mitochondrial reorganization of adipose tissue, most likely reflecting increased use of intracellular lipid.

**Exenatide had limited effects on glucose tolerance**

This NAFLD model was based on nondiabetic, wild-type rats to minimize the effects of exenatide on diabetes control. However, improvement in hepatic lipid accum-
mulation might be due to an improvement in glucose intolerance, which occasionally develops in obese animals. Thus, we performed IPGTTs in rats in the HFD-Ex(-) and HFD-Ex(+) groups. Interestingly, fasting plasma glucose levels were slightly higher in the HFD-Ex(-) group than in the HFD-Ex(+) group, but no significant differences were observed at 15, 30, 60, 90, or 120 min after glucose injection (Figure 7). The nondiabetic profiles and the similar responses in both groups suggest that the effects of exenatide on lipid metabolism are unlikely to be due to improvements in glucose intolerance.

**Adipose tissue AMPK is not activated by exenatide**

Following an increase in intracellular AMP, AMPK plays an essential role in the consumption of intracellular lipid by suppressing fatty acid synthesis and stimulating fatty acid oxidation\(^\text{[34]}\). To determine whether AMPK activation was involved in the effects of exenatide, we determined the protein expression of total AMPK and P-AMPK in adipose tissue. As shown in Figure 8, there were no obvious differences in AMPK or P-AMPK levels among the three groups.

**DISCUSSION**

The mechanism by which GLP-1 and its analogs improve hepatic steatosis is still not fully understood, although changes in hepatic lipid metabolism are thought to be involved in these effects\(^{[20-23]}\). Because hepatic lipid content is determined by intrahepatic lipogenesis and lipolysis, as well as the extent of fatty acid influx into the liver, changes in lipid use in skeletal muscle and adipose tissue may contribute to hepatic lipid metabolism. Thus, we investigated the effects of exenatide, a GLP-1 receptor agonist, on lipid metabolism in the liver, skeletal muscle, and adipose tissue. To minimize the effects of exenatide on glycemic control in the diabetic state, we used a nondiabetic, HFD-induced rat NAFLD model. Exenatide reduced lipid accumulation in the liver and adipose tissue and decreased the size of adipocytes. The reduction of body weight gain by exenatide was accompanied by a significant reduction in food intake. Using indirect calorimetry, we showed that exenatide increased oxygen consumption and reduced the RER. These findings suggest that reduced food intake and increased
Figure 6  Effects of exenatide on the expression levels of mitochondrial morphologic regulators in adipose tissue. Genes involved in mitochondrial fission [mitofusin-1 (Mfn1) and mitofusin-2 (Mfn2) and optic atrophy-1 (Opa1)] were significantly greater in the high-fat diet (HFD)-Ex(+) group than in the control and HFD-Ex(-) groups. The fold changes were calculated as the ratio of the expression level in the HFD-Ex(+) or HFD-Ex(-) group to that in the control group. n = 8, *P < 0.05 between groups.

Figure 7  Effect of exenatide on AMP-activated protein kinase activation in adipose tissue. Immunoblotting for total AMP-activated protein kinase (AMPK), phosphorylated AMPK (P-AMPK), and β-actin were performed. The protein levels of total AMPK and P-AMPK were not significantly different among the three groups. HFD: High-fat diet.

Figure 8  Effects of exenatide on glucose tolerance. Intraperitoneal glucose tolerance tests (IPGTTs) were performed in the high-fat diet (HFD)-Ex(+) and HFD-Ex(-) groups at week 12 of feeding. Fasting plasma glucose levels were slightly lower in the HFD-Ex(+) group than in the HFD-Ex(-) group, but no significant differences were observed at the other times during the IPGTTs.
muscle. However, lipolytic genes were upregulated by exenatide in adipose tissue. Notably, the expression levels of HSL, CPT1, LCAD, and ACOX1 were significantly greater in the HFD-Ex(+)-group than in the control and HFD-Ex(-)-groups. To evaluate whether these changes were associated with changes in nutrient oxidation, we analyzed the expression levels of catalase and SOD2, which are responsible for eliminating ROS produced during oxidative phosphorylation. We showed that exenatide significantly upregulated the expression of both enzymes. Therefore, exenatide seemed to promote nutrient oxidation, especially of lipid, in adipose tissue. To analyze the effects of exenatide on lipid use, we determined the expression levels of genes regulating mitochondrial morphology, which responds to changes in the nutritional environment. In particular, intracellular lipid content is greatly affected by the correlation between mitochondrial fusion and fission. In this study, we showed that exenatide significantly upregulated the expression levels of Mfn1, Mfn2, and Opal, which regulate mitochondrial fusion and promote the consumption of intracellular lipid. Taken together, our observations suggest that exenatide enhanced lipid use in adipose tissue, which contributed to the improvement in hepatic steatosis, most likely by reducing lipid influx into the liver.

The mechanisms by which GLP-1 modulates lipid use in adipose tissue are largely unknown. The GLP-1 receptor has been detected in 3T3-L1 adipocytes and in human adipose tissue and in adipose tissue, this was associated with elevated plasma norepinephrine levels. Furthermore, intracerebroventricular infusion of GLP-1 decreased lipid storage in white adipose tissue in a manner that was partially mediated via sympathetic nerve activation. These findings are consistent with our observation that exenatide enhanced adipose tissue expression of HSL, which is activated by the sympathetic nervous system via the cAMP-dependent pathway. Not only white adipose tissue, but also brown adipose tissue might be involved in the actions of GLP-1 observed in this study. Recently, Lockie et al. reported that intracerebroventricular injection of GLP-1 induced thermogenesis in brown adipose tissue, accompanied with increased activity of innervated sympathetic fibers. Taken together, we hypothesize that GLP-1 enhances lipid utility in both the adipose tissues, lipolysis in white adipose tissue and thermogenesis in brown adipose tissue, leading to increased energy consumption, resulting in the improvement of hepatic steatosis. However, the precise roles of these adipose tissues need further investigation.

In conclusion, this study showed that reduced food intake and enhanced lipid use by exenatide in adipose tissue contributed to an improvement in hepatic steatosis in a rat model of HFD-induced NAFLD. The mechanism by which exenatide (and therefore GLP-1) modulates lipid metabolism in adipose tissue should be investigated further.

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