FGF-21 as a novel metabolic regulator

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Diabetes mellitus is a major health concern, affecting more than 5% of the population. Here we describe a potential novel therapeutic agent for this disease, FGF-21, which was discovered to be a potent regulator of glucose uptake in mouse 3T3-L1 and primary human adipocytes. FGF-21–transgenic mice were viable and resistant to diet-induced obesity. Therapeutic administration of FGF-21 reduced plasma glucose and triglycerides to near normal levels in both ob/ob and db/db mice. These effects persisted for at least 24 hours following the cessation of FGF-21 administration. Importantly, FGF-21 did not induce mitogenicity, hypoglycemia, or weight gain at any dose tested in diabetic or healthy animals or when overexpressed in transgenic mice. Thus, we conclude that FGF-21, which we have identified as a novel metabolic factor, exhibits the therapeutic characteristics necessary for an effective treatment of diabetes.

Introduction

While the majority of the 22 known members of FGF family have been primarily associated with mitosis, development, transformation, angiogenesis, and survival (1–5), recent data shows that they may play important roles in defining and regulating functions of some endocrine-relevant tissues and organs, as well as modulating various metabolic processes. For example, FGF-10 is implicated in some endocrine-relevant tissues and organs, as well as modulating function of this protein and its potential therapeutic application.

Results

Identification of FGF-21 in vitro bioactivity. Using a glucose uptake assay to search for novel proteins with therapeutic potential to treat diabetes mellitus, we found that human recombinant FGF-21 stimulated glucose incorporation in differentiated mouse 3T3-L1 adipocytes, as well as in human primary adipocytes after 24-hour treatment of the cells with the protein (Figure 1, A and B). Since FGF-21 did not induce glucose uptake in undifferentiated 3T3-L1 fibroblasts, human primary preadipocytes, muscle L6–glucose transporter–4myc (L6-GLUT-4myc) myoblasts and myotubes (22), or liver clone 9 cells, the FGF-21 effect appeared to be adipocyte specific.

The effects of FGF-21 on glucose uptake in adipocytes were insulin independent, additive to the activity of insulin upon cotreatment (Figure 1C), and not modulated by addition of exogenous heparin. In contrast to the rapid response elicited by insulin, the predominant effect of FGF-21 on glucose uptake required at least 4 hours of cell treatment, and it was substantially diminished in the presence of cycloheximide (1 μg/ml), a protein synthesis inhibitor (23) (Figure 1D). These observations led us to hypothesize that the mode of action for FGF-21 requires transcriptional activation.

To identify a potential mechanism at the molecular level by which FGF-21 increases glucose uptake, we examined whether it modulates the expression levels of the glucose transporters GLUT1 and GLUT4 in 3T3-L1 adipocytes. FGF-21 treatment (1 μg/ml) led to a significant increase in GLUT1 mRNA and protein but not those of GLUT4 (Figure 1, E and F). FGF-21–dependent GLUT1 upregulation was further demonstrated in vivo following a bolus injection in ob/ob mice. Four hours after s.c. administration of FGF-21 (500 μg/animal), an increase in GLUT1 mRNA was specifically detected in white adipose tissue but not in muscle, liver, kidney, and brain (Figure 1G).

Additional studies revealed that early FGF-21–induced signaling in 3T3-L1 adipocytes included heparin-independent tyrosine phosphorylation of Akt and phospho-Akt, which were transiently increased by FGF-21 treatment (Figure 1H). These results suggest that FGF-21 signals through the PI3K/Akt and MAPK pathways, as described for other members of the FGF family.

Nonstandard abbreviations used: BAT, brown adipose tissue; BMP-9, bone morphogenic protein-9; EC50, 50% effective concentration; FGF, FGF receptor; FRS-2, FGF receptor substrate-2; GLP-1, glucagon-like peptide-1; GLUT, glucose transporter; HFHC, high-fat/high-carbohydrate diet; HMEC, primary human mammary epithelial cell; HUVEC, human umbilical vein endothelial cell; OGTT, oral glucose tolerance test; PCNA, proliferative cell nuclear antigen; ZDF, Zucker diabetic fatty.

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phorylation of FGFR substrate–2 (FRS-2), a docking protein linking FGFRs to the Ras/MAPK pathway (24), and transient activation of MAPK (Figure 2A). All these in vitro activities are typically initiated upon activation of FGFR-mediated pathways (25).

FGFR-1 and FGFR-2 may represent FGF-21–corresponding receptors. The sequence characteristics and signaling profile of FGF-21 indicate that its receptor may belong to the FGFR superfamily. The expression of FGFR-1 and FGFR-2, including several splice variants of these receptors, was readily detected in 3T3-L1 cells by RT-PCR and immunoblot analysis. While FGFR-5 was also detected by RT-PCR, significantly lower levels of FGFR-3 and no expression of FGFR-4 were observed. We immunoprecipitated FGFR-1 and FGFR-2 from 3T3-L1 adipocytes with specific anti-bodies and detected in both cases 2 tyrosine-phosphorylated proteins of approximately 120–150 kDa in FGF-21–stimulated cells (Figure 2B), while no phosphorylation was observed in FGFR-3 immunoprecipitates under similar conditions (data not shown). These tyrosine-phosphorylated bands were later reprobed with anti–FGFR-1 and anti–FGFR-2 antibodies, respectively (Figure 2B), which indicates that they may represent activated forms of FGFR-1 and FGFR-2. Importantly, the observed FGF-21–dependent phosphorylation was adipocyte specific, since it was not detected in 3T3-L1 preadipocytes.

FGF-21 does not induce in vitro mitogenicity. As a class, FGFs are generally known to induce cell proliferation. Therefore, we examined the mitogenic potential of FGF-21 in cells typically sensitive to FGFs. FGF-21 did not induce proliferation of 3T3-L1, NIH 3T3, or BALB/c 3T3 fibroblasts, monkey epithelial 4MRb5 cells, primary human mammary epithelial cells (HMECs), or human umbilical vein endothelial cells (HUVECs), either in the absence or presence of exogenous heparin. In contrast, FGF-7, FGF-1, and FGF-2 stimulated the growth of these cells. Moreover, in costim-
FGF-21 stimulates phosphorylation in 3T3-L1 adipocytes. (A) FGF-21 induces phosphorylation of MAPK and FRS-2 in 3T3-L1 adipocytes. Upon stimulation, cells were lysed, and phospho-specific antibodies were used to determine phosphorylation of MAPK and FRS-2 in immunoblots. After immunoblots were stripped, anti-MAPK and anti-FRS-2 antibodies were used to confirm that protein loads were equal. For MAPK experiment, cells were stimulated with FGF-21 for the indicated times. For FRS-2 experiment, cells were stimulated with FGF-21 or FGF-1 (positive control). (B) FGF-21 stimulates tyrosine phosphorylation of FGFR-1 and FGFR-2 in 3T3-L1 adipocytes. Cells were stimulated with FGF-21 and lysed. FGFR-1 and FGFR-2 immunoprecipitates were analyzed in immunoblots with anti-phosphotyrosine antibodies. After stripping, anti-FGFR-1 and anti-FGFR-2 antibodies were used to confirm that protein loads were equal. pErk, phospho-Erk; PY, phosphotyrosine.

FGF-21–transgenic mice. In order to evaluate the effect of enforced expression of FGF-21 in vivo, we generated FGF-21–transgenic mice that overexpressed the human protein from the liver using the apoE promoter. As measured by an FGF-21–specific ELISA, the plasma concentrations of FGF-21 in the transgenic animals ranged between 70 and 150 ng/ml.

These FGF-21–transgenic mice were viable and at 2 months of age had glucose levels similar to those of their wild-type littermates. However, at 9 months, differences between transgenic and wild-type mice became apparent. FGF-21–transgenic animals weighed significantly less, had lower fasted glucose levels (Table 1) and less fat in liver, retained more brown adipose tissue, had subcutaneous adipocytes of smaller size (Figure 5, A and B), and exhibited improved glucose clearance and insulin sensitivity relative to control littermates as measured during OGTT (data not shown).

Several members of FGF family have been shown to induce therapeutically undesirable in vivo proliferation of various cell types (1–5, 26). Therefore, we examined FGF-21–transgenic mice for their potential to develop tumors throughout their lifespan. As evidenced by histological analysis, transgenic mice overexpressing FGF-21 did not develop liver tumors or show evidence of any other tissue hyperplasia up to 10 months of age (Figure 5C).

FGF-21 does not induce proliferation and does not block FGF-7–dependent mitogenicity on 4MB5 cells. Cells were stimulated as indicated with different concentrations of FGF-7, FGF-21, and FGF-21 in the presence of a constant concentration of heparin and FGF-21 in the presence of a constant concentration of FGF-7.
We challenged FGF-21 transgenic animals by feeding them a high-fat/high-carbohydrate (HFHC) diet for 15 weeks. Intriguingly, FGF-21–transgenic mice consumed almost twice as much food as wild-type littermates when the amounts were normalized to body weights and calculated as the actual amount of food eaten per animal per day (Table 1). Despite the significant increase in caloric intake, they did not gain as much weight as wild-type controls and were also resistant to diet-induced obesity (Figure 6, A and B).

Discussion
Several secreted polypeptides, including insulin, glucagon-like peptide–1 (GLP-1), adiponectin, and others are ultimately involved in the regulation of glucose homeostasis, which thus makes them clinically relevant pharmacological agents or attractive candidates for novel medicines for the treatment of diabetes mellitus (27). Recent reports on bone morphogenic protein–9 (BMP-9) (28) and FGF-19 (12, 13), and our findings with FGF-21, have shown that the other proteins also constitute this list of promising biomolecules.

FGF-21 bioactivity was discovered through a cell-based functional screen aimed at identifying novel secreted molecules that affect glucose uptake on mouse 3T3-L1 adipocytes and was found to be very potent in this assay (EC$_{50}$, $\sim$0.5 nM) (Figure 1A). With comparable potency, FGF-21 was active on differentiated human primary adipocytes (Figure 1B), which indicates that FGF-21 bioactivity is not limited to murine adipocytes. The follow-up analysis on the initial observation in the glucose uptake assay revealed what we believe to be a novel and unique mechanism of the FGF-21 mode of action. FGF-21 effects appeared to be insulin independent and additive to insulin activity upon coadministration (Figure 1C). FGF-21 needed to be present on cells for several hours to produce a robust response in glucose uptake, and the effect was significantly diminished by the protein synthesis inhibitor cycloheximide (Figure 1D). While insulin is known to work in a rapid, hormone-like manner, we hypothesized that FGF-21 activity is likely to be mediated through changes in gene expression. Indeed, we showed that FGF-21 induced a signifi-
cant upregulation of the insulin-independent glucose transporter GLUT1 in 3T3-L1 adipocytes (Figure 1, E and F) and further confirmed this finding in vivo when we administered FGF-21 to ob/ob mice (Figure 4G). Thus, in contrast to insulin, which is known to function via GLUT4 translocation (29), FGF-21 may primarily act through upregulation of cellular GLUT1 in these cells.

In addition to the changes in GLUT1, we observed a modest reduction in GLUT4 levels after 48 and 72 hours of cell stimulation with FGF-21 (Figure 1F). While FGF-21 stimulation caused a decrease in GLUT4 levels in vitro, it did not appear to negatively impact glucose uptake (Figure 1C), which suggests either that the decrease in GLUT4 levels after 48 and 72 hours of cell stimulation with FGF-21 is not sufficient to affect glucose transport or that other compensatory mechanisms are at work in 3T3-L1 adipocytes. Moreover, we observed improved insulin sensitivity in FGF-21–administered diabetic rodents even under enforced overexpression (Figure 2A). In contrast, while heparin or heparin-like molecules did not stimulate MAPK activation and FRS-2 phosphorylation (25) over constant infusion of FGF-21 in db/db mice (Figure 4G and data not shown). Thus, the reduction observed in GLUT4 in 3T3-L1 adipocytes does not appear to be functionally relevant.

FGF-21 is a typical FGF molecule with respect to its ability to stimulate MAPK activation and FRS-2 phosphorylation (25) (Figure 2A). In contrast, while heparin or heparin-like molecules are considered to be essential for the biological activity of proteins of the FGF family (30), none of the FGF-21–induced in vitro responses observed in 3T3-L1 or human adipocytes were heparin regulated. Importantly, FGF-21 appears to be mitogenically inactive in vitro when tested on several otherwise FGF-sensitive cell lines and primary cells (Figure 3). This further establishes FGF-21 as a unique protein within the FGF family, as FGFs are well known to induce proliferation (1–5). Whereas the exact cause of the nonmitogenic character of the in vitro action of FGF-21 is currently unknown, these data help significantly in validating FGF-21 as a potential protein therapeutic.

The fact that FGF-21 induced tyrosine phosphorylation of FGFR-1 and FGFR-2 (Figure 2B) suggests that these molecules may function as FGF-21 receptors. Although they carry readily detectable and functional FGFR-1 and/or FGFR-2 molecules, it is, however, currently unclear why several FGF-sensitive cells that were tested for FGF-21 bioactivity do not respond to FGF-21 stimulation. Moreover, in preliminary experiments with all commercially available FGFR extracellular domain–Fc fusion proteins (R&D Systems), we were unable to demonstrate direct interaction between any of these FGFR variants and FGF-21, despite the fact that we clearly observed binding for both FGFR-1 and FGFR-2 (data not shown). Thus, FGF-21 may be physically interacting with different splice variants of FGFR-1 and FGFR-2 that are induced upon adipocyte differentiation. Alternatively, FGF-21–dependent activation of these receptors may require a fat cell–specific modification or additional cofactor.

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Control (M)</th>
<th>Tg (M)</th>
<th>P value</th>
<th>Control (F)</th>
<th>Tg (F)</th>
<th>P value</th>
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<tr>
<td>Body weight (g)</td>
<td>50.4 ± 0.7</td>
<td>29.1 ± 3.37</td>
<td>&lt; 0.001</td>
<td>ND</td>
<td>ND</td>
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<td>Fasted glucose (mg/dl)</td>
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<td>67 ± 8.1</td>
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<td>ND</td>
<td>ND</td>
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<tr>
<td>Food intake (g/g body wt/wk)</td>
<td>0.42 ± 0.02</td>
<td>0.76 ± 0.03</td>
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<td>0.55 ± 0.01</td>
<td>0.88 ± 0.04</td>
<td>&lt; 0.001</td>
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<tr>
<td>Leptin (ng/ml)</td>
<td>63.0 ± 1.97</td>
<td>15.6 ± 4.12</td>
<td>&lt; 0.001</td>
<td>61.4 ± 3.64</td>
<td>18.26 ± 6.97</td>
<td>&lt; 0.001</td>
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<tr>
<td>Glucagon (pg/ml)</td>
<td>116 ± 7.12</td>
<td>93.8 ± 8.54</td>
<td>0.08</td>
<td>141 ± 9.5</td>
<td>93 ± 6.55</td>
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<tr>
<td>Body temperature (°C)</td>
<td>35.58 ± 0.09</td>
<td>35.4 ± 0.27</td>
<td>NS</td>
<td>36.2 ± 0.23</td>
<td>36.5 ± 0.17</td>
<td>NS</td>
</tr>
</tbody>
</table>

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4Parameters measured in 9-month-old mice on a regular chow. 6Parameters measured in diet-induced obese mice during or after HFHC feeding for 15 weeks.

**Figure 5**

Histological analysis of FGF-21–transgenic and control mice. (A) H&E staining of brown fat. Notice an increase in intensity of brown fat in the FGF-21–transgenic mouse compared with the wild-type mouse. (B) H&E staining of subcutaneous white fat. Notice the smaller adipocytes in the FGF-21 mouse compared with the wild type. (C) H&E staining of livers from FGF-21–transgenic and wild-type mice. There are no differences between the 2. Magnification, ×200 (A–C). (D) PCNA staining of the livers from FGF-21–infused and saline-treated db/db mice. PCNA immunostaining shows very low proliferation (less than 5%) of hepatocytes (brown staining, arrows) in both the control and treated groups. Magnification, ×400.
FGF-21 did not stimulate glucose uptake on insulin-sensitive liver clone 9 and muscle L6-GLUT-4myc cells and on 3T3-L1 fibroblasts. Also, we were unable to detect FGF-21 activity in proliferation assays on several cell lines and primary cells of a different nature, which further indicates that FGF-21 effects might be adipocyte specific. Nevertheless, we recently observed a clear FGF-21 response on cells of nonfat origin. Unexpectedly, FGF-21 (1 μg/ml) showed efficacy in modulating glucagon secretion from isolated rat islets (Figure 7), while no effect on insulin secretion was observed. Thus, the specificity of FGF-21 bioactivity remains to be further studied.

The administration of FGF-21 to diabetic ob/ob and db/db mice and obese ZDF rats led to significant lowering of circulating glucose and triglycerides, as well as a reduction in fasted insulin levels and improved glucose clearance during an OGTT (Figure 4, A–H). All these effects were observed after at least 3 days of injections and were more pronounced after 7 days of administration. Since no changes in levels of fed and fasted glucose, circulating lipid levels, insulin levels, and glucose disposal during OGTT were observed after a single s.c. injection of FGF-21, it appears that beneficial FGF-21–dependent effects require that animals be exposed to the protein multiple times. However, once the reduction in circulating glucose was achieved, FGF-21–induced changes were sustained for at least 24 hours (Figure 4F). Thus, despite its short elimination half-life, FGF-21 induced an extended pharmacodynamic effect in these diabetic animals. Taken together, these observations are remarkable in highlighting the difference in time action between FGF-21 and insulin.

Although potent in correcting elevated glucose levels in ob/ob and db/db mice, FGF-21 did not induce hypoglycemia in normal or diabetic rodents in either fasted or fed states (Figure 4, A, C–F, and H) at efficacious or significantly higher doses, and no hypoglycemia was seen in fasted FGF-21–transgenic mice (Table 1). This further distinguishes the effects of FGF-21 from those of insulin, which induced a significant reduction of blood glucose in lean animals (Figure 4E). Moreover, FGF-21 did not affect food intake or body weight/composition of diabetic or lean mice and rats over the course of 2 weeks of administration (doses ranging from 25 μg/kg/d to 8 mg/kg/d).

Further insights into the FGF-21 mechanism of action can be gleaned from the phenotype of FGF-21–transgenic mice. These animals are viable and are not metabolically distinguishable from wild-type littermates at 2 months of age. However, they appeared to be resistant to the age-related impairment of glucose metabolism since they had lower plasma glucose levels at 9 months (Table 1). Moreover, when challenged on HFHC diet for 15 weeks, FGF-21–transgenic mice were resistant to diet-induced weight gain and fat accumulation (Figure 6, A and B), even though they consumed more food when the amounts were normalized to body weights (Table 1). We also observed lower levels of circulating leptin (Table 1). The reduction in leptin is consistent with lower adiposity in the transgenic animals and may be a primary cause of the increased food intake in the transgenic mice (31). However, these changes in feeding behavior are unlikely to have been induced by a direct effect of FGF-21, since no impact on food intake in rodents administered the protein was observed. There was also a decrease in circulating glucagon levels (Table 1), which is consistent with the in vitro observations made with rat pancreatic islets (Figure 7).

There was no evidence of poor nutrient absorption in FGF-21–transgenic animals. Thus, another potential reason for the observed resistance to diet-induced obesity may be an effect of FGF-21 on energy expenditure. However, if this is true, it was not reflected in any changes in rectal body temperatures (Table 1). Moreover, when challenged on HFHC diet for 15 weeks, FGF-21–transgenic mice are resistant to diet-induced weight gain and fat accumulation. (A) Average cumulative weight gain of FGF-21–transgenic and wild-type mice fed an HFHC diet for 15 weeks. The values (±SE) shown are the average of the measurements of at least 5 animals in a group. P < 0.05 for all time points for male (M) wild-type versus FGF-21–transgenic mice; and for weeks 6–15 for female (F) wild-type versus FGF-21–transgenic mice. (B) Body composition of male FGF-21–transgenic and wild-type mice before and after feeding on an HFHC diet for 15 weeks as determined by nuclear magnetic resonance. P < 0.002 for lean and fat mass of FGF-21–transgenic versus wild-type mice.

**Figure 6**

![Graph showing cumulative weight gain](image)

**Figure 7**

![Graph showing glucagon secretion](image)
The FGF family member most closely related to FGF-21 is FGF-19, with 31% amino acid sequence identity between these 2 molecules (21). The phenotype of transgenic mice overexpressing FGF-19 (12, 13) is strikingly reminiscent of that of mice overexpressing FGF-21. However, we have uncovered a fundamental in vivo difference that clearly distinguishes these 2 molecules from each other. While transgenic mice overexpressing FGF-19 were resistant to high-fat diet-induced obesity, they also developed histologically detectable liver tumors. Furthermore, wild-type mice that were injected with FGF-19 for 6 days had an increase in hepatocellular proliferation (26). In contrast to FGF-19–overexpressing animals, FGF-21–transgenic mice did not form tumors in liver or show histological evidence of hyperplasia in any other tissue after 10 months of age (Figure 5C). Nevertheless, in order to further determine the potential of FGF-21 to stimulate liver mitogenicity in vivo, we administered FGF-21 to db/db mice via ALZET pumps at an efficacious 11 ng/kg/day of FGF-21 for 7 days and measured the levels of several secreted polypeptides in circulation (Table 2). While we were able to achieve a clear glucose-lowering effect in the study (Figure 4A), only insulin and glucagon levels were changed in a statistically significant manner. The reduction of insulin levels is consistent with our observation in ob/ob mice during OGTT (Figure 4G) and is suggestive of improvements in insulin sensitivity in FGF-21–treated mice.

GLUT1 and glucagon potentially mediate the mode of action of FGF-21. We were able to detect FGF-21–dependent upregulation of GLUT1 message specifically in white fat upon bolus injection into ob/ob mice (Figure 1G), which thus confirms our in vitro observations on 3T3-L1 adipocytes. The increase in GLUT1 may mechanistically be linked to FGF-21–dependent glucose lowering in diabetic rodents. Alternatively, or in concert, the glucose lowering effect of FGF-21 is likely to result from reduced glucagon secretion from pancreatic α cells, since FGF-21 inhibits glucagon release in vitro (Figure 7) and is lowered in FGF-21–transgenic mice (Table 1).

The observation of glucagon lowering in FGF-21–injected ob/ob mice (Table 2) further strengthens the hypothesis that this hormone is an important mediator of FGF-21 in vivo effects. There is accumulating evidence supporting a pathophysiological role of glucagon in the development and progression of type 2 diabetes. Basal glucagon is inappropriately elevated and its suppression is impaired following food consumption, which leads to increased hepatic glucose production and aggravation of the hyperglycemia associated with the disease (33, 34). Interestingly, attenuation of signaling through the glucagon receptor leads to normalization of plasma glucose and triglyceride levels in diabetic animals (35).

Despite substantial progress in understanding the pathophysiology of diabetes mellitus and the development of new drugs to treat diabetic patients, this disease remains a major health problem (36). New treatments are required that will allow an efficacious regulation of systemic insulin resistance without inducing hepatic insulin resistance and hypoglycemia, or weight gain. FGF-21 thus holds promise as an effective therapeutic agent for the treatment of diabetes.

### Methods

**Expression and purification of FGF-21.** A pET30a vector was used to express human FGF-21 in the Escherichia coli strain BL21(DE3) (Novagen; EMD Biosciences Inc.). FGF-21 product accumulated in the insoluble fraction. Inclusion bodies were prepared by standard centrifugation method. We solubilized inclusion bodies by bringing granule pellets to 10 times the original volume in 50 mM Tris-HCL, pH 9.0, 7 M urea and homogenizing the material. The protein mixture was adjusted to pH 11, stirred for 1 hour, readjusted to pH 9.0, and loaded onto a Q Sepharose Fast Flow (Amersham Biosciences). Anion-exchange (AEX) chromatography was done in 50 mM Tris-HCL, pH 9.0, 7 M urea, 1 mM DTT and with a 0–400 mM NaCl gradient elution. The eluted AEX pool was treated with 10 mM DTT for 2 hours at room temperature and diluted 10-fold with 10 mM cysteine/7 M urea. The protein was refolded by dialysis against 20 mM glycine, pH 9.0, for 48 hours.
research article

at 4°C. Further purification was carried out with reversed-phase high-performance liquid chromatography (RP-HPLC) performed with a Grace Vydac C18 column run in H₂O/0.1% trifluoroacetic acid/acetonitrile mobile phase with a 0–50% acetonitrile gradient; size–exclusion chromatography on Superdex 75 (Amersham Biosciences) in PBS, pH 7.4; and AEX chromatography on MonoQ (Amersham Biosciences) in 50 mM Tris, pH 8.0, with 0–300 mM NaCl gradient. The final FGF-21 pool was dialyzed into PBS, pH 7.4, sterile filtered, and stored at –80°C.

Cell culture, adipocyte differentiation, glucose uptake, and mitochondria experiments. 3T3-L1, NIH 3T3, BALB/c 3T3, 4MR5, and clone 9 cells were from American Type Culture Collection; HMECs and HUVECs from Clonetics Corp.; and human primary adipocytes from Zen-Bio Inc. A previously described 3T3-L1 adipocyte differentiation protocol (39) was adapted for Cytoprotostar T 96-well plates (Amersham Biosciences). 3T3-L1 fibroblasts were seeded at 25,000 cells/well density; the differentiation was induced 2 days later in DMEM supplemented with 10% FBS, 0.25 μM dexamethasone, 0.5 mM 3-isobutyl-1-methylxanthine, and 5 μg/ml insulin (48 hours); and the medium was changed to DMEM/10% FBS/5μg/ml insulin (48 hours). Thereafter, the cells were incubated for an additional 9–20 days in DMEM/10% FBS (changed every other day). Primary human adipocytes were seeded in Cytoprotostar T 96-well plates at 15,000 cells/well density; differentiated in Adipocyte Medium (AM; Zen-Bio Inc.) with 0.05 mM IBMX, 0.1 μM dexamethasone, 10 mM insulin, and 1 μM rosiglitazone (14 days); and thereafter kept in AM (changed every other day). For glucose uptake, adipocytes were starved for 3 hours in DMEM/0.1% BSA, stimulated with FGF-21 for 24 hours, and washed twice with KRP buffer (15 mM HEPES, pH 7.4, 118 mM NaCl, 4.8 mM KCl, 1.2 mM MgSO₄, 1.3 mM CaCl₂, 1.2 mM KH₂PO₄, 0.1% BSA), and 100 μl of KRP buffer containing 2-deoxy-μ-[14C]glucose (2-DOG) (0.1 μCi, 100 μM) was added to each well. Control wells contained 100 μl KRP buffer with 2-DOG (0.1 μCi, 10 μM) to monitor for nonspecificity. The uptake reaction was carried out for 1 hour at 37°C, terminated by addition of cytochalasin B (20 μM), and measured using Wallac 1450 MicroBeta counter (Perkin Elmer). For mitochondria experiments, cells were grown to confluence, starved for 24 hours in DMEM/0.5% FCS, incubated for 18 hours, and incubated with 0.25 μCi [3H]succinate per well for 2 hours. Cell lysates were then harvested and counted. 

RNA extraction, cDNA synthesis, quantitative PCR. We used an RNaseqky 96 Kit (QIAGEN Inc.) to extract RNA from cells and TRIzol reagent (Invitrogen Corp.) to extract RNA from tissues. We performed reverse transcription using a SuperScript First-Strand Synthesis Kit (Invitrogen Corp.). The forward and reverse primer sequences for GLUT1 were 5′-GCCCCAAGGTTATGTA-3′ and 5′-CTGCGGAGTGTGAGGTGATG-3′, respectively. The probe sequence was 5′-TTCTACAATCAAACATG-3′. To normalize for differences in the amount of total RNA added to each reaction, we performed amplification of 18S ribosomal RNA as an endogenous control.

Immunoblotting, immunoprecipitation, and multiplex assays. 3T3-L1 adipocytes were starved for 18 hours, stimulated with FGF-21 (1 μg/ml) for 10 minutes or for the indicated times (Figures 1F and 2A), and lysed (40), and soluble fractions were analyzed. Antibodies were: anti-phospho-MAPK (Thr202/Tyr204), anti-MAPK, anti-phospho-IRS-2 (Y196) (Cell Signaling Technology); anti-IRS-2 (H-91) and anti-FGFR-2 (C-17) (Santa Cruz Bio-technology Inc.); anti-phosphotyrosine (4G10; Upstate); rabbit polyclonal: anti-Glut1 against the 29 C-terminal amino acids of the human sequence, anti-Glut4 (41), and anti-FGFR-1 against the 15 C-terminal amino acids of the mouse sequence. For immunodetection, goat anti-mouse and anti-rabbit HRP conjugates (Bio-Rad Laboratories) and ECL detection system (Amersham Biosciences) were used. We measured hormone and adipokine levels in circulation of vehicle-treated and FGF-21–injected ob/ob mice using Multiplex assay kits from LINCO Research Inc.

Tissue preparation, histology analysis, and immunostaining. Tissues were fixed overnight in zinc-buffered formalin and then transferred to 70% ethanol prior to processing through paraffin. Five-micrometer sections were stained with H&E. Adjacent 5-micrometer sections were placed on positively charged slides. The slides were then baked overnight at 60°C in an oven and then deparaffinized in xylene and rehydrated through graded alcohols to water. Antigen retrieval was performed by immersing the slides in Target Retrieval Solution for 20 minutes at 90°C, cooling at 25°C for 10 minutes, and washing in water; we then proceeded with immunostaining. All subsequent staining steps were performed on the Autostimmunostainer; incubations and all washes were done at 25°C in 50 mM Tris-Cl, pH 7.4, containing 0.05% Tween-20. Slides were blocked with protein blocking solution for 25 minutes, and the PCNA antibody (PC10 clone) was incubated at a dilution of 1:10 for 1 hour. A biotinylated antibody plus streptavidin-HRP kit was then applied and followed with 3,3′-diaminobenzidine (DAB) staining. The slides were briefly counterstained with hematoxylin. All immunoreagents and the Autostimmunostainer were from Dako Corp.

Pancreatic islet isolation and hormone release studies. Pancreatic islets from male Wistar rats (200 g; Harlan Winkelmann GmbH) were isolated and cultured as described previously (35). For measurements of glucagon and insulin release, islets were starved in Earle’s balanced salt solution medium containing 1 mM glucose for 30 minutes. Groups of 10 (glucagon) or 3 (insulin) islets were selected and transferred into 0.3 ml of EBSB medium with tested compounds. Islets were further incubated for 90 minutes at 37°C with vehicle or FGF-21 (1 μg/ml), supernatants were collected, and hormone content was measured.

In vivo protocols. The protocols used in these studies were approved by the Eli Lilly Research Laboratories Institutional Animal Care and Use Committee. Mice were maintained in a controlled environment (21 ± 2°C, 50–60% humidity, 12-hour light-dark cycle, lights on at 6 am). Male ob/ob and db/db mice were from Harlan Teklad, fed Purina 5008 Chow, and had free access to food and water. FGF-21 was administered by s.c. injection in saline. For OGTT, the animals were fasted 16 hours and challenged with an oral glucose load (2.5 g/kg) 1 hour after the last injection. Blood samples were taken from conscious, fed animals by tail snap, and glucose and plasma triglyceride levels were determined using Precision G Blood Glucose Testing System (Abbott Laboratories) and Hitachi 912 Clinical Chemistry analyzer (Roche Diagnostics Corp.), respectively. Insulin and leptin levels were determined with murine ELISA kits (Crystal Chem Inc.). Male obese or lean ZDF rats were obtained from Charles River Laboratories Inc. and housed singly in a humidity and temperature-controlled environment (21 ± 2°C, 50–60% humidity, 12-hour light-dark cycle, lights on at 6 am) with free access to food (Purina 5008 Chow) and water for 2 weeks prior to start of the experiment. The day before the study, all animals were tail bled, and plasma glucose was analyzed on a Hitachi 912 Clinical Chemistry analyzer (Roche Diagnostics Corp.). Rats were then randomized based on their glucose levels and body weights and placed into groups. Animals were dosed with vehicle (0.9% saline), insulin (Humulgin; Eli Lilly and Company), or FGF-21 for 7 continuous days of twice-daily administration. On days 3 and 7, fed rats were bled (by tail snap) at 1-hour after administration of the last dose, and plasma glucose was assayed as described above.

The human apoE promoter including its hepatic control region (42) was used to express the human FGF-21 cDNA in transgenic mice. The transgenic vector was linearized and microinjected into C57BL/6Ntac eggs by standard methods (43). We identified transgenic mice by PCR using transgene-specific primers and confirmed transgene expression by real-time quantitative PCR on RNA isolated from livers as well as by ELISA on plasma obtained from the transgenic mice using an FGF-21 polyclonal antibody.

For high-fat feeding, all mice were housed individually in Micro-Isolator cages (Lab Products Inc.) and maintained from age 24 days on high-fat.
A wide-line nuclear magnetic resonance (NMR) instrument (Bruker BioSpin Corp.) was used to quantify tissue mass. Unanesthetized mice were placed into a 5-cm diameter glass cylinder that was lowered into the instrument. Data was obtained for 4.5 minutes (3 determinations at 1.5-minute intervals) and analyzed by the manufacturer’s software. The mean of triplicate determinations for apparent muscle mass, fat mass, and free water mass was calculated for each mouse. Coefficient of variation of all 3 masses determined for a live moving mouse was less than 3%.

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