Fatty acid metabolism in adipocytes: functional analysis of fatty acid transport proteins 1 and 4

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Abstract The role of fatty acid transport protein 1 (FATP1) and FATP4 in facilitating adipocyte fatty acid metabolism was investigated using stable FATP1 or FATP4 knockdown (kd) 3T3-L1 cell lines derived from retrovirus-delivered short hairpin RNA (shRNA). Decreased expression of FATP1 or FATP4 did not affect preadipocyte differentiation or the expression of FATP1 (in FATP4 kd), FATP4 (in FATP1 kd), fatty acid translocase, acyl-coenzyme A synthetase 1, and adipocyte fatty acid binding protein but did lead to increased levels of perilipin a and caveolin-1, and adipocyte fatty acid binding protein but did lead to increased levels of perilipin a and caveolin-1. Both FATP1 and FATP4 kd adipocytes exhibited reduced triacylglycerol deposition and corresponding reductions in diacylglycerol and monoacylglycerol levels compared with control cells. FATP1 kd adipocytes displayed an ~25% reduction in basal 3H-labeled fatty acid uptake and a complete loss of insulin-stimulated 3H-labeled fatty acid uptake compared with control adipocytes. In contrast, FATP4 kd adipocytes as well as HEK-293 cells overexpressing FATP4 did not display any changes in fatty acid influx. FATP4 kd cells exhibited increased basal lipolysis, whereas FATP1 kd cells exhibited no change in lipolytic capacity. Consistent with reduced triacylglycerol accumulation, FATP1 and FATP4 kd adipocytes exhibited enhanced 2-deoxyglucose uptake and a complete loss of insulin-stimulated 2-deoxyglucose uptake compared with control adipocytes. These findings define unique and distinct roles for FATP1 and FATP4 in adipose fatty acid metabolism.

Supplementary key words fatty acid influx • basal lipolysis • triacylglycerol synthesis • acyl-coenzyme A synthetase • 2-deoxyglucose uptake

Dysregulation in adipose fatty acid metabolism is a significant contributing factor to the development of obesity and associated metabolic diseases, such as type 2 diabetes, hypertension, and cardiovascular disease (1–3). Central to this imbalance are differing rates of long-chain fatty acid (LCFA) influx, efflux, and metabolism by adipose tissue. Although appreciated for decades, the molecular mechanisms that control and mediate fatty acid flux in fat cells remain poorly defined from structural, mechanistic, and regulatory viewpoints.

Although diffusion may play a fundamental role in the transbilayer movement of LCFA, molecular and genetic evidence from loss- or gain-of-function studies have identified a number of proteins facilitating some component of the fatty acid influx process (4–8). Proteins implicated in fatty acid uptake are fatty acid translocase (CD36), acyl-CoA synthetases [fatty acid transport protein (FATP) and acyl-coenzyme A synthetase (ACSL) family members], plasma membrane fatty acid binding protein, and caveolin-1. The relative contribution of each polypeptide to overall cellular fatty acid influx has not been quantitatively evaluated.

FATPs are a family of membrane-bound proteins that catalyze the ATP-dependent esterification of LCFA and very LCFA to their acyl-CoA derivatives (9). The FATPs bear 20–40% sequence identity to the long-chain ACSL class of proteins that function in long-chain acyl-CoA production. In mammals, six different isoforms of FATP (FATP1 to FATP6) have been identified with tissue-specific expression patterns (10). White adipose tissue predominantly expresses FATP1, FATP4, and ACSL1, whereas brown adipose tissue additionally expresses ACSL5. FATP1 is a 63 kDa protein localized primarily to high-density membranes and to a lesser extent in the plasma and low-density membrane fractions of murine adipocytes and 3T3-L1 cells (5). FATP1 (as well as ACSL1) was identified using an expression clone strategy designed to identify proteins that enhanced LCFA uptake (11). Evidence for the role of FATPs in fatty acid transport has been qualitatively evaluated by various loss-of-function/gain-of-function model systems. Stable HEK-293 cell lines over-

Abbreviations: ACSL1, acyl-coenzyme A synthetase 1; AFABP/aP2, adipocyte fatty acid binding protein; CD36, fatty acid translocase; C/EBPα, CCAAT/enhancer binding protein α; FATP1, fatty acid transport protein 1; kd, knockdown; KRH, Krebs-Ringer’s HEPES; LCFA, long-chain fatty acid; PPARγ, peroxisome proliferator-activated receptor γ; RNAi, RNA interference; shRNA, short hairpin RNA.

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expressing murine FATP1 demonstrate increased LCFA uptake and triacylglycerol accumulation (12). A transgenic mouse model with cardiac-specific expression of FATP1 demonstrated increased myocardial LCFA uptake (13). Disruption of the FATP1 homolog expressed in yeast, fatlp, markedly impaired LCFA uptake (14), and a murine FATP1 knockout mouse exhibited reduced muscle acyl-CoA levels and increased insulin sensitivity (15).

FATP4 is the closest homolog of FATP1 (60.3% identity) that is expressed in adipose tissue (16). Its role in adipose tissue metabolism is largely unknown. However, FATP4 is also expressed in skeletal muscle, heart, skin, and liver and is the principal fatty acid transporter in the small intestine, localized to the apical side of enterocytes, where it is thought to mediate the uptake of dietary fatty acids (17). FATP4 null mice displayed features of a human neonatally lethal restrictive dermopathy that has been associated with a disturbed function in the epidermal barrier (18–20). FATP4 encodes an ACSL with substrate specificity to very LCFAAs that may be required for the synthesis of lipids crucial in the formation of a healthy epidermis (21, 22). Polymorphisms in the human FATP4 gene locus have identified this gene as a candidate for the insulin resistance syndrome (23). Moreover, FATP4 expression levels correlated with measures of acquired obesity and insulin resistance (24). These observations indicate the importance of the study of FATP4 function in adipocyte fatty acid uptake and metabolism.

Our long-term goal is to identify and define in quantitative terms the mechanisms controlling LCFA flux in mammalian cells and the roles of specific proteins implicated in the influx reaction. In this report, we evaluated the specific role(s) of FATP1 and FATP4 in mediating LCFA influx and efflux using FATP1/FATP4 knockdown (FATP1/FATP4kd) 3T3-L1 adipocytes produced using lentiviral delivery of short hairpin RNA (shRNA) targeted toward FATP1 or FATP4. We report here that FATP1 facilitates the insulin-stimulated component of LCFA uptake but has only a minor role in basal LCFA uptake in 3T3-L1 adipocytes. FATP4 does not play a rate-limiting role in either basal or insulin-stimulated fatty acid uptake. FATP4 kd adipocytes exhibited increased basal lipolysis, suggesting a role in fatty acid reesterification in 3T3-L1 adipocytes.

MATERIALS AND METHODS

Materials

Cell culture reagents were obtained from Invitrogen. Porcine insulin, puromycin, cytochalasin B, and deoxyglucose were obtained from Sigma-Aldrich. Geneticin was obtained from Gibco/BRL Life Technologies. Nonradioactively labeled fatty acids were obtained from Nu-Chek Prep, Inc. (Elysian, MN). [3H]oleic acid and [3H]lignoceric acid were obtained from American Radiochemicals Co. [3H]palmitic acid, [3H]arachidonic acid, and [14C]2-deoxy-o-glucose were obtained from Amersham Pharmacia Biotech. Antibodies used were as follows: rabbit anti-CD36, rabbit antiperoxisome proliferator-activated receptor γ (PPARγ), and rabbit anti-CCAAT/enhancer binding protein α (C/EBPα; obtained from Santa Cruz Biotechnology, Inc.); rabbit anti-GLUT4 (a gift from Dr. H. Haspel, Charles River Laboratory, Wilmington, MA); rabbit anti-AcS1 (a gift from Dr. Rosalind Coleman, University of North Carolina, Chapel Hill, NC); rabbit anti-FATP4 (a gift from Dr. Paul Watkins, Kennedy Krieger Research Institute, Baltimore, MD); and HRP-coupled IgGs (obtained from Jackson ImmunoResearch Laboratories, Inc.). All other reagents were of analytical grade and obtained from Sigma.

Cell culture conditions

3T3-L1 preadipocytes were cultured and differentiated into adipocytes as described previously (25). Briefly, preadipocytes were cultured in DMEM containing 10% calf serum. Two days after reaching confluence, cells were induced to differentiate in DMEM supplemented with 10% FBS, 174 μM insulin, 0.5 mM methylisobutylxanthine, and 0.25 μM dexamethasone. Two days after initiation of differentiation, dexamethasone and methylisobutylxanthine were withdrawn from the medium, whereas insulin was withdrawn after 4 days. Differentiated adipocytes were maintained in DMEM and 10% FBS until mature (days 8–12).

Generation of FATP1 kd and FATP4 kd 3T3-L1 adipocytes using lentivirus-delivered RNA interference

The lentivirus-based RNA interference (RNAi) vector pLKO1 (kindly provided by Sheila Stewart at the Whitehead Institute, Cambridge, MA) was used for siRNA-mediated FATP1 kd in cultured 3T3-L1 cells. This vector was shown to stably express shRNAs under the control of the RNA polymerase III promoter of the U6 gene in nondividing cells (26). Oligomers 60 bp in length containing a stem-loop structure directed against FATP1 and FATP4 were synthesized and cloned into the AgAl/EO-Rl site in pLKO1. Four siRNA sequence variants for each gene were synthesized and analyzed. Based on the ability of the lentiviral RNAi vector to effectively silence the expression of FATP1/FATP4 by 75% or more in HEK-293T cells transiently cotransfected with a FATP1/FATP4 expression vector and each of the four lentiviral RNAi vectors, one of the gene sequence variant constructs was selected for the generation of recombinant lentiviruses. The selected oligomer targeting the FATP1 nucleotide sequence was 5′-TGCTGTAGCCACACCTGTTCC-3′ (nucleotide positions 342–361) and that targeting the FATP4 nucleotide sequence was 5′-GGCCAGGCTCTCATTCT-3′ (nucleotide positions 519–536). A construct expressing shRNA against a scrambled FATP1 sequence (5′-TGGTTCTTCAAGAGGGGATG-3′) was used as a control. Recombinant lentiviruses were packaged in HEK-293T cells and harvested at 24, 48, and 72 h later (4). 3T3-L1 fibroblasts were transduced with the lentiviruses for 4–6 h in the presence of 6 μg/ml polybrene at a multiplicity of infection of ~50–100. Cells were allowed to recover for 48 h before transduction before the addition of selection media containing 2 μg/ml puromycin. Stable kd cell lines were generated from a heterogeneous pool of puromycin-resistant 3T3-L1 fibroblasts.

Generation of stable HEK-293 cells expressing FATP4

FATP4 subcloned into pcDNA3.0 (Invitrogen) or vector control was linearized and introduced into HEK-293 cells by electroporation. HEK-293 cells are an excellent model system to evaluate FATP4 function in lipid metabolism because they are a well-defined cell system, grow easily in culture, and have been shown to tolerate FATP expression (12). Dilutions of the electroporated cells were plated in DMEM containing 10% FBS and incubated at 37°C and 5% CO2. Selection was initiated after 48 h with the addition of 400 μg/ml geneticin. After 8 days, colonies were selected using cloning rings and individual lines were developed. Once established, several lines were analyzed for FATP4...
expression. The cell lines and vector control cells were maintained in 400 μg/ml genetin. FATP4-overexpressing cell lines were analyzed for total cellular lignoceryl (C24:0) CoA synthetase activities and oleate (C18:1) uptake by a procedure similar to that used for 3T3-L1 adipocytes.

**Immunoblot analysis**

3T3-L1 adipocytes were lysed in a buffer containing 50 mM Tris-HCl, pH 7.5, 50 mM sodium fluoride, 5 mM sodium pyrophosphate, 1 mM ethylenediamine tetraacetic acid, 1 mM dithiothreitol, 0.1 mM phenylmethyl sulfonyl fluoride, 10% glycerol, and protease and phosphatase inhibitors. Crude cell extracts (50–100 μg of total protein) were separated by electrophoresis on a denaturing SDS-polyacrylamide gel and transferred to nitrocellulose or polyvinylidene difluoride membranes. The membranes were blocked with 5% nonfat milk in TBST (100 mM Tris, pH 7.4, 0.9% sodium chloride, and 0.05% Tween-20) for 1 h at room temperature. After incubation with primary antibodies, the membranes were incubated with secondary antibodies conjugated to horseradish peroxidase. Antibody reactivity was detected by chemiluminescence, and protein abundance was quantitated by densitometry using a FujiFilm FLA-5000 detector.

**Analysis of cellular fatty acid uptake**

3T3-L1 adipocytes (day 8) were preincubated for 3 h in Krebs-Ringer’s HEPS (KRH) buffer (pH 7.4) containing 120 mM NaCl, 4.7 mM KCl, 2.2 mM CaCl₂, 10 mM HEPS, 1.2 mM KH₂PO₄, 1.2 mM MgSO₄, and 5.4 mM glucose. Stock solutions (5 mM) of nonradioactive fatty acids were prepared. Radioactive lipid analysis

- Analysis of cellular fatty acid uptake
  - 3T3-L1 adipocytes were plated on 13 mm optical glass coverslips and differentiated as described previously. On day 6, the cells were washed free of serum and maintained in DMEM for 2 h. Insulin was added (50 ng/ml), and after 30 min the cells were washed in PBS and fixed in 3% paraformaldehyde for 30 min at 25°C. After fixation, the cells were rinsed in PBS containing 0.01% digoxin and incubated for 2 h at 25°C in blocking buffer containing 0.01 M phosphate, 5% goat serum, 5% glycerol, 1% cold water fish gelatin, and 0.01% digoxin. The cells were subsequently incubated overnight at 4°C in a 1:50 dilution of rabbit anti-FATP1 or anti-FATP4 antibody or in a 1:100 dilution of rabbit anti-GLUT4 antibody in PBS containing 0.01% digoxin. After washing, the coverslips were incubated for 1 h at 25°C in a 1:400 dilution of Alexa Fluor 488-conjugated donkey anti-rabbit IgG in PBS with 0.01% digoxin. After washing, the coverslips were incubated at 25°C in DMEM with 7.7 μM TOPRO3 (Molecular Probes) for nuclear staining, then washed, mounted, and visualized by confocal microscopy.

**Confocal microscopy**

Monolayers were viewed using a Bio-Rad MRC-1024 confocal microscope attached to a Nikon Diaphot inverted microscope equipped with a 15 mW krypton/argon laser. Excitation filters allowing 488 and 647 nm were used sequentially to visualize the Alexa Fluor 488 and TOPRO3 probes, respectively. Digital images were collected using LaserSharp version 3.2 software (Bio-Rad) and analyzing using Image Pro Plus version 4.5 software (Media Cybernetics, Silver Spring, MD).

**Analysis of 2-deoxyglucose uptake**

Glucose uptake in 3T3-L1 adipocytes was carried out as described (30). Briefly, cells were serum-starved in KRH buffer supplemented with 0.5% BSA and 2 mM sodium pyruvate (pH 7.4) and incubated either with or without 100 nM insulin for 30 min at 37°C. Glucose uptake was initiated by the addition of [²⁴C]2-deoxy-o-glucose to a final assay concentration of 100 μM at 37°C. After 5 min, 2-deoxyglucose uptake was terminated by three washes with ice-cold KRH buffer, and the cells were solubilized with 0.8 ml of KRH buffer containing 1% Triton X-100. The incorporated radioactivity was determined by scintillation counting. Nonspecific 2-deoxyglucose uptake was measured in the presence of 20 μM cytocholins B and subtracted from the total glucose uptake assayed to determine specific uptake.

**RESULTS**

To assess the role of FATP1 and FATP4 in fatty acid metabolism in adipocytes, we used stable 3T3-L1 adipocyte
FATP1 kd and FATP4 kd cell lines derived from lentivirus-delivered shRNA targeting either protein. Such kd pre-adipocytes grew at a normal rate and differentiated using the standard methylisobutylxanthine, dexamethasone, and insulin protocol. An essentially complete loss of FATP1 expression was observed in cells expressing FATP1 sequence-specific shRNA (FATP1 kd), indicating that the protein is not required for adipose conversion. Expression of shRNA directed toward FATP4 (FATP4 kd) produced a cell line exhibiting ~10% of the control FATP4 level (Fig. 1). Immunoblotting of protein extracts from FATP1 kd, FATP4 kd, and control cells revealed an ~50% increase in the expression of PPARγ and an ~20% increase in C/EBPα protein. Despite the increase in expression of key adipogenic transcription factors, the expression of proteins regulated by PPARγ and implicated in some facet of fatty acid influx (CD36, ACSL1, FATP4/FATP1) and/or the PPARγ target genes adipocyte fatty acid binding protein (AFABP/aP2), CD36, and FATP were unchanged in abundance in both cell lines (Fig. 1).

Both FATP1 kd and FATP4 kd adipocytes exhibited reduced accumulation of triacylglycerol. Oil Red O staining of triacylglycerol droplets was reduced markedly, exhibiting smaller lipid droplet sizes in FATP1 kd and FATP4 kd 3T3-L1 adipocytes relative to the scrambled control (which was not different from uninfected or vector-infected adipocytes; results not shown). Consistent with the reduced Oil Red O staining, FATP1 kd and FATP4 kd cells exhibited decreased triacylglycerol, diacylglycerol, and monoacylglycerol levels. FATP4 kd cells, but not FATP1 kd cells, exhibited a decrease in free fatty acid level (Fig. 2).

FATP1 is an ACSL with broad substrate specificity (C16:0 vs. C24:0 esterification) but a rather low enzymatic reaction rate relative to other fatty acid CoA ligases. Conversely, FATP4 has a high ACSL reaction rate relative to FATP1 and ACSL1 and has a substrate preference for very long-chain (C24:0) over long-chain (C16:0) fatty acids (21). To evaluate the effect of FATP1 kd and FATP4 kd on total cellular ACSL activity, extracts were prepared and assayed for fatty acid esterification using a variety of fatty acid substrates. As shown in Table 1, kd of FATP1 resulted in an ~15–40% increase in cellular C16:0, C18:1, and C20:4 esterification activity but essentially no change in total cellular C24:0 ACSL activity. Compared with FATP1 kd adipocytes, FATP4 kd adipocytes displayed a 20–25% decrease in cellular C16:0, C18:1, and C20:4 ACSL activities and no change in total cellular C24:0 ACSL. The decrease in total ACSL activity for either kd cell line (10–25%) correlated well with the measured decrease in triacylglycerol, diacylglycerol, and monoacylglycerol levels in the cell (Fig. 2).

Because there was a significant, albeit modest, decrease in total cellular ACSL activities as well as triacylglycerol levels, we assessed the role that FATP1 and FATP4 may play in fatty acid uptake. Stahl and colleagues (5) have reported that insulin stimulates the translocation of FATP1 from intracellular sites to the plasma membrane. To assess this, 3T3-L1 adipocytes were serum-starved and then incubated with or without insulin for 30 min, and the expression of FATP1, FATP4, and GLUT4 was evaluated using secondary immunofluorescence. As shown in Fig. 3, the majority of immunoreactive GLUT4 translocated to the plasma membrane, as did some immunoreactive FATP1 (estimated to be 10%). In contrast to FATP1 and GLUT4, FATP4 did not appear to be localized to the plasma membrane under basal conditions and did not translocate to the plasma membrane in the presence of insulin.

To parallel the translocation studies for FATP1 and FATP4 shown immunochemically with biochemical analysis, the cellular influx of [3H]labeled fatty acids of different chain lengths was evaluated under basal and insulin-stimulated conditions. As shown in Fig. 4A, under basal conditions, compared with control cells, FATP1 kd adipocytes displayed an ~25% decrease in fatty acid uptake for [3H]palmitic acid, [3H]oleic acid, and [3H]arachidonic acid. Because of its poor solubility, influx studies with C24:0 were not performed. For control 3T3-L1 adipocytes, insulin stimulation led to an ~15–40% increase in fatty acid influx for [3H]palmitic acid, [3H]oleic acid, and [3H]arachidonic acid. The increase in [3H]palmitic and [3H]oleic acid uptake in response to insulin was com-
pletely lost in FATP1 kd cells, indicating a crucial role of FATP1 in insulin-stimulated fatty acid influx. This is consistent with the translocation of FATP1 to the plasma membrane in response to insulin (Fig. 3) and is indicative of the role of FATP1 in fatty acid uptake as a critical function of its cellular location. The increase in [3H]arachidonic acid uptake with insulin stimulation in FATP1 kd cells is not completely lost but is decreased by ~20% compared with the response of control cells to insulin. This suggests that in addition to FATP1, another ACSL with substrate specificity for arachidonic acid may facilitate its cellular uptake.

Despite FATP4 having the highest ACSL enzyme reaction rates relative to other cellular ACSLs, such as FATP1 and ACSL1, FATP4 kd adipocytes did not demonstrate any change in [3H]palmitic, [3H]oleic, or [3H]arachidonic acid uptake relative to the control cells under both basal and insulin-stimulated conditions (Fig. 4B). This is in agreement with the results of fatty acid influx studies carried out with different stable HEK-293 cell lines expressing varying amounts of FATP4 (Fig. 5). The amount of FATP4 expressed by each individual cell line was analyzed by immunoblotting and densitometric analysis and represented as arbitrary FATP4 units. As shown in Fig. 5A, the ACSL activity for a C24:0 fatty acid substrate varied proportionately to the amount of FATP4 being expressed. However, the varying expression levels of FATP4 in HEK-293 cells did not affect the rate of cellular fatty acid influx for [3H]oleic acid (Fig. 5B). Thus, unlike FATP1, FATP4 is not translocated to the plasma membrane in response to insulin and is not rate-limiting for basal or insulin-stimulated fatty acid uptake.

To contrast the results of fatty acid influx observed in FATP1 kd and FATP4 kd adipocytes with measures of fatty acid efflux, control, FATP1 kd, and FATP4 kd adipocytes were evaluated for their ability to carry out basal and forskolin-stimulated lipolysis. Lipolysis was measured as the amount of glycerol and fatty acids released from cells as a result of triglyceride hydrolysis. As shown in Fig. 6.
glycerol and fatty acid release in control, FATP1 kd, and FATP4 kd adipocytes exhibited no significant differences between all cell types under forskolin-stimulated conditions. Consistent with the smaller droplet size, FATP1 kd adipocytes exhibited reduced basal fatty acid release. In contrast, FATP4 kd adipocytes exhibited an ~30% increase in glycerol and an ~75% increase in fatty acid release during basal lipolysis.

Insulin stimulated the translocation of FATP1 to the plasma membrane, which correlated with the increase in fatty acid uptake observed in control adipocytes that was diminished in FATP1 kd adipocytes. As opposed to FATP1, FATP4 remained localized to intracellular membranes even with insulin stimulation and did not affect fatty acid uptake. To further understand the unique roles of these two fatty acid transporters in fat, we analyzed the differences in the metabolism of palmitate into various complex lipid pools after cellular influx in FATP1 kd, FATP4 kd, and control adipocytes under basal and insulin-stimulatory conditions. As shown in Table 2, under both basal and insulin-stimulated conditions, the vast majority of the fatty acid (>90%) is activated to CoA esters and incorporated into neutral lipids, primarily triacylglycerol. A very small fraction (only 2%) of fatty acids are retained intracellularly without being metabolized (Table 2). Comparison of lipid profiles between FATP1 kd and control adipocytes indicated that although there was an ~15% decrease in total fatty acid uptake in the FATP1 kd adipocytes under basal conditions, there was essentially a 100% decrease in the insulin-stimulated fraction of uptake. A corresponding decrease in fatty acyl-CoA levels and triacylglycerol synthesis was observed in FATP1 kd adipocytes compared with the control. These results are consistent with a requirement for FATP1 in the insulin-stimulated component of LCFA influx and triacylglycerol synthesis in 3T3-L1 adipocytes. Although FATP4 did not play a role in fatty acid uptake under basal conditions, an ~40% decrease in the fatty acyl-CoA pools

**Fig. 3.** Immunolocalization by confocal microscopy of FATP1 and FATP4 compared with the glucose transporter GLUT4 under basal and insulin-stimulatory conditions in 3T3-L1 adipocytes. Serum-starved day 6 3T3-L1 adipocytes were treated with or without 50 ng/ml insulin for 30 min. Fluorescent detection was enabled by incubation with the secondary antibody Alexa Fluor 488 donkey anti-rabbit IgG (green) and subsequent nuclei staining with TOPRO3 (blue).
was observed in FATP4 kd adipocytes relative to the control (Table 3). The mechanistic basis for this is unclear, but it may suggest that other proteins may be rate-limiting for LCFA influx but that FATP4 plays a role in internalized lipid esterification. With insulin stimulation, however, no change was observed in fatty acyl-CoA levels or in any other complex lipid class pool analyzed.

Because both FATP1 kd and FATP4 kd adipocytes had reduced lipid contents compared with the control cells, and reduced triacylglycerol deposition is often correlated with increased hexose uptake (31, 32), we evaluated the loss of each FATP isoform on basal and insulin-stimulated 2-deoxyglucose uptake. Interestingly, there was an ~30% increase in basal and insulin-stimulated glucose uptake in FATP1 kd adipocytes compared with the control (Fig. 7).

DISCUSSION

Since its discovery in 1994, FATP1 has been investigated for its role in fatty acid transport and regulation. Various overexpression systems and a knockout mouse model have implicated FATP1 in fatty acid uptake (13, 15). FATP1 transcription is regulated by multiple systems: negatively by insulin and positively by a PPARγ-dependent mechanism (33, 34). Consistent with this, FATP1 expression in muscle and fat is increased in obese diabetic animals, and mice...
null for FATP1 exhibit reduced skeletal muscle LCFA uptake and resistance to high-fat diet-induced insulin resistance (15, 35). In fat cells, rosiglitazone, a PPARγ agonist, increases the expression of both CD36 and FATP1, suggesting that the lipid-lowering effects of this insulinsensitizing drug may be exerted at the level of adipose LCFA influx (36). Thus, the identification of a precise role for FATP1 in fatty acid influx may be crucial to understanding the mechanism of the beneficial insulinsensitizing effects of this widely used class of drugs.

Although loss- and gain-of-function model systems have defined a role of FATP4 as a major intestinal fatty acid transporter and in the maintenance of the skin’s epidermal barrier function, its role in adipocyte fatty acid uptake and lipid metabolism is less well defined. FATP4 expression in primary human placental trophoblasts is regulated by PPARγ and retinoid X receptor (37). Genetic polymorphisms in humans support a role of FATP4 in insulin sensitivity (23). Indeed, heterozygotes for a G209S polymorphism (serine frequency of 5%) exhibited lower body mass index, lower serum fatty acids and triglycerides, reduced systolic blood pressure, and diminished insulin levels. FATP4 expression levels correlate with acquired obesity that is independent of genetic background (24).

Using a lentivirus-delivered RNAi kd technique, we succeeded in suppressing the FATP1/FATP4 protein expression levels in 3T3-L1 adipocytes essentially quantitatively. Interestingly, loss of FATP1 and FATP4 independently led to an increase in the expression of both C/EBPα and PPARγ. The mechanistic basis for this increase is not clear but may be related to reduced PPARγ degradation affecting negative feedback regulation of the receptor, as opposed to changes in activating factors (38). Despite the increased expression of these key transcription factors, other PPARγ targets were not increased in expression, including AFABP/ap2, ACSL1, and CD36. Knockout of FATP1 or FATP4 in 3T3-L1 adipocytes led to small changes in total cellular long-chain ACSL activities without causing any change in cellular very long-chain ACSL activity.
Depletion of FATP1 expression resulted in an essentially quantitative loss in insulin-stimulated oleic and palmitic acid uptake and an \(~20\%\) decrease in insulin-stimulated arachidonic acid influx. Significant reduction in FATP1 expression level, however, caused only a small \(~5\%\) decrease in basal LCFA influx for all fatty acids analyzed. Depletion of FATP4, on the other hand, did not affect either basal or insulin-stimulated fatty acid uptake, and overexpression of FATP4 in HEK-293 cells did not affect cellular fatty acid influx rates. We (Fig. 3) and others (5) have shown that in 3T3-L1 adipocytes, insulin can stimulate the translocation of FATP1 from intracellular membranes to the plasma membrane. However, as opposed to GLUT4, only a small fraction (estimated to be \(<10\%)\) of total FATP1 translocated. As such, the increase in the relative abundance of the enzyme at the plasma membrane correlates with increased LCFA influx and may be crucial to regulation of the fatty acid transport function of FATP1. Our results with FATP4 kd adipocytes indicate that although FATP4 has a high ACSL reaction rate relative to FATP1 and ACSL1, it is localized to internal membranes and not the plasma membrane, which could be the reason why it does not contribute to either insulin-stimulated or basal fatty acid uptake. In contrast to our studies, FATP4 overexpressed in COS cells (which too was localized to the endoplasmic reticulum) did result in a net increase in LCFA influx (39). It is not clear whether these contradictory findings are the result of differences in the absolute level of FATP4 expression, differences in experimental assay conditions, or simply a difference in the cell culture system used.

Our results do not eliminate the possibility of other proteins functioning in insulin-stimulated LCFA influx. Indeed, insulin-stimulated arachidonic acid uptake is not completely lost in FATP1 kd adipocytes, suggesting that another ACSL could participate in insulin-stimulated arachidonic acid fatty acid influx. ACSL1, which has been suggested to form a complex with FATP1 (6), could participate in some facet of insulin-stimulated or basal LCFA influx. What is not clear in this study is what facilitates basal LCFA influx in adipocytes. Insulin stimulation of LCFA influx is fatty acid-specific and is quantitatively modest \((\sim 15\%\)–40\%) relative to insulin-stimulated hexose uptake \((5\%\) to 20-fold). Other factors (caveolin-1, CD36, ACSL1) are likely contributors to basal LCFA influx.

Fatty acid reestherification within the adipocyte can vary by 30–70\% during periods of basal lipolysis, affecting the net output of lipid from the adipocyte (40). The basal

### Table 2. Complex lipid synthesis in FATP1 kd and scrambled 3T3-L1 adipocytes

<table>
<thead>
<tr>
<th>Variable</th>
<th>Scrambled Control</th>
<th>FATP1 kd</th>
<th>Scrambled Control</th>
<th>FATP1 kd</th>
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<tr>
<td>Total incorporation</td>
<td>6.78 ± 0.25</td>
<td>5.83 ± 0.21&lt;sup&gt;a&lt;/sup&gt;</td>
<td>9.00 ± 0.38</td>
<td>6.22 ± 0.26&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>Cellular lipid class</td>
<td></td>
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<tr>
<td>Fatty acids</td>
<td>0.09 ± 0.01</td>
<td>0.07 ± 0.003&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.07 ± 0.01</td>
<td>0.04 ± 0.01&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>Fatty acyl-CoA</td>
<td>0.71 ± 0.03</td>
<td>0.55 ± 0.05&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.98 ± 0.07</td>
<td>0.78 ± 0.07&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Neutral lipids</td>
<td>4.32 ± 0.12</td>
<td>3.02 ± 0.10&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.53 ± 0.24</td>
<td>4.38 ± 0.45&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>Neutral lipid class</td>
<td></td>
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<tr>
<td>Triacylglycerol</td>
<td>2.51 ± 0.13</td>
<td>2.13 ± 0.09&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4.69 ± 0.03</td>
<td>3.07 ± 0.24&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Diacylglycerol</td>
<td>0.13 ± 0.02</td>
<td>0.14 ± 0.01</td>
<td>0.53 ± 0.07</td>
<td>0.46 ± 0.02&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Monoacylglycerol</td>
<td>0.26 ± 0.02</td>
<td>0.28 ± 0.01</td>
<td>0.83 ± 0.09</td>
<td>0.71 ± 0.01&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Serum-starved 3T3-L1 adipocytes were incubated with \([^{3}H\]palmitic acid bound to albumin for 5 min at 37°C in the absence (basal) and presence of 100 nM insulin. Cellular lipids were extracted and fractionated, and the incorporation of radiolabel into various lipid pools was determined. The results are representative of three independent experiments.

<sup>a</sup> P < 0.05 comparing experimental with scrambled control values.

### Table 3. Complex lipid synthesis in FATP4 kd and scrambled 3T3-L1 adipocytes

<table>
<thead>
<tr>
<th>Variable</th>
<th>Scrambled Control</th>
<th>FATP4 kd</th>
<th>Scrambled Control</th>
<th>FATP4 kd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total incorporation</td>
<td>6.78 ± 0.25</td>
<td>5.83 ± 0.21&lt;sup&gt;a&lt;/sup&gt;</td>
<td>9.00 ± 0.38</td>
<td>6.22 ± 0.26&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Cellular lipid class</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatty acids</td>
<td>0.09 ± 0.01</td>
<td>0.07 ± 0.003&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.07 ± 0.01</td>
<td>0.04 ± 0.01&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Fatty acyl-CoA</td>
<td>0.71 ± 0.03</td>
<td>0.55 ± 0.05&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.98 ± 0.07</td>
<td>0.78 ± 0.07&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Neutral lipids</td>
<td>4.32 ± 0.12</td>
<td>3.02 ± 0.10&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.53 ± 0.24</td>
<td>4.38 ± 0.45&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Neutral lipid class</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Triacylglycerol</td>
<td>2.51 ± 0.13</td>
<td>2.13 ± 0.09&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4.69 ± 0.03</td>
<td>3.07 ± 0.24&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Diacylglycerol</td>
<td>0.13 ± 0.02</td>
<td>0.14 ± 0.01</td>
<td>0.53 ± 0.07</td>
<td>0.46 ± 0.02&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Monoacylglycerol</td>
<td>0.26 ± 0.02</td>
<td>0.28 ± 0.01</td>
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</tbody>
</table>

Serum-starved 3T3-L1 adipocytes were incubated with \([^{3}H\]palmitic acid bound to albumin in the absence (basal) and presence of 100 nM insulin. Cellular lipids were extracted and fractionated, and the incorporation of radiolabel into various lipid pools was determined. The results are representative of three independent experiments.

<sup>a</sup> P < 0.05 comparing experimental with scrambled control values.
The lipolytic rate is proportional to triacylglycerol deposition, and in general, larger fat cells have greater rates of basal lipolysis than do small fat cells (41). However, the mechanism and the components involved in basal lipolysis are less well characterized. Here, we show that under basal lipolytic conditions, FATP4 knockdown (kd) adipocytes exhibited an increase in the amount of glycerol and fatty acid released relative to a control scrambled cell line. One explanation for this is that the ACSL activity of FATP4 may facilitate some component of the CoA-dependent reesterification of fatty acids derived from basal lipolysis of the triacylglycerol droplet. Other ACSLs, such as ACSL1, which has been found to be associated with the lipid droplet, may also play a role in fatty acid reesterification during basal lipolysis (42). However, alternative explanations also exist.

Experiments analyzing the distribution of [3H]palmitate into various complex lipids indicate that in 3T3-L1 adipocytes, the vast majority of incoming fatty acids are converted to their acyl-CoA derivatives and preferentially shunted into the triacylglycerol synthesis pathway. In FATP1 kd adipocytes, a decrease in LCFA influx was coupled with reduced acyl-CoA levels as well as triacylglycerol, diacylglycerol, and monoacylglycerol pools. Importantly, the LCFA pool was not increased but also similarly reduced, consistent with the model that the ACSL activity of FATP1 is critical for facilitating LCFA influx. These results are in agreement with the observations of Stuhlsatz-Krouper, Bennett, and Schaffer (43), who have shown that mutation of FATP1 serine 250 to alanine not only reduced the catalytic activity of the enzyme but also eliminated LCFA influx, implying that catalysis is functionally linked to uptake. In contrast to FATP1 kd adipocytes, FATP4 kd adipocytes revealed no change in basal or insulin-stimulated cellular fatty acid influx. Under basal conditions, FATP4 kd adipocytes revealed a decrease in the incorporation of [3H]palmitate into acyl-CoA pools but not triglyceride pools. The mechanistic basis for this is undetermined but suggests that under basal conditions, FATP4 functions in LCFA esterification but that other proteins may mediate the rate-controlling steps in internalization. With insulin stimulation, however, no changes in the fatty acyl-CoA pools incorporating [3H]palmitate were observed, consistent with the anti-lipolytic effects of the hormone insulin and the proposed role of FATP4 in basal lipolysis. Stralfors and colleagues (44) recently reported that the conversion of fatty acids to triacylglycerol occurs on or around the plasma membrane of rat adipocytes. Our results reported here are consistent with this view and imply that acyl-CoA production at the plasma membrane may be mechanistically linked to triacylglycerol synthesis via some type of organized lipid synthesis machinery.

Both FATP1 kd and FATP4 kd adipocytes exhibited increased insulin-stimulated glucose uptake. FATP1 knockout mice exhibit a similar increase in insulin-stimulated glucose uptake in soleus muscle compared with wild-type mice (45). Although the increase in glucose uptake may be quantitatively modest, over time small changes in glucose uptake have important metabolic consequences, including insulin sensitivity, such as that observed in FATP1 knockout mice and humans expressing either the S209 or G209 polymorphism of the FATP4 gene. In both FATP1 kd and FATP4 kd cells, the abundance of several potential lipid regulators (diacylglycerol, LCFA) (46) of insulin signaling is altered. Consequently, the development of FATP1/FATP4 kd adipocytes may provide an opportunity to identify lipid-derived signaling pathways that originate from altered triacylglycerol levels that affect insulin resistance in adipocytes.

In summary, although FATP1 and FATP4 both possess ACSL enzyme activities and share 60.3% sequence identity, each has unique functional roles in the adipocyte. FATP1 plays a minor role in basal fatty acid uptake, and by virtue of its translocation to the plasma membrane from intracellular membranes in response to insulin, plays a major role in insulin-stimulated fatty acid uptake. FATP4 is an intracellular ACSL that does not play a rate-limiting role in either basal or insulin-stimulated fatty acid uptake and may be involved in fatty acid reesterification after lipolysis. FATP1 and FATP4, by virtue of their distinctive
cellular locations and roles, affect triglyceride lipid drop-
let size and other complex lipid pools, both of which have
been implicated in the development of adipocyte and insu-
lin resistance.

The authors thank Dr. Paul Watkins for advice on the selection
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