PKCλ in liver mediates insulin-induced SREBP-1c expression and determines both hepatic lipid content and overall insulin sensitivity

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PKCλ is implicated as a downstream effector of PI3K in insulin action. We show here that mice that lack PKCλ specifically in the liver (L-λ.KO mice), produced with the use of the Cre-loxP system, exhibit increased insulin sensitivity as well as a decreased triglyceride content and reduced expression of the sterol regulatory element–binding protein-1c (SREBP-1c) gene in the liver. Induction of the hepatic expression of Srebp1c and of its target genes involved in fatty acid/triglyceride synthesis by fasting and refeeding or by hepatic expression of an active form of PI3K was inhibited in L-λ.KO mice compared with that in control animals. Expression of Srebp1c induced by insulin or by active PI3K in primary cultured rat hepatocytes was inhibited by a dominant-negative form of PKCλ and was mimicked by overexpression of WT PKCλ. Restoration of PKCλ expression in the liver of L-λ.KO mice with the use of adenovirus-mediated gene transfer corrected the metabolic abnormalities of these animals. Hepatic PKCλ is thus a determinant of hepatic lipid content and whole-body insulin sensitivity.


Introduction

The liver is essential for both carbohydrate and lipid homeostasis. Individuals with type 2 diabetes often exhibit impairment of insulin action in the liver (1), and liver-specific inhibition of insulin signaling in mice results in glucose intolerance and dyslipidemia (2), indicating the physiological importance of hepatic insulin action in energy homeostasis. Among the signaling molecules activated by insulin, PI3K plays a key role in the metabolic actions of this hormone (3, 4). Prevention of the insulin-induced activation of PI3K in the liver of mice thus results in glucose intolerance and dyslipidemia (5).

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Nonstandard abbreviations used: atypical PKC (aPKC); sterol regulatory element–binding protein-1c (SREBP-1c); glucose-6-phosphatase catalytic subunit (G6PC); insulin receptor substrate (IRS); glucokinase (GCK); IκB kinase-β (IKKβ).

However, the signaling molecules that function downstream of PI3K to mediate the metabolic actions of insulin in living animals have remained unclear. Two atypical PKC (aPKC) isozymes, PKCλ and PKCζ (6), have been identified in mammals. We have previously shown that PKCλ acts downstream of PI3K in PDGF or insulin signaling in cultured cells (7, 8). Furthermore, evidence suggests that 3′-phosphoinositide–dependent kinase-1 (PDK-1), thought to be a key mediator of PI3K signaling, contributes to the activation of AGC protein kinases (which include Akt, p70 S6 kinase, p90ρk, and aPKC) by phosphorylating these enzymes on residues located in their activation loops (9, 10). On the basis of these various observations, we hypothesized that PKCλ participates in insulin action in vivo. To verify this hypothesis, using homologous recombination, we generated mice that harbor a PKCλ gene containing loxP sites. Disruption of the corresponding aPKC genes in Caenorhabditis elegans and Drosophila melanogaster resulted in embryonic death (11, 12). As expected, PKCλ-deficient mice generated from the floxed PKCλ transgenic animals also died during embryonic development (K. Akimoto et al., unpublished observations).

Given that the liver is one of the most important target organs of insulin, we next generated mice in which...
the floxed PKCα gene was specifically deleted in the liver as a result of Cre recombinase expression in this organ. Characterization of these animals has now revealed that PKCα mediates the regulatory effect of insulin on hepatic triglyceride content by contributing to the expression of the gene for sterol regulatory element–binding protein-1c (SREBP-1c), and that the lack of PKCα in the liver results in increased insulin sensitivity.

Methods

Animals. Mice harboring a floxed PKCα gene in which exon 5 was flanked by loxP sequences (PKCαlox/lox mice) were generated by homologous recombination (K. Akimoto et al., unpublished observations). Mice that express Cre recombinase under the control of the albumin gene promoter (Alb-Cre mice) (13) were provided by D. LeRoith (Diabetes Branch, National Institute of Diabetes and Digestive and Kidney Diseases, NIH, Bethesda, Maryland, USA). We used only male mice for the present studies. For the fasting-refedding experiments, mice in the fasted group were deprived of food for 24 hours; mice in the refeed group were deprived of food for 24 hours and then allowed access to food for 12 hours before analysis. The liver X receptor agonist T0901317 (kindly provided by K. Murakami, Kyorin Pharmaceutical Co., Tokyo, Japan) was administered daily by oral gavage at a dose of 10 mg/kg body mass for 4 days. For oral glucose intake experiments, mice deprived of food for 16 hours were loaded orally with glucose (2 g/kg body mass). For in vivo adenovirus-mediated gene transfer experiments, mice were injected with the indicated adenovirus vector (1 × 10⁸ PFU) via the tail vein 72 hours before experiments.

Analysis of metabolic parameters. Blood glucose and plasma insulin concentrations were determined as described (5). For glucose tolerance and insulin tolerance tests, mice deprived of food for 16 hours were injected intraperitoneally with glucose (2 g/kg body mass); mice in the randomly fed state were injected intraperitoneally with human regular insulin (0.75 U/kg). Serum leptin and adiponectin concentrations were measured with a mouse leptin ELISA kit (Moriga Institute of Biological Science, Yokohama, Japan) and a mouse/rat adiponectin ELISA kit (Otsuka Pharmaceutical Co. Ltd., Tokyo, Japan), respectively. Serum cholesterol, triglyceride, and FFA concentrations were determined with a cholesterol C-II kit, a triglyceride G kit, and a NEFA C kit, respectively (Wako Pure Chemical Industries Ltd., Osaka, Japan). For assay of the cholesterol and triglyceride contents of liver or hind limb skeletal muscle, lipids were extracted from the tissue as described (14) and the concentrations of the analytes in the extract were determined with a cholesterol C-II kit or a triglyceride G kit.

Northern blot, immunoblot, kinase activity, real-time quantitative RT-PCR analysis, and primary culture of hepatocytes. Total RNA (~15 μg) was subjected to Northern blot analysis essentially as described (15); autoradiograms were visualized and signal intensity was quantitated with a BAS2000 image analyzer (Fujiﬁlm Co., Tokyo, Japan). The probes for the genes encoding PPAR-α, acyl-CoA oxidase-1, and uncoupling protein-2 mRNA’s (mouse full-length cDNAs) were synthesized by PCR; the other probes were as described (5, 16, 17). Primary cultures of rat hepatocytes were prepared and subjected to adenosine infection as described (15).

For assay of the expression of the genes encoding SREBP-1 and fatty acid synthase, cells infected or not with adenoviruses were incubated for 6 hours and 20 hours, respectively, with 100 nM insulin or with 10 μM T0901317; for assay of the expression of the genes encoding phosphoenolpyruvate carboxykinase-1 (PKC-1) and glucose-6-phosphatase catalytic subunit (G6PC), cells were incubated for 6 hours with 500 nM dexamethasone and 0.1 mM pCPT-cAMP in the absence or presence of 100 nM insulin. Adenovirus vectors encoding a dominant-negative mutant of PKCα (AxCAα.KD), WT PKCα (AxCAα.WT) (8), or a Myc epitope–tagged active form of P13K (the 110-kDa catalytic subunit fused with a myristoylation signal sequence at its NH₂-terminus; AxCAMyr-p110) (15, 18) were described previously, and that encoding β-gal (AxCALacZ) was kindly provided by I. Saito (University of Tokyo, Tokyo, Japan). The antibodies specific for mouse SREBP-1c were as described (14).

For assay of the abundance of PKCα and PKCζ, total tissue homogenates were subjected to immunoprecipitation with antibodies to PKCα (αζ190) or to PKCζ (αζ170) (8), and the resulting precipitates were subjected to immunoblot analysis with antibodies to PKCα/β (Transduction Laboratories, Lexington, Kentucky, USA) or to PKCζ (Life Technologies Inc., Rockville, Maryland, USA), respectively. Antibodies that recognize both PKCα and PKCζ (C-20, a rabbit polyclonal antibody, and C-20-G, a goat polyclonal antibody) were obtained from Santa Cruz Biotechnology (Santa Cruz, California, USA). For immunodepletion of aPKC, liver homogenates were subjected to three sequential immunoprecipitations with antibodies to PKCα (αζ190) or with αζ170. The supernatants of the immunoprecipitations were then subjected to immunoblot analysis with antibodies to PKCα/β (Transduction Laboratories, Lexington, Kentucky, USA) or to PKCζ (Life Technologies Inc., Rockville, Maryland, USA), respectively. Antibodies that recognize both PKCα and PKCζ (C-20, a rabbit polyclonal antibody, and C-20-G, a goat polyclonal antibody) were obtained from Santa Cruz Biotechnology (Santa Cruz, California, USA). For immunodepletion of aPKC, liver homogenates were subjected to three sequential immunoprecipitations for 120 minutes with αζ190 or with αζ170. The super-
natants of the immunoprecipitations were then subjected to immunoblot analysis with C-20-G and the precipitates were subjected to immunoblot analysis with C-20. The kinase activity of aPKC was assayed in the immunoprecipitates with αζ190 or with αζ170 as described previously (8). For real-time quantitative reverse transcription and PCR analysis, cDNA synthesized from total RNA was evaluated in a sequence detector (model 7900; Applied Biosystems, Foster City, California, USA) with specific primers and SYBR Green PCR Master Mix (Applied Biosystems). The relative abundance of mRNA’s was calculated with 36B4 mRNA as the invariant control. The primers used were as follows: mouse Srebplα, 5'-GGAGCAGACACTGGCGGAGA-3' (sense) and 5'-GCATAGGGGGCCGCTCA-3' (antisense); mouse Srebplc, 5'-ATCGGCCGAGAATGTGGGGGTGTGCTGTCGTC-3' (sense) and 5'-AAGGGCTGGCTGTTTGGTATGACCTGAGGAGG-3' (antisense). The primers for mouse 36B4 were as described previously (5).
Results

Generation of mice with liver-specific deficiency of PKCα. We bred PKCαlox/lox mice with Alb-Cre mice (13). We then bred the PKCαlox/lox, Alb-Cre offspring of this cross with PKCαlox/lox mice. The offspring of this breeding were born in a Mendelian ratio (PKCα+/+, n = 12, or 9.9%; PKCαlox/+, Alb-Cre, n = 14, or 11.6%; PKCαlox/+, Alb-Cre, n = 10, or 8.1%; PKCαlox/lox, Alb-Cre, n = 33, or 27.3%; PKCαlox/lox, Alb-Cre, n = 15, or 12.4%; PKCαlox/lox, Alb-Cre, n = 18, or 14.9%).

Two closely related isoforms comprise aPKC: PKCζ and PKCζ (6). We first investigated the amounts of PKCα and PKCζ in liver homogenates of PKCα+/+ (WT) mice. After three sequential immunoprecipitations with antibodies to PKCα, or to PKCζ, the corresponding isoforms of aPKC were almost completely depleted from the homogenates (Figure 1a). aPKC protein, detected by antibodies that recognize both PKCα and PKCζ, was present both in the PKCα-depleted and the PKCζ-depleted homogenates, suggesting that liver contains both PKCα and PKCζ. The relative abundance of each isoform was comparable. The amount of PKCα in the liver of PKCαlox/lox, Alb-Cre (L-λKO) mice was markedly reduced compared with that in the liver of WT, PKCαlox/+, Alb-Cre (WT-Cre), and PKCαlox/+ (λlox/lox) animals (Figure 1b). In contrast, the hepatic abundance of PKCζ was similar among all four genotypes of mice.

Given the similarity in the hepatic expression level of PKCα in WT, WT-Cre, and λlox/lox mice, which indicates that neither the insertion of the loxP sequences in the PKCα gene nor the expression of Cre recombinase alone affected the abundance of PKCα, we performed subsequent experiments with L-λKO and λlox/lox mice. The kinase activity of PKCα, but not that of PKCζ, was greatly reduced in the liver of L-λKO mice compared with that in the liver of λlox/lox mice (Figure 1c). The abundance of PKCα in other tissues, including skeletal muscle, adipose tissue, the pancreas, the lung, and the kidney, did not differ between L-λKO and λlox/lox mice (Figure 1d). The abundance of PKCζ in the two genotypes of mice was similar in all tissues we examined. The gross appearance and histology of the liver, including the arrangement of hepatocytes in plates and the structure of hepatic lobules, appeared normal in L-λKO mice (data not shown). The serum levels of aspartate aminotransferase, alanine aminotransferase, alkaline phosphatase, lactate dehydrogenase, and albumin also did not differ significantly between L-λKO and λlox/lox mice (data not shown). These results indicate that the lack of PKCα did not affect the development or general function of the liver.

Metabolic characteristics of L-λKO mice. The body mass, mass of the liver, and mass of epididymal fat tissue of L-λKO mice were similar to those of λlox/lox mice (Table 1). The serum concentrations of triglyceride, cholesterol, FFAs, leptin, and adiponectin in the randomly fed state also did not differ between mice of the two genotypes. Although the blood glucose concentration in the randomly fed state was similar in the two types of mice, the plasma concentration of insulin in L-λKO mice was significantly lower than that in λlox/lox mice. Blood glucose concentrations during a glucose tolerance test were similar in both L-λKO and λlox/lox mice (Figure 2a). Again, however, the increase in plasma insulin concentration induced by glucose intake was smaller in L-λKO mice than in λlox/lox animals (Figure 2b). Moreover, the glucose-lowering effect of exogenously administered insulin was greatly diminished in L-λKO mice compared with λlox/lox mice (Figure 2c).

![Figure 1](https://example.com/figure1.png)

The abundance and kinase activity of PKCα and PKCζ in mice with liver-specific PKCα deficiency. (a) Total homogenates prepared from the liver of 20-week-old PKCα+/+ mice were subjected to three sequential immunoprecipitations with antibodies to PKCα (depleted PKCα) or to PKCζ (deplete PKCζ). The resultant supernatants were subjected to immunoprecipitation with antibodies to PKCα, to PKCζ, or with antibodies that recognize both PKCα and PKCζ (Pan), and the precipitates were subjected to immunoblot analysis with antibodies that recognize both PKCα and PKCζ (Pan). (b) Total homogenates prepared from the liver of 18-week-old PKCα+/+ (WT); PKCα+/+, Alb-Cre (WT-Cre); PKCαlox/lox (λlox/lox); or PKCαlox/+, Alb-Cre (L-λKO) mice were subjected to immunoprecipitation with antibodies to PKCα or to PKCζ, and the resulting precipitates were subjected to immunoblot analysis with corresponding antibodies. (c) Total homogenates prepared from the liver of λlox/lox or L-λKO mice were subjected to immunoprecipitation (IP) with antibodies to PKCα or to PKCζ, and the resulting precipitates were assayed for kinase activity. (d) Extracts of the indicated tissues prepared from λlox/lox or L-λKO mice were subjected to immunoprecipitation (IP) with antibodies to PKCα or PKCζ, and the resulting precipitates were subjected to immunoblot analysis (IB) with corresponding antibodies. Data in a, b, and d are representative of at least three mice of each genotype; those in c are mean ± SEM of values from six mice. *p < 0.01 for the indicated comparison (ANOVA).
We and other investigators have shown that the effect of insulin on the expression of Srebp1 is mediated by a PI3K-dependent pathway (15, 23). We therefore next took advantage of the fact that systemic infusion of adenoviral vectors results in liver-specific expression of exogenous genes (5). Infusion of AxCAMyr-p110, but not of AxCALacZ, resulted in the expression of the Myr-p110 protein in the liver of both L-λKO and λlox/lox mice (Figure 2i); expression of Myr-p110 was not detected in skeletal muscle or adipose tissue (data not shown). Infusion of AxCAMyr-p110, but not of AxCALacZ, also resulted in a reduction in the blood glucose concentration of both L-λKO and λlox/lox mice in the fasted state, suggesting that activation of hepatic PI3K signaling lowers blood glucose concentration. However, the glucose-lowering effect of AxCAMyr-p110 was greater in L-λKO mice than in the control animals, consistent with our observation that the glucose-lowering effect of exogenously administered insulin was exaggerated in L-λKO mice (Figure 2c).

These observations indicated that the insulin sensitivity of L-λKO mice was increased.

**Altered hepatic gene expression in L-λKO mice.** Early events of hepatic insulin signaling, including phosphorylation of insulin receptor substrate-1 (IRS-1), IRS-2, and Akt, did not differ between L-λKO and λlox/lox mice after bolus injection of insulin (Figure 2d). We have previously shown that PKCδ contributes to PI3K-dependent gene expression induced by growth factors (7). We therefore examined L-λKO mice for the hepatic expression of genes that are regulated by insulin. The abundance of mRNA’s for glucokinase (GCK), PKC-1, and G6PC in the liver of randomly fed animals was similar in L-λKO and λlox/lox mice (Figure 2e). However, the amount of transcripts encoding SREBP-1, a transcription factor that regulates the expression of genes important in triglyceride synthesis (19, 20), as well as the amount of those encoding fatty acid synthase, the gene for which is regulated by SREBP-1 (19, 20), were reduced by approximately 50% in the liver of L-λKO mice.

The expression of Srebp1 and its target genes in the liver is induced when mice are refed after starvation (21, 22), a treatment that also results in an increase in the circulating insulin concentration. The increases in the hepatic expression of Srebp1, Fas, and the gene for stearoyl-CoA desaturase-1 (SCD-1; another target of SREBP-1) (19) induced by refeeding were inhibited by about 50%, 35%, and 25%, respectively, in L-λKO mice (Figure 2f). Of the two splice variants of Srebp1 mRNA (19), only the abundance of Srebp1c mRNA, not that of Srebp1a mRNA, is increased in the liver in response to insulin or refedding (22). The induction of Srebp1c expression in the liver in response to refeeding was inhibited by about 50% in L-λKO mice (Figure 2g). Moreover, immunoblot analysis with antibodies specific for SREBP1c (14) revealed that the increase in the amount of this protein in a nuclear fraction of the liver induced by refeeding was markedly reduced in L-λKO mice (Figure 2h).

**Table 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>λlox/lox</th>
<th>L-λKO</th>
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</thead>
<tbody>
<tr>
<td>18-week-old mice</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body mass (g)</td>
<td>31.7 ± 0.7</td>
<td>31.8 ± 0.5</td>
</tr>
<tr>
<td>Liver mass (g)</td>
<td>1.52 ± 0.03</td>
<td>1.49 ± 0.06</td>
</tr>
<tr>
<td>Epididymal fat mass (g)</td>
<td>0.31 ± 0.03</td>
<td>0.34 ± 0.03</td>
</tr>
<tr>
<td>12-week-old mice</td>
<td></td>
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<tr>
<td>Blood glucose (mg/dl)</td>
<td>111.3 ± 4.2</td>
<td>119.4 ± 2.2</td>
</tr>
<tr>
<td>Plasma insulin (pg/ml)</td>
<td>518 ± 38</td>
<td>356 ± 37a</td>
</tr>
<tr>
<td>Serum cholesterol (mg/dl)</td>
<td>107.8 ± 4.4</td>
<td>112.0 ± 4.3</td>
</tr>
<tr>
<td>Serum triglyceride (mg/dl)</td>
<td>101.6 ± 8.3</td>
<td>107.4 ± 5.9</td>
</tr>
<tr>
<td>Serum FFAs (mEq/l)</td>
<td>0.91 ± 0.07</td>
<td>0.95 ± 0.05</td>
</tr>
<tr>
<td>Serum leptin (ng/ml)</td>
<td>1.34 ± 0.26</td>
<td>1.39 ± 0.22</td>
</tr>
<tr>
<td>Serum adiponectin (µg/ml)</td>
<td>13.9 ± 0.3</td>
<td>14.6 ± 0.4</td>
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Data are from male mice in the randomly fed state at the indicated ages. Values are mean ± SEM of 15–27 animals. *P < 0.05 vs. λlox/lox (Student’s t test).
Figure 2
Glucose and insulin tolerance, insulin signaling, and hepatic gene expression in mice with liver-specific deficiency of PKCλ. (a–c) Blood glucose (a) and plasma insulin (b) concentrations during a glucose-tolerance test in L-λKO and λlox/lox mice at 14 weeks of age, and blood glucose concentration during an insulin tolerance test at 12 weeks of age (c). Data are mean ± SEM of values from nine to 20 mice. *P < 0.05 vs. the corresponding value for λlox/lox mice (Student’s t test). (d) Tyrosine phosphorylation of IRS-1 and IRS-2 and serine phosphorylation of Akt in the liver of λlox/lox or L-λKO mice induced by a bolus injection of insulin. Liver homogenates prepared 2 minutes after administration of insulin (5 U/kg of body mass) or saline were subjected to immunoprecipitation with antibodies to IRS-1 or to IRS-2, and the resulting precipitates were subjected to immunoblot analysis with antibodies to phosphotyrosine (PY). Alternatively, liver homogenates were subjected directly to immunoblot analysis with antibodies specific for phosphorylated Akt (p-Akt). Data are representative of six mice of each genotype. (e–g) Total RNA extracted from the liver of λlox/lox or L-λKO mice (18 weeks of age) in the randomly fed state (n = 8) (e) or after fasting with or without refeeding (n = 4–7) (f and g) was either separately combined and subjected to Northern blot analysis (e and f) or subjected individually to RT-PCR analysis (g) for the indicated mRNA’s. Ethidium bromide staining of 28S rRNA is also shown for Northern analysis. *P < 0.01 (ANOVA). (h) The nuclear fraction of liver homogenates prepared from λlox/lox or L-λKO mice after fasting with or without refeeding was subjected to immunoblot analysis with antibodies to SREBP-1c. Data shown are from two mice and are representative of four to six animals. (i and j) Mice (λlox/lox or L-λKO) 16–18 weeks of age (n = 10–16) were injected with AxCAMyr-p110 or AxCALacZ and were subsequently deprived of food for 16 hours. The abundance of Myr-p110 in liver homogenates was then examined by immunoblot analysis with antibodies to Myc (i, lower panel), blood glucose concentration was determined (i, lower panel), and the amounts of Srebp1 and Fas mRNA’s among separately combined total RNA extracted from the liver were evaluated by Northern analysis (j). *P < 0.05, **P < 0.01 (ANOVA). (k) Total RNA extracted from the liver of λlox/lox or L-λKO mice treated with either T0901317 or vehicle was separately combined and subjected to Northern blot analysis for Srebp1 and Fas mRNA’s. Data are shown for two mice and are representative of four animals.
hepatic expression of these genes was slightly exaggerated in L-λKO mice compared with that apparent in $\lambda^{lac/lac}$ animals (Figure 3f). These results thus suggested that PKCλ signaling is not required for either the hepatic accumulation of glycogen or for inhibition of the expression of gluconeogenesis genes in the liver. The slight enhancement of refeeding-induced suppression of Pck1 and G6pc expression apparent in L-λKO mice may be related to the increased insulin sensitivity of these animals.

**Effects of dominant-negative and WT PKCλ on insulin-induced expression of Srebp1 in cultured hepatocytes.** To confirm a causal relation between PKCλ deficiency and the altered hepatic expression of Srebp1 in L-λKO mice, we examined the effect of PKCλ signaling on the abundance of Srebp1 mRNA in primary cultures of rat hepatocytes. Incubation of the cells with insulin induced an increase in the amounts of Srebp1 and Fas mRNAs (Figure 4a), and this effect was inhibited by adenovirus-mediated expression of λKD, which acts in a dominant-negative manner (7, 8). Expression of λKD also inhibited the increase in the amount of Srebp1 mRNA induced by Myr-p110 (Figure 4b). In contrast, λKD did not affect either the insulin-induced inhibition of Pck1 and G6pc expression (Figure 4c) or the expression of Srebp1 induced by T0901317 (Figure 4d), indicating that PKCλ signaling specifically contributes to insulin-induced expression of Srebp1. Moreover, expression of recombinant WT PKCλ increased the abundance of Srebp1 and Fas mRNA’s in the absence of insulin (Figure 4e), indicating that PKCλ signaling is sufficient for the induction of these genes.

Restoration of PKCλ expression reverses the decrease in hepatic lipid content and the increase in insulin sensitivity in L-λKO mice. To verify that the altered insulin sensitivity and hepatic triglyceride content of L-λKO mice are attributable to the lack of PKCλ in the liver, we restored the hepatic expression of this enzyme in L-λKO animals. Infusion of AxCAλWT into L-λKO mice resulted in the expression of PKCλ in the liver at a level similar to that apparent in $\lambda^{lac/lac}$ mice (Figure 5a). The restoration of PKCλ expression in the liver increased both the abundance of Srebp1 mRNA and the triglyceride content in this organ of L-λKO mice. Blood glucose concentration was similar in L-λKO mice infused with AxCAλWT or with AxCAλLacZ and in $\lambda^{lac/lac}$ mice infused with AxCAλLacZ or with PBS. The plasma insulin concentration of L-λKO mice was increased by infusion of AxCAλWT, but not of AxCAλLacZ, to an extent similar to that apparent in $\lambda^{lac/lac}$ mice infused with AxCAλLacZ or with PBS (Figure 5b). Moreover, the enhancement of the glucose-lowering effect of exogenously administered insulin apparent in L-λKO mice was also reversed by restoration of PKCλ expression in the liver (Figure 5c). These results thus indicate that the changes in the expression of Srebp1 and in triglyceride

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**Figure 3**

Hepatic lipid and glycogen content and the expression of genes involved in β-oxidation and gluconeogenesis in mice with liver-specific PKCλ deficiency. (a–c) Triglyceride (a) and cholesterol (b) content of the liver and triglyceride content of hind limb muscle (c) of L-λKO and $\lambda^{lac/lac}$ mice in the randomly fed state at 18 weeks of age. Data are expressed as mg analyte/g wet tissue and are the mean ± SEM from four mice. *P < 0.05 (Student’s t test). (d) Total RNA extracted from the liver of $\lambda^{lac/lac}$ or L-λKO mice (n = 8) at 18 weeks of age and in the randomly fed state was separately combined and subjected to Northern blot analysis for mRNA’s encoding PPAR-α, acyl-CoA oxidase-1 (ACOX-1), and uncoupling protein-2 (UCP-2). (e) Hepatic glycogen content of $\lambda^{lac/lac}$ or L-λKO mice at 20 weeks of age before (Pre) and 2 hours after (Post) oral glucose intake. Data are mean ± SEM from four to six mice. (f) Total RNA extracted from the liver of $\lambda^{lac/lac}$ or L-λKO mice (18 weeks of age) after fasting with or without refeeding (n = 4–7) was separately combined and subjected to Northern blot analysis with probes specific for Pck1 or G6pc mRNA’s.
content in the liver as well as in whole-body insulin sensitivity apparent in L-λKO mice are directly attributable to the lack of PKCλ in the liver.

Discussion

On the basis of observations with cultured cells (7, 8), we hypothesized that PKCλ participates in insulin action in vivo as a downstream effector of PI3K. Our present results now demonstrate such a function for PKCλ, at least in the liver. Several of the metabolic effects of insulin in the liver are exerted through the regulation of gene expression. We have previously shown that the regulation by insulin of the expression of Gck, Srebp1c, G6pc, and Pck1 in mouse liver is mediated by PI3K (5). Of these four genes, each of which participates in the metabolic actions of insulin, we have now revealed that the expression of Srebp1c, a key regulator of fatty acid and triglyceride synthesis (19, 20), is regulated by PKCλ acting downstream of PI3K.

At present, a signaling pathway that links PKCλ and the expression of Srebp1c remains unclear. Cycloheximide, an inhibitor of general protein synthesis, has been shown to prevent insulin-induced expression of Srebp1c in cultured hepatocytes (25), suggesting that de novo protein synthesis is required for this action of insulin. PKCλ thus may contribute to induce expression of such a protein involved in the transcriptional activation of Srebp1c.

The hepatic expression of Srebp1c induced by refeeding or by an active PI3K was markedly, but not completely, prevented in L-λKO mice, suggesting that the induction of Srebp1c is not solely dependent on PKCλ signaling. Given that the liver expresses both PKCλ and PKCζ, PKCζ may be responsible for the residual signaling of Srebp1c. A membrane-targeted form of Akt that exhibits higher kinase activity than does WT Akt increases the abundance of Srebp1c mRNA when it is expressed in primary cultured hepatocytes (23), suggesting that Akt, a downstream effector of PI3K, may also contribute to the induction of Srebp1c. However, we have previously shown that the inhibition of endogenous Akt activity with the use of a dominant-negative mutant of the kinase did not prevent, but rather augmented, insulin-induced expression of Srebp1c (15). Moreover, in ob/ob mice and a mouse model with lipodystrophic diabetes, the abundance of Srebp1c mRNA is increased, whereas insulin-induced phosphorylation of Akt is markedly reduced in the liver of these animals (26). Mice lacking Akt2, a major isoform of Akt in the liver, have been established (27). The physiological importance of Akt in the induction of Srebp1c in vivo may be revealed by characterization of the mutant mice.
Atypical PKC isozymes are evolutionarily conserved proteins required for the formation of apical-basal polarity in cells (28), which is important for the structural organization and function of organs. However, the structures of hepatic lobules and hepatocyte plates and the serum parameters of general liver function appeared normal in L-\(\lambda\)KO mice. This observation may be attributable to the fact that disruption of the PKC\(\lambda\) gene was accomplished by Cre recombinase expressed under the control of the promoter of the albumin gene, which is a marker gene of fully differentiated hepatocytes. A role for PKC\(\lambda\) in the development of cellular polarity in the liver might be revealed by characterization of hepatectomy-induced liver regeneration in L-\(\lambda\)KO mice, given that the liver regenerates predominantly through the replication of mature hepatocytes under this experimental condition (29).

An unexpected finding of the present study was that L-\(\lambda\)KO mice exhibit increased insulin sensitivity. The tissue-specific disruption of a gene important for insulin signaling thus paradoxically resulted in an increase in whole-body insulin sensitivity. A similar phenomenon remains unclear. Evidence suggests that the alteration of fatty acids/triglyceride metabolism in insulin’s target tissues is an important determinant of insulin sensitivity. The increase in circulating FFAs leads to insulin resistance and the accumulation of triglyceride in skeletal muscle (31), and triglyceride content in the liver or in skeletal muscle negatively correlates with insulin sensitivity in humans (32, 33). Leptin and adiponectin, the two major fat-derived hormones, increase insulin sensitivity and concomitantly reduce hepatic triglyceride content (probably by promoting fatty acid oxidation) in an animal model of insulin resistance or in humans with lipodystrophic diabetes (34–36). Moreover, overexpression of lipoprotein lipase in liver or skeletal muscle resulted in an increase in fatty acid metabolites and consequently in the accumulation of triglyceride in the respective tissue, as well as insulin resistance (37). The decrease in the hepatic expression of the lipogenic genes and the subsequent alterations in fatty acid metabolism in L-\(\lambda\)KO mice may thus be related to the increased insulin sensitivity of these animals.

TNF-\(\alpha\) secreted from adipose tissue is implicated in the development of obesity-induced insulin resistance (38). Atypical PKC is activated by cytokines, including TNF-\(\alpha\) and IL-1 (39, 40), and directly phosphorylates and activates I-\(\kappa\)B kinase-\(\beta\) (IKK\(\beta\)) (41). Administration of salicylic acid derivatives that inhibit IKK\(\beta\) (42) was shown to increase insulin sen-
sitivity both in rodent models of diabetes and in human subjects (43, 44). Moreover, heterozygous disruption of the IKKβ gene ameliorated the insulin resistance of obese model mice (44). It is therefore possible that the hepatic deficiency of PKCα in L-λKO mice results in inhibition of a TNF-α/PKCα/IKKβ signaling pathway and a consequent increase in whole-body insulin sensitivity.

Transgenic mice that overexpress lipoprotein lipase in skeletal muscle or the liver exhibit an impairment of the insulin-induced increase in PI3K activity associat
ed with IRS-1 or IRS-2, respectively (37). Moreover, administration of salicylic acid derivatives enhanced insulin-induced tyrosine phosphorylation of the insulin receptor in genetically obese animals (44). However, we did not detect changes in the insulin-induced phosphorylation of IRS proteins or of Akt in the liver of L-λKO mice. Although we cannot exclude the possibility that a small increase in the extent of insulin signaling went undetected under our experimental conditions, it is possible that the enhancement of insulin action apparent in L-λKO mice occurs at a step other than IRS or Akt phosphorylation. Evidence suggests that PKCζ participates in a negative feedback pathway of insulin signaling leading to the phosphorylation of IRS proteins in cultured cells (45). Given that the insulin-induced phosphorylation of IRS proteins was not significantly increased in the liver of L-λKO mice, PKCα appears not to participate in such a negative feedback pathway in mouse liver.

In summary, we have shown that, among the various metabolic actions of insulin, PKCα specifically contributes to induction of the expression of Srebp1c and of its target genes important in triglyceride synthesis in the liver. Animal models of insulin resistance or obesity often manifest increases both in lipid content and in the expression of Srebp1c in the liver (26, 46). Reagents that block PKCα signaling specifically in the liver might thus prove effective for reducing hepatic Srebp1c expression and consequently hepatic triglyceride content, as well as for ameliorating insulin resistance.

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