The critical role of atypical protein kinase C in activating hepatic SREBP-1c and NFκB in obesity

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Abstract Obesity is frequently associated with systemic insulin resistance, glucose intolerance, and hyperlipidemia. Impaired insulin action in muscle and paradoxical diet/insulin-dependent overproduction of hepatic lipids are important components of obesity, but their pathogenesis and inter-relationships between muscle and liver are uncertain. We studied two murine obesity models, moderate high-fat-feeding and heterozygous muscle-specific PKC-α knockout, in both of which insulin activation of atypical protein kinase C (aPKC) is impaired in muscle, but conserved in liver. In both models, activation of hepatic sterol receptor element binding protein-1c (SREBP-1c) and NFκB (nuclear factor-kappa B), major regulators of hepatic lipid synthesis and systemic insulin resistance, was chronically increased in the fed state. In support of a critical mediatory role of aPKC, in both models, inhibition of hepatic aPKC by adenosvirally mediated expression of kinase-inactive aPKC markedly diminished diet/insulin-dependent activation of hepatic SREBP-1c and NFκB, and concomitantly improved hepatosteatosis, hypertriglyceridemia, hyperinsulinemia, and hyperglycemia. Moreover, in high-fat–fed mice, impaired insulin signaling to IRS-1-dependent phosphatidylinositol 3-kinase, PKB/Akt and aPKC in muscle and hyperinsulinemia were largely reversed.‡‡ In obesity, conserved hepatic aPKC-dependent activation of SREBP-1c and NFκB contributes importantly to the development of hepatic lipogenesis, hyperlipidemia, and systemic insulin resistance. Accordingly, hepatic aPKC is a potential target for treating obesity-associated abnormalities.—Sajan, M. P., M. L. Standaert, S. Nimal, U. Varanasi, T. Pastoor, S. Mastorides, U. Braun, M. Leitges, and R. V. Farese. The critical role of atypical protein kinase C in activating hepatic SREBP-1c and NFκB in obesity. J. Lipid Res. 2009, 50: 1133–1145.

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Obesity, particularly when accompanied by systemic insulin resistance, glucose intolerance, and hyperlipidemia (i.e., a “metabolic syndrome”) is a global health problem and a frequent forerunner of type 2 diabetes mellitus. Whereas both exogenous/diet-induced and genetically determined obesity can produce insulin resistance and metabolic syndrome features, vice versa, systemic insulin resistance can produce obesity and metabolic syndrome features. However, mechanisms underlying lipid abnormalities and insulin resistance in these situations, and the critical interplay between muscle and liver, are poorly understood.

The high-fat–fed (HFF) mouse model is useful for studying diet-induced obesity-related insulin resistance. In our experience, feeding mice a Western-type 20% milk high-fat diet for 3–4 weeks leads to diminished insulin activation of phosphatidylinositol (PI) 3-kinase (PI3K) effectors, atypical protein kinase C (aPKC) and protein kinase B (PKB/Akt) in muscle (1, 2), with little or no effect on hepatic aPKC and PKB/Akt activation (1). In this HFF model, we have observed no increases in basal (unstimulated) activities of conventional (α,β2) or novel (δ,ε) PKCs in liver, despite observing increases in muscle (unpublished). Accordingly, our HFF model may partly differ from others wherein higher dietary fat was used, thereby activating hepatic novel PKCs.

Insulin signaling to aPKC and PKB/Akt (particularly the PKBβ/Akt2 isoform) is important, as these kinases control key metabolic processes, viz., glucose transport in muscle is controlled by both aPKC and PKB/Akt, enzymes regulating hepatic glucose output are mainly controlled by PKB/Akt (3, 4), and hepatic sterol receptor element binding protein-1c (SREBP-1c), which trans-activates multiple genes involved in lipid synthesis, can be controlled by both aPKC (3, 4) and PKB/Akt (5, 6). Also, hepatic NFκB (nuclear

Abbreviations: aPKC, atypical protein kinase C; SREBP-1c, hepatic sterol receptor element binding protein-1c; KO, knockout; NFκB, nuclear factor-kappa B.

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factor-kappa B), which is activated in HFF mice and linked to systemic insulin resistance (7, 8) and inflammation, can be activated by aPKC through (a) phosphorylation/activation of IκB kinase (IKBk), which phosphorylates IκB, thereby releasing NFκB for translocation to nuclear transcription sites (9); and (b) phosphorylation/activation of the p65/RelA subunit of NFκB (10). However, insulin effects on IκBk and NFκB are unknown.

Differences in activation of aPKC and PKB/Akt in muscle and liver in HFF mice most likely reflect tissue-specific variations in PI3K activation by insulin receptor substrates (IRS), IRS-1 and IRS-2. However, definitive information on PI3K activation in HFF mice is lacking, and findings in other HFF models are inconsistent. In rats fed 58% lard, activation of hepatic IRS-1 and IRS-2-dependent PI3K is oddly enough enhanced (11); in rats fed 21% milk fat, activation of muscle aPKC by insulin in vivo and PI-3,4,5-(PO)3 (PIP3) in vitro is impaired, but activation of IRS-1 and IRS-2-dependent PI3K is intact (12); in rats fed 65% fat, aPKC and PKB activation in muscle is diminished (13).

Germaine to tissue-specific differences in aPKC/PKB activation, findings from knockout mice suggest that IRS-1 and IRS-2 activate separate PI3K pools that couple differently to these downstream effectors during insulin action, depending upon the tissue. Thus, in IRS-1 knockout mice, insulin activation of both PKB/Akt (14, 15) and aPKC (15) is impaired in muscle, whereas in liver, PKB/Akt activation is impaired (14, 15), but aPKC activation is conserved (15). In IRS-2-deficient hepatocytes, activation of aPKC, as well as PKB/Akt, is impaired (16). To summarize, IRS-1 controls both aPKC and PKB/Akt in muscle, whereas in liver, IRS-2 controls aPKC, and both IRS-1 and IRS-2 control PKB/Akt activation by insulin.

In HFF mice, we found that inhibition of hepatic aPKC by adenovirally mediated expression of kinase-inactive (KI) aPKC largely reversed excessive increases in hepatic SREBP-1c and IκBk/ NFκB activities, thereby improving downstream targets of SREBP-1c and NFκB, hyperlipidemia, insulin signaling in muscle, hyperinsulinemia, and hyperglycemia. Similarly, in a genetic obesity model, heterozygous muscle-specific knockout of PKC-ζ (M-ζ-Het-KO) mice [wherein (a) aPKC activation is selectively impaired in muscle, thereby compromising insulin-stimulated glucose transport, (b) insulin signaling and actions in liver and adipocytes are intact, and (c) feeding- and insulin-dependent activation of hepatic SREBP-1c and IκBk/NFκB is excessive, thereby producing abdominal obesity, hepatosteatosis, hyperlipidemia, and glucose intolerance (17)], we observed comparable dependency of hepatic SREBP-1c and IκBk/NFκB on hepatic aPKC and, moreover, similar phenotypic improvements following administration of adenovirus expressing KI-aPKC.

EXPERIMENTAL PROCEDURES

Experimental mice

In HFF studies, male C57Bl/6 mice, 8–12 weeks of age, were obtained from Harlan Industries, housed in a temperature-
In some cases, assays were conducted in the presence of 10 μM PIP₃, which maximally (like exogenous insulin treatment) activates aPKCs immunoprecipitated from muscles of control noninsulin-treated rodents (12, 17). After incubation, 32P-labeled substrate was trapped on P-81 filter papers and counted.

PKB/Akt activation

Total PKBα/β (Akt1/2) enzyme activity was measured using a kit obtained from Upstate Cell Signaling, as described (1, 2, 12, 15, 17–23). In brief, PKB/Akt was immunoprecipitated from lysates with rabbit polyclonal antibodies, collected on Sepharose-AG beads, and incubated as per kit directions. Total PKB/Akt activation was also assessed by immunoblotting for phosphorylation of serine-473.

PI3K activation

IRS-1–dependent and IRS-2–dependent PI3K activities were determined as described (1, 2, 12, 15, 17–23). In brief, IRS-1 and IRS-2 immunoprecipitates were incubated with PI and examined for incorporation of 32PO₄ into PI-3-PO₄, which was purified by thin layer chromatography and quantified with a BioRad Molecular Analyst Phosphor-Imager system.

Western analyses

Western analyses were conducted as described (1, 2, 12, 15, 17–23) using the following antibodies and antisera for immune detection after resolution of lysate proteins on SDS-PAGE: (a) rabbit polyclonal anti-PKC-ζ/λ antisera (Santa Cruz Biotechnologies); (b) rabbit polyclonal anti-PKB antisera (Upstate Cell Signaling); (c) rabbit polyclonal anti-phospho-serine-473-PKB antisera (New England BioLabs); (d) rabbit polyclonal anti-IRS-1 antisera (Upstate Cell Signaling); (e) rabbit polyclonal anti-IRS-2 antisera (Upstate Cell Signaling); (f) rabbit polyclonal anti-p85/PI3K antisera (Upstate Cell Signaling); (g) rabbit polyclonal anti-thr-410-PKC-ζ (or thr-411-PKC-λ) antisera (Upstate Cell Signaling); (h) rabbit polyclonal anti-SREBP-1 (Neomarkers, Inc.); and anti-phosphoRelA subunit of NFκB (Santa Cruz Biotechnologies).

Glucose uptake into skeletal muscle in vivo

Glucose uptake was determined as described (12, 17, 20, 21). Briefly, mice were injected IP with 0.9% saline containing tracer amounts of [3H]2-deoxyglucose (transported and phosphorylated but not metabolized hexose) and [14C]glucose (a non-transported hexose used to correct for nonspecific trapping of extra-cellular fluid in muscle), and where indicated, insulin (1U/kg). 10 min later, muscle samples and serum were obtained. Total hexose (largely glucose uptake) was calculated from the specific activity of serum hexose (i.e., [3H]2-deoxyglucose radioactivity divided by serum glucose level) and muscle uptake of [3H]2-deoxyglucose.

Adenoviral studies

Adenoviruses were propagated in HEK-293 cells, purified by cesium chloride centrifugation and dialyzed against Krebs Ringer phosphate buffer. Adenovirus vector or adenovirus encoding KI-PKC-ζ [2.5 × 10¹² plaque-forming units (PFU)/kg body weight] was administered intravenously (IV; tail vein) to HFF mice or Mx-Het-KO mice. After 4 days, mice were subjected to overnight fasting or continued feeding of their usual diet for 24 h, as indicated. On the fifth day, where indicated, mice were injected IM with saline or insulin in saline, and 15 min later, mice were killed and liver and muscle samples were obtained. Note that (a) adenoviral treatments did not increase serum liver-derived enzymes, aspartate aminotransferase (AST), or alanine aminotransferase (ALT), ruling out a nonspecific hepatitis; (b) in HFF mice, insulin signaling in muscle dramatically increased after administration of adenovirus encoding KI-PKC-ζ, corroborating that adenovirus did not substantially enter or produce untoward effects in muscle; (c) in HFF mice, aPKC activity was diminished in liver, but substantially increased in muscle following administration of adenovirus encoding KI-PKC-ζ, in keeping with exclusive functional localization of adenovirus in liver; (d) aPKC levels were increased in liver but not in muscle, further attesting to liver localization of adenovirus encoding KI-PKC-ζ; (e) unlike hepatic aPKC activity, hepatic PKB/Akt activity was unchanged or, if anything, slightly increased above normal after administration of adenovirus encoding KI-PKC-ζ, indicating that insulin signaling to nonaPKC factors was not impaired; and (f) food intake was unaffected by adenoviral treatments. In attempts to analogously use adenovirus encoding KI-PKB, there were marked decreases in food intake and body weight, thus invalidating this approach. PKC-ζ and PKC-λ can function interchangeably during insulin action, and IK forms of either isoform inhibit both aPKC isoforms.

Measurement of SREBP-1c, FAS, ACC, IL-1β, and TNFα mRNA

As described (17), tissues were added to Trizol reagent (Invitrogen), and RNA was extracted and purified with the RNA-Easy Mini-Kit from Qiagen (Valencia, CA) and RNAase-free DNase set (Qiagen) as per kit instructions, quantified by measuring A₂₆₀/A₂₈₀, further checked for purity by electrophoresis on 1.2% agarose gels, and mRNA quantified by quantitative real-time reverse transcriptase-polymerase chain reaction (RT-PCR). Reverse transcription was accomplished with TaqMan reverse transcription reagent from Applied Biosystems (Foster City, CA). SREBP-1c mRNA was measured with a SYBR Green kit (Applied Biosystems) using nucleotide primers ATCGGCGCGGAAGCT- GTGCGGTTAGCGTC (forward) and ACTGTCCTTGTTGACTAGCTGGAGGAC (reverse). Mouse fatty acid synthase mRNA (FAS) was measured with primers GAGGCACCTCAAGTGGCTGA (forward) and GTGAGTTTGCTGCTGTCGT (reverse). Mouse acetyl CoA carboxylase (ACC) mRNA was measured with primers GACCTCAGAATTTGCTGAC (forward) and AGAAGACCTGTTCTGCTG (reverse). Mouse interleulin-1β (IL-1β) mRNA was measured with primers TGAGCCATTGACAGTCCAG (forward) and ATGAGCAAATGTCGGTAG (reverse). Mouse glucose-6-phosphatase (G6Pase) mRNA was measured with primers TGCTGCTCACTTTCCCACCAG (forward) and TCTCCAAATGTCGGTAG (reverse). Mouse phosphoenolpyruvate carboxykinase (PEPCK) mRNA was measured with primers GACGGCTGCTCCACG (forward) and TCTCCAAATGTCGGTAG (reverse). Mouse adiponectin mRNA was measured with primers TGAAGACTGCTGAGTGATCA (forward) and AAAGAACCTTATAGCCCCCCTTGA (reverse).

Nuclear fraction preparation

As described (17), liver nuclei were prepared with NE-PER Nuclear and Cytoplasmic Extraction Reagents obtained from Pierce Biotechnology (Cat. No. 78833). Levels of the active SREBP-1 fragment and active p65/RelA subunit of NFκB were measured in these nuclear preparations, which were also used for electrophoretic mobility shift assays (EMSA).
Fig. 1. Effects of adenoviral-mediated expression of kinase-inactive (KI) PKC-ζ on basal and feeding-induced activities of aPKC (A), PKB (B), and IRS-1-dependent PI3K (C) in vastus lateralis muscle, serum insulin levels (D), and basal and feeding-induced activity of aPKC (E), expression and nuclear levels of SREBP-1c (F), and expression of FAS (G) and ACC (H) in liver of high-fat–fed mice. High-fat–fed mice were injected IV with adenovirus vector (Vec) or adenovirus encoding KI-PKC-ζ (KI-ζ) and 4 days later (to allow time for expression), mice were fasted overnight 16–20 h (clear bars) or maintained on the high-fat diet (shaded bars). For comparisons in assays, normal-chow–fed mice were similarly fasted or maintained on their usual normal chow (low-fat) diet. The mice were killed on the next day (fifth day after initial virus treatment), and muscles, livers, and sera were harvested. In the inset in panel A, aPKCs were immunoprecipitated from muscles of normal-chow–fed (LO) or high-fat–fed (HI) mice treated with adenovirus vector (VEC) or adenovirus encoding KI-ζ, and assayed in absence (clear bars) or presence (shaded bars) of 10 μM PIP3. Values are mean ± SEM of (N) determinations. Asterisks indicate $P < 0.05$ (*), $P < 0.01$ (**), and $P < 0.001$ (***), for feeding-stimulated values versus adjacent fasting values of mice fed a comparable high or normal (low fat) diet, or in the inset of panel A, PIP3-treated versus untreated. Portrayed $P$ values depict comparisons of indicated groups (viz., insulin-stimulated adenovirus vector versus insulin-stimulated adenovirus encoding KI-PKC-ζ in high-fat–fed mice). All $P$ values were determined by ANOVA. Insets show 10 μM PIP3-dependent activation of aPKC immunoprecipitated from muscles of indicated mice (Panel A); representative autoradiograms of PIP3–32PO4, the lipid product of the PI3K assay (C); expressed KI-PKC-ζ–induced increases in levels of hepatic total aPKC (E); and a representative immunoblot of the active nuclear SREBP-1 fragment (F).
Electrophoretic mobility shift assays

NFκB-dependent shifts in mobility of specific 32P-labeled DNA sequences was measured with a kit and NFκB consensus nucleotide probes (5′-AGTTGAGGGGACTTTCCCAGGC-3′ and 3′TCACACTCCCGAGGGTTCCG-5′) obtained from Invitrogen [Cat. Nos. E3050 (kit) and E3291 (probe)].

Serum insulin, triglyceride, free fatty acids, cholesterol, and glucose levels

Serum insulin, triglycerides, free (non-esterified) fatty acids (FFA), total cholesterol, HDL-cholesterol, and glucose levels were measured as described (17).

Liver triglycerides

Liver triglycerides were measured as described (17).

Statistical evaluations

Data are expressed as mean ± SE, and P values were determined by a two-way ANOVA and the least-significant multiple comparison method.

RESULTS

HFF mice

Insulin signaling in muscle and liver of HFF mice. Impairments in insulin activation of aPKC and PKB/Akt previously observed in muscles of HFF mice (1, 2) were presently found to be associated with (a) markedly diminished activation of IRS-1— but not IRS-2—dependent PI3K (insulin activation data not shown, but see Fig. 1C for impaired effects of feeding and Fig. 2B for impaired insulin effects on aPKC activation); (b) poor responsiveness of aPKC immunoprecipitated from HFF muscle to direct addition of the lipid product of PI3K, PIP3 (Fig. 1A inset and Fig. 2B) versus excellent response in aPKC immunoprecipitated from muscles of normal-chow–fed mice; and (c) marked impairment in insulin-stimulated glucose transport (Fig. 2A). This impairment in aPKC responsiveness to insulin and PIP3 in HFF muscle was not explained by diminished phosphoinositide-dependent protein kinase-1(PDK1)–dependent thr-411 phosphorylation, which was intact and in fact largely activated even “basally” in HFF mice (Fig. 2C), perhaps by endogenous hyperinsulinemia (Fig. 1D); rather, the impairment apparently reflected reduced PIP3–dependent auto-phosphorylation, allosteric modification, and/or aPKC catalytic activity that occurs subsequent to PDK-1 action (24–26).

In HFF liver, along with reported intactness of insulin effects on aPKC and PKB/Akt (1), the activation of both IRS-1— and IRS-2—dependent PI3K by insulin was indistinguishable from that seen in normal liver (not shown).

Insulin-like signaling effects of feeding in muscle and liver of normal-chow-fed mice. Relative to overnight-fasted mice, normal chow feeding was associated with higher activities of muscle aPKC (Fig. 1A), muscle PKB/Akt (Fig. 1B), muscle IRS-1–dependent PI3K (Fig. 1C), hepatic aPKC (Fig. 1E), hepatic PKB/Akt (see Ref. 6), and, moreover, hepatic SREBP-1c expression, as per mRNA and active nuclear fragment levels (Fig. 1F), and SREBP-1c–regulated expression of hepatic FAS (Fig. 1G) and ACC (Fig. 1H). These effects of feeding on signaling are qualitatively similar to those of insulin (1), but overnight fasting diminishes basal activities of insulin-sensitive signaling factors (viz., IRS-1/2–dependent PI3K, aPKC, and PKB/Akt in both muscle and liver), and feeding elicits submaximal but presumably physiological increases that can be further amplified by exogenous insulin treatment.

Effects of insulin on IKKβ/NFκB and SREBP-1c in liver and muscle of normal-chow-fed mice. As discussed above, IKKβ and NFκB are regulated by aPKC (7–10), but insulin effects are
unknown. We found that, like SREBP-1c, insulin treatment for 6 h activated IKKβ and NFκB (active nuclear levels of the p65RelA/NFκB subunit and NFκB-dependent EMSA gel-shift activity) in livers of normal-chow–fed mice (Fig. 3). Different from liver, in muscle, 6-h insulin treatment failed to increase IKKβ and NFκB activation despite increasing expression and activity of SREBP-1c (Fig. 3).

**Dependence of feeding-dependent increases in hepatic activities of IKKβ/NFκB and SREBP-1c on aPKC in normal-chow-fed mice.**

It was previously reported that partial depletion of hepatic aPKC by liver-specific knockout of PKC-λ in mice is accompanied by diminished normal-chow-feeding–induced SREBP-1c activation, and enhanced glucose tolerance and insulin sensitivity, relative to wild-type mice (4). Presently, we found that, using Cre-loxP methods (i.e., administration of adenovirus expressing Cre-recombinase to mice with floxed PKC-λ genes) (17) provoked a partial but substantial loss of aPKC selectively in liver (muscle aPKC levels were unaffected), and this was accompanied by marked inhibition of feeding-induced increases in activities of not only hepatic SREBP-1c but also of IKKβ/NFκB in normal-chow–fed mice (Fig. 4). With respect to the residual hepatic immunoreactive hepatic aPKC (Panel A) after treatment with adenovirus encoding Cre-recombinase to selectively deplete hepatic PKC-λ, mouse liver contains substantial amounts of PKC-ζ mRNA and protein (see Ref. 17 and presently confirmed).

**Fig. 3.** Effects of insulin on IKKβ activity (A), nuclear NFκB p65/RelA/NFκB levels (C), NFκB electrophoretic mobility shift assay (EMSA) activity (E), SREBP-1c mRNA (B), and active nuclear SREBP-1 fragment levels (D) in liver and skeletal muscle. Long-acting glargine insulin (60mU/gm body wt) or physiological saline was administered subcutaneously to normal-chow–fed mice at approximately 8 AM, 6 h before killing and harvesting of liver and muscle. Values are mean ± SEM of (N) determinations. P values (as per ANOVA) depict comparisons of indicated groups (viz., insulin-stimulated versus saline-treated control mice). In bar grams, values were normalized to unity for each tissue and do not reflect marked differences in immunoreactivity between tissues. Immunoblots are shown for histone (H) loading controls (note lack of significant differences between samples), as well as for NFκB (N) and SREBP-1 (S).
Effects of feeding in muscle and liver of HFF mice. Relative to normal-chow–fed mice, in HFF mice, feeding-dependent increases in activities of aPKC (Fig. 1A), PKB/Akt (Fig. 1B), and IRS-1–dependent PI3K (Fig. 1C) were markedly diminished in muscle; however, in liver, as with insulin stimulation (1), feeding-dependent increases in aPKC activity (Fig. 1E) and PKB/Akt activation/phosphorylation were unaltered (see Ref. 1 and note in Fig. 7 intact feeding-dependent activation of PKB/Akt-dependent G6Pase and PEPCK genes). Thus, even with physiological dietary-induced increases in insulin secretion, aPKC and PKB/Akt activation was largely conserved in HFF liver.

In keeping with conserved hepatic aPKC activation and the presence of insulin resistance and hyperinsulinemia (Fig. 1D) in HFF mice, fasting and feeding-dependent increases in activities of aPKC (Fig. 1A), PKB/Akt (Fig. 1B), and IRS-1–dependent PI3K (Fig. 1C) were markedly diminished in muscle; however, in liver, as with insulin stimulation (1), feeding-dependent increases in aPKC activity (Fig. 1E) and PKB/Akt activation/phosphorylation were unaltered (see Ref. 1 and note in Fig. 7 intact feeding-dependent activation of PKB/Akt-dependent G6Pase and PEPCK genes). Thus, even with physiological dietary-induced increases in insulin secretion, aPKC and PKB/Akt activation was largely conserved in HFF liver.

In keeping with conserved hepatic aPKC activation and the presence of insulin resistance and hyperinsulinemia (Fig. 1D) in HFF mice, fasting and feeding-dependent increases in hepatic SREBP-1c mRNA (Fig. 1F), SREBP-1c active nuclear fragment levels (Fig. 1F), and ACC mRNA (Fig. 1H) were inordinately increased, relative to chow-fed mice. On the other hand, FAS mRNA was similarly increased in fed HFF and normal-chow–fed mice (Fig. 1G), perhaps reflecting maximal activation.

In livers of HFF mice, there were marked increases in activity of IKKβ, active nuclear levels of p65/RelA/NFκB subunit, and nuclear NFκB-dependent EMSA gel-shift activity; in contrast to 6-h insulin treatment, NFκB activity was not altered by acute 15-min insulin treatment (Fig. 5B).

Effects of KI-PKC-ζ on hepatic NFκB activation. As with SREBP-1c activation, treatment of HFF mice with adenovirus encoding KI-PKC-ζ markedly diminished the inordinate HFF-dependent increases in IKKβ (Fig. 5A) and NFκB activities (Fig. 5B) [total cellular hepatic p65/RelA/NFκB levels were not altered before or after KI-PKC-ζ treatment (not shown)]. In addition, there were decreases in mRNA levels of hepatic cytokines, IL1-β, and TNFα (Fig. 6A), genes regulated by NFκB.

Effects of KI-PKC-ζ on insulin signaling in muscle. Remarkably, in HFF mice the impairments in feeding-dependent
activation of IRS-1–dependent PI3K (Fig. 1C), aPKC (Fig. 1A), PKB/Akt (Fig. 1B), and the defect in aPKC responsiveness to PIP3 (Fig. 1A inset) in muscle were largely reversed to or toward normal after treatment with adenovirus encoding KI-PKC-ζ. Levels of aPKC, IRS-1, and PKB/Akt in HFF muscle were unaltered (not shown).

**Effects of KI-PKC-ζ on serum insulin levels.** Feeding provoked increases in serum insulin levels (Fig. 1D), and such increases were inordinate in HFF mice. Moreover, administration of adenovirus encoding KI-PKC-ζ markedly diminished serum insulin levels of fed HFF mice virtually to normal. This improvement in serum insulin presumably at least partly reflected improved insulin action in muscle.

**Effects of KI-PKC-ζ–mediated inhibition of hepatic aPKC on serum triglyceride, cholesterol, and glucose levels.** Along with inordinate increases in HFF-dependent activation of hepatic

![Fig. 5. Effects of adenoviral-mediated expression of kinase-inactive PKC-ζ on hepatic IKKβ activity (A), hepatic nuclear levels of the p65RelA subunit of NFκB (B), and NFκB-dependent EMSA mobility shifts (B), in high-fat–fed (HFF) mice. As in Fig. 1, where indicated, HFF mice were injected IV with adenovirus vector (Vec) or adenovirus encoding KI-PKC-ζ (KI-ζ), and 5 days later (to allow time for expression), mice were either fasted overnight or fed, or fed and treated IM for 15 min with saline or insulin in saline. For comparisons in assays, chow-fed (low fat) mice were similarly examined. Values are mean ± SEM of (N) determinations and P values (as per ANOVA) depict comparisons of indicated groups. Representative immunoblot of nuclear levels of the p65/RelA subunit of NFκB, and a representative autoradiogram of NFκB-dependent EMSA mobility shifts (arrow indicates electrophoretic mobility of the NFκB-DNA complex as determined with the kit standard (B). F indicates the electrophoretic front, as well as relative changes in multiple samples in the indicated groups.**
SREBP-1c, the serum levels of triglycerides, total cholesterol, and glucose were elevated above those seen in normal-chow–fed mice and, more interestingly, diminished substantially toward normal after 5 days of treatment with adenovirus encoding KI-PKC-ζ (Fig. 6A).

Effects of KI-PKC-ζ–mediated inhibition of hepatic aPKC on hepatic G6Pase and PEPCK expression. Like insulin, feeding in normal-chow–fed mice provoked decreases in expression of hepatic enzymes important in gluconeogenesis and glucose release [viz., as per PEPCK and G6Pase mRNA levels (Fig. 7)]. In HFF mice, fasting levels of these mRNAs trended downward, perhaps reflecting inhibitory effects of hyperinsulinemia, and feeding elicited further decreases in these mRNAs (Fig. 7). Interestingly, administration of adenovirus encoding KI-PKC-ζ, if anything, caused a further downward trend (albeit statistically insignificant) in fasting levels of these mRNAs. (However, note statistically significant decreases in fasted G6Pase and PEPCK mRNA levels elicited by adenovirus encoding KI-PKC-ζ in studies of Mλ-Het-KO mice described below.) Most importantly, mRNA levels of G6Pase and PEPCK in fed mice were comparably low, regardless of either dietary fat content (i.e., high fat versus low fat) or treatment with adenovirus.

![Fig. 6.](image-url) Effects of administration of adenovirus encoding kinase-inactive PKC-ζ (KI-ζ) on fasting serum levels of triglycerides, free fatty acids (FFA), total cholesterol, and glucose; and hepatic levels of triglycerides, ACC mRNA, IL-1β mRNA, and TNFα mRNA in high-fat–fed mice (A) and heterozygous muscle-specific PKC-λ knockout (Mλ-Het-KO) mice (B). WT = wild-type mice. Vec = adenovirus vector. Rel U = relative units. Values are mean ± SEM of (N) determinations and P values (as per ANOVA) depict comparisons of indicated groups.
encoding KI-PKC-ζ. These findings suggested that feeding/insulin regulation of these genes in both presently studied obesity models was essentially intact and, moreover, in concert with the idea that feeding/insulin-induced decreases in expression of G6Pase and PEPCK genes are independent of aPKC and instead largely depend on PKB/Akt. In fact, as further discussed below in studies of Mα-Het-KO mice, as administration of adeno-virus encoding KI-PKC-ζ clearly diminished G6Pase and PEPCK mRNA levels in fasting mice, it is possible that aPKC contributes to the maintenance of higher levels of these mRNAs in fasting conditions; such maintenance would most likely be independent of but reversible by insulin treatment.

Mα-Het-KO mice

In Mα-Het-KO mice, we reported that muscle aPKC levels are diminished, insulin activation of residual muscle aPKC activation is impaired, and insulin-stimulated glucose transport in muscle is diminished. On the other hand, normal-chow-feeding–dependent hepatic SREBP-1c and FAS activation is inordinately increased, and insulin activation of PKB/Akt in both muscle and liver is intact or, if anything, enhanced (17). Moreover, Mα-Het-KO mice have hyperinsulinemia, mild hyperglycemia, hyperlipidemia, and hepatosteatosis (17). Presently, as in HFF mice, administration of adeno-virus encoding KI-PKC-ζ to Mα-Het-KO mice elicited decreases in feeding-dependent activation of hepatic aPKC (Fig. 8A), and this was attended by decreases in (a) hepatic levels of SREBP-1c mRNA (Fig. 8B), active nuclear SREBP-1c fragment (Fig. 8C), and ACC mRNA (Fig. 8D); (b) activities of hepatic IKKβ (Fig. 8E) and NFκB, as per EMSA gel-shift activity (Fig. 8F) and levels of the active nuclear p65/RelA/NFκB subunit (Fig. 8G); and (c) mRNA levels of NFκB-regulated cytokines, IL-1β (Fig. 6B) and TNFα (Fig. 6B). Hepatic triglyceride levels, and serum levels of triglycerides, free fatty acids, and glucose, all of which are elevated in Mα-Het-KO mice (17), were similarly elevated in adeno-virus vector-treated Mα-Het-KO mice and, more importantly, diminished to levels seen in wild-type mice, along with similar downward trends in serum cholesterol levels following administration of adeno-virus encoding KI-PKC-ζ and inhibition of hepatic aPKC (Fig. 6B). As in HFF studies, hepatic levels of G6Pase and PEPCK mRNA were comparably low in fed wild-type and Mα-Het-KO mice, regardless of treatment administration of the latter group with adeno-virus encoding KI-PKC-ζ (Fig. 7). On the other hand, as discussed above, the fasting levels of these mRNAs were significantly diminished by treatment with adeno-virus encoding KI-PKC-ζ in Mα-Het-KO mice, perhaps suggesting that aPKC contributes to maintaining expression of G6Pase and PEPCK genes in the fasting state (also note similar downward trends of these mRNAs with adeno-viral/KI-ζ treatment in high-fat studies).

DISCUSSION

In livers of both obesity models, HFF and Mα-Het-KO mice, the expression of SREBP-1c and levels of its active nuclear fragment were, as expected, inordinately elevated but, even more importantly, diminished markedly following inhibition of hepatic aPKC activity by adeno-virally mediated expression of KI-PKC-ζ. It therefore seems clear that aPKC played a critical role in feeding/insulin-dependent increases in hepatic SREBP-1c expression in both obesity models. Moreover, it was important to see in both obesity models that decreases in activation of hepatic aPKC and expression of SREBP-1c, within 5 days of treatment with...
adenovirus encoding KI-PKC-z, were attended by (a) substantial decreases in hepatic mRNA levels of SREBP-1c–regulated genes, FAS and ACC, and (b) marked improvements (virtually to normal) in hepatic triglyceride levels and serum levels of triglycerides, free fatty acids, total cholesterol, insulin, and glucose. Thus, it is clear that hepatic aPKC plays a crucial role in hepatic lipid synthesis and the pathogenesis of hepatosteatosis and hyperlipidemia in these murine obesity models.

Perhaps equally important were findings in both obesity models showing that hepatic IKKb and NFkB activities and genes of NFkB-regulated cytokines, IL-1b and TNFalpha, which collectively have been linked to the development of systemic insulin resistance in HFF mice (7, 8), were inordinately increased. Again, treatment with adenovirus encoding KI-PKC-z diminished hepatic IKKb and NFkB activities and IL-1b and TNFalpha mRNA levels. In this regard, it was important to find in normal-chow–fed mice that (a) insulin treatment over 6 h provoked increases in hepatic IKKb and NFkB activities and (b) liver-specific knockouts (following administration of adenovirus encoding Cre-recombinase to PKC-l–floxed mice) markedly diminished feeding effects on hepatic IKKb and NFkB. Thus, it appears that both insulin and feeding (perhaps via endogenous insulin, at least in part) activate hepatic IKKb/NFkB as well as hepatic SREBP-1c, and both activations are to a great extent dependent on hepatic aPKC.

Notably, in HFF mice, within 5 days of adenoviral treatment with KI-PKC-z and subsequent decreases in hepatic SREBP-1c and IKKb/NFkB activities, there were remarkable...
improvements in insulin signaling to IRS–1–dependent PI3K, aPKC, and PKB/Akt in skeletal muscle. Moreover, hyperinsulinemia in HFF mice was largely reversed by this treatment with adenovirus encoding KI-PKC-ζ, presumably reflecting, at least partly, the improvement of insulin action in muscle. On the other hand, in MixerKO mice, other than for impaired aPKC activation owing to the irreversible depletion of PKC-α, there are no impairments in insulin signaling in muscle (17), thus precluding our ability to observe alterations (i.e., improvements) in insulin signaling in muscle following inhibition of hepatic aPKC.

Of further interest, ancillary findings in presently used HFF mice that insulin effects on IRS–1–dependent PI3K (but not IRS–2–dependent PI3K) were impaired in muscle, and insulin effects on both IRS–1– and IRS–2–dependent PI3K were intact in liver suggested that (a) impaired activation of IRS–1–dependent PI3K accounted for impaired insulin signaling to aPKC and PKB/Akt in muscle and (b) intact activation of both IRS–1– and IRS–2–dependent PI3K in liver accounted for conserved activation of hepatic PKB/Akt (and subsequent regulation of G6Pase, PEPCK, and SREBP-1c genes) and hepatic aPKC in HFF mice. Our findings further suggested that, in addition to impaired IRS–1–dependent PI3K activation, impaired responsiveness of aPKC to PIP3 contributed to diminished aPKC activation in HFF muscle.

From the present findings, it may be reasoned that persistent hyperinsulinemia in obesity and other insulin-resistant states contributes importantly to increases seen in hepatic IKKβ and NFκB activities through the activation of hepatic aPKC. However, other aPKC activators (e.g., cytokines and lipids) may also contribute to increases in aPKC, IKKβ, and NFκB activities in liver and other tissues in these insulin-resistant states. In either case, inhibition of IKKβ by high-dose salicylate therapy improves insulin action in muscle and liver in insulin-resistant rodents (7,8), presumably by diminishing NFκB-dependent circulating inflammatory cytokines, such as IL-6 (7,8) and TNF-α. Accordingly, it is likely that improvements in insulin signaling in muscle presently observed in HFF mice after treatment with adenoviruses that inhibit hepatic aPKC at least partly reflect diminished hepatic IKKβ/NFκB activation by insulin and possibly other agonists.

Although we were able to significantly diminish expression of hepatic lipid-synthesizing enzymes and both hepatic and serum lipid levels, there were only modest statistically insignificant decreases in actual liver size during the 5-day period of treatment of HFF mice with adenovirus encoding KI-PKC-ζ. Nevertheless, there was remarkable improvement in serum insulin levels and the ability of insulin to activate IRS–1–dependent PI3K, aPKC, and PKB/Akt in muscles of HFF mice following adenoviral/ KI-PKC-ζ treatment. Whether improvements in insulin signaling in muscle were caused by decreases in hepatic lipid synthesis and diminished serum lipid levels, or diminished hepatic NFκB activation, or both, is uncertain.

From the present findings, it may be surmised that chronic activation of hepatic aPKC in hyperinsulinemic states is associated with undesirable consequences of (a) excessive sensitivity of aPKC to PIP3 contributed to diminished aPKC activation, or both, is uncertain.

REFERENCES


