Stearoyl-CoA desaturase 1 deficiency increases fatty acid oxidation by activating AMP-activated protein kinase in liver

Pawel Dobrzyń, Agnieszka Dobrzyń, Makoto Miyazaki, Paul Cohen, Esra Asilmaz, D. Grahame Hardie, Jeffrey M. Friedman, and James M. Ntambi

Departments of *Biochemistry and †Nutritional Sciences, University of Wisconsin, Madison, WI 53706; ‡Laboratory of Molecular Genetics and *Howard Hughes Medical Institute, The Rockefeller University, New York, NY 10021; and †Division of Molecular Physiology, School of Life Sciences, Dundee University, Dundee DD1 5EH, United Kingdom

Communicated by Henry Lardy, University of Wisconsin, Madison, WI, March 9, 2004 (received for review December 23, 2003)

Stearoyl-CoA desaturase (SCD) catalyzes the rate-limiting step in the biosynthesis of monounsaturated fatty acids. Mice with a targeted disruption of the SCD1 isoform have reduced body adiposity, increased energy expenditure, and up-regulated expression of several genes encoding enzymes of fatty acid β-oxidation in liver. The mechanisms by which SCD deficiency leads to these metabolic changes are presently unknown. Here we show that the phosphorylation and activity of AMP-activated protein kinase (AMPK), a metabolic sensor that regulates lipid metabolism during increased energy expenditure is significantly increased (−40%, P < 0.01) in liver of SCD1 knockout mice (SCD1+/−). In parallel with the activation of AMPK, the phosphorylation of acetyl-CoA carboxylase at Ser-79 was increased and enzymatic activity was decreased (−35%, P < 0.001), resulting in decreased intracellular levels of malonyl-CoA (−47%, P < 0.001). An SCD1 mutation also increased AMPK phosphorylation and activity and increased acetyl-CoA carboxylase phosphorylation in leptin-deficient ob/ob mice. Lower malonyl-CoA concentrations are known to derepress carnitine palmitoyltransferase 1 (CPT1). In SCD1+/− mice, CPT1 and CPT2 activities were significantly increased (in both cases ~60%, P < 0.001) thereby stimulating the oxidation of mitochondrial palmitoyl-CoA. Our results identify AMPK as a mediator of increased fatty acid oxidation in liver of SCD1-deficient mice.

Stearoyl-CoA desaturase is a key enzyme involved in the biosynthesis of monounsaturated fatty acids. The preferred substrates are palmitoyl-CoA and stearoyl-CoA, which are converted to palmitoleyl-CoA and oleoyl-CoA, respectively. These products are the most abundant monounsaturated fatty acids of phospholipids, triglycerides, cholesterol esters, and wax esters (1). Overall, the expression of SCD can influence membrane fluidity, lipid metabolism, and adiposity. Increased SCD activity and alterations in the balance between saturated and monounsaturated fatty acids have been implicated in various diseases including cancer, diabetes, atherosclerosis, and obesity (2).

To investigate the physiological function of SCD, we created mice with a targeted disruption of the SCD1 gene (SCD1+/−) (3). We established that SCD1+/− mice have reduced body adiposity and increased insulin sensitivity, and are resistant to diet-induced weight gain relative to wild-type mice. The resistance to diet-induced obesity is due to increased energy expenditure (4). SCD1+/− mice also have increased fasting levels of plasma ketone bodies but reduced levels of plasma insulin and leptin. Moreover, mice with mutations in the SCD1 gene accumulate less fat in their adipose tissue and have lower levels of triglyceride and cholesterol esters in liver than wild-type animals (5). In SCD1+/− mice, the expression of several genes encoding enzymes of fatty acid oxidation are up-regulated, whereas genes encoding enzymes of lipid synthesis are down-regulated (4).

Leptin is an adipocyte-derived hormone that plays a pivotal role in regulating food intake and energy expenditure. Leptin stimulates the oxidation of fatty acids and uptake of glucose and reduces the accumulation of lipids in nonadipose tissues. Recently, leptin was found to repress RNA levels and enzymatic activity of SCD1 in liver (6). Ob/ob mice with SCD1 mutations were significantly less obese than ob/ob controls and had markedly increased energy expenditure with reduced triglyceride storage in liver (6). SCD1 is therefore a component of the novel metabolic response to leptin signaling, and SCD1 repression accounts for a significant proportion of the effects of leptin on energy expenditure and body weight. The signaling pathways that mediate the metabolic effects of leptin remain largely unknown. Leptin has been found to selectively stimulate phosphorylation and activation of the e2 catalytic subunit of AMP-activated protein kinase (AMPK), an enzyme that has been found to be a principal mediator of the effects of leptin on fatty acid oxidation in muscle (7).

AMPK is a heterotrimeric enzyme that is conserved from yeast to humans and functions as a gauge to monitor cellular energy stores. Numerous mechanisms of AMPK action on lipid and carbohydrate metabolism have been proposed (8–10). AMPK regulates the expression of genes of lipid synthesis by modulating the activities of transcription factors and coactivators (11). Phosphorylation of p380 by AMPK inhibits its interaction with several nuclear receptors, i.e., peroxisome proliferator-activated receptors and thyroid hormone, retinoic acid, and retinoid X receptors, resulting in either activation or repression of gene expression (12). Phosphorylation of carbohydrate-response-element-binding protein by AMPK blocks DNA binding and mediates inhibition of glucose-induced gene transcription (13). AMPK activation also suppresses the expression of SREBP-1c, a key transcription factor regulating genes of fatty acid and triglyceride biosynthesis (14). In addition to regulating gene transcription, AMPK regulates (by phosphorylation/dephosphorylation) the activity of enzymes of fatty acid and cholesterol synthesis (15–18).

Phosphorylation of acetyl-CoA carboxylase (ACC) at Ser-79 by AMPK leads to inhibition of ACC activity and decreased malonyl-CoA content. Malonyl-CoA is required for fatty acid biosynthesis and also inhibits the mitochondrial carnitine palmitoyltransferase shuttle system, the rate-limiting step in the import and oxidation of fatty acids in mitochondria (19). ACC catalyzes a pivotal step in fuel metabolism as it links fatty acid and carbohydrate metabolism through the shared intermediate acetyl-CoA. ACC2 knockout mice show increased fatty acid oxidation in muscle, heart, and liver and are lean (20). Thus, we hypothesized that AMPK acting through the inhibition of ACC would be one mechanism accounting for increased fatty acid

Abbreviations: ACC, acetyl-CoA carboxylase; AMPK, AMP-activated protein kinase; CPT, carnitine palmitoyltransferase; SCD, stearoyl-CoA desaturase

To whom correspondence should be addressed at: Department of Biochemistry, University of Wisconsin, 433 Babcock Drive, Madison, WI 53706. E-mail: ntambi@biochem.wisc.edu.

© 2004 by The National Academy of Sciences of the USA
oxidation in the livers of SCD1-deficient mice. Indeed, we found that the phosphorylation and activity of AMPK are increased in SCD1/−/− mice and we show that phosphorylation and inactivation of ACC results in decreased levels of malonyl-CoA and activation of carnitine palmitoyltransferase 1 (CPT1) leading to increased palmitate oxidation in liver mitochondria of SCD1/−/− mice.

Materials and Methods

Animals. The generation of SCD1−/− and ab/ab;ob/ob mice has been described (3, 6). Twelve-week-old prebred homozygous (SCD1−/−) and wild-type (SCD1+/+) male mice on a 129SV background were used. The ab/ab;ob/ob and ab/ab;ob/ob control mice on a C57BL/6 background were 16 weeks old. Mice were maintained on a 12-h dark/light cycle and fed a normal nonpurified diet (5006 test diet, PMI Nutrition International, Richmond, IN). The breeding of these animals was in accordance with the protocols approved by the Animal Care Research Committees of the University of Wisconsin and The Rockefeller University Laboratory Animal Research Center.

Preparation of Mitochondria and Measurement of Mitochondrial Fatty Acid Oxidation. Mitochondria were were isolated essentially as described by Vance (21). The mixture used to measure mitochondrial fatty acid oxidation contained, in a final volume of 2.5 ml, 2 ml of modified Krebs-Henseleit buffer (pH 7.4), 0.2 mM [14C]palmitoyl-CoA, 0.68 mM [3H]carnitine, [14C]sodium bicarbonate, [γ-32P]ATP, [14C]acetate-CoA, [14C]palmitic acid, and [14C]palmitoyl-CoA were purchased from American Radiolabeled Chemicals (St. Louis). SAMS peptide and anti-phospho-ACC antibody were obtained from Upstate (Waltham, MA). Anti-ACC1, anti-ACC2, and anti-CPT1 antibodies were from Alpha Diagnostic (San Antonio, TX). Other chemicals were purchased from Sigma or Fisher Scientific.

Measurement of AMPK Activity. The CPT1 assay was performed as described by Brocard et al. (30). Briefly, 200 μg of mitochondrial protein was added to the assay medium containing 20 mM Hapes (pH 7.3), 75 mM KCl, 2 mM KCN, 1% fat-free BSA, 70 μM palmitoyl-CoA, 0.25 mM L-[3H]carnitine, with or without 10, 30, 50, or 100 μM malonyl-CoA. Samples were incubated at 37°C for 3 min. The reaction was stopped by the addition of 0.5 ml of 4 M ice-cold perchloric acid. Mitochondria were centrifuged, the pellet was washed with 500 μl of 2 mM perchloric acid, and centrifugation was repeated. The resulting pellet was then resuspended in 800 μl of ddH2O and extracted with 600 μl of butanol. Three hundred microliters of the butanol-phase was counted by liquid scintillation. CPT2 activity was measured in Tween 20 extracts of whole mitochondria according to Kołodziej et al. (31). Purified mitochondria (1–2 mg of protein) were treated with Tween 20 (3 μl of detergent per mg of protein) for 40 min at 0°C, with two periods (10 s) of sonication. CPT2 activity in the supernatant was assayed in the same manner as CPT1 activity described above. The enzyme was not sensitive to malonyl-CoA.

Incorporation of [14C]Palmitic Acid into Liver Lipids. Ten micromolar (Ci; 1 Ci = 37 GBq) of [14C]palmitic acid suspended in albumin was administered into the tail vein. Ten minutes after administration of the label, the liver was extracted and homogenized. Lipids were extracted (32) and assayed for radioactivity in a liquid scintillation counter.

Protein Determination. Protein concentration was measured by the Bradford method with BSA as a standard.

Statistical Analyses. Results were analyzed by using the Student’s t test. A difference of P < 0.05 was considered significant. Values are presented as means ± SD (n = 5 mice per group in the case of SCD1+/+ and SCD1−/− mice, and n = 3 in the case of ab/ab;ob/ob and ab/ab;ab/ob mice).

Results

AMPK Is Activated in SCD1−/− Mice. One of the mechanisms that could account for the increased energy expenditure in SCD1-deficient mice is the activation of AMPK. AMPK phosphorylation was increased 52% in SCD1−/− mice relative to the wild-type controls (Fig. L4). We then assayed AMPK activity by SAMS peptide phosphorylation in the presence of saturating

of human AMPK and Ser-79 of rat ACC. Protein levels of α1 and α2 AMPK, and ACC1, ACC2, and CPT1, were determined by using specific antibodies. Anti-AMPK α1 and α2 and anti-AMPK-pT172 antibodies were obtained as described (26, 27).

The proteins were visualized by using ECL (Amersham Biosciences) as described by the manufacturer and quantified by densitometry. ACC activity in the 6% PEG 8000 fraction was determined by using the [14C]bicarbonate fixation assay as described (28).
poration of [3H]acetyl-CoA into palmitic acid in the presence of levels in the acid soluble liver extract by measuring the incorporated malonyl-CoA concentrations, we assayed malonyl-CoA in SCD1/H11002 mice served in SCD1 enzymes encoding genes of lipid biosynthesis previously published data) consistent with reduced levels of mRNAs of reflecting a decrease in ACC mRNA (M.M. and J.M.N., unpublished data).  

Although CPT1 protein level was slightly increased (18%, P < 0.05) (Fig. 3A), CPT1 activity was 63% higher in SCD1/−/− mice relative to wild-type controls (50.9 ± 4.5 μM of carnitine; P < 0.001) (Fig. 3B). The lower Km value for enzyme purified from liver of SCD1/−/− mice (35.1 ± 1.4 μM carnitine) relative to that from wild-type mice (50.9 ± 4.5 μM of carnitine; P < 0.001) is consistent with increased CPT1 activity. CPT2 activity was also higher in SCD1/−/− mice relative to wild-type controls (322.43 nmol/min/mg of protein and 200.96 nmol/min/mg of protein, respectively; P < 0.001) (Fig. 3B). During increased fatty acid oxidation, hepatic CPT1 becomes less sensitive to inhibition by malonyl-CoA. The CPT1 activity isolated from livers of SCD1/−/− mice was less sensitive to inhibition by malonyl-CoA than the enzyme from wild-type mice (86% and 68% of inhibition in presence of 100 μM malonyl-CoA, respectively; P < 0.01) (Fig. 3C).

To determine whether SCD1 deficiency increased fatty acid utilization, we injected [14C]palmitate into the tail vein and

**Increased Mitochondrial Fatty Acid Oxidation in Mice with Disruptions in SCD1.** A fall in malonyl-CoA would be expected to result in increased activities of CPT1 and CPT2, enzymes responsible for activated fatty acid transport into mitochondria for β-oxidation. Although CPT1 protein level was slightly increased (18%, P < 0.05) (Fig. 3A), CPT1 activity was 63% higher in SCD1/−/− mice relative to wild-type controls (260.76 nmol/min/mg of protein in SCD1/−/− and 159.68 nmol/min/mg of protein in SCD1/+/+ mice; P < 0.001) (Fig. 3B). The lower Km value for enzyme
assayed its incorporation into lipids. As shown in Fig. 4A, [14C]palmitate incorporation into storage lipids was decreased in SCD1−/− mice compared to SCD1+/+ controls. However, the rate of β-oxidation, as assayed by the oxidation of [14C]palmitoyl-CoA in liver mitochondria, was >2-fold (P < 0.01) higher in SCD1−/− mice compared to wild-type controls (Fig. 4B).

**SCD1 Deficiency Increases AMPK Activity in Ob/ob Leptin-Deficient Mice.** Leptin has been shown to increase fatty acid oxidation in muscle both directly and indirectly via nervous stimulation from the brain, and in both cases this is associated with activation of the α2 catalytic subunit of AMPK (7). To explore the effects of SCD1 deficiency on AMPK-mediated fatty acid oxidation in leptin-deficient mice, ob/ob mice were intercrossed with ab/ab′ mice, which have a natural mutation in the SCD1 gene to generate the ab/ob′ and ab′/ob mice (6). These double-mutant mice showed a significant increase in AMPK phosphorylation (≈2-fold; Fig. 5A) and activity (≈44%, P < 0.05; Fig. 5B), and an increase in ACC phosphorylation at Ser-79 (≈2-fold; Fig. 5C) and decrease in ACC1 and ACC2 protein levels (Fig. 5C) relative to ab′/ob′ and ob′/ob controls. The ACC activity was also decreased in ab′/ob′ and ob′/ob mice (data not shown).

**Discussion**

We have previously shown that loss of SCD1 function activates genes of fatty acid oxidation and reduces expression of genes that encode enzymes of fatty acid synthesis in liver (4). The signals induced by SCD1 deficiency leading to increased fatty acid oxidation were not known. However, in the present study we found that SCD1 deficiency activates AMPK, an enzyme that functions as a fuel gauge to monitor the status of cellular energy. We found that activated AMPK increased ACC phosphorylation, a well known mechanism for ACC inactivation, thereby resulting in reduced malonyl-CoA levels. The reduction in malonyl-CoA levels derepresses CPT1 leading to an increase in the transport of fatty acids into mitochondria and their subsequent oxidation. These observations, shown schematically in Fig. 6, begin to provide the mechanisms for increased fatty acid oxidation in SCD1−/− animals.

The mitochondrial carnitine system plays a crucial role in β-oxidation. CPT1 catalyzes the esterification of long-chain acyl-CoAs to L-carnitine for transport into mitochondria for fatty acid oxidation. The acyl-carnitine conjugate is converted back to the acyl-CoA ester inside mitochondria by CPT2 (19). SCD1−/− animals. The mitochondrial carnitine system plays a crucial role in β-oxidation. CPT1 catalyzes the esterification of long-chain acyl-CoAs to L-carnitine for transport into mitochondria for fatty acid oxidation. The acyl-carnitine conjugate is converted back to the acyl-CoA ester inside mitochondria by CPT2 (19).
activities and decreased $K_{m}$ value for CPT1. Also, CPT1 gene expression is up-regulated (4) and protein level is slightly increased (Fig. 3A) in these animals relative to wild-type controls. Malonyl-CoA is an allosteric inhibitor of CPT1. During energy excess, the increased malonyl-CoA inhibits CPT1 activity, preventing the oxidation of newly formed fatty acids bound for energy storage. On the other hand, during starvation and exercise malonyl-CoA levels fall to permit the oxidation of fatty acids for energy production (34). Malonyl-CoA levels are decreased ~2-fold in SCD1−/− liver resulting in CPT1 activation. The CPT1 from livers of SCD1−/− mice was also found to be less sensitive to inhibition by malonyl-CoA than the enzyme from wild-type mice. Decreased sensitivity to CPT1 inhibition by malonyl-CoA has been observed during increased fatty acid oxidation (19) and is consistent with increased fatty acid oxidation in livers of SCD1−/− mice.

Malonyl-CoA formation is mainly regulated by changes in the activity of the ACC and malonyl-CoA deacylase. ACC activity is controlled by various mechanisms including changes in degree of polymerization, allosteric regulation by citrate and glutamate, and covalent modification by phosphorylation/dephosphorylation (35). Although several protein kinases can phosphorylate ACC, it is currently accepted that in intact hepatocytes and in the liver in vivo this phosphorylation, which leads to inactivation of the enzyme, is mainly mediated by AMPK (36, 37). AMPK inactivates ACC by phosphorylation at Ser-79 (38). We found higher ACC phosphorylation at Ser-79 in SCD1−/− mice. In all studies, AMPK activated by other agents, increased ACC phosphorylation in SCD1−/− mouse liver. Studies are underway to determine the effects of SCD1 deficiency on regulation of ACC activity in liver and adipose tissue.

Malonyl-CoA formation is mainly regulated by changes in the activity of the ACC and malonyl-CoA deacylase. ACC activity is controlled by various mechanisms including changes in degree of polymerization, allosteric regulation by citrate and glutamate, and covalent modification by phosphorylation/dephosphorylation (35). Although several protein kinases can phosphorylate ACC, it is currently accepted that in intact hepatocytes and in the liver in vivo this phosphorylation, which leads to inactivation of the enzyme, is mainly mediated by AMPK (36, 37). AMPK inactivates ACC by phosphorylation at Ser-79 (38). We found higher ACC phosphorylation at Ser-79 in SCD1−/− mice. In all studies, AMPK activated by other agents, increased ACC phosphorylation in SCD1−/− mouse liver. Studies are underway to determine the effects of SCD1 deficiency on regulation of ACC activity in liver and adipose tissue.

In all studies, AMPK activated by other agents, increased ACC phosphorylation in SCD1−/− mouse liver. Studies are underway to determine the effects of SCD1 deficiency on regulation of ACC activity in liver and adipose tissue.

We thank Dr. Salih J. Wakis (Baylor College of Medicine, Houston) for providing purified fatty acid synthetase. This work was supported by National Institute of Health Grants ROI-DK52381 (to J.M.N.), ROI-DK41096 (to J.M.F.), and MSTEP GM07739 (to P.C.). American Heart Association Postdoctoral Fellowship 0420051Z (to A.D.), Wellcome Trust Grant 065565 (to D.G.H.), and European Commission Grant QLG1-CT-2001-01488 (to D.G.H.).