Sirt1 protects against high-fat diet-induced metabolic damage

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The identification of new pharmacological approaches to effectively prevent, treat, and cure the metabolic syndrome is of crucial importance. Excessive exposure to dietary lipids causes inflammatory responses, deranges the homeostasis of cellular metabolism, and is believed to constitute a key initiator of the metabolic syndrome. Mammalian Sirt1 is a protein deacetylase that has been reported to be involved in resveratrol-induced protection from a high-fat diet and has the ability to improve glucose homeostasis in rodents, but direct proof for the implications of Sirt1 has remained elusive. Here, we report that mice with moderate overexpression of Sirt1 under the control of its natural promoter exhibit fat mass gain similar to wild-type controls when exposed to a high-fat diet. Higher energy expenditure appears to be compensated by a parallel increase in food intake. Interestingly, transgenic Sirt1 mice under a high-fat diet show lower lipid-induced inflammation along with better glucose tolerance, and are almost entirely protected from hepatic steatosis. We present data indicating that such beneficial effects of Sirt1 are due to at least two mechanisms: induction of antioxidant proteins MnSOD and Nrf1, possibly via stimulation of PGC1α, and lower activation of proinflammatory pathways TNFα and IL-6 via down-modulation of NFκB activity. Together, these results provide direct proof of the protective potential of Sirt1 against the metabolic consequences of chronic exposure to a high-fat diet.

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iven by the need for potent and safe options to treat obesity, diabetes, and the metabolic syndrome, numerous efforts are currently underway to achieve a better understanding of molecular networks controlling cellular glucose, lipid, and energy metabolism (1–3). It is generally accepted that gene–environment interactions (such as the effect of high-fat diets on the molecular pathways that maintain energy homeostasis) play a key role in the pathogenesis of the metabolic syndrome (4). Intriguingly, several reports recently showed that specific dietary fatty acids can directly activate Toll-like receptors, which are better known as components of the innate immune system recognizing bacteria-derived fatty acids (5–7). The resulting immune response promotes the systemic activation of proinflammatory pathways including NFκB, TNFα, or IL-6 (5, 6). This chain of events is believed to ultimately lead to insulin resistance, setting in motion the vicious cycle of the metabolic syndrome (8).

Recently, a series of studies in several organisms revealed multiple important links of the Sirtuin family of proteins with energy metabolism and inflammation (9–11). Also known as silent information regulator 2 (Sir2)-related enzymes, the Sirtuins have been well conserved throughout evolution and represent a family of nicotinamide adenine dinucleotide-dependent enzymes that deacetylate residues of acetylated lysine. The mammalian sirtuins Sirt1–Sirt7 are implicated in a number of cellular and physiological functions including gene silencing, apoptosis, mitochondrial function, energy homeostasis, and longevity (12). Among its multiple reported targets, Sirt1 deacetylates and thereby activates PGC1α, an essential cofactor in mitochondrial biogenesis driving metabolic rate (10). Thus, activation of Sirt1 may represent a promising strategy for preventing and treating metabolic syndrome (13). This hypothesis has gained support recently from newly developed chemical activators of Sirt1 that boost mitochondrial capacity and improve whole-body glucose homeostasis (14). However, these small molecules could impinge on multiple members of the Sirtuin family, as well as on other targets yet to be discovered. To directly test the effect of Sirt1 on the metabolic impairment induced by chronic exposure to dietary lipids, we generated mice with moderate overexpression of Sirt1 and analyzed their metabolic phenotype.

Results

Generation of Sirt1 Transgenic Mice. Transgenesis was performed by using a large genomic construct (174 kb) containing the entire Sirt1 gene in its natural genomic context (Fig. 1A). In general, these large genomic transgenes have the advantage of providing a pattern of tissue expression very similar or identical to the endogenous gene (15). The Sirt1 genomic construct used also contains the adjacent gene DnaJ12 (Fig. 1A). This gene belongs to a large family of heat shock proteins, the DnaJ/Hsp40 family, with >40 members in mammalian genomes (16). We reasoned that the likely effect of increasing the expression of DnaJ12 is of little relevance because of the large number of paralogs already present in the genome, the lack of previous evidence implicating Hsp40 proteins in the processes explored in this report, and the absence of effect of DnaJ12 inhibition on the molecular pathways affected by Sirt1 (see below). Transgenesis was performed by standard microinjection of fertilized oocytes. One founder mouse was identified that contained a single complete copy of the Sirt1 genomic insert and that transmitted the transgenic allele to the progeny (supporting information (SI) Fig. S1 and Fig. S2). This line of transgenic mice is abbreviated here as Sirt1-tg or simply tg.

Expression of Sirt1 was analyzed in mouse embryonic fibroblasts (MEFs) (Fig. 1B), as well as in different tissues from Sirt1-tg mice (Fig. 1C), and it was found that Sirt1 was moderately overexpressed in all of the tissues tested. Quantitative RT-PCR indicated a homogeneous level of overexpression (ranging from 2- to 4-fold in liver, brown adipose tissue, and muscle; for these values, see Fig. 2B and Fig. S3 B and E). This increase in Sirt1 mRNA was paralleled by a similar increase in protein levels (ranging from 2- to 4-fold in different tissues; see Fig. 1C). In the case of liver, a more extensive quantification of the protein levels indicated an average overexpression of ∼3-fold (2.7 ± 0.35, n = 7). Functionality of the transgene was confirmed genetically by rescue of three overt phenotypes present in Sirt1 knockout mice, namely, partially penetrant perinatal lethality and low weight and microphthalmia of the
surviving mice (17). In brief, Sirt1(-/-tg) mice were born and viable at the expected Mendelian ratio, with no indication of perinatal lethality, had a normal weight, and did not present with microphthalmia (Fig. S4).

**Balanced Energy Homeostasis of Sirt1 Transgenic Mice.** Deficiency for Sirt1 has previously been shown to reduce body weight in mice (17) and Fig. S4). Therefore, we began our characterization by examining the effects of moderate Sirt1 overexpression on the regulation of body weight, food intake, and energy balance regulation. Body weights and body lengths of 8- to 10-week-old transgenic Sirt1 mice did not differ from wild-type (WT) control mice on a standard diet (SD) (Fig. 2A, and data not shown). Subsequent exposure for 19 weeks to a high-fat diet (HFD) did not lead to significant differences in body weight (Fig. 2A), fat mass (Fig. 2C), or lean mass (Fig. 2D), although a trend toward lower body weight and fat mass was observed in tg mice on HFD compared with WT controls. Neither plasma leptin levels nor adiponectin levels differed between genotypes on either SD or HFD (Table S1). Noteworthy, tg mice exhibited increased food intake compared with WT mice on HFD (Fig. 2B). This increase in food intake was corroborated by using in-depth analysis with an automated food intake-monitoring system (Fig. S3A). Therefore, we examined next whether the increase in caloric intake of tg mice on HFD was compensated by a concomitant increase in energy expenditure. Consistent with this hypothesis, indirect calorimetry revealed that tg mice showed higher energy expenditure than WT mice on HFD (Fig. 2E Right and F). No differences were observed in mice fed SD (Fig. 2E Left and F). Real-time PCR analysis of UCP1 levels in brown adipose tissue (BAT) suggested that BAT thermogenesis was not the cause for this increase in energy expenditure, despite overexpression of Sirt1 in BAT (Fig. S3B). We next tested activity-induced thermogenesis by monitoring motor activity in a specific home cage beam break system, but failed to find significant changes in total locomotion (Fig. S3C), ambulatory movement, or stationary movement (Fig. S3D). The energetic cost of muscular activity seemed also unchanged, as indicated by a comparable expression of UCP3 and of several mitochondrial respiratory chain enzymes in the quadriceps muscle, despite overexpression of Sirt1 (Fig. S3E). No differences in respiratory quotient were found, suggesting comparable fuel-partitioning patterns in WT and tg mice (Fig. S3F). In summary, although Sirt1 transgenic mice present a modest increase in food intake under HFD, this is compensated by a similarly modest increase in energy expenditure, thus indicating a balanced energy homeostasis.

**Sirt1 Transgenic Mice Are Protected from HFD-Induced Hepatic Steatosis.** Chronic HFD exposure causes accumulation of lipids in the liver, a process leading to fatty liver disease, also known as Nonalcoholic Fatty Liver Disease (NAFLD) or Nonalcoholic Steato-Hepatitis (NASH) (19). Sirt1 has been implicated in the control of lipid metabolism (9). We therefore investigated hepatic accumulation of lipids by oil red staining of frozen liver sections (Fig. 3A). As expected, small amounts of lipid droplets were found in liver sections of both WT and tg mice after 19 weeks on SD. In contrast, after 19 weeks of HFD, WT mice presented with severe hepatosteatosis, including massive accumulation of large lipid droplets. Importantly, Sirt1 tg mice were almost entirely protected from

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**Fig. 2.** Transgenic Sirt1 mice are protected from HFD-induced hepatosteatosis. (A) Oil red staining lipid droplets in frozen liver sections (3 per group) from both wild-type (WT) or transgenic (tg) mice on a standard diet (SD) or after high-fat diet (HFD) exposure for 19 weeks. (Scale bars, 50 μm.) (B) Gene expression analysis (real-time PCR) of hepatic Sirt1 and the transcription factor SREBP1c. n = 7–8 per group; means ± SEM; *, P < 0.05; ***, P < 0.001.
NAFLD, showing a low number of lipid droplets with small diameters (Fig. 3A). A common feature of NAFLD is the deregulation of enzymes involved in fat metabolism, a process tightly controlled by a number of specific regulators, being particularly relevant the SREBP transcription factors (20). In agreement with the observed Sirt1-mediated protection from hepatosteatosis, we found that Sirt1 tg mice presented lower levels of SREBP1c mRNA in response to HFD (Fig. 3B). We conclude that Sirt1 protects from NAFLD.

Transgenic Sirt1 Mice Are Protected from HFD-Induced Hepatic Glucose Intolerance. Based on reports showing that NAFLD can also be a direct consequence of peripheral insulin resistance with an elevated transport of free fatty acids from adipose tissue to the liver (21), we next examined whether glucose tolerance and insulin resistance differed between genotypes at different ages and on different diets. After 8 weeks of diet exposure, overnight fasting glucose levels were similar between genotypes on both SD and HFD (Table S1). In addition, insulin, cholesterol, and triglyceride levels did not differ between genotypes and diets (Table S1). After 18 weeks of exposure to HFD, glucose levels were increased in mice fed a HFD, indicating the expected HFD-induced systemic glucose intolerance in both genotypes. However, although peak values were similar for WT and tg mice on the HFD, the transgenic mice on HFD decreased their blood glucose levels more rapidly than WT controls on the same diet. Area-under-the-curve (AUC) values revealed a significantly better preserved glucose tolerance of tg mice on HFD compared with WT mice on HFD (Fig. 4A Right).

Because we observed substantial protection from hepatic lipid deposition by Sirt1 overexpression, we hypothesized a similar protective effect on hepatic glucose metabolism. We therefore performed a pyruvate tolerance test (PTT; Fig. 4B) in mice after 16 weeks of SD or HFD by intraperitoneally administering pyruvate, a precursor in the synthesis of glucose during gluconeogenesis, a process mainly localized in the liver and, to a smaller extent, the kidney. Subsequent measurement of circulating glucose levels at glucose and free fatty acid levels under ad libitum feeding conditions revealed no differences between genotypes on either SD or HFD (Table S1). To assess the impact of chronic HFD exposure on glucose homeostasis in more detail, the mice were subjected to a glucose tolerance test (GTT) after 7 weeks of SD or HFD exposure (Fig. 4A). Both WT and tg mice on SD were comparable throughout the study, indicating normal glucose tolerance. Administration i.p. of glucose led to a more rapid increase of blood glucose levels in mice fed a HFD, indicating the expected HFD-induced systemic glucose intolerance in both genotypes. However, although peak values were similar for WT and tg mice on the HFD, the transgenic mice on HFD decreased their blood glucose levels more rapidly than WT controls on the same diet. Area-under-the-curve (AUC) values revealed a significantly better preserved glucose tolerance of tg mice on HFD compared with WT mice on HFD (Fig. 4A Right).

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Exposure to a high-fat diet and diet-induced obesity lead to a chronic inflammatory reaction, which is believed to be critical for the development of insulin resistance (22). Accordingly, the expression of IL-6 and TNFα, two major proinflammatory cytokines, was significantly enhanced in livers of WT mice on a chronic HFD (Fig. 5A). Transgenic mice on HFD, however, still exhibited low levels of inflammatory markers, comparable to those seen in WT and tg mice on chow diet. IL-6 and TNFα are regulated by NFκB, which in turn is activated by dietary lipids through the Toll-like receptor TLR4 (5). Interestingly, Sirt1 has been described to inhibit NFκB activity (23–25). To evaluate whether NFκB is down-modulated by Sirt1 in our mouse model, we performed the following in vivo and in vitro assays. Lipopolysaccharide (LPS) is an inflammatory agent that activates a wide range of responses partly mediated by TLR4 and NFκB. In the liver, NFκB plays an antiapoptotic role and provides protection against LPS-induced liver failure (26, 27). Consistent with Sirt1 tg mice having lower levels of NFκB activity, Sirt1-tg mice on SD revealed a marked LPS hypersensitivity compared with WT controls (Fig. 5B). In addition, we examined whether NFκB activation differs in mouse embryonic fibroblasts derived from tg and WT mice by using a reporter gene assay with luciferase under the transcriptional control of NFκB responsive elements. Indeed, TNFα stimulation resulted in significantly lower activation of NFκB activation in Sirt1-tg cells (2.8-fold) compared with WT cells (5-fold) (Fig. 5C). As mentioned above, the Sirt1 transgene also carries the adjacent gene Dnajc12 (see Fig. 1A). To rule out the possibility that the lower NFκB activity observed in Sirt1 tg cells could be a consequence of Dnajc12, we performed the same assay in the presence of an shRNA that significantly decreases Dnajc12 mRNA levels (10-fold inhibition) (Fig. 5D). We observed that Sirt1-tg cells exhibited lower NFκB activity both in the absence or presence of shDnajc12 (Fig. 5E). These results implicate Sirt1, and not Dnajc12, as the gene responsible for the lower NFκB activity of Sirt1-tg cells.

In addition to the reduced expression of inflammatory cytokines, the expression of the antioxidant proteins manganese superoxide dismutase (MnSOD) and the nuclear respiratory factor 1 (Nrf1), a master regulator in the protection from reactive oxygen species, were both increased in tg mice on both SD and HFD, compared with WT mice (Fig. 5D). Both genes, MnSOD and Nrf1, have been demonstrated to be induced by PGC1α (28), which in turn is positively regulated by Sirt1 (10, 13). In summary, the overexpression of Sirt1 appears to protect tg mice from HFD-induced hepatic inflammation through decreasing the NFκB-mediated induction of inflammatory cytokines, as well as by the activation of antioxidant enzymes, possibly mediated by PGC1α.

**Discussion**

We show here that modest overexpression of Sirtuin-1 (Sirt1) protects hepatic lipid and glucose metabolism from damage inflicted by a high-fat diet. Sirt1 has previously been implicated in the molecular control of aging and cell proliferation, but more recently has also been proposed to play a role in protection from metabolic syndrome. However, the proposed involvement of Sirt1 in protection from metabolic syndrome is based mostly on indirect evidence by using chemical activators of Sirt1. In particular, two studies have demonstrated beneficial effects of resveratrol on mice on a high-fat diet, including improved insulin sensitivity, lower steatosis, and increased survival (29, 30). More recently, selective Sirt1 activators have been shown to have beneficial effects on mitochondrial and metabolic function in obese rodents and offer potential for treating age-related metabolic diseases such as type 2 diabetes (14). However, although these studies compellingly argue in favor of the role of Sirt1 in protecting against a high-fat diet, all of these chemical activators may impinge on other members of the Sirtuin family as well as on a diverse range of pathways, as with resveratrol (31).

To directly address the role of Sirt1 in protection from the detrimental metabolic consequences of high-fat diet exposure, we have engineered transgenic overexpression of Sirt1 in mice by introducing an additional transgenic copy of the full-length Sirt1 gene in the genome, which thereby remained under the control of its own promoter. Other Sirt1 transgenic mice reported express the transgene in restricted tissues, for example, endocrine pancreas, brain, or heart (32–35). Most recently, Bordone and colleagues (36) described a mouse model with overexpression of Sirt1 in a restricted...
number of tissues that include white and brown adipose tissue, but
not in muscle and liver, which are relevant for the metabolic
syndrome. In contrast to these mouse models, ours constitutes a
model where Sirt1 is overexpressed under its own promoter,
thereby following the physiological pattern of expression, including
metabolically relevant tissues, such as liver, muscle, white and
brown adipose tissue, jejunum, ileum, colon, spleen, thymus, and
kidney. In addition, our strategy generates a modest overexpression
of Sirt1. Together, these features make our Sirt1-tg mice an ideal
model to explore the systemic effects of pharmacological interven-
tions targeted to Sirt1.

Moderate Sirt1 overexpression in our mice led to a small increase
in energy expenditure, which, however, did not translate into a
significantly lower fat mass. In part, this is likely because of an
unexpected increase in food intake, a phenomenon that has not
been previously described as a consequence of Sirt1 overexpression.
More interestingly, our present findings suggest that Sirt1 activators
may hold promise for the treatment of nonalcoholic fatty liver
disease (NAFLD). The pathogenesis of NAFLD is complex, but
modulation of key transcription factors regulating hepatic lipid
metabolism, such as sterol regulatory element binding protein 1
(SREBP1), has been proposed to carry great potential for the
prevention from HFD-induced hepatosteatosis observed in mice
overexpressing Sirt1. A specific and effective drug treatment for
NAFLD is currently not available. Our encouraging observations
presented here therefore warrant further study to evaluate Sirt1 as
a potential target for the treatment of NAFLD.

Concomitant with the development of hepatosteatosis, hepatic
inflammation is an established risk factor for the development of
hepatic insulin resistance and glucose intolerance (39). Hepatic
insulin resistance and glucose intolerance, in turn, can stimulate the
development and progression of hepatosteatosis (40), thereby
fueling and promoting a detrimental cycle that is believed to
represent a key mechanistic component of the metabolic syndrome.
Under fasting conditions, Sirt1 has a negative effect on insulin
sensitivity and glucose tolerance (41). However, under fed condi-
tions, activation of Sirt1 improves glucose homeostasis and insulin
sensitivity (14, 29, 30, 42). Importantly, overexpression of Sirt1 in
tissues such as white or brown fat, but not in muscle and liver,
improves glucose tolerance (35). In our mice, moderate and sys-
temic Sirt1 expression under its own promoter regulation results in
improvement of glucose homeostasis and insulin sensitivity (39).
Moreover, overexpression of Sirt1 in tissues such as white or brown fat, but not in muscle and liver, improves glucose tolerance (35). In our mice, moderate and systemic Sirt1 expression under its own promoter regulation results in improvement of glucose homeostasis and insulin sensitivity (39).

A well-established target of Sirt1 deacetylation (28). These effects
contribute to the prevention of HFD-induced hepatosteatosis observed in mice overexpressing Sirt1. A specific and effective drug treatment for NAFLD is currently not available. Our encouraging observations presented here therefore warrant further study to evaluate Sirt1 as a potential target for the treatment of NAFLD.

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NFκB activity has previously been shown to be inhibited by Sirt1
(23–25). We confirmed such inhibition of NFκB in embryonic
fibroblasts derived from Sirt1-tg mice. Hepatic NFκB signaling is
activated by high-fat diet exposure and triggers insulin resistance
(43), thereby linking inflammation with obesity-induced insulin
resistance (44). Inhibition of NFκB activity by Sirt1 overexpression

Fig. 5. Transgenic Sirt1 mice are protected from hepatic inflammation. (A) Gene expression analyses (real-time PCR) of the proinflammatory cytokines IL-6 and TNFα in livers of WT and tg mice on SD or HFD (19 weeks) (n = 7–8 per group; means ± SEM; *, P < 0.05). (B) Kaplan–Meier plot of survival curves of WT and tg mice on SD after injection of lipopolysaccharide (LPS) (n = 5 per group). (C) Luciferase reporter gene assay of WT and tg mouse embryonic fibroblasts after transfection with a pNFκB-Luc reporter vector and stimulation with 10 ng/ml of TNFα. Luminescence was measured 6 h after TNFα incubation. (n = 6–8 per group; means ± SEM; *, P < 0.05). (D) Gene expression analyses (real-time PCR) of the antioxidant enzymes MnSOD and Nrf1 in livers of WT and tg mice on SD or HFD (19 weeks) (n = 7–8 per group; means ± SEM; *, P < 0.05; **, P < 0.01). (E) Model of Sirt1 effects on known molecular pathways linking dietary lipids, hepatosteatosis, and hepatic glucose intolerance.
may—in conjunction with the activation of antioxidant enzymes such as MnSOD and Nrf1—explain the prevention from hepatic inflammation, diet-induced glucose intolerance, and hepatosteatosis observed here (Fig. 5c, E).

In summary, moderate Sirt1 overexpression under control of its natural promoter in mice prevents HFD-induced glucose intolerance and nonalcoholic fatty liver disease. Our results indicate that this effect may result, in part, from prevention of HFD-induced activation of the proinflammatory NFκB pathway together with up-regulation of PGClα and its antioxidant targets such as MnSOD or Nrf1. Finally, the anti-inflammatory actions of Sirt1 open up aspects that could link Sirt1 with aging or cancer.

Methods

Transgenesis and Animal Experimentation. A large genomic DNA segment (174 kb) containing the murine Sirt1 gene and cloned into the BAC (Bacterial Artificial Chromosome) vector pBAC3.6 was obtained from CHORI (identification no. RP23-119223) (http://www.chori.org). Pronuclei of fertilized oocytes, derived from intercrosses between (C57BL6/J x DBA/2J) F1 males and (C57BL6/J x (C3H/HeJ x DBA/2J) F1 females, were injected i.p. with 20 mg/kg of 6-hydroxydopamine (6-OHDA) or with an additional weekly i.p. injection of lipopolysaccharide (LPS) (5 mg/kg) for 2 months old and for a total of 19 additional weeks. To assess LPS susceptibility in each genotype, mice were injected i.p. with 20 mg/kg of Escherichia coli-derived LPS septonine 0111:B4 (Sigma).

All studies were approved by and performed according to the ethical guidelines of the University of Cincinnati and the Spanish National Cancer Research Center (CNIO).

22. DNA, RNA, and Protein Analyses. Southern and Northern blot analyses were performed by using standard procedures (probes and primers are detailed in Table S2). Western blot analysis was performed following standard procedures. For detection of Sirt1, we used rabbit polyclonal antibody ab12193 (AbCam), working dilution 1:2,000; and for β-actin, we used monoclonal antibody AC-15 (Sigma), 1:5,000.
23. Mouse Embryonic Fibroblasts. Luciferase assays were done by using Lipo-fection LXI and PLUS reagent (Invitrogen) for the transfections. We used pNFκB-Luc (Clontech) reporter vector and E1f-β-Refiila vector as transfection control. TNFa (Promega) was added at 10 ng/ml and luminescence was measured 6 h later by using a Glomax luminometer (Promega).
24. Metabolic Phenotyping. Tail blood was collected 2 h after the onset of the light phase either after an overnight fast, or in ad libitum fed mice by using EDTA-coated Microvette cups (Sarstedt), and immediately chilled on ice. Determinations were performed by using standard methods (see SI Methods). Metabolic performance and activity were studied by using an automated combined indirect calorimetry system (TSE Systems GmbH) and a multidimensional infrared light beam system (see SI Methods). Glucose, insulin, and pyrurate tolerance tests were performed according to standard procedures (see SI Methods).

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