Role of the AMPK/SREBP-1 pathway in the development of orotic acid-induced fatty liver

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Abstract Orotic acid (OA), an intermediate in pyrimidine metabolism, has been used for a variety of purposes, such as dietary supplements. Although it is well documented that OA induces fatty liver in a species-specific manner, the precise molecular mechanisms remain unclear. The present study investigated the role of the adenosine monophosphate-activated protein kinase (AMPK)-sterol regulatory element-binding protein-1 (SREBP-1) pathway in the OA-induced fatty liver. Treatment with OA suppressed the phosphorylation of AMPK via proteasomal degradation of upstream kinase LKB1 and induced activation of SREBP-1 in both human hepatoma cell lines and primary rat hepatocytes. OA-induced SREBP-1 transcriptional activity was suppressed by cotreatment with aminoimidazole carboxamide ribonucleotide (AICAR) or metformin, or by overexpression of constitutively active AMPK (CA-AMPK) in the human hepatoma cell line. Importantly, in vivo data corroborated these results. Feeding 1% OA with diet decreased the phosphorylation of AMPK and increased the maturation of SREBP-1 and the expression of SREBP-responsive genes in the rat liver. OA-induced lipid accumulation was also completely inhibited by rapamycin. Mouse hepatocytes and mice were resistant to OA-induced lipogenesis because of little if any response in AMPK and downstream effectors.

In conclusion, OA induces hepatic lipogenesis, mediated predominantly by the AMPK/SREBP-1 pathway in rat hepatocytes and human hepatoma cell lines.—Jung, E.-J., S-W. Kwon, B.-H. Jung, S.-H. Oh, and B.-H. Lee. Role of the AMPK-SREBP-1 pathway in the development of orotic acid-induced fatty liver. J. Lipid Res. 2011. 52: 1617–1625.

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Induction of fatty liver in rats by orotic acid (OA; 6-carboxyuracil) administration was first observed in 1955 (1). Since then, OA has been investigated by many and has been used as a chemical inducer of fatty liver (2, 3). Although somewhat inconclusive, the reported mechanisms of OA-induced fatty liver include impairment of fatty acid oxidation, stimulation of lipogenesis, and reduction in lipid transport from the liver (4, 5). OA-induced fatty liver is species specific, and thus far, only the rat has been found to be susceptible. Durschlag and Robinson demonstrated that pharmacokinetic factors determined species specificity in OA-induced hepatotoxicity (6). However, the precise molecular mechanism by which OA induces fat accumulation, specifically in the rat liver, has remained unclear. Identification of molecular targets of OA effects and susceptibility are of great importance in terms of scientific as well as practical aspects. The major source of OA in a typical adult diet is milk and dairy products, which contribute about 0.005% of the total solids, a level at which rats do not show hepatic changes. However, considering the high content of OA in many dietary supplements, vitamin and mineral complexes, and muscle-building products widely sold on the market, we should be wary of possible health effects posed to humans.

AMP-activated protein kinase (AMPK), a heterotrimeric enzyme complex, is the key regulator of energy metabolism in cells. The energy-sensing motif of the enzyme monitors the energy status of cells and controls its activity by phosphorylation at T172 (7). In the liver, activation of AMPK phosphorylates and inactivates the rate-limiting enzymes of lipogenesis, such as acetyl-CoA carboxylase (ACC) (8). AMPK is classically regulated by various metabolic stresses that cause an increase in the AMP/ATP ratio or

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other cellular energy and metabolic states, such as glyco-
gen, lipid, and NAD/NADH redox potential (9–11). How-
ever, recent studies have suggested that other unidentified
pathways can regulate AMPK, regardless of cellular energy
status. Metformin and rosiglitazone phosphorylate AMPK
without any change in cellular energy state (12). Leptin
has been found to stimulate AMPK through both AMP-
dependent and AMP-independent mechanisms (13).
AMPK is phosphorylated by upstream kinases, among
which serine/threonine kinase 11 (LKB1) has been identi-
fied as a major AMPK kinase in the liver (14). LKB1 is con-
sidered to be constitutively active; however, in some cases,
altered expression or activity of LKB1 is associated with
the phosphorylation of AMPK (15). It is well documented
that AMPK phosphorylation inhibits sterol regulatory ele-
ment-binding protein-1 (SREBP-1), the key transcription
factor responsible for fatty acid synthesis, through mam-
malian target of rapamycin (mTOR) and liver X receptor-α
(LXRA) (16). Conversely, inhibition of AMPK has been
suggested as a central event causing the development of
chemical-induced fatty liver. Repressed AMPK activates
anabolic pathways, such as fatty acid synthesis, and inhibits
catabolic pathways, such as fatty acid oxidation. In studies
performed with hepatocytes and in the livers of ethanol-
fed mice, You et al. demonstrated that inhibition of AMPK
leads to the activation of lipogenesis mediated by SREBP-1
(17). Similar results were obtained in studies with cigarette
smoking and the saturated fatty acid palmitate (18, 19).
AMPK positively regulated fatty acid oxidation by activat-
ing peroxisome proliferator-activated receptor (pPARE)
and PPARγ coactivator (PGC)-1 (20). Thus, inhibition of
AMPK by chemicals or physiological state may contribute
to the intracellular accumulation of lipids.

The first step in OA metabolism is the reaction with
phosphoribosyl pyrophosphate (PRPP) to form orotidine-
5’-monophosphate. Depletion of PRPP by an OA dose is
followed by a reduction in purine biosynthesis, including
ATP, and defects in lipid transport from the liver (21).
Recent studies have suggested an alternative mechanism of
OA toxicity in which altered transcription of genes in-
volved in fatty acid metabolism contribute to fatty liver;
however, the exact mechanism of the gene expression
changes remains to be elucidated (22). To understand the
molecular mechanism of OA-induced fatty liver, we tested
the effects of OA on the AMPK/SREBP-1 pathway in hu-
mans hepatoma cell lines and rat or mouse hepatocytes as
well as in rats and mice in vivo. Here, we report that OA
activates SREBP-1 by AMPK inhibition in rat hepatocytes
and human hepatoma cell lines in vitro and in rats
in vivo.

MATERIALS AND METHODS

Materials

Anti-AMPK, anti-phospho-AMPK (Thr172), anti-ACC, anti-
phospho-ACC (Ser79), anti-p70S6Kinase, anti-phosphor-p70S6Ki-
nase (Thr389), anti-GAPDH, and anti-mTOR were purchased
from Cell Signaling Technology, Inc. (Beverly, MA). Anti-SREBP-1,
anti-LKB1, anti-c-Myc, siLKB1 and anti-Flag were prepared from
Santa Cruz Biotechnology, Inc. (Santa Cruz, CA). Nile red, orotic
acid monohydrate, aminomimidazole carboxamide ribonucleotide
(AICAR), and metformin were obtained from Sigma Chemical
Co. (St. Louis, MO). We purchased lactacystin and radicicol from
Calbiochem (San Diego, CA). Rapamycin were obtained from
Selleck Chemicals, LLC (Houston, TX).

Cell culture

SK-Hep1and HepG2 human hepatoma, H4IEC3 rat hepato-
toma, and HeLa cells were cultured in Dulbecco’s Minimal Essential
Medium (DMEM; Gibco-BRL, Rockville, MD), supplemented with
10% fetal bovine serum, 3.7 mg/ml sodium bicarbonate, 100 units/ml penicillin,
and streptomycin. Cells were incubated in a 37°C incubator in an atmosphere of 5% in air. SK-Hep1,
an immortal human cell line derived from the ascetic fluid of a pa-
tient with adenocarcinoma of the liver, is used frequently as a
representative hepatoma line. Rat and mouse hepatocytes were
isolated from SD rats and C57/BL6 mice by collagenase perfu-
sion as described (23, 24).

Real-time RT-PCR

Total RNA from livers and cells with or without OA were iso-
lated using EASY BLUE total RNA extraction kit (INTRON Bio-
technology, Korea), then reverse transcribed using SuperScript™
III First-Strand Synthesis System (Invitrogen, Carlsbad, CA).
Expression of mRNA was quantified by using SYBR Green PCR Mas-
ter Mix and performed with ABI Prism 7000 Sequence Detection
System (Applied Biosystems, Foster City, CA) with cDNA synthet-
sis for FAS, LXRA, SREBP-1a, SREBP-1c, ACC, SCD1, L-PK, and
GAPDH. The primers used for these genes are listed in Table 1.
The data were analyzed using ABI Prism Software version 1.5
(Applied Biosystems) and were normalized with glyceraldehyde
3-phosphate dehydrogenase (GAPDH) levels.

Western blot analysis

Chemicals were dissolved in DMSO or distilled water, and cells
were incubated in serum-free or 1% serum media with or without
chemicals. The final concentration of vehicle in media was main-
tained at 0.1% (v/v), and appropriate vehicle controls were used in
all cases. Immunoblotting for SREBP-1, phosphor-AMPK
(Thr172), AMPK, phosphor-ACC (Ser79), ACC, LKB1, phosphor-
S6K1 (Thr389), S6K1, mTOR, phosphor-Raptor (Ser792), Raptor,
and GAPDH were performed by established procedures.
Bands were visualized using a chemiluminescence detection system
(ChemiDoc™ XRS system, Bio-Rad Laboratories, Inc., Hercules,
CA) according to the manufacturer’s instructions. Protein con-
centrations were determined using the method for DC protein assay
(Bio-Rad Laboratories) using BSA as a standard.

Transient transfection and reporter gene assay

The luciferase reporter constructs, SRE-TK-Luc, were kind
gifts from Dr. M. O. Lee (Seoul National University, Korea).
The expression constructs constitutively active AMPK (CA-AMPK)
and dominant-negative AMPK (DN-AMPK; T172A), which were
provided by Dr. S. G. Kim (Seoul National University, Korea),
were originally from Dr. J. Ha (Kyung Hee University, Korea)
and Dr. Y. Kanno (Toho University, Japan), respectively. The
plasmids of pCMV-RL were purchased from Promega Co. (Ma-
dison, WI). The expression plasmids of pEGFP-LKB1 were obtained
from Dr. J. Ha. Cells were transfected with appropriate plasmid
constructs (SRE-TK-Luc, CA-AMPK, DN-AMPK, and pEGFP-
LKB1) by using the LipofectAMINE 2000 (Invitrogen) as recom-
manded by the manufacturer, and they were incubated in 1% serum
media with or without OA. pCMV-RL plasmids were
cotransfected as an internal control. Luciferase activities were measured by using the Dual-Luciferase assay detection kit according to manufacturer’s instructions (Promega). Luciferase activity was detected using a Centro LB960 luminometer (Berthold Technologies, Oak Ridge, TN). Transfection of siRNAs specific to LKB1 into SK-Hep1 cells was performed with LipofectAMINE 2000 (Invitrogen) according to the manufacturer’s instructions. The cells were further incubated for 24 h prior to treatment with OA for 24 h.

**Determination of adenine nucleotides**

Frozen liver tissues of rat or mice and SK-Hep1, HepG2, primary rat, or mouse hepatocytes were washed with PBS and homogenized with perchloric acid (PCA). The samples were processed in parallel, and no positive staining was observed.

**Oil Red O staining**

For Oil Red O staining, frozen liver tissues were cut into 7 µm with Probe-On-Plus Slides (Thermo Fisher Scientific) and affixed to microscope slides. Sections were reacted with Oil Red O solution for 7 min at 60°C, and then incubated with 85% propylene glycol for 3 min. After rinsing with water, sections were stained with Harris hematoxylin for counterstaining.

**Liver triglyceride content analysis**

Liver TG content was determined by a modified Folch method described previously (27). Briefly, 50 mg liver tissue was homogenized in chloroform/methanol (2/1, v/v) at 60°C, and then incubated with 85% propylene glycol for 3 min. After rinsing with water, sections were stained with Harris hematoxylin for counterstaining.

**Electrophoretic mobility shift assay**

The labeled probe for the SRE of the FAS genes (5′-CATCCG-GCATCACCCCACCGAGGCG-3′) was incubated with nuclear extract obtained from OA-treated cells. Electrophoretic mobility shift assay (EMSA) was carried out using Liteshift Chemiluminescent EMSA kit (Thermo Fisher Scientific, Inc., Rockford, IL) as recommended by the manufacturer. Reaction complexes were visualized using a chemiluminescence detection system (ChemDoc™ XRS system, Bio-Rad Laboratories).

**Statistical analysis**

All values are presented as the means ± SE of at least three independent experiments. Significant differences were obtained using Student’s t-test. A difference was considered significant at P < 0.05.

**RESULTS**

**OA activates SREBP-1 in rat hepatocytes and human hepatoma cell lines**

SREBP-1 is a membrane-bound transcription factor that regulates lipid homeostasis by controlling the expression of genes for lipid metabolism. Increased hepatic lipogenesis by activation of SREBP-1 may contribute to the development of chemical-induced fatty liver (28). We first examined the effects of OA on SREBP-1 activation in various hepatic

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**TABLE 1. Sequences of real-time RT-PCR primers**

| Gene      | Forward Sequences | Reverse Sequences | Source |
|-----------|-------------------|-------------------|--------|
| hSREBP-1a | 5′-CTGCTGACCCACATCGAGAC-3′ | 5′-GATGCTCATGTCGCACGCTT-3′ | Ref. 46 |
| hSREBP-1c | 5′-GGAGGGTGAAGGGCCAC-3′ | 5′-AGGGGTTGAGCTCAACTC-3′ | Ref. 47 |
| hFASN     | 5′-CCGGTGGCAGCTATCCTCAG-3′ | 5′-GCGCTGGCCAGCTTACCT-3′ | NM_004104 |
| hSOD1     | 5′-TGGATGGTCAGGGAGG-3′ | 5′-ATGGTGCAAGTGATTG-3′ | NM_005063 |
| hLPRK     | 5′-ATGGTTGCTGAGGGGA-3′ | 5′-AGTGATGGAACTTTTTGGGGA-3′ | NM_198834 |
| hGAPDH    | 5′-AGTCACAGGTGTTGTCG-3′ | 5′-TTGTTTTGGAGGATCTGGC-3′ | NM_002046 |
| rSREBP-1  | 5′-ATGGTTGCTGAGGGGA-3′ | 5′-AGTGATGGAACTTTTTGGGGA-3′ | Ref. 48 |
| rFAS      | 5′-CTGCTGACCCACATCGAGAC-3′ | 5′-GATGCTCATGTCGCACGCTT-3′ | NM_017352 |
| rSOD1     | 5′-TGGATGGTCAGGGAGG-3′ | 5′-ATGGTGCAAGTGATTG-3′ | NM_199192 |
| rLPRK     | 5′-ATGGTTGCTGAGGGGA-3′ | 5′-AGTGATGGAACTTTTTGGGGA-3′ | NM_051627 |
| rGAPDH    | 5′-AGTCACAGGTGTTGTCG-3′ | 5′-TTGTTTTGGAGGATCTGGC-3′ | NM_022193 |
cells by Western blot analysis. Treatment with OA resulted in a substantial and dose-dependent increase in the amount of mature SREBP-1 protein in both human hepatoma SK-Hep1 and HepG2 cell lines. Similar results were obtained in primary rat hepatocytes in which the expression of mature SREBP-1 was increased, although a decrease in the precursor form was observed (Fig. 1A). A dose-dependent increase in the mRNA for Srebp-1c was observed in the SK-Hep1, HepG2, and primary rat hepatocytes (Fig. 1B).

OA inhibits AMPK phosphorylation in rat hepatocytes and human hepatoma cell lines

AMPK is a key energy sensor in the cells that ultimately control the lipid metabolism machinery. Although AMPK is classically regulated by the cellular energy status, it has been reported that chemicals or chemical mixtures can also regulate the activity of AMPK. To understand the potential mechanisms by which OA induces SREBP-1 activation, we examined the effects of OA on the phosphorylation of AMPK, because phosphorylation on the Thr172 residue is essential for its activation (29). Incubation of human and rat hepatoma cell lines with OA for 24 h resulted in the dose-dependent reduction in phosphorylation of AMPK despite increased expression of AMPK, resulting in the decrease in the pAMPK/AMPK ratio. Similar results were obtained when primary rat hepatocytes were treated with OA (Fig. 1C). Activation of AMPK leads to the phosphorylation and inhibition of ACC. We found that ACC phosphorylation was suppressed by OA treatment. The decreased phosphorylation of AMPK and ACC by OA was largely prevented by addition of metformin or AICAR (Fig. 1D).

Whereas rats are susceptible to OA-induced fatty liver, mice are known to be resistant (6). To understand the molecular mechanisms responsible for the species difference in OA effects, we examined the effects of OA on AMPK and SREBP-1 proteins in primary cultured mouse hepatocytes. Neither the maturation of SREBP-1 protein nor the phosphorylation of AMPK was affected by OA in these cells (supplementary Fig. I).

Activation of AMPK attenuates OA-induced expression of lipogenic genes

Phosphorylation of AMPK suppresses expression of SREBP-1 in vitro and in vivo (30, 31), whereas inhibition of AMPK augments expression of SREBP-1 and thus induces fatty liver. To identify the role of AMPK in the activation of SREBP-1 by OA, we transfected SK-Hep1 cells with a eukaryotic expression vector expressing constitutively active AMPK protein tagged with Myc epitope, and then the level of mature SREBP-1 was determined following OA treatment. Results are summarized in Fig. 2A. Basal and OA-induced expression of mature SREBP-1 protein was completely antagonized by CA-AMPK. Transfection with DN-AMPK tagged with Flag significantly increased the basal mature SREBP-1 expression, whereas no effect was shown in OA-treated cells (Fig.2A). We next examined whether OA increased the expression of SREBP-1 target genes that are involved in fatty acid synthesis. When the levels of Fas, Srebp-1a, Srebp-1c, Acc, Scd-1, and L-Pk gene transcripts were measured by quantitative real-time PCR using gene-specific primers, we found that their mRNA expression was increased dose dependently in OA-treated cells. Combination treatment with AICAR prevented the OA-associated increase in the mRNA levels (Fig. 2B). Consequently, AICAR completely abrogated the effects of OA on intracellular lipid accumulation measured using Nile-red staining (Fig. 2C).

We next performed reporter gene analysis using a reporter gene containing SRE sequences and a gel-shift assay in SK-Hep1 and HepG2 cells. Treatment of cells with OA resulted in a dose-dependent increase in luciferase activity (Fig. 3A). OA-induced luciferase activity was considerably diminished by cotreatment with metformin or AICAR or by cotransfection of CA-AMPK. Conversely, introduction of DN-AMPK to cells markedly augmented the OA effect on SRE luciferase activity (Fig. 3A). We also observed an increase in the nuclear SREBP-1-dependent gel-shift activity. Supershift analysis confirmed the DNA binding of SREBP-1 (Fig. 3B). Together, these data suggested that OA induces the maturation and transcriptional activity of SREBP-1 through AMPK inhibition in human and rat hepatocytes.

OA induces proteasomal degradation of LKB1

Control of protein stability via the proteasomal degradation pathway plays an important role in regulating many cellular processes. We asked whether the inhibition of AMPK phosphorylation by OA might be associated with
the proteasomal degradation of AMPK kinase. We examined the effects of OA on the expression levels of various AMPK kinases. Treatment of SK-Hep1 cells with OA decreased the expression of LKB1, one of the major AMPK kinases expressed in the liver (Fig. 4A). Other AMPK kinases, such as CaMKKα or CaMKKβ, were unaffected by OA (data not shown). To determine whether LKB1 could mediate the OA effects on AMPK phosphorylation, we compared the results of LKB1-deficient cells with that of LKB1-expressing cells in their response to OA. To that end, we compared AMPK phosphorylation and SREBP-1 activation in HeLa cells deficient or reconstituted with LKB1 as well as in SK-Hep1 cells wild-type or silenced with LKB1 siRNA. Western blot analysis of AMPK is shown in Fig. 4B. AMPK phosphorylation was not affected by OA in either LKB1-deficient HeLa cells or LKB1-silenced SK-Hep1 cells, whereas overexpression of LKB1 to HeLa cells restored the effect. Similar results were observed in SK-Hep1 cells. OA induced expression and activation of SREBP-1 and its target genes in SK-Hep1 cells. However, knockdown of LKB1 abolished the effects of OA (Fig. 4C).

The stability of LKB1 is regulated by the interaction with hsp90, which prevents its degradation by the proteasome. Our results and those of other groups suggest that the stability of LKB1 is decreased by the hsp90 inhibitor radicicol and that cotreatment with the proteasomal inhibitor lactacystin prevents its degradation (Fig. 4D, left panel) (32). We next treated OA to HeLa cells expressing wild-type LKB1 in the absence or presence of lactacystin, and then examined intracellular levels of LKB1 by immunoblotting. These experiments revealed that the decrease in expression of LKB1 by OA was completely recovered by combination treatment with lactacystin (Fig. 4D). These data suggested that OA inhibits AMPK phosphorylation at least partly by proteasomal degradation of the upstream kinase LKB1.

OA activates SREBP-1 in rats in vivo

To test whether the data from our in vitro experiments could be reproduced in vivo, rats and mice were fed OA in the diet for seven days. Consistent with a previous study (33), rats fed OA showed increased hepatic TG levels and hepatic steatosis. Hematoxylin-eosin (HE) and Oil Red O staining of liver sections obtained from OA-treated rats clearly showed that rats were susceptible to OA-induced fatty liver (Fig. 5A). OA treatment significantly and dose-dependently increased the hepatic TG level by 2-
4-fold compared with the control (Fig. 5B). Next we determined the expression and phosphorylation of the protein levels in the liver tissue. In line with the in vitro data shown above, the expression of AMPK and ACC were increased and the phosphorylation of the proteins were decreased, resulting in the significant decrease in the pAMPK/AMPK ratio and the pACC/ACC ratio (Fig. 5D). Similar results were obtained when we analyzed the expression and phosphorylation of Raptor in which we observed a net decrease in the pRaptor/Raptor ratio. The expression and phosphorylation of S6K1 were increased by OA treatment, leading to an increase in the pS6K1/S6K1 ratio. The level of mature SREBP-1 was increased in rat liver (Fig. 5D). Increases in protein expression, such as AMPK, ACC, and S6K, by OA in vitro and in vivo can be ascribed to the activation of mTOR, which remains to be explained in later experiments. However, little if any change was observed in mice in terms of fatty liver and phosphorylation of AMPK. Moreover, expression of mature SREBP-1 was even decreased in mouse liver (supplementary Fig. II). The AMP/ATP ratio was not changed in vitro or in vivo (supplementary Table I). To confirm that nuclear SREBP-1 is functional in vivo, we examined the mRNA levels of Lxr-α, SREBP-1, Ace, Scd-1, and Fas using real-time PCR. Increased expression of the genes was observed in the OA-fed group (Fig. 5C).

**DISCUSSION**

OA is an intermediate in pyrimidine metabolism that is readily synthesized in mammals and is also found in large quantities in cow’s milk (36). Owing to the beneficial effects on the absorption of essential nutrients as well as on heart function (37), OA has been used as a dietary supplement and in vitamin and mineral complexes. OA has also been used worldwide as a tonic and for anabolic purposes. However, administration of large amounts of OA has been reported to induce fatty liver in the rat (1). The reported mechanisms of OA-induced fatty liver include impairment of fatty acid oxidation, stimulation of lipogenesis, and reduction in lipid transport from the liver (4, 5). Although liver fatty change by OA is evident and severe, the precise molecular mechanisms remain poorly understood. Additionally, the effects of OA are species specific; thus, the possible human health effects of OA have not been clearly identified (38).

Here, we describe the novel finding that the AMPK/mTOR/SREBP-1 pathway is involved in the OA-induced fatty liver. Our study demonstrated that OA inhibited the phosphorylation of AMPK and increased the activation of SREBP-1 in rat hepatocytes and human hepatoma cell lines. Activation of SREBP-1 and SREBP-regulated promoter by OA was mediated through AMPK inhibition, as verified by cotreatment with AMPK activators metformin and AICAR or by cotransfection of the constitutively active form of AMPK mutant in a SRE-luciferase assay. The decrease in the AMPK phosphorylation by OA can be ascribed, at least in part, to the proteasomal degradation of LKB1. Primary cultured mouse hepatocytes were resistant to OA treatment, as shown by the unchanged expression...
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However, the OA responses in rat hepatocytes and human hepatoma cell lines were almost identical, indicating the possibility that humans might also be susceptible. Further experiments using the primary cultured human hepatocytes are needed to more clearly predict human health effects. Consistent with these in vitro findings, rats fed OA for seven days exhibited severe fatty liver with significantly reduced phosphorylation of hepatic AMPK and increased activation of SREBP-1. In contrast, cotreatment with rapamycin inhibited OA responses in the liver in terms of nuclear SREBP-1 activation and consequent hepatic TG accumulation. Figs. 1D and 5D show the increased expression of protein levels (including AMPK, ACC, Raptor, S6K1, and SREBP-1) which is supposed to be ascribed to mTOR activation by OA. mTOR regulates protein synthesis and cell growth by phosphorylating S6K1 and eukaryotic initiation factor 4E-binding protein 1 (4EBP1). Phosphorylation of S6K1 facilitates the recruitment and translation of a specific mRNA subset that contains a 5′ polypyrimidine tract (39). Phosphorylation of 4EBP1 releases eIF4E, which initiates translation (40).

The present study highlights the involvement of the AMPK/mTOR/SREBP-1 axis in OA-induced fatty liver. AMPK negatively regulates mTOR complex 1 (mTORC1), a central controller of cell growth, protein synthesis, mitochondrial biogenesis, and lipogenesis. Phosphorylation of AMPK by upstream kinase induces fatty acid oxidation and inhibits lipogenesis in the liver through suppression of SREBP-1 (30). Inhibition of mTORC1 with rapamycin or knockdown of Raptor, an active component of mTORC1, blocks Akt-induced SREBP-1 activation and lipogenesis, indicating a close relationship between AMPK, mTORC1, and SREBP-1 activation (16). The AMPK/mTOR/SREBP-1 axis has recently been shown to be a key molecular target in chemical- and diet-induced fatty liver. You et al. demonstrated that inhibition of AMPK plays a key role in ethanol-induced fatty liver by activating hepatic lipogenesis controlled by SREBP-1 and by suppressing hepatic free fatty acid oxidation (17). Vinciguerra et al. reported that high circulating free fatty acids, such as oleic acid, activates mTOR/S6K pathway and induces insulin resistance in primary cultured rat hepatocytes (42). Impairment of lipid metabolism through the modulation of AMPK activity was also reported when hepatocytes were treated with second-hand cigarette smoke (18). They showed that second-hand cigarette smoke stimulates lipid accumulation in the liver and that this effect is mediated by AMPK and SREBP-1. Furthermore, they showed that inactivation of AMPK stimulates activation of SREBP-1 and leads to an increase in lipid accumulation. In a separate experiment, Syed et al. found that exposure of cigarette smoke condensate to human bronchial epithelial cells resulted in increased phosphorylation of mTOR, which is required for the insulin-stimulated induction of SREBP-1 expression (43). Note that the in vitro effects of cigarette smoking were recently verified in a cross-sectional study of 8,442

**Fig. 5.** Induction of fatty liver in the rats fed diet supplemented with OA. Male SD rats were fed diets containing 0, 0.5, or 1% OA for seven days. TG accumulation was assessed by HE and Oil Red O staining as well as by the determination of hepatic TG contents (A, B). LXR-α, SREBP-1, Acc, Scd-1, and Fas transcript levels were analyzed using real-time PCR (C). Western blot analysis using a specific antibody was used to examine the expression of the proteins in the rat liver homogenates. Band densities were determined using an image analysis system, normalized to that of GAPDH, and expressed as a percentage of the vehicle-treated control (D). Each bar represents the mean ± SE of the results obtained from five rats. *P < 0.05, **P < 0.01, ***P < 0.001 compared with vehicle control.

**Fig. 6.** Rapamycin (RPM) inhibits OA-induced lipogenesis. Male SD rats were divided into three groups, and then treated as follows for seven days: group I (control; Ctrl), normal diet + vehicle; group II (OA), 1% OA diet + vehicle; group III (OA + RPM), 1% OA diet + RPM. (A) Hepatic TG concentrations were determined using the serum triglyceride determination kit. (B) Fixed liver sections were subjected to HE and Oil Red O staining as well as immunohistochemistry assays with SREBP-1 antibody. Representative microphotographs of liver specimens from all groups of rats are shown. (C) The levels of mRNA of the indicated genes involved in lipogenesis were determined by real-time PCR. Each bar represents the mean ± SE of the results obtained from six rats. *P < 0.05, **P < 0.01, ***P < 0.001.
subjects. The prevalence rate of nonalcoholic fatty liver disease was significantly higher among cigarette smokers versus nonsmokers. Moreover, the prevalence ratio increases with the amount of cigarettes smoked per day (44). Although the precise effects of OA in humans are unknown, we must not exclude the possibility that OA consumption by diet and dietary supplements can induce fatty liver in humans. A quantitative risk assessment is needed to address the issue.

One of the novel findings in the present study is the identification of a molecular target that responds differently between the rat and mouse. Previously, the likely cause of the interspecies differences in OA hepatotoxicity has been thought to be metabolic differences. Mice accumulated less of the OA dose in the liver and excreted much more in the urine than did rats, thereby rendering them resistant to OA toxicity (6). Feeding an arginine-deficient diet to rats leads to a marked fatty liver by an elevated plasma concentration of OA. Additionally, mice, hamsters, and rabbits were resistant to fatty liver largely because of their high urinary excretion rate of OA (45). Apart from this pharmacokinetic issue, no other information has been available concerning species-specific mechanisms of OA hepatotoxicity. Our results showed that the most striking difference between the rat and mouse hepatocytes in primary culture is AMPK phosphorylation and SREBP-1 activation in response to OA exposure. Whereas decreased phosphorylation of AMPK and modulation of a series of downstream events leading to fatty acid synthesis and lipogenesis were observed in rat hepatocytes and human hepatoma cell lines, mouse hepatocytes were resistant to OA with regard to the AMPK/SREBP-1-dependent lipogenic pathway. Similar results were observed in animal studies using SD rats and C57BL/6 mice. These two species showed completely different responses to OA in terms of AMPK/SREBP-1 signaling and development of steatosis, indicating that not only pharmacokinetic but also pharmacodynamic factors participate in determining interspecies differences. Considering the very similar responses of human hepatoma cell lines and rat hepatocytes to the AMPK/SREBP-1 pathway, humans could be a species that may be sensitive to OA-induced fatty liver. Further experiments using primary cultured human hepatocytes and comprehensive human pharmacokinetic studies will be needed to define human health effects. The effects of OA could be even greater in obese and insulin-resistant diabetic patients if we consider the poor sensitivity of these patients to insulin-induced downstream effectors, including AMPK and SREBP-1. Regular ethanol consumption and cigarette smoke may also synergistically affect OA-induced fatty liver.

In summary, we demonstrated that OA induces the SREBP-1-induced lipogenesis pathway through mTOR-p70S6K activation and that reduced AMPK phosphorylation contributed to the activation of S6K1 phosphorylation. Moreover, we discovered that phosphorylation of AMPK is partially decreased by OA-induced LKB1 proteasomal degradation (Fig. 7). Our study provides some critical information needed for an understanding of the molecular mechanisms of OA-induced fatty liver and of species differences in susceptibility. OA induces lipogenesis, mediated predominantly by the AMPK/mTOR/SREBP-1 pathway in rat hepatocytes and human hepatoma cell lines.

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![Fig. 7. Proposed mechanism of OA-induced lipogenesis by the AMPK/SREBP-1 pathway.](image-url)
Role of AMPK in orotic acid-induced fatty liver