

Critical role of PA28 γ in hepatitis C virus-associated steatogenesis and hepatocarcinogenesis

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Hepatitis C virus (HCV) is a major cause of chronic liver disease that frequently leads to steatosis, cirrhosis, and eventually hepatocellular carcinoma (HCC). HCV core protein is not only a component of viral particles but also a multifunctional protein because liver steatosis and HCC are developed in HCV core gene-transgenic (CoreTg) mice. Proteasome activator PA28 γ /REG γ regulates host and viral proteins such as nuclear hormone receptors and HCV core protein. Here we show that a knockout of the PA28 γ gene induces the accumulation of HCV core protein in the nucleus of hepatocytes of CoreTg mice and disrupts development of both hepatic steatosis and HCC. Furthermore, the genes related to fatty acid biosynthesis and *srebp-1c* promoter activity were up-regulated by HCV core protein in the cell line and the mouse liver in a PA28 γ -dependent manner. Heterodimer composed of liver X receptor α (LXR α) and retinoid X receptor α (RXR α) is known to up-regulate *srebp-1c* promoter activity. Our data also show that HCV core protein enhances the binding of LXR α /RXR α to LXR-response element in the presence but not the absence of PA28 γ . These findings suggest that PA28 γ plays a crucial role in the development of liver pathology induced by HCV infection.

fatty acid | proteasome | sterol regulatory element-binding protein (SREBP) | RXR α | LXR α

Hepatitis C virus (HCV) belongs to the Flaviviridae family, and it possesses a positive, single-stranded RNA genome that encodes a single polyprotein composed of \approx 3,000 aa. The HCV polyprotein is processed by host and viral proteases, resulting in 10 viral proteins. Viral structural proteins, including the capsid (core) protein and two envelope proteins, are located in the N-terminal one-third of the polyprotein, followed by nonstructural proteins.

HCV infects >170 million individuals worldwide, and then it causes liver disease, including hepatic steatosis, cirrhosis, and eventually hepatocellular carcinoma (HCC) (1). The prevalence of fatty infiltration in the livers of chronic hepatitis C patients has been reported to average \approx 50% (2, 3), which is higher than the percentage in patients infected with hepatitis B virus and other liver diseases. However, the precise functions of HCV proteins in the development of fatty liver remain unknown because of the lack of a system sufficient to investigate the pathogenesis of HCV. HCV core protein expression has been shown to induce lipid droplets in cell lines and hepatic steatosis and HCC in transgenic mice (4–6). These reports suggest that HCV core protein plays an important role in the development of various types of liver failure, including steatosis and HCC.

Recent reports suggest that lipid biosynthesis affects HCV replication (7–9). Involvement of a geranylgeranylated host protein, FBL2, in HCV replication through the interaction with NSSA suggests that the cholesterol biosynthesis pathway is also important for HCV replication (9). Increases in saturated and monounsaturated fatty acids enhance HCV RNA replication, whereas increases in polyunsaturated fatty acids suppress it (7). Lipid homeostasis is regulated by a family of steroid regulatory element-binding proteins (SREBPs), which activate the expression of >30 genes involved in

the synthesis and uptake of cholesterol, fatty acids, triglycerides, and phospholipids. Biosynthesis of cholesterol is regulated by SREBP-2, whereas that of fatty acids, triglycerides, and phospholipids is regulated by SREBP-1c (10–14). In chimpanzees, host genes involved in SREBP signaling are induced during the early stages of HCV infection (8). SREBP-1c regulates the transcription of acetyl-CoA carboxylase, fatty acid synthase, and stearoyl-CoA desaturase, leading to the production of saturated and monounsaturated fatty acids and triglycerides (15). SREBP-1c is transcriptionally regulated by liver X receptor (LXR) α and retinoid X receptor (RXR) α , which belong to a family of nuclear hormone receptors (15, 16). Accumulation of cellular fatty acids by HCV core protein is expected to be modulated by the SREBP-1c pathway because RXR α is activated by HCV core protein (17). However, it remains unknown whether HCV core protein regulates the *srebp-1c* promoter.

We previously reported (18) that HCV core protein specifically binds to the proteasome activator PA28 γ /REG γ in the nucleus and is degraded through a PA28 γ -dependent pathway. PA28 γ is well conserved from invertebrates to vertebrates, and amino acid sequences of human and murine PA28 γ s are identical (19). The homologous proteins, PA28 α and PA28 β , form a heteroheptamer in the cytoplasm, and they activate chymotrypsin-like peptidase activity of the 20S proteasome, whereas PA28 γ forms a homoheptamer in the nucleus, and it enhances trypsin-like peptidase activity of 20S proteasome (20). Recently, Li and colleagues (21) reported that PA28 γ binds to steroid receptor coactivator-3 (SRC-3) and enhances the degradation of SRC-3 in a ubiquitin- and ATP-independent manner. However, the precise physiological functions of PA28 γ are largely unknown *in vivo*. In this work, we examine whether PA28 γ is required for liver pathology induced by HCV core protein *in vivo*.

Results

PA28 γ -Knockout HCV Core Gene Transgenic Mice. To determine the role of PA28 γ in HCV core-induced steatosis and the development of HCC *in vivo*, we prepared PA28 γ -knockout core gene transgenic mice. The PA28 γ -deficient, PA28 γ ^{-/-} mice were born without

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Abbreviations: CoreTg, HCV core gene-transgenic; HCC, hepatocellular carcinoma; HCV, hepatitis C virus; LXR, liver X receptor; LXRE, liver X receptor-response element; MEF, mouse embryonic fibroblast; ROS, reactive oxygen species; RXR, retinoid X receptor; SRC-3, steroid receptor coactivator-3; SREBP, sterol regulatory element-binding protein.

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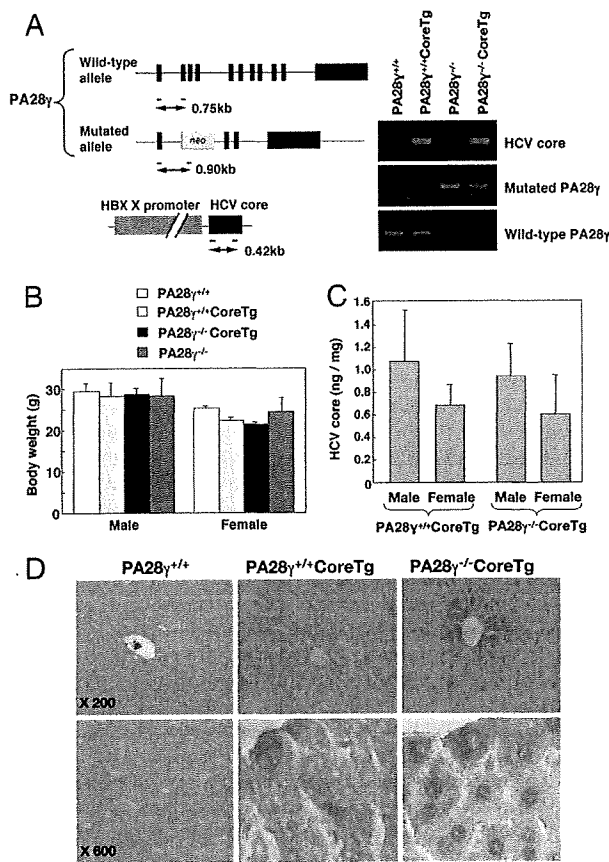


Fig. 1. Preparation and characterization of PA28 γ -knockout HCV core-transgenic mice. (A) The structures of the wild-type and mutated PA28 γ genes and the transgene encoding the HCV core protein under the control of the HBV X promoter were investigated. Positions corresponding to the screening primers and sizes of PCR products are shown. PCR products of the HCV core gene as well as wild-type and mutated PA28 γ alleles were amplified from the genomic DNAs of PA28 $\gamma^{+/+}$, PA28 $\gamma^{+/+}$ CoreTg, PA28 $\gamma^{-/-}$, and PA28 $\gamma^{-/-}$ CoreTg mice. (B) Body weights of PA28 $\gamma^{+/+}$, PA28 $\gamma^{+/+}$ CoreTg, PA28 $\gamma^{-/-}$ CoreTg, and PA28 $\gamma^{-/-}$ mice at the age of 6 months. (C) HCV core protein levels in the livers of PA28 $\gamma^{+/+}$ CoreTg and PA28 $\gamma^{-/-}$ CoreTg mice were determined by ELISA (mean \pm SD, $n = 10$). (D) Localization of HCV core protein in the liver. Liver sections of PA28 $\gamma^{+/+}$, PA28 $\gamma^{+/+}$ CoreTg, and PA28 $\gamma^{-/-}$ CoreTg mice at the age of 2 months were stained with anti-HCV core antibody.

appreciable abnormalities in all tissues examined, with the exception of a slight retardation of growth (22). HCV core gene-transgenic (PA28 $\gamma^{+/+}$ CoreTg) mice were bred with PA28 $\gamma^{-/-}$ mice to create PA28 $\gamma^{+/+/-}$ CoreTg mice. The PA28 $\gamma^{+/+/-}$ CoreTg offspring were bred with each other, and PA28 $\gamma^{-/-}$ CoreTg mice were selected by PCR using primers specific to the target sequences (Fig. 1A). No significant differences in body weight were observed among the 6-month-old mice, although PA28 $\gamma^{-/-}$ mice exhibited a slight retardation of growth (Fig. 1B). A similar level of PA28 γ expression was detected in PA28 $\gamma^{+/+}$ CoreTg and PA28 $\gamma^{+/+}$ mice (see Fig. 5B). The expression levels and molecular size of HCV core protein were similar in the livers of PA28 $\gamma^{+/+}$ CoreTg and PA28 $\gamma^{-/-}$ CoreTg mice (Fig. 1C; see also Fig. 5B).

PA28 γ Is Required for Degradation of HCV Core Protein in the Nucleus and Induction of Liver Steatosis. HCV core protein has been detected at various sites, such as the endoplasmic reticulum, mitochondria, lipid droplets, and nucleus of cultured cell lines, as well as in hepatocytes of PA28 $\gamma^{+/+}$ CoreTg mice and hepatitis C patients

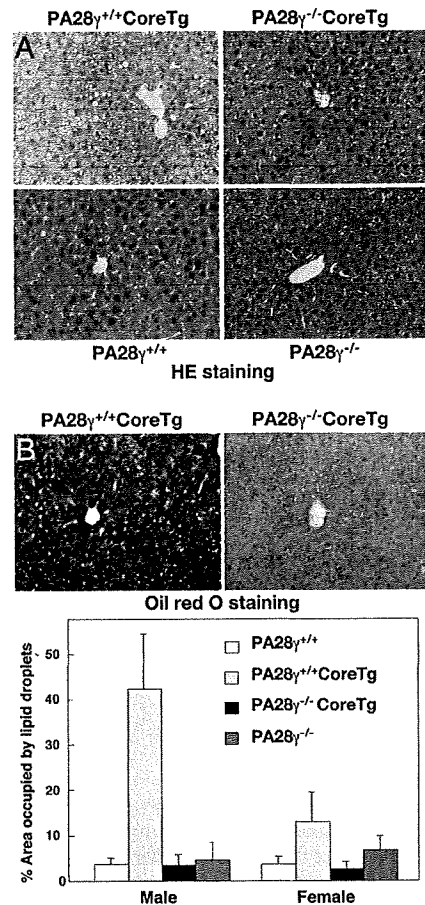


Fig. 2. Accumulation of lipid droplets by expression of HCV core protein. (A) Liver sections of the mice at the age of 6 months were stained with hematoxylin/eosin (HE). (B) (Upper) Liver sections of PA28 $\gamma^{+/+}$ CoreTg and PA28 $\gamma^{-/-}$ CoreTg mice at the age of 6 months were stained with oil red O. (Lower) The area occupied by lipid droplets of PA28 $\gamma^{+/+}$ (white), PA28 $\gamma^{+/+}$ CoreTg (gray), PA28 $\gamma^{-/-}$ CoreTg (black), and PA28 $\gamma^{-/-}$ (dark gray) mice was calculated by Image-Pro software (MediaCybernetics, Silver Spring, MD) (mean \pm SD, $n = 10$).

(6, 23, 24). Although HCV core protein is predominantly detected in the cytoplasm of the liver cells of PA28 $\gamma^{+/+}$ CoreTg mice, as reported in ref. 6, in the present study a clear accumulation of HCV core protein was observed in the liver cell nuclei of PA28 $\gamma^{-/-}$ CoreTg mice (Fig. 1D). These findings clearly indicate that at least some fraction of the HCV core protein is translocated into the nucleus and is degraded through a PA28 γ -dependent pathway. Mild vacuolation was observed in the cytoplasm of the liver cells of 4-month-old PA28 $\gamma^{+/+}$ CoreTg mice, and it became more severe at 6 months, as reported in ref. 25. Hematoxylin/eosin-stained liver sections of 6-month-old PA28 $\gamma^{+/+}$ CoreTg mice exhibited severe vacuolating lesions (Fig. 2A), which were clearly stained with oil red O (Fig. 2B Upper), whereas no such lesions were detected in the livers of PA28 $\gamma^{-/-}$ CoreTg, PA28 $\gamma^{+/+}$, or PA28 $\gamma^{-/-}$ mice at the same age. The areas occupied by the lipid droplets in the PA28 $\gamma^{+/+}$ CoreTg mouse livers were ≈ 10 and 2–4 times larger than those of male and female of PA28 $\gamma^{+/+}$, PA28 $\gamma^{-/-}$, and PA28 $\gamma^{-/-}$ CoreTg mice, respectively (Fig. 2B Lower). These results suggest that PA28 γ is required for the induction of liver steatosis by HCV core protein in mice.

PA28 γ Is Required for the Up-Regulation of SREBP-1c Transcription by HCV Core Protein in the Mouse Liver. To clarify the effects of a knockout of the PA28 γ gene in PA28 $\gamma^{+/+}$ CoreTg mice on lipid

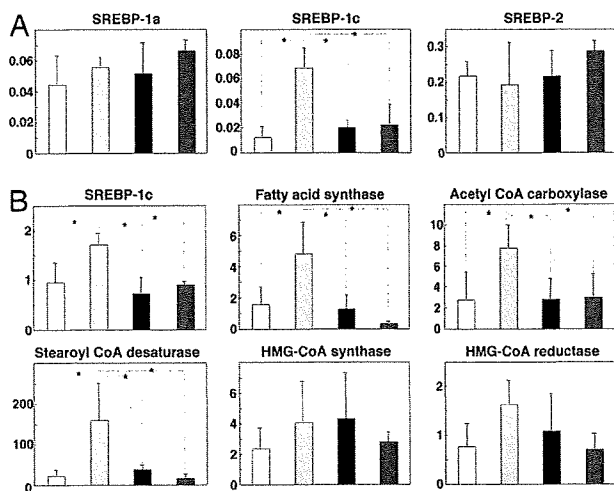


Fig. 3. Transcription of genes regulating lipid biosynthesis in the mouse liver. (A) Total RNA was prepared from the livers of 2-month-old mice; and the transcription of genes encoding SREBP-1a, SREBP-1c, and SREBP-2 was determined by real-time PCR. (B) The transcription of genes encoding SREBP-1c, fatty acid synthase, acetyl-CoA carboxylase, stearoyl-CoA desaturase, HMG-CoA synthase, and HMG-CoA reductase of 6-month-old mice was measured by real-time PCR. The transcription of the genes was normalized with that of hypoxanthine phosphoribosyltransferase, and the values are expressed as relative activity ($n = 5$; $*$, $P < 0.05$; $**$, $P < 0.01$). The transcription of each gene in PA28 $\gamma^{+/+}$, PA28 $\gamma^{+/+}$ CoreTg, PA28 $\gamma^{-/-}$ CoreTg, and PA28 $\gamma^{-/-}$ mice is indicated by white, gray, black, and dark gray bars, respectively.

metabolism, genes related to the lipid biosyntheses were examined by real-time quantitative PCR. Transcription of SREBP-1c was higher in the livers of PA28 $\gamma^{+/+}$ CoreTg mice than in those of PA28 $\gamma^{+/+}$, PA28 $\gamma^{-/-}$, and PA28 $\gamma^{-/-}$ CoreTg mice at 2 months of age, but no such increases in SREBP-2 and SREBP-1a were observed (Fig. 3A). Although transcription of SREBP-1c and its regulating enzymes, such as acetyl-CoA carboxylase, fatty acid synthase, and stearoyl-CoA desaturase, was also enhanced in the livers of 6-month-old PA28 $\gamma^{+/+}$ CoreTg mice compared with the levels in the livers of PA28 $\gamma^{+/+}$, PA28 $\gamma^{-/-}$, and PA28 $\gamma^{-/-}$ CoreTg mice, no statistically significant differences were observed with respect to the transcription levels of cholesterol biosynthesis-related genes that are regulated by SREBP-2 (e.g., HMG-CoA synthase and HMG-CoA reductase) (Fig. 3B). These results suggest the

following: (i) the up-regulation of SREBP-1c transcription in the livers of mice requires both HCV core protein and PA28 γ ; and (ii) the nuclear accumulation of HCV core protein alone, which occurs because of the lack of degradation along a PA28 γ -dependent proteasome pathway, does not activate the *srebp-1c* promoter.

HCV Core Protein Indirectly Potentiates *srebp-1c* Promoter Activity in an LXR α /RXR α -Dependent Manner. LXR α , which is primarily expressed in the liver, forms a complex with RXR α and synergistically potentiates *srebp-1c* promoter activity (16). Activation of RXR α by HCV core protein suggests that cellular fatty acid synthesis is modulated by the SREBP-1c pathway, although HCV core protein was not included in the transcription factor complex in the electrophoresis mobility shift assay (EMSA) (17). To analyze the effect of HCV core protein and PA28 γ on the activation of the *srebp-1c* promoter, we first examined the effect of HCV core protein on the binding of the LXR α /RXR α complex to the LXR-response element (LXRE) located upstream of the SREBP-1c gene (Fig. 4A). Although a weak shift of the labeled LXRE probe was observed by incubation with nuclear extracts prepared from 293T cells expressing FLAG-tagged LXR α and HA-tagged RXR α , a clear shift was obtained by the treatment of cells with 9-*cis*-retinoic acid and 22(*R*)-hydroxycholesterol, ligands for LXR α and RXR α , respectively. In contrast, coexpression of HCV core protein with LXR α and RXR α potentiated the shift of the probe irrespective of the treatment with the ligands. Addition of 500 times the amount of nonlabeled LXRE probe (competitor) diminished the shift of the labeled probe induced by the ligands and/or HCV core protein. Furthermore, coincubation of the nuclear fraction with antibody to FLAG or HA tag but not with antibody to either HCV core or PA28 γ caused a supershift of the labeled probe. These results indicate that HCV core protein does not participate in the LXR α /RXR α -LXRE complex but indirectly enhances the binding of LXR α /RXR α to the LXRE.

The activity of the *srebp-1c* promoter was enhanced by the expression of HCV core protein in 293T cells, and it was further enhanced by coexpression of LXR α /RXR α (Fig. 4B). Enhancement of the *srebp-1c* promoter by coexpression of HCV core protein and LXR α /RXR α was further potentiated by treatment with the ligands for LXR α and RXR α . The cells treated with 9-*cis*-retinoic acid exhibited more potent enhancement of the *srebp-1c* promoter than those treated with 22(*R*)-hydroxycholesterol. HCV core protein exhibited more potent enhancement of the *srebp-1c* promoter in cells treated with both ligands than in those treated with either ligand alone. These results suggest that HCV core protein poten-

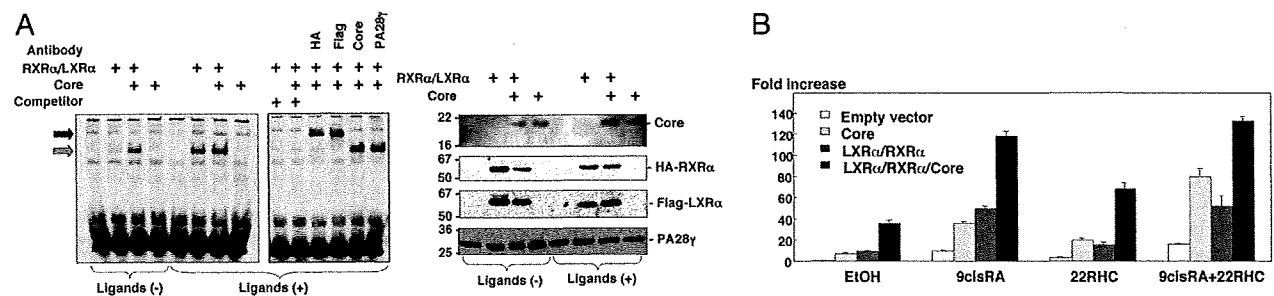


Fig. 4. Activation of the *srebp-1c* promoter by HCV core protein. (A) FLAG-LXR α and HA-RXR α were expressed in 293T cells together with or without HCV core protein. Ligands for LXR α and RXR α dissolved in ethanol [Ligands (+)] or ethanol alone [Ligands (-)] were added to the culture supernatant at 24 h posttransfection. Cells were harvested at 48 h posttransfection, and nuclear extracts were mixed with the reaction buffer for EMSA in the presence or absence of antibody (100 ng) against HA, FLAG, HCV core or PA28 γ , or nonlabeled LXRE probe (Competitor). (Left) The resulting mixtures were subjected to PAGE and blotted with horseradish peroxidase/streptavidin. The mobility shift of the LXRE probe and its supershift are indicated by a gray and black arrow, respectively. (Right) Expression of HCV core, HA-RXR α , FLAG-LXR α , and PA28 γ in cells was detected by immunoblotting. (B) Effects of ligands for RXR α , 9-*cis*-retinoic acid (9cisRA), and for LXR α , 22(*R*)-hydroxycholesterol (22RHC), on the activation of the *srebp-1c* promoter in 293T cells expressing RXR α , LXR α , and/or HCV core protein. Ligands were added into the medium at 24 h posttransfection at a concentration of 5 μ M, and the cells were harvested after 24 h of incubation.

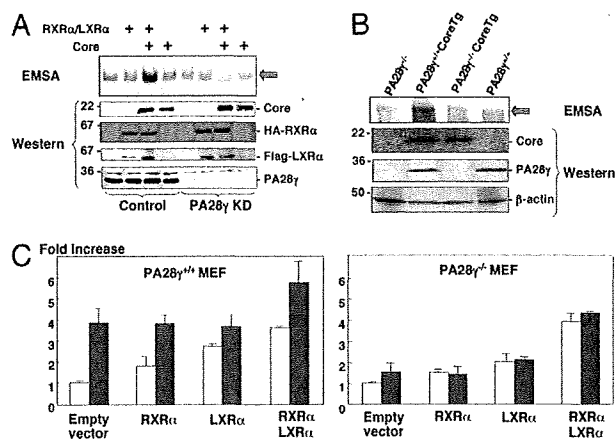


Fig. 5. PA28 γ is required for HCV core-dependent activation of the *srebp-1c* promoter. (A) Effect of PA28 γ knockdown on the LXR α /RXR α -DNA complex. FLAG-LXR α and HA-RXR α were expressed in FLC4 (control) or PA28 γ -knockdown (PA28 γ KD) cells together with or without HCV core protein. Cells were harvested at 48 h posttransfection, and nuclear extracts were mixed with the reaction buffer for EMSA. (Upper) The resulting mixtures were subjected to PAGE and blotted with horseradish peroxidase-streptavidin. The mobility shift of the LXRE probe is indicated by an arrow. (Lower) Expression of HCV core, HA-RXR α , FLAG-LXR α , and PA28 γ in cells was detected by immunoblotting. (B) Effect of PA28 γ knockdown on the LXR α /RXR α -DNA complex in the mouse liver. (Upper) Nuclear extracts were prepared from the livers of 2-month-old PA28 $\gamma^{-/-}$, PA28 $\gamma^{+/+}$ CoreTg, PA28 $\gamma^{-/-}$ CoreTg, and PA28 $\gamma^{+/+}$ mice and subjected to EMSA. The mobility shift of the LXRE probe is indicated by an arrow. (Lower) The expression of HCV core, PA28 γ , and β -actin in the livers of the mice was detected by immunoblotting. (C) Effect of HCV core protein on *srebp-1c* promoter activity in PA28 γ -knockout fibroblasts. A plasmid encoding firefly luciferase under the control of the *srebp-1c* promoter was transfected into MEFs prepared from PA28 $\gamma^{+/+}$ (Left) or PA28 $\gamma^{-/-}$ (Right) mice together with a plasmid encoding a *Renilla* luciferase. An empty plasmid or plasmids encoding mouse RXR α or LXR α were also cotransfected into the cells together with (gray bars) or without (white bars) a plasmid encoding HCV core protein. Luciferase activity under the control of the *srebp-1c* promoter was determined, and it is expressed as the fold increase in relative luciferase activity after standardization with the activity of *Renilla* luciferase.

tiates *srebp-1c* promoter activity in an LXR α /RXR α -dependent manner.

HCV Core Protein Activates the *srebp-1c* Promoter in an LXR α /RXR α - and PA28 γ -Dependent Manner. To examine whether PA28 γ is required for HCV core-induced enhancement of *srebp-1c* promoter activity in human liver cells, a PA28 γ -knockdown human hepatoma cell line (FLC4 KD) was prepared. Enhancement of binding of the LXRE probe to LXR α /RXR α by coexpression of HCV core protein and LXR α /RXR α in FLC4 cells was diminished by knockdown of the PA28 γ gene (Fig. 5A). Furthermore, formation of the LXR α /RXR α -LXRE complex was enhanced in the livers of PA28 $\gamma^{+/+}$ CoreTg mice but not in those of PA28 $\gamma^{-/-}$, PA28 $\gamma^{+/+}$, or PA28 $\gamma^{-/-}$ CoreTg mice (Fig. 5B). The expression of the HCV core protein in the mouse embryonic fibroblasts (MEFs) of PA28 $\gamma^{+/+}$ mice induced the activation of the mouse *srebp-1c* promoter through the endogenous expression of LXR α and RXR α (Fig. 5C Left). Further enhancement of the activation of the *srebp-1c* promoter by HCV core protein in PA28 $\gamma^{+/+}$ MEFs was achieved by the exogenous expression of both LXR α and RXR α . However, no enhancing effect of HCV core protein on *srebp-1c* promoter activity was observed in PA28 $\gamma^{-/-}$ MEFs (Fig. 5C Right). These results support the notion that HCV core protein enhances the activity of the *srebp-1c* promoter in an LXR α /RXR α - and PA28 γ -dependent manner.

Table 1. HCC in mice at 16–18 months of age

Mouse and sex	Total no. of mice	No. of mice developing HCC	Incidence, %
PA28 $\gamma^{+/+}$ CoreTg			
Male	17	5	29.4
Female	28	3	10.7
PA28 $\gamma^{+/-}$			
Male	16	0	0
Female	4	0	0
PA28 $\gamma^{-/-}$			
Male	23	0	0
Female	13	0	0
PA28 $\gamma^{-/-}$ CoreTg			
Male	15	0	0
Female	21	0	0

PA28 γ Plays a Crucial Role in the Development of HCC in PA28 $\gamma^{+/+}$ CoreTg Mice. The incidence of hepatic tumors in male PA28 $\gamma^{+/+}$ CoreTg mice older than 16 months was significantly higher than that in age-matched female PA28 $\gamma^{+/+}$ CoreTg mice (6). We reconfirmed here that the incidence of HCC in male and female PA28 $\gamma^{+/+}$ CoreTg mice at 16–18 months of age was 29.4% (5 of 17 mice) and 10.7% (3 of 28 mice), respectively. To our surprise, however, no HCC developed in PA28 $\gamma^{-/-}$ CoreTg mice (males, 15; females, 21), although, as expected, no HCC was observed in PA28 $\gamma^{+/-}$ (males, 16; females, 4) and PA28 $\gamma^{-/-}$ mice (males, 23; females, 13) (Table 1). These results clearly indicate that PA28 γ plays an indispensable role in the development of HCC induced by HCV core protein.

Discussion

HCV core protein is detected in the cytoplasm and partially in the nucleus and mitochondria of culture cells and hepatocytes of transgenic mice and hepatitis C patients (6, 23, 24, 26). Degradation of HCV core protein was enhanced by deletion of the C-terminal transmembrane region through a ubiquitin/proteasome-dependent pathway (27). We previously reported (18) that PA28 γ binds directly to HCV core protein and then enhances degradation of HCV core protein in the nucleus through a proteasome-dependent pathway because HCV core protein was accumulated in nucleus of human cell line by treatment with proteasome inhibitor MG132. In this work, accumulation of HCV core protein was observed in nucleus of hepatocytes of PA28 $\gamma^{-/-}$ CoreTg mice (Fig. 1D). This result directly demonstrates that HCV core protein migrates into the nucleus and is degraded through a PA28 γ -dependent pathway. However, HCV core protein accumulated in the nucleus because knockout of PA28 γ gene abrogated the ability to cause liver pathology, suggesting that interaction of HCV core protein with PA28 γ in the nucleus is prerequisite for the liver pathology induced by HCV core protein. We have previously shown (18) that HCV core protein is degraded through a PA28 γ -dependent pathway, and Minami *et al.* (28) reported that PA28 γ has a cochaperone activity with Hsp90. Therefore, degradation products of HCV core protein by means of PA28 γ -dependent processing or correct folding of HCV core protein through cochaperone activity of PA28 γ might be involved in the development of liver pathology. We do not know the reason why knockout of the PA28 γ gene does not affect the total amount of HCV core protein in the liver of the transgenic mice. PA28 γ -dependent degradation of HCV core protein may be independent of ubiquitination, as shown in SRC-3 (21), whereas knockdown of PA28 γ in a human hepatoma cell line enhanced the ubiquitination of HCV core protein [supporting information (SI) Fig. 6], suggesting that lack of PA28 γ suppresses a ubiquitin-independent degradation but enhances a ubiquitin-dependent degradation of HCV core protein. Therefore, the total amount of HCV

core protein in the liver of the mice may be unaffected by the knockout of the PA28 γ gene.

Our results suggest that the interaction of HCV core protein with PA28 γ leads to the activation of the *srebp-1c* promoter along an LXR α /RXR α -dependent pathway and the development of liver steatosis and HCC. HCV core protein was not included in the LXR α /RXR α -LXRE complex (Fig. 3A), suggesting that HCV core protein indirectly activates the *srebp-1c* promoter. Cytoplasmic HCV core protein was shown to interact with Sp110b, which is a transcriptional corepressor of RAR α -dependent transcription, and this interaction leads to the sequestering of Sp110b in the cytoplasm, resulting in the activation of RAR α -dependent transcription (29). The sequestration of an unidentified corepressor of the LXR α /RXR α heterodimer in the cytoplasm by HCV core protein may also contribute to the activation of the *srebp-1c* promoter. Although the precise physiological function of PA28 γ -proteasome activity in the nucleus is not known, PA28 γ has previously been shown (21) to regulate nuclear hormone receptors by means of the degradation of its coactivator SRC-3 and to participate in the fully Hsp90-dependent protein refolding (28). It appears reasonable to speculate that degradation or refolding of HCV core protein in a PA28 γ -dependent pathway might be involved in the modulation of transcriptional regulators of various promoters, including the *srebp-1c* promoter. Saturated or monounsaturated fatty acids have been shown to enhance HCV RNA replication in Huh7 cells containing the full-length HCV replicon (7). The up-regulation of fatty acid biosynthesis by HCV core protein may also contribute to the efficient replication of HCV and to the progression of HCV pathogenesis.

Expression of HCV core protein was reported to enhance production of reactive oxygen species (ROS) (30), which leads to carbonylation of intracellular proteins (31). Enhancement of ROS production may trigger double-stranded DNA breaks and result in the development of HCC (30, 32, 33). HCV core protein could enhance the protein carbonylation in the liver of the transgenic mice in the presence but not in the absence of PA28 γ (SI Fig. 7), suggesting that PA28 γ is required for ROS production induced by HCV core protein. Development of HCC was observed in PA28 $\gamma^{+/+}$ CoreTg mice but not in PA28 $\gamma^{-/-}$ CoreTg mice (Table 1). Enhancement of ROS production by HCV core protein in the presence of PA28 γ might be involved in the development of HCC in PA28 $\gamma^{+/+}$ CoreTg mice.

It is well known that resistant viruses readily emerge during the treatment with antiviral drugs targeting the viral protease or replicase, especially in the case of infection with RNA viruses. Therefore, antivirals targeting the host factors that are indispensable for the propagation of viruses might be an ideal target for the development of antiviral agents because of a lower rate of mutation than that of viral genome, if they have no side effects to patients. Importantly, the amino acid sequence of PA28 γ of mice is identical to that of human, and mouse PA28 γ is dispensable because PA28 γ knockout mice exhibit no abnormal phenotype except for mild growth retardation. Therefore, PA28 γ might be a promising target for an antiviral treatment of chronic hepatitis C with negligible side effects.

In summary, we observed that a knockout of the PA28 γ gene from PA28 $\gamma^{+/+}$ CoreTg mice induced the accumulation of HCV core protein in the nucleus and disrupted the development of both steatosis and HCC. Activation of the *srebp-1c* promoter was up-regulated by HCV core protein both *in vitro* and *in vivo* through a PA28 γ -dependent pathway, suggesting that PA28 γ plays a crucial role in the development of liver pathology induced by HCV infection.

Materials and Methods

Histology and immunohistochemistry, real-time PCR, and detection of proteins modified by ROS are discussed in *SI Materials and Methods*.

Plasmids and Reagents. Human PA28 γ cDNA was isolated from a human fetal brain library (18). The gene encoding HCV core protein was amplified from HCV strain J1 (genotype 1b) (34) and cloned into pCAG-GS (35). Mouse cDNAs of RXR α and LXR α were amplified by PCR from the total cDNAs of the mouse liver. The RXR α and LXR α genes were introduced into pEF-FLAGSpGBK (36) and pcDNA3.1 (Invitrogen, Carlsbad, CA), respectively. The targeting fragment for human PA28 γ knockdown (GGATCCGGTGGATCAGGAAGTGAAGTTCAAGAGACTTCACTTCTGATCCACCTTTTTTGGAAAAGCTT) was introduced into the BamHI and HindIII sites of pSilencer 4.1 U6 hygro vector (Ambion, Austin, TX). Mouse anti-FLAG (M2) and mouse anti- β -actin antibodies were purchased from Sigma (St. Louis, MO). Rabbit polyclonal antibody against synthetic peptides corresponding to amino acids 70–85 of PA28 γ was obtained from AFFINITY (Exeter, U.K.). Horseradish peroxidase-conjugated goat anti-mouse and anti-rabbit IgGs were purchased from ICN Pharmaceuticals (Aurora, OH). Rabbit anti-HCV core protein was prepared by immunization with recombinant HCV core protein (amino acids 1–71), as described in ref. 24. Mouse monoclonal antibody to HCV core protein was kindly provided by S. Yagi (37). The plasmid for expression of HA-tagged ubiquitin was described in ref. 27.

Preparation of PA28 γ -Knockout HCV CoreTg Mice. The generation of C57BL/6 mice carrying the gene encoding HCV core protein genotype 1b line C49 and that of PA28 $\gamma^{-/-}$ mice have been reported previously (22, 25). Both strains were crossed with each other to create PA28 $\gamma^{-/-}$ CoreTg mice. PA28 $\gamma^{-/-}$ CoreTg mice were identified by PCR targeted at the PA28 γ or HCV core gene (22, 25). Using 1 μ g of genomic DNA obtained from the mouse tail, the PA28 γ gene was amplified by PCR with the following primers: sense, PA28-3 (AGGTGGATCAGGAAGTGAAGCTCAA); and antisense, PA28 γ -5cr (CACCTCACTTGTGATCCGCTCTCTGAAAGAATCAACC). The targeted sequence for the PA28 γ -knockout mouse was detected by PCR using the PA28-3 primer and the PAKO-4 primer (TGCAGTTCATTCAGGGCACCGGACAG). The transgene encoding HCV core protein was detected by PCR as described in ref. 25. The expression of PA28 γ and HCV core protein in the livers of 6-month-old mice was confirmed by Western blotting with mouse monoclonal antibody to HCV core protein, clone 11-10, and rabbit antibody to PA28 γ . Mice were cared for according to the institutional guidelines. The mice were given ordinary feed, CRF-1 (Charles River Laboratories, Yokohama, Japan), and they were maintained under specific pathogen-free conditions.

All animal experiments conformed to the Guidelines for the Care and Use of Laboratory Animals, and they were approved by the Institutional Committee of Laboratory Animal Experimentation (Research Institute for Microbial Diseases, Osaka University).

Preparation of Mouse Embryonic Fibroblasts. MEFs were prepared as described in ref. 22. MEFs were cultured at 37°C under an atmosphere of 5% CO₂ in Dulbecco's modified Eagle's medium (Sigma) supplemented with 10% FBS, penicillin, streptomycin, sodium pyruvate, and nonessential amino acids.

Transfection and Immunoblotting. Plasmid vectors were transfected into the MEFs and 293T cells by liposome-mediated transfection by using Lipofectamine 2000 (Invitrogen). The amount of HCV core protein in the liver tissues was determined by an ELISA as described in ref. 37. The cell lysates were subjected to SDS/PAGE (12.5% gel), and they were then transferred onto PVDF membranes. Proteins on the membranes were treated with specific antibody and Super Signal Femto (Pierce, Rockford, IL). The results were then visualized by using an LAS3000 imaging system (Fuji Photo Film, Tokyo, Japan). The method of immunoprecipitation test is described in ref. 18.

Reporter Assay for *srebp-1c* Promoter Activity. The genomic DNA fragment encoding the *srebp-1c* promoter region (located from residues -410 to +24) was amplified from a mouse genome. The fragment was introduced into the KpnI and HindIII sites of pGL3-Basic (Promega, Madison, WI), and it was designated as pGL3-*srebp-1c*Pro. The plasmids encoding RXR α and LXR α were transfected into MEFs together with pGL3-*srebp-1c*Pro and a control plasmid encoding *Renilla* luciferase (Promega). The total DNA for transfection was normalized by the addition of empty plasmids. Cells were harvested at 24 h posttransfection. The ligand of RXR α , 9-*cis*-retinoic acid (Sigma), and that of LXR α , 22(*R*)-hydroxylcholesterol (Sigma) were added at a final concentration of 5 μ M each to the culture medium of 293T cells transfected with pGL3-*srebp-1c*Pro together with expression plasmids encoding RXR α , LXR α , and HCV core protein at 24 h posttransfection. Cells were harvested 24 h after treatment. Luciferase activity was measured by using the dual-luciferase reporter assay system (Promega). Firefly luciferase activity was standardized with that of *Renilla* luciferase, and the results are expressed as the fold increase in relative luciferase units.

Electrophoresis Mobility Shift Assay (EMSA). EMSA was carried out by using a LightShift Chemiluminescent EMSA kit (Pierce) according to the manufacturer's protocol. Nuclear extract of the cell lines and liver tissue was prepared with an NE-PER nuclear

and cytoplasmic extraction reagent kit (Pierce). Briefly, double-stranded oligonucleotides for EMSA were prepared by annealing both strands of each LXRE of the *srebp-1c* promoter (5'-GGACGCCCGCTAGTAACCCCGGC-3') (16). Both strands were labeled at the 5' ends with biotin. The annealed probe was incubated for 20 min on ice with nuclear extract (3 μ g of protein) in a reaction buffer containing 10 mM Tris-HCl (pH 7.5), 50 mM KCl, 1 mM DTT, 0.05 μ g/ μ l poly(dI-dC), 2.5% glycerol, 0.05% Nonidet P-40, and 0.1 nM labeled probe, with or without 1 mM nonlabeled probe. The resulting mixture was subjected to PAGE (5% gel) at 120 V for 30 min in 0.5 \times TBE. The DNA-protein complex was transferred to a Hybond N+ membrane (Amersham, Piscataway, NJ), incubated with horseradish peroxidase-conjugated streptavidin, and visualized by using an LAS3000 imaging system.

Statistical Analysis. The results are expressed as the mean \pm SD. The significance of differences in the means was determined by Student's *t* test.

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Involvement of the PA28 γ -Dependent Pathway in Insulin Resistance Induced by Hepatitis C Virus Core Protein[∇]

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The hepatitis C virus (HCV) core protein is a component of nucleocapsids and a pathogenic factor for hepatitis C. Several epidemiological and experimental studies have suggested that HCV infection is associated with insulin resistance, leading to type 2 diabetes. We have previously reported that HCV core gene-transgenic (PA28 $\gamma^{+/+}$ CoreTg) mice develop marked insulin resistance and that the HCV core protein is degraded in the nucleus through a PA28 γ -dependent pathway. In this study, we examined whether PA28 γ is required for HCV core-induced insulin resistance *in vivo*. HCV core gene-transgenic mice lacking the PA28 γ gene (PA28 $\gamma^{-/-}$ CoreTg) were prepared by mating of PA28 $\gamma^{+/+}$ CoreTg with PA28 γ -knockout mice. Although there was no significant difference in the glucose tolerance test results among the mice, the insulin sensitivity in PA28 $\gamma^{-/-}$ CoreTg mice was recovered to a normal level in the insulin tolerance test. Tyrosine phosphorylation of insulin receptor substrate 1 (IRS1), production of IRS2, and phosphorylation of Akt were suppressed in the livers of PA28 $\gamma^{+/+}$ CoreTg mice in response to insulin stimulation, whereas they were restored in the livers of PA28 $\gamma^{-/-}$ CoreTg mice. Furthermore, activation of the tumor necrosis factor alpha promoter in human liver cell lines or mice by the HCV core protein was suppressed by the knockdown or knockout of the PA28 γ gene. These results suggest that the HCV core protein suppresses insulin signaling through a PA28 γ -dependent pathway.

Hepatitis C virus (HCV) is the causative agent in most cases of acute and chronic non-A, non-B hepatitis (15). Over one-half of patients with the acute infection evolve into a persistent carrier state (24). Chronic infection with HCV frequently induces hepatic steatosis, cirrhosis, and eventually hepatocellular carcinoma (22) and is known to be associated with diseases of extrahepatic organs, including an essential mixed cryoglobulinemia, porphyria cutanea tarda, membranoproliferative glomerulonephritis, and type 2 diabetes (13).

HCV is classified into the genus *Hepacivirus* of the family *Flaviviridae* and possesses a viral genome consisting of a single positive-strand RNA with a nucleotide length of about 9.5 kb. This viral genome encodes a single polyprotein composed of approximately 3,000 amino acids (9). The polyprotein is post-translationally cleaved by host cellular peptidases and viral proteases, resulting in 10 viral proteins (6, 10, 12). The HCV core protein is known to interact with viral-sense RNA of HCV to form the viral nucleocapsid (44). The HCV core protein is cleaved off at residue 191 by the host signal peptidase to release it from the E1 envelope protein and then by the host signal peptide peptidase at around amino acid residues 177 to 179 within the C-terminal transmembrane region (30, 39, 40). The mature core protein is retained mainly on the endoplasmic reticulum, although a portion moves to the nucleus and mitochondria (11, 51).

Recent epidemiological studies have indicated that type 2

diabetes is an HCV-associated disease (7, 29). However, it remains unclear how insulin resistance is induced in patients chronically infected with HCV, since there is no suitable model for investigating HCV pathogenesis. Type 2 diabetes is a complex, multisystemic disease with pathophysiology that includes a high level of hepatic glucose production and insulin resistance, which contribute to the development of hyperglycemia (8, 18). Although the precise mechanism by which these factors contribute to the induction of insulin resistance is difficult to understand, a high level of insulin production by pancreatic β cells under a state of insulin resistance is common in the development of type 2 diabetes. The hyperinsulinemia in the fasting state that is observed relatively early in type 2 diabetes is considered to be a secondary response that compensates for the insulin resistance (8, 18).

The HCV core protein is also known as a pathogenic factor that induces steatosis and hepatocellular carcinoma in mice (33, 35). Previously, we reported that insulin resistance occurs in HCV core gene-transgenic mice due at least partly to an increase in tumor necrosis factor alpha (TNF- α) secretion (47) and that the HCV core protein is degraded through a PA28 γ /REG γ (11S regulator)-dependent pathway in the nucleus (32). It is well known that PA28 γ enhances latent proteasome activity, although the biological significance of PA28 γ is largely unknown, with the exception that PA28 γ is known to regulate steroid receptor coactivator 3 (28). Although several reports suggested that the degradation of insulin receptor substrate (IRS) proteins by a ubiquitin-dependent proteasome activity contributes to insulin resistance (43, 50), the involvement of the HCV core protein in cooperation with PA28 γ in the stability of IRS proteins and in the development of insulin resis-

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tance is not known. In this study, we examined the involvement of PA28 γ in the induction of insulin resistance by the HCV core protein in vivo.

MATERIALS AND METHODS

Preparation of PA28 γ -knockout HCV core gene-transgenic mice. C57BL/6 mice carrying the gene encoding HCV core protein genotype 1b (PA28 $\gamma^{+/+}$ CoreTg) line C49 and PA28 $\gamma^{-/-}$ mice have been described previously (35, 36). These two genotypes were crossbred to create PA28 $\gamma^{+/+}$ -CoreTg mice. PA28 $\gamma^{+/+}$ -CoreTg mice were bred to generate PA28 $\gamma^{-/-}$ -CoreTg mice (35, 36). The HCV core gene and the target sequence to knock out the PA28 γ gene were identified by PCR. The mice were given ordinary feed (CRF-1; Charles River Laboratories, Yokohama, Japan) and were maintained under specific-pathogen-free conditions.

Glucose tolerance test. The mice were fasted for more than 16 h before glucose administration. D-Glucose (1 g/kg body weight) was intraperitoneally administered to the mice. Blood samples were taken from the orbital sinus at the indicated time points. The plasma glucose concentration was measured by means of a MEDI-SAFE Mini blood glucose monitor (TERUMO, Tokyo, Japan). The serum insulin level was determined by a Mercodia (Uppsala, Sweden) ultrasensitive mouse insulin enzyme-linked immunosorbent assay (ELISA).

Insulin tolerance test. The mice were fed freely and then fasted during the study period. Human insulin (2 U/kg body weight) (Humulin; Eli Lilly, Indianapolis, IN) was intraperitoneally administered to the mice. The plasma glucose concentration was measured at the indicated time and was normalized based on the glucose concentration at the time just before insulin administration.

Histological analysis of pancreatic islets. Pancreas tissues were fixed with paraformaldehyde, embedded in paraffin, sectioned, and stained with hematoxylin and eosin. The relative islet area and islet number were determined with Image-Pro PLUS image analyzing software (NIPPON ROPER, Tokyo, Japan).

Estimation of tumor necrosis factor alpha and HCV core protein. Mouse TNF- α was measured by using a mouse TNF- α ELISA kit (Pierce, Rockford, IL) and normalized based on the amount of total protein in each sample. The protein concentration was estimated by using a BCA protein assay kit (Pierce). The amount of HCV core protein in the liver tissues was determined by using an ELISA system as described previously (4).

In vivo insulin stimulation and immunoblot analysis. Mice were fasted for more than 16 h before insulin stimulation and then anesthetized with ketamine and xylazine. Five units of insulin were injected into the mice via the interior vena cava. Livers of the mice were collected 5 min after the insulin injection and frozen in liquid nitrogen. Immunoblot analyses of the HCV core protein, PA28 γ , and each of the insulin-signaling molecules were carried out with the liver tissue homogenates prepared in the homogenizing buffer containing 25 mM Tris-HCl (pH 7.4), 10 mM Na₃VO₄, 100 mM NaF, 50 mM Na₄P₂O₇, 10 mM EGTA, 10 mM EDTA, 2 mM phenylmethylsulfonyl fluoride, and 1% Nonidet P40 supplemented with Complete Protease Inhibitor Cocktail (Roche Diagnostics, Mannheim, Germany) (53). Tissue lysates were subjected to sodium dodecyl sulfate-2% to 15% gradient polyacrylamide gel electrophoresis (PAG Mini DAIIICHI 2/15 13W; Daiichi Diagnostics, Tokyo, Japan) and electrotransferred onto polyvinylidene difluoride membranes (Immobilon-P; Millipore, Bedford, MA). The protein transferred onto the membrane was reacted with rabbit anti-HCV core (32), rabbit anti-Akt (Cell Signaling, Danvers, MA), rabbit anti-phospho-Ser473-Akt (Cell Signaling), rabbit anti-IRS1 (Upstate, Lake Placid, NY), rabbit anti-phospho-Tyr608 mouse insulin receptor substrate 1 (Sigma, St. Louis, MO), or rabbit anti-IRS2 (Upstate) polyclonal antibody and then incubated with horseradish peroxidase-conjugated anti-rabbit antibody. Blotted protein was visualized using Super Signal Femto (Pierce) and an LAS3000 imaging system (Fuji Photo Film, Tokyo, Japan).

Quantitative reverse transcription-PCR (RT-PCR). Total RNA was isolated from mouse liver using an RNeasy kit (QIAGEN, Valencia, CA). The RNA preparation was treated with a TURBO DNA-free kit (Ambion, Austin, TX) to remove DNA contamination in the samples. The first-strand cDNAs were synthesized by a first-strand cDNA synthesis kit (Amersham Biosciences, Franklin Lakes, NJ). The targeted cDNA was estimated by using Platinum SYBR Green qPCR Super Mix UDC (Invitrogen, Carlsbad, CA) according to the manufacturer's protocol. The fluorescent signal was measured by using an ABI Prism 7000 (Applied Biosystems, Foster City, CA). The genes encoding mouse TNF- α , IRS1, IRS2, and hypoxanthine phosphoribosyl transferase were amplified with the following primer pairs: 5'-GGTACAACCCATCGGCTGGCA-3' (forward) and 5'-GCGACGTGGAAGTGGCAGAAG-3' (reverse) for TNF- α , 5'-ATAG

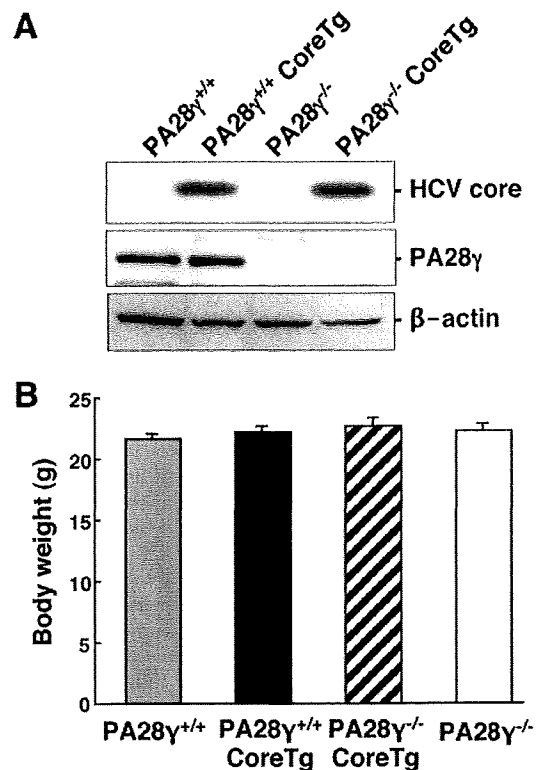


FIG. 1. Characterization of HCV core gene-transgenic mice deficient in the PA28 γ gene. (A) Expression of the HCV core protein and PA28 γ in the livers of PA28 $\gamma^{+/+}$, PA28 $\gamma^{+/+}$ CoreTg, PA28 $\gamma^{-/-}$, and PA28 $\gamma^{-/-}$ CoreTg mice. Lysates obtained from liver tissues of the mice (100 μ g protein/lane) were subjected to sodium dodecyl sulfate-polyacrylamide gel electrophoresis and immunoblotting using antibodies to the HCV core protein, PA28 γ , and β -actin. (B) Body weights of the mice. Body weights of 2-month-old mice were measured ($n = 7$ in each group). There were no statistically significant differences in body weights among the mice ($P > 0.05$).

CTCTGAGACCTTCTCAGCACCTAC-3' (forward) and 5'-GGAGTGGCCCT CATTGCTGCCTAA-3' (reverse) for IRS1, 5'-AGCCTGGGATAATGGTG ACTATACCGA-3' (forward) and 5'-TTGTGGGCAAAGGATGGGGACAC T-3' (reverse) for IRS2, and 5'-CCAGCAAGCTTGCAACCTTAACCA-3' (forward) and 5'-GTAATGATCAGTCAACGGGGGAC-3' (reverse) for hypoxanthine phosphoribosyl transferase. Each PCR product was found as a single band with the correct size by agarose gel electrophoresis (data not shown).

Reporter assay for TNF- α promoter activity. The promoter region of the TNF- α gene (located from residues -1260 to +140) was amplified from mouse genomic DNA and was then introduced into the KpnI and BglII sites of pGL3-Basic (Promega, Madison, WI) (25). The resulting plasmid was designated as pGL3-tnf- α Pro. The gene encoding the HCV core protein was amplified from HCV strain J1 (genotype 1b) and cloned into pCAG-GS (1, 38). To avoid contamination with endotoxin from *Escherichia coli*, the plasmid DNA was purified by using an EndoFree Plasmid Maxi kit (QIAGEN). The total amount of transfected DNA was normalized by the addition of empty plasmids. Plasmid vector was transfected into hepatoma cell lines by lipofection using Lipofectamine 2000 (Invitrogen). Cells were harvested at 24 h posttransfection. Luciferase activity was determined by using the Dual-Luciferase Reporter Assay system (Promega). Firefly luciferase activity was normalized to coexpressed *Renilla* luciferase activity. The amount of firefly luciferase activity was presented as the increase (n -fold) relative to the value for the sample lacking the HCV core protein, which was taken to be 1.0. PA28 γ -knockdown cell lines were established by using pSilencer 2.1 U6 Hygro (Ambion) according to the manufacturer's protocol.

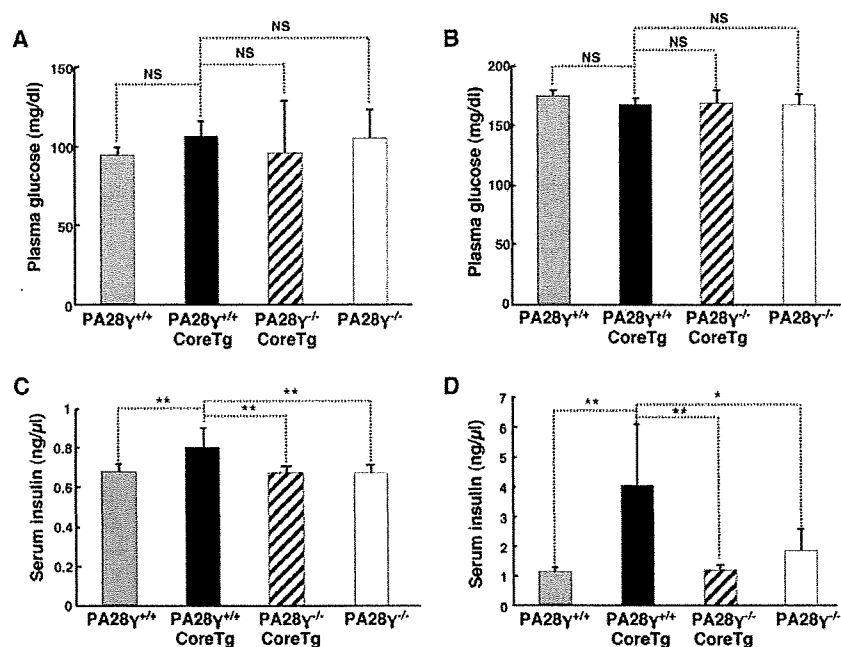


FIG. 2. Knockout of the PA28 γ gene inhibited the hyperinsulinemia induced by HCV core protein. Plasma glucose levels of PA28 $\gamma^{+/+}$, PA28 $\gamma^{+/+}$ CoreTg, PA28 $\gamma^{-/-}$ CoreTg, and PA28 $\gamma^{-/-}$ mice under fasting (A) or fed (B) conditions ($n = 7$ in each group) are shown. Serum insulin levels in fasting (C) or fed (D) mice ($n = 7$ in each group) are also shown. Values are represented as means \pm standard deviations. * $P < 0.05$; ** $P < 0.01$. NS, not statistically significant.

Statistical analysis. The results are presented as means \pm standard deviations. The significance of the differences was determined by Student's t test. P values of < 0.05 were considered statistically significant.

RESULTS

HCV core gene-transgenic mice deficient in the PA28 γ gene.

To investigate the role of PA28 γ in the development of insulin resistance in HCV core gene-transgenic (PA28 $\gamma^{+/+}$ CoreTg)

mice, we generated HCV core gene-transgenic mice deficient in the PA28 γ gene (PA28 $\gamma^{-/-}$ CoreTg). A PA28 $\gamma^{+/+}$ CoreTg mouse expressing an amount of PA28 γ equal to that of its normal littermates (Fig. 1A) was crossed with a PA28 $\gamma^{-/-}$ mouse to generate a PA28 $\gamma^{+/-}$ CoreTg mouse. PA28 $\gamma^{+/-}$ CoreTg mice were bred with each other, and a PA28 $\gamma^{-/-}$ CoreTg mouse was selected by PCR. The HCV core protein was expressed in PA28 $\gamma^{+/+}$ CoreTg and PA28 $\gamma^{-/-}$ CoreTg

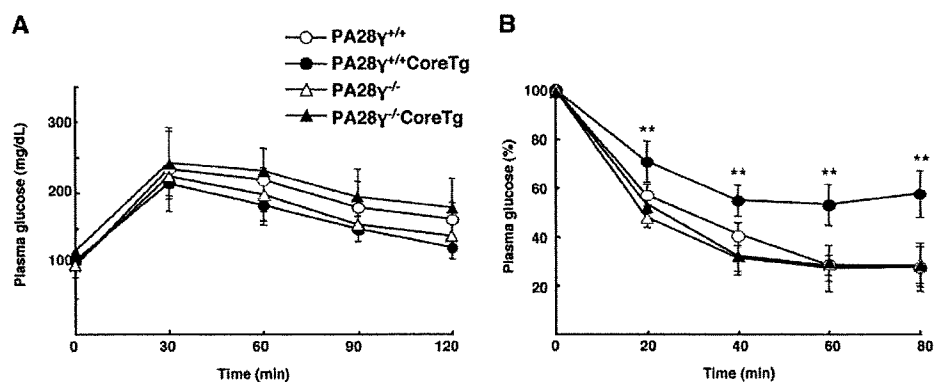


FIG. 3. Knockout of the PA28 γ gene inhibits the insulin resistance induced by the HCV core protein. (A) Glucose tolerance test. D-Glucose was intraperitoneally administered to mice fasted for more than 16 h at 1 g/kg of body weight. Plasma glucose levels were estimated at the indicated times ($n = 5$ in each group). There were no significant differences in glucose levels among the mice ($P > 0.05$). (B) Insulin tolerance test. Human insulin (2 units/kg body weight) was intraperitoneally administered to the mice, and the plasma glucose levels were estimated at the indicated times. Values were normalized to the baseline glucose concentration at the time of insulin administration ($n = 5$ in each group). The values for the PA28 $\gamma^{+/+}$ (open circles), PA28 $\gamma^{+/+}$ CoreTg (closed circles), PA28 $\gamma^{-/-}$ (open triangles), and PA28 $\gamma^{-/-}$ CoreTg (closed triangles) mice are represented as means and \pm standard deviations. Significant differences in insulin sensitivity ($P < 0.01$) in PA28 $\gamma^{+/+}$ CoreTg mice compared to that in PA28 $\gamma^{+/+}$, PA28 $\gamma^{-/-}$, or PA28 $\gamma^{-/-}$ CoreTg mice are indicated by double asterisks (**). There were no significant differences among PA28 $\gamma^{+/+}$, PA28 $\gamma^{-/-}$, and PA28 $\gamma^{-/-}$ CoreTg mice ($P > 0.05$).

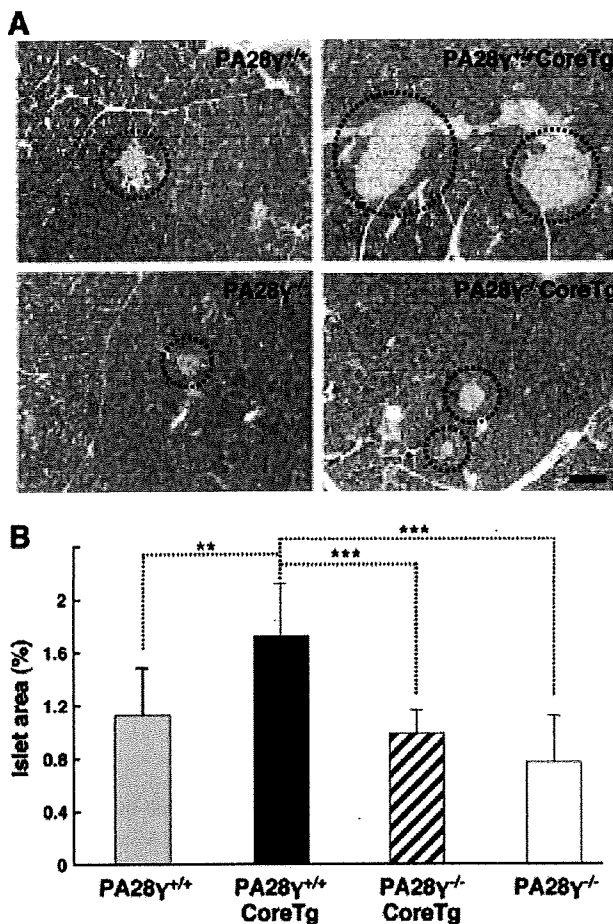


FIG. 4. PA28 γ participated in the enlargement of pancreatic islets induced by the HCV core protein. (A) Histological sections prepared from pancreas tissues of PA28 $\gamma^{+/+}$, PA28 $\gamma^{+/+}$ CoreTg, PA28 $\gamma^{-/-}$, and PA28 $\gamma^{-/-}$ CoreTg mice were stained with hematoxylin and eosin. Dotted circles indicate pancreatic islets. (B) The area occupied by pancreatic islets was measured by computer software in three different fields of every six randomly selected sections of 10 mice per genotype and is represented as a percentage of the total pancreatic area. ** $P < 0.01$; *** $P < 0.001$. The scale bar indicates 100 μ m.

mice but not in PA28 $\gamma^{+/+}$ (normal littermates) or PA28 $\gamma^{-/-}$ mice. PA28 γ was found at a similar level in PA28 $\gamma^{+/+}$ CoreTg and PA28 $\gamma^{+/+}$ mice but was not present in either PA28 $\gamma^{-/-}$ or PA28 $\gamma^{-/-}$ CoreTg mice (Fig. 1A). The expression of the HCV core protein in the livers of 2-month-old male mice was slightly higher in PA28 $\gamma^{-/-}$ CoreTg (1.36 ± 0.44 ng/mg of total protein; $n = 7$) than in PA28 $\gamma^{+/+}$ CoreTg (1.23 ± 0.22 ng/mg of total protein; $n = 7$) mice, but these values were not significantly different ($P > 0.05$). Insulin sensitivity is dependent on several conditions such as body weight, obesity, and liver steatosis (26). PA28 $\gamma^{-/-}$ mice were slightly smaller than their normal littermates (PA28 $\gamma^{+/+}$) at more than 3 months old, as described previously (36), but this was not significantly different in 2-month-old mice (Fig. 1B). PA28 $\gamma^{+/+}$ CoreTg mice exhibited severe hepatic steatosis from 4 months of age (35). To avoid the influence of hepatic steatosis and body weight on the examination of insulin resistance, 2-month-old mice were

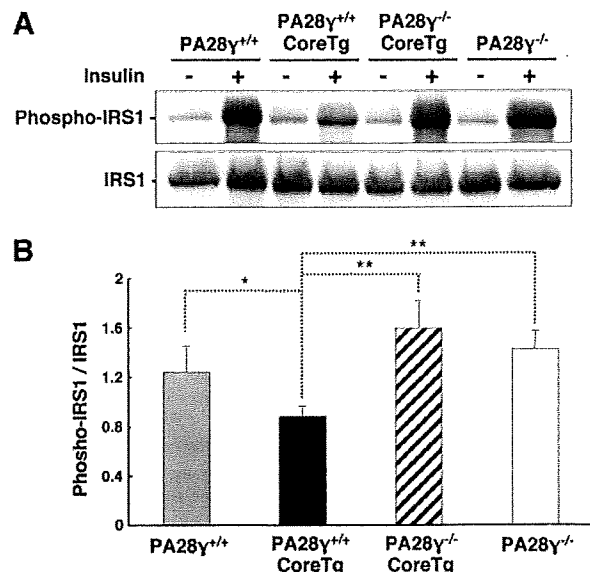


FIG. 5. PA28 γ participated in the inhibition of the tyrosine phosphorylation of IRS1 induced by the HCV core protein. Liver tissues from PA28 $\gamma^{+/+}$, PA28 $\gamma^{+/+}$ CoreTg, PA28 $\gamma^{-/-}$, and PA28 $\gamma^{-/-}$ CoreTg mice were prepared after administration of insulin (+) or phosphate-buffered saline (-). The samples (100 μ g of total protein) were examined by immunoblotting with antibodies against IRS1 and phospho-Tyr608 of mouse IRS1 (A). Phosphorylated IRS1 was estimated from the density on the immunoblotted membrane by using computer software (B) ($n = 5$ in each group). The data presented are representative of three independent experiments. * $P < 0.05$; ** $P < 0.01$.

used in this study. Figure 1B shows the body weights of 2-month-old mice. There were no significant differences in body weight among PA28 $\gamma^{+/+}$ CoreTg, PA28 $\gamma^{-/-}$ CoreTg, PA28 $\gamma^{-/-}$, and PA28 $\gamma^{+/+}$ mice. Steatosis was not detected in the livers of the 2-month-old mice (data not shown).

PA28 γ is involved in the development of hyperinsulinemia and insulin resistance in PA28 $\gamma^{+/+}$ CoreTg mice. In our previous study, we found a significant difference in serum insulin levels, but not in plasma glucose levels, between PA28 $\gamma^{+/+}$ CoreTg mice and normal littermates (47). To determine the involvement of PA28 γ in the development of insulin resistance in PA28 $\gamma^{+/+}$ CoreTg mice, we examined here the plasma glucose and insulin levels in the mice under fasting and fed conditions. Although no significant difference in plasma glucose levels was observed in the mice under either fasting (Fig. 2A) or fed (Fig. 2B) conditions, serum insulin levels were significantly higher in PA28 $\gamma^{+/+}$ CoreTg mice than in PA28 $\gamma^{+/+}$ mice under both conditions (Fig. 2C and D), as described previously (47). In contrast, the serum insulin concentration in PA28 $\gamma^{-/-}$ CoreTg mice was recovered to a normal level similar to that of PA28 $\gamma^{+/+}$ and PA28 $\gamma^{-/-}$ mice under either fasting (Fig. 2C) or fed (Fig. 2D) conditions.

To determine the glucose intolerance among the mice, glucose was administered to the mice after fasting, and the plasma glucose level was then determined. There was no significant difference among the genotypes at any time point in the glucose tolerance test (Fig. 3A), suggesting that the volume of glucose was maintained at a normal level by the higher concentration of insulin in PA28 $\gamma^{+/+}$ CoreTg mice. In our previ-

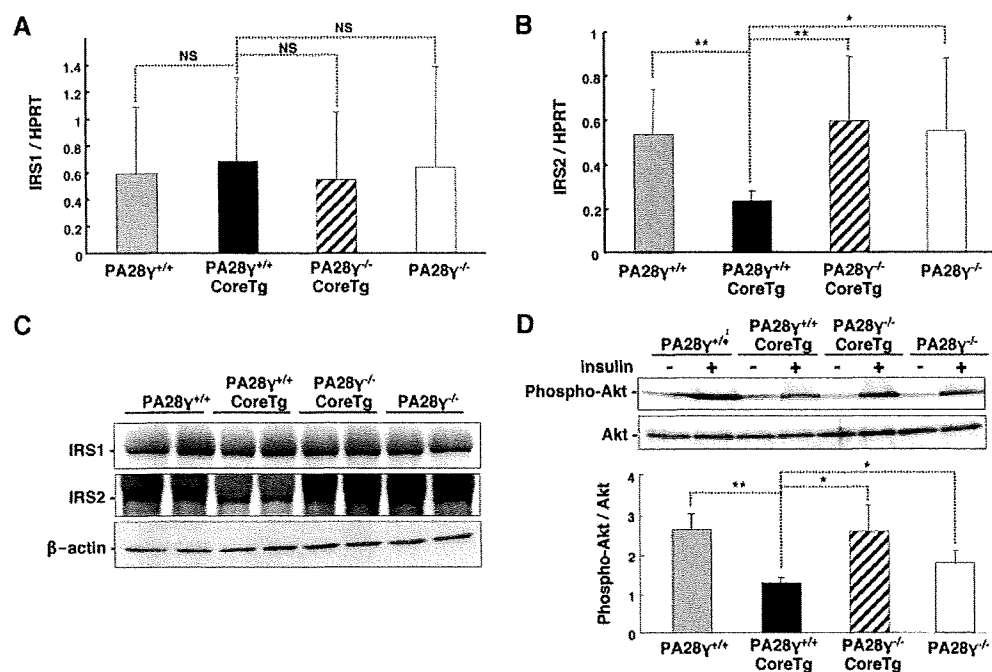


FIG. 6. PA28 γ participated in the inhibition of the IRS2 expression and Akt phosphorylation induced by HCV core protein. The transcription of IRS1 (A) and IRS2 (B) was estimated by quantitative RT-PCR ($n = 5$ in each group). (C) The expression levels of IRS1 and IRS2 in the livers of the mice were determined by immunoblotting with specific antibodies. (D) Phosphorylation of Akt in the livers of the mice was examined by immunoblotting with antibodies against Akt and phosphorylated Akt. The ratio of Akt phosphorylation was determined by computer software based on the densities of phosphorylated Akt and a total amount of Akt ($n = 3$ in each group). The data presented are representative of three independent experiments. * $P < 0.05$; ** $P < 0.01$. NS, not statistically significant; HPRT, hypoxanthine phosphoribosyl transferase.

ous study, the reduction in the plasma glucose concentration after insulin administration was impaired in PA28 $\gamma^{+/+}$ CoreTg mice (47). In this study, PA28 $\gamma^{-/-}$ CoreTg mice exhibited a normal insulin level comparable to those of PA28 $\gamma^{+/+}$ and PA28 $\gamma^{-/-}$ mice by an insulin tolerance test, in contrast to PA28 $\gamma^{+/+}$ CoreTg mice, in which a high concentration of plasma glucose was detected at all time points, as previously reported (Fig. 3B). These data suggest that hyperinsulinemia was induced in PA28 $\gamma^{+/+}$ CoreTg mice to compensate for insulin resistance and retain a physiological level of plasma glucose and that PA28 γ participates in the development of hyperinsulinemia and insulin resistance in PA28 $\gamma^{+/+}$ CoreTg mice.

Morphology of pancreatic islets. Hyperinsulinemia and insulin resistance are expected to enlarge the pancreatic islet mass due to the overexpression of insulin. Our previous report showed the enlargement of the pancreatic islets in PA28 $\gamma^{+/+}$ CoreTg mice. To clarify whether a knockout of the PA28 γ gene restores the enlarged pancreatic islets to their normal size, the morphology of the pancreatic islets of the mice was evaluated by histologic examination (Fig. 4A). The relative islet area in the pancreatic cells of the PA28 $\gamma^{-/-}$ CoreTg mice was smaller than that of PA28 $\gamma^{+/+}$ CoreTg mice and comparable to that of PA28 $\gamma^{+/+}$ and PA28 $\gamma^{-/-}$ mice (Fig. 4B). Infiltration of inflammatory cells within or surrounding the islets was not found in all genotypes of mice. These results suggest that PA28 γ also participates in the enlargement of pancreatic islets induced in PA28 $\gamma^{+/+}$ CoreTg mice.

PA28 γ impairs the insulin-signaling pathway through the suppression of both tyrosine phosphorylation of IRS1 and expression of IRS2. Insulin binds to insulin receptors, resulting in the activation of downstream signaling (26). The activated insulin receptors phosphorylate themselves, IRS1, and IRS2. Phosphorylated IRS1 and IRS2 can activate phosphatidylinositol 3 (PI3)-kinase signaling, leading to the activation of glucose metabolism and cell growth. Our previous report showed that tyrosine phosphorylation of IRS1 is suppressed in the livers of PA28 $\gamma^{+/+}$ CoreTg mice and that the administration of anti-TNF- α antibody restores insulin sensitivity (47). We examined whether a knockout of the PA28 γ gene could restore the tyrosine phosphorylation of IRS1. Tyrosine phosphorylation of IRS1 was suppressed in the livers of PA28 $\gamma^{+/+}$ CoreTg mice in response to insulin stimulation, whereas it was recovered in PA28 $\gamma^{-/-}$ CoreTg mice to levels comparable to those in PA28 $\gamma^{+/+}$ and PA28 $\gamma^{-/-}$ mice (Fig. 5).

Chronic hyperinsulinemia downregulates the expression of IRS2, which is one of the essential components of the insulin-signaling pathway in the liver (46). However, in our previous study, we showed that there was no significant difference in the phosphorylation of IRS2 between PA28 $\gamma^{+/+}$ CoreTg mice and their normal littermates (47). To gain more insight into the mechanisms of regulation of IRS expression, we determined the transcription and translation of IRS1 and IRS2 in the livers of the mice by real-time PCR and Western blotting, respectively. Although there was no significant difference in IRS1 expression at either the transcriptional or translational level among the mice

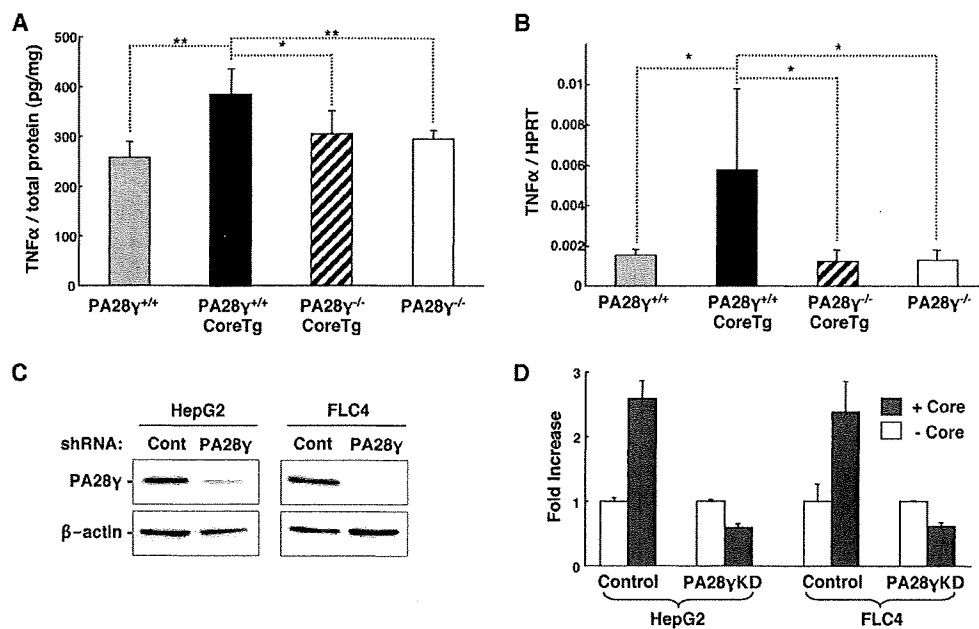


FIG. 7. PA28 γ was required for activation of the TNF- α promoter by the HCV core protein. (A) Expression of TNF- α in the livers of mice was determined by ELISA ($n = 5$ in each group). (B) TNF- α mRNA in the livers of mice was examined by quantitative RT-PCR ($n = 5$ in each group). (C) Knockdown of the expression of PA28 γ in the HepG2 and FLC-4 cell lines by the introduction of a plasmid encoding a short hairpin RNA (shRNA) targeted to the PA28 γ gene. The expression levels of PA28 γ and β -actin were determined by immunoblotting with specific antibodies. (D) Promoter activity of TNF- α in the presence or absence of the HCV core protein was determined by luciferase assay in the PA28 γ -knockdown and control cell lines. The data presented are representative of three independent experiments. HPRT, hypoxanthine phosphoribosyl transferase.

(Fig. 6A and C), the expression of IRS2 was clearly impaired in PA28 γ ^{+/+}CoreTg mice at both the transcriptional and translational levels compared with that in other mice (Fig. 6B and C). The serine/threonine protein kinase Akt is phosphorylated by phosphoinositide-dependent kinase 1 (PDK1) under the activated condition of IRS family proteins (26). The insulin-induced phosphorylation of Akt was suppressed in the livers of PA28 γ ^{+/+}CoreTg mice but not in those of PA28 γ ^{+/+}, PA28 γ ^{-/-}, or PA28 γ ^{-/-}CoreTg mice (Fig. 6D). These results suggest that the expression of the HCV core protein in the livers of mice in the presence of PA28 γ impairs the insulin-signaling pathway through the suppression of both the tyrosine phosphorylation of IRS1 and the expression of IRS2.

PA28 γ is required for activation of the TNF- α promoter by HCV core protein. TNF- α is an adipokine (54) and suppresses the signaling pathway of IRS1 and IRS2 (14, 42). Several reports suggested that the serum TNF- α level is higher in HCV patients than in healthy individuals (19, 37). Elevations of TNF- α levels have also been demonstrated in the livers of PA28 γ ^{+/+}CoreTg mice (47). To determine the involvement of PA28 γ in the enhancement of TNF- α expression, the expression of TNF- α in the livers of each genotype was determined by ELISA and real-time PCR (Fig. 7A and B). Transcription and translation of TNF- α were increased in the livers of PA28 γ ^{+/+}CoreTg mice but were restored in the livers of PA28 γ ^{-/-}CoreTg mice to levels comparable to those of PA28 γ ^{+/+} and PA28 γ ^{-/-} mice. To determine the effect of PA28 γ expression on the promoter activity of TNF- α in human liver cells, PA28 γ -knockdown human hepatoma cell lines HepG2 and FLC4 were

established by the introduction of a plasmid encoding a short hairpin RNA targeting the PA28 γ gene in the cell lines. The expression of PA28 γ was clearly suppressed in the cell lines (Fig. 7C). The expression of HCV core protein in the hepatoma cell lines potentiated TNF- α promoter activity, whereas the promoter activation by the HCV core protein was suppressed in the PA28 γ -knockdown cell lines (Fig. 7D). These results suggest that PA28 γ is required for the activation of the TNF- α promoter induced by the expression of the HCV core protein in human hepatoma cell lines.

DISCUSSION

HCV infection has a close association with type 2 diabetes, which is a polygenic disease with a pathophysiology that includes a defect in insulin secretion, increased hepatic glucose production, and resistance to the action of insulin (2, 8, 18). Insulin binds to insulin receptors, which exhibit tyrosine kinase activity, leading to the autophosphorylation and phosphorylation of IRS (56). Tyrosine phosphorylation in IRS proteins leads to the interaction between IRS proteins and the regulatory subunit p85 of PI3-kinase, which enhances glucose uptake and inhibits lipolysis (21). Activated PI3-kinase phosphorylates phosphatidylinositol 4,5-bisphosphate to produce phosphatidylinositol 3,4,5-triphosphate, which contributes to the activation of PDK1 (55). Activated PDK1 phosphorylates downstream substrates including Akt and other kinases (55). A diabetic phenotype that included insulin resistance was found in IRS2-knockout mice with normal growth (57), although a

knockout of the IRS1 gene has been shown to lead to growth retardation and insulin resistance but not overt diabetes (5, 52). The double knockdown of IRS1 and IRS2 genes in the liver induces hyperinsulinemia and insulin resistance in mice (53). The reduction of both IRS1 and IRS2 under conditions of insulin resistance and hyperinsulinemia (3) and in the livers of *ob/ob* mice, an obese diabetic mouse model (20), has been reported previously. In the present study, the expression of the HCV core protein reduced the phosphorylation of tyrosine on IRS1 and the production of IRS2 in the livers of mice but did not completely abolish the activities of these genes, suggesting that residual activities of IRS transfer a faint signal to the downstream region of IRS. Therefore, PA28 $\gamma^{+/+}$ CoreTg mice may exhibit a milder phenotype than IRS1- and/or IRS2-knockout mice. In this study, knockout of the PA28 γ gene restored the insulin sensitivity and signaling of IRS1 and IRS2 in PA28 $\gamma^{+/+}$ CoreTg mice, suggesting that the expression of the HCV core protein leads to the dysfunction of both IRS1 and IRS2 through a PA28 γ -dependent pathway.

Our previous study suggested that the induction of TNF- α by the HCV core protein plays a role in insulin resistance (47). An increase in TNF- α levels has been correlated with obesity and insulin resistance in animal models and humans (14, 42). However, the mechanism by which TNF- α induces insulin resistance is not completely known. The expression of TNF- α has been shown to be increased in PA28 $\gamma^{+/+}$ CoreTg mice, resulting in the suppression of phosphorylation of IRS1, and insulin sensitivity in PA28 $\gamma^{+/+}$ CoreTg was improved by the administration of an anti-TNF- α antibody (47). In the present study, the expression level of TNF- α in PA28 $\gamma^{-/-}$ CoreTg mice was similar to that in PA28 $\gamma^{-/-}$ mice or their normal littermates. The expression of the HCV core protein enhanced the promoter activity of the TNF- α gene in human liver cell lines but not in those with a knockdown of the PA28 γ gene by RNA interference (Fig. 7D). These data suggest that PA28 γ plays a crucial role in HCV core-induced expression of TNF- α . Sterol regulatory element-binding proteins (SREBPs) were shown to be increased at the stage of viremia in HCV-infected chimpanzees (49). SREBPs are known to regulate not only the biosynthesis of lipid but also the transcription of IRS2 and TNF- α (17, 45). Therefore, it might be feasible to speculate that the HCV core protein may cooperate with PA28 γ to regulate the expression of SREBPs.

Houstis et al. previously reported that reactive oxygen species (ROS) are increased in both cellular and mouse models of insulin resistance induced by treatment with TNF- α or dexamethasone and that insulin sensitivity was restored by treatment with small antioxidant molecules (16). The HCV core protein potentiates ROS production in hepatoma cells and HCV core gene-transgenic mice (23, 34, 41). Accelerated production of ROS results in mitochondrion dysfunction, which contributes to a decrease in fatty acid oxidation. Defects in mitochondrial fatty acid oxidation enhance the production of intracellular fatty acyl coenzyme A (CoA) and diacylglycerol (48, 58). Mitochondrion dysfunction and accumulation of lipid droplets in mice expressing the HCV core or the full-length HCV polyprotein have been reported (27, 34). An increase in lipid droplets also leads to the accumulation of fatty acid CoA and diacylglycerol (48, 58). Fatty acyl CoA and diacylglycerol nonspecifically activate the Ser/Thr kinase cascade, leading to the enhancement of the serine phosphorylation of IRS1 (26). Serine phosphorylation on IRS1 blocks the tyrosine

phosphorylation of IRS1 by insulin receptors (26). In the present study, however, serine phosphorylation of IRS1 in PA28 $\gamma^{+/+}$ CoreTg mice was similar to that in PA28 $\gamma^{-/-}$ CoreTg mice (data not shown). TNF- α signaling pathways other than the accumulation of ROS and fatty acid intermediates may also participate in the inhibition of tyrosine phosphorylation on IRS1 in PA28 $\gamma^{+/+}$ CoreTg mice.

How does the HCV core protein induce TNF- α production? Our previous report suggests that the HCV core protein is degraded through a PA28 γ -dependent pathway (32). Recently, PA28 γ has been shown to participate in the proteasome-dependent degradation of steroid receptor coactivator 3 (28). Degradation products of the HCV core protein via the PA28 γ -dependent pathway may regulate the promoter activity of the TNF- α gene. PA28 proteins are necessary and sufficient to fully reconstitute Hsp90-initiated refolding together with Hsc70 and Hsp40 (31). Therefore, it might also be feasible to speculate that the HCV core protein refolded by an Hsp90/PA28 γ -dependent pathway activates the promoter of the TNF- α gene together with an unknown transcription factor(s) or regulator(s).

In conclusion, the data obtained in this study suggest that the expression of the HCV core protein enhances the production of TNF- α and suppresses the phosphorylation of tyrosine on IRS1 and the production of IRS2 through a PA28 γ -dependent pathway, thereby leading to insulin resistance. PA28 γ may be a novel target for the treatment of HCV-induced diabetes.

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Hepatitis C Virus Nonstructural Protein 5A Modulates the Toll-Like Receptor-MyD88-Dependent Signaling Pathway in Macrophage Cell Lines[∇]

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Hepatitis C virus (HCV) infection induces a wide range of chronic liver injuries; however, the mechanism through which HCV evades the immune surveillance system remains obscure. Blood dendritic cells (DCs) play a pivotal role in the recognition of viral infection and the induction of innate and adaptive immune responses. Several reports suggest that HCV infection induces the dysfunction of DCs in patients with chronic hepatitis C. Toll-like receptor (TLR) has been shown to play various roles in many viral infections; however, the involvement of HCV proteins in the TLR signaling pathway has not yet been precisely elucidated. In this study, we established mouse macrophage cell lines stably expressing HCV proteins and determined the effect of HCV proteins on the TLR signaling pathways. Immune cells expressing NS3, NS3/4A, NS4B, or NS5A were found to inhibit the activation of the TLR2, TLR4, TLR7, and TLR9 signaling pathways. Various genotypes of NS5A bound to MyD88, a major adaptor molecule in TLR, inhibited the recruitment of interleukin-1 receptor-associated kinase 1 to MyD88, and impaired cytokine production in response to TLR ligands. Amino acid residues 240 to 280, previously identified as the interferon sensitivity-determining region (ISDR) in NS5A, interacted with the death domain of MyD88, and the expression of a mutant NS5A lacking the ISDR partially restored cytokine production. These results suggest that the expression of HCV proteins modulates the TLR signaling pathway in immune cells.

Hepatitis C virus (HCV) belongs to the family *Flaviviridae* and possesses a positive, single-stranded RNA genome that encodes a single polyprotein composed of approximately 3,000 amino acids. HCV polyprotein is processed by host and viral proteases, resulting in 10 viral proteins. Viral structural proteins, including the capsid protein and two envelope proteins, are located in the N-terminal one-third of the polyprotein, followed by nonstructural proteins. HCV infects 170 million people worldwide and frequently leads to cirrhosis and hepatocellular carcinoma (36). In over one-half of patients, acute infection evolves into a persistent carrier state, presumably due to the ability of HCV to incapacitate the activation of the host immune mechanisms. Dendritic cells (DCs) are one type of potent antigen-presenting cell in vivo and play a crucial role in the enhancement and regulation of cell-mediated immune reactions. Since DCs express various costimulatory and/or adhesion molecules, they can activate even naïve T cells in a primary response. The role of the response of HCV antigen-specific T cells in viral clearance or persistence has been in-

vestigated extensively in both humans and chimpanzees (6, 27, 48, 51). These studies suggest that acute HCV infections followed by viral clearance are associated with a high frequency of HCV-specific CD4⁺ and CD8⁺ T-cell responses that can persist (27, 51), while chronic HCV infections are characterized by weak and restricted CD4⁺ and CD8⁺ T-cell responses that are not sustained (51).

Toll-like receptors (TLRs) are membrane-bound receptors that can be activated by the binding of molecular structures conserved among families of microbes. More than 10 different TLRs have been identified to date (2). They are highly conserved among mammals and are expressed in a variety of cell types. TLR binding and stimulation by pathogen-associated molecules is followed by a cascade of intracellular events that culminate in the expression of multiple genes (2). TLR signaling is mediated primarily by the adaptor protein myeloid differentiation factor 88 (MyD88), which triggers the activation of transcription factors, such as NF- κ B, that are essential for the expression of proinflammatory cytokine genes (2). This pathway also leads to the potent production of type I interferon (IFN) through the activation of IFN regulatory factor 7 (IRF7) upon stimulation of TLR7 or TLR9 (22). In contrast, Toll/interleukin-1 (IL-1) receptor homology domain-containing adaptor-inducing IFN- β (TRIF/TICAM-1) mediates the production of type I IFNs primarily through the activation of IRF3 in response to TLR3 or TLR4 stimulation (2). Type I IFN induces the maturation of DCs by increasing both the expression of costimulatory molecules such as CD80, CD86, and CD40 and antigen presentation via major histocompatibility

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complex class I in addition to classical endogenous antigen presentation; it also facilitates the cross-presentation of viral antigens. A cumulative report has shown that DC activation via TLR signaling is a prerequisite for the subsequent induction of vigorous T-cell responses (42). Some viral proteins have been shown to inhibit the TLR-dependent signaling pathway through interactions with the downstream adaptor molecules, suggesting that the alteration of TLR-mediated signals is one of the mechanisms of virus-induced immune modulation (49). Dysfunction of DCs in patients with chronic HCV infection due to immaturation caused by the direct infection of DCs by HCV or by interactions with HCV proteins has been reported previously (4, 21). On the other hand, there have also been contrasting reports suggesting a lack of impairment of DC function in both chimpanzees and humans chronically infected with HCV (26, 32). Thus, at present, alterations in the TLR signaling pathway in the immune cells of patients with chronic hepatitis C virus infection are not well understood.

In the present study, we examined the effect of HCV proteins on TLR function in murine macrophage cell lines stably expressing HCV proteins. The expression of NS3, NS3/4A, NS4B, or NS5A was found to impair the activation of the TLR signaling pathways, and NS5A interacted with MyD88 through the IFN sensitivity-determining region (ISDR) and impaired cytokine production. To the best of our knowledge, this is the first demonstration of NS5A as an immunomodulator of TLR signaling pathways through the direct interaction with an adaptor molecule in immune cells.

MATERIALS AND METHODS

Cell culture. Human embryonic kidney 293T cells and mouse macrophage RAW264.7 cells were maintained in Dulbecco's modified Eagle's medium (Sigma, St. Louis, MO) containing 10% fetal calf serum. All cells were cultured at 37°C in a humidified atmosphere with 5% CO₂.

Plasmids and viruses. DNA fragments encoding each of the HCV structural and nonstructural proteins were generated from a full-length cDNA clone of genotype 1b strain J1 (1) by PCR using *Pfu* Turbo DNA polymerase (Stratagene, La Jolla, CA). The fragments were cloned into pCAGGs-puro/N-Flag, in which the sequence encoding a Flag tag is inserted at the 5' terminus of the cloning site of pCAGGs-puro (37). A protease-deficient NS3/4A mutant with Ser¹³⁹ replaced with Ala (S139A) was generated by the method of splicing by overlap extension and cloned into pCAGGs-puro. NS5A genes were amplified by PCR from HCV clones of strains of J1 (genotype 1b), H77c (genotype 1a, kindly provided by J. Bukh), and JFH1 (genotype 2a, kindly provided by T. Wakita) and cloned into pcDNA3.1Flag/HA (38). The NS5A deletion mutants were prepared as described previously (16). DNA fragments encoding a human MyD88, human Toll-IL-1 receptor domain-containing adapter protein (TIRAP), and human TRIF-related adapter molecule (TRAM) were amplified by reverse transcription-PCR from total RNA of THP-1 cells and cloned into pcDNA3.1-C-Myc-His (Invitrogen, Carlsbad, CA) and pcDNA3.1Flag/HA. Murine IPS-1 (mIPS-1) was amplified from total RNA of RAW264.7 cells by reverse transcription-PCR and cloned into pcDNA3.1Flag/HA. Human MyD88 deletion mutants and a mIPS-1 mutant with Cys⁵⁰⁸ replaced by Ala (C508A) were generated by the method of splicing by overlap extension and cloned into pcDNA3.1Flag/HA. pCMVIRAK1-myc and pCMVIRAK4-myc, encoding IL-1 receptor-associated kinase 1 (IRAK-1) and IRAK-4, respectively, were prepared as described previously (53). pEFBossTTCAM-I-HA was kindly provided by T. Seya (44). All PCR products were confirmed by sequencing by using an ABI PRISM 310 genetic analyzer (Applied Biosystems, Tokyo, Japan). Vesicular stomatitis virus (VSV) (Indiana strain, NCP12.1) (19) was kindly provided by M. A. Whitt.

Establishment of stable cell lines expressing HCV proteins. pCAGGs-puro/N-Flag plasmids encoding HCV proteins were transfected into RAW264.7 cells by liposome-mediated transfection using Lipofectamine 2000 (Invitrogen) and selected with 10 µg/ml of puromycin (InvivoGen, San Diego, CA). After about 2 to 3 weeks of selection, several clones were isolated, and cell lysates of each clone were immunoblotted with each of specific mouse anti-HCV antibody (1) or

anti-Flag M2 mouse monoclonal antibody (Sigma). Macrophage cell lines stably expressing HCV proteins and a control cell line obtained by transfection with an empty pCAGGs-puro vector were maintained in the presence of puromycin (10 µg/ml) throughout the experiments.

Immunoprecipitation and immunoblotting. Cells were seeded onto a six-well tissue culture plate 24 h before transfection. The plasmids were transfected by the lipofection method, and the cells were harvested at 48 h posttransfection, washed three times with 1 ml of ice-cold phosphate-buffered saline (PBS), and suspended in 0.4 ml lysis buffer containing 20 mM Tris-HCl (pH 7.4), 135 mM NaCl, 1% Triton X-100, 10% glycerol, and protease inhibitor cocktail tablets (Roche Molecular Biochemicals, Mannheim, Germany). Cell lysates were incubated for 30 min at 4°C and centrifuged at 14,000 × g for 15 min at 4°C. The supernatant was immunoprecipitated with 1 µg of mouse monoclonal anti-Flag M2, anti-hemagglutinin (HA) 16B12 (HA.11; BabCO, Richmond, CA), or anti-hexahistidine (Santa Cruz Biotechnology, Santa Cruz, CA) antibody and 10 µl of protein G-Sepharose 4B Fast Flow beads (Amersham Pharmacia Biotech, Franklin Lakes, NJ) at 4°C for 90 min. The immunocomplex was precipitated with the beads by centrifugation at 5,000 × g for 1 min and then washed five times with 0.4 ml of 20 mM Tris-HCl (pH 7.4) containing 135 mM NaCl and 0.05% Tween 20 (TBST buffer) by centrifugation. The proteins binding to the beads were boiled in 20 µl of sample buffer and then subjected to sodium dodecyl sulfate–12.5% polyacrylamide gel electrophoresis and transferred onto polyvinylidene difluoride membranes (Millipore, Tokyo, Japan). The membranes were blocked with TBST containing 5% skim milk at room temperature for 1 h; incubated with mouse monoclonal anti-Flag M2, anti-HA 16B12, or anti-hexahistidine monoclonal antibody at room temperature for 1 h; and then incubated with horseradish peroxidase-conjugated anti-mouse immunoglobulin G (IgG) antibody at room temperature for 1 h. The cell lines (2 × 10⁶ cells/well) were stimulated with various doses of lipopolysaccharide (LPS) derived from *Salmonella enterica* serovar Minnesota (Re-595) (Sigma), peptidoglycans (PGN) derived from *Staphylococcus aureus* (Sigma), R-837 (InvivoGen), or phosphorothioate-stabilized mouse CpG (mCpG) oligodeoxynucleotides (ODN1668) (TCC-ATG-ACG-TTC-CTG-ATG-CT) (Invitrogen) for the times indicated, and the phosphorylation status of extracellular signal-regulated kinase (ERK) was determined by immunoblotting using antibodies specific to ERK1/2 or phosphorylated ERK1/2 (T202/Y204) (Cell Signaling Technology, Inc., Beverly, MA). Cells (1 × 10⁶ cells/well) were treated with various doses of mouse IFN-α (PBL Biomedical Laboratories, New Brunswick, NJ) or VSV for 24 h, and the phosphorylation status of double-stranded RNA-dependent protein kinase (PKR) and signal transducer and activator of transcription 1 (STAT1) was determined by immunoblotting using antibodies specific to STAT1 (Cell Signaling), phosphorylated STAT1 (Cell Signaling), or phosphorylated PKR (BioSource International, Inc., Camarillo, CA). The immune complexes were visualized with Super Signal West Femto substrate (Pierce, Rockford, IL) and detected by using an LAS-3000 image analyzer system (Fujifilm, Tokyo, Japan).

Cytokine production and enzyme-linked immunosorbent assay (ELISA). To evaluate cytokine production in macrophage cell lines expressing HCV proteins, cells were seeded onto 96-well plates at a concentration of 1 × 10⁵ cells/well and stimulated with various doses of LPS, PGN, R-837, or mCpG. After 24 h of incubation, culture supernatants were collected, and IL-6 production was determined by using an OptEIA mouse IL-6 set purchased from BD Pharmingen (San Diego, CA).

Real-time PCR. The cell lines (3 × 10⁶ cells/well) were stimulated with R-837, LPS, PGN, mCpG, VSV, and polyinosine-poly(C) [poly(I:C)] (InvivoGen) for the times indicated, and the expression of mRNA of cytokines, chemokines, and TLR genes was determined by real-time PCR. Total RNA was prepared from the macrophage cell lines using an RNeasy Mini kit (QIAGEN). First-strand cDNA was synthesized using a ReverTra Ace (TOYOBO, Japan) and oligo(dT)₂₀ primer. Each cDNA was estimated by Platinum SYBR Green qPCR SuperMix UDG (Invitrogen) according to the manufacturer's protocol. Fluorescent signals were analyzed by using an ABI PRISM 7000 apparatus (Applied Biosystems). Mouse Ccl2, IFN-β, IFN-α1, IFN-α4, and IL-1-α genes were amplified with primer pairs 5'-GCATCCACGTGTGGCTCA-3' and 5'-CTCCAGCCTACTC ATTGGGATCA-3', 5'-ACACCAGCCTGGCTTCCATC-3' and 5'-TTGGAG CTGGAGCTGCTTATAGTTG-3', 5'-AGCCTTGACACTCCTGGTACAAAT G-3' and 5'-TGGGTCAGCTCACTCAGGACA-3', 5'-GCTCAAGCCATCCT TGTGCTAA-3' and 5'-CATGAGCTGATGGAGTGC-3', and 5'-ITGGTTA AATGACCTGCAACAGGA-3' and 5'-AGGTCCGGTCTCACTACCTGTGAT G-3', respectively. The mouse TLR2, TLR3, TLR4, TLR7, TLR9, and GAPDH (glyceraldehyde-3-phosphate dehydrogenase) genes were amplified using primer pairs 5'-AGCTCTTTGGCTCTTCTG-3' and 5'-AGAAGTGGGGGATATGC-3', 5'-AAATCCTTGGCTTGGCGAAGTG-3' and 5'-TCAGTTGGCGGTGTGT CAAGAG-3', 5'-GCCTCGAATCTGAGCAAACA-3' and 5'-CTTCTGCCCGGTAAGGTCCA-3', 5'-TCTGAGGAGCTCTGCTCTTGA-3' and 5'-CAAG GCATGTCCTAGGTGGTGA-3', 5'-ACCAATGGCACCCCTGCCATA-3' and 5'-

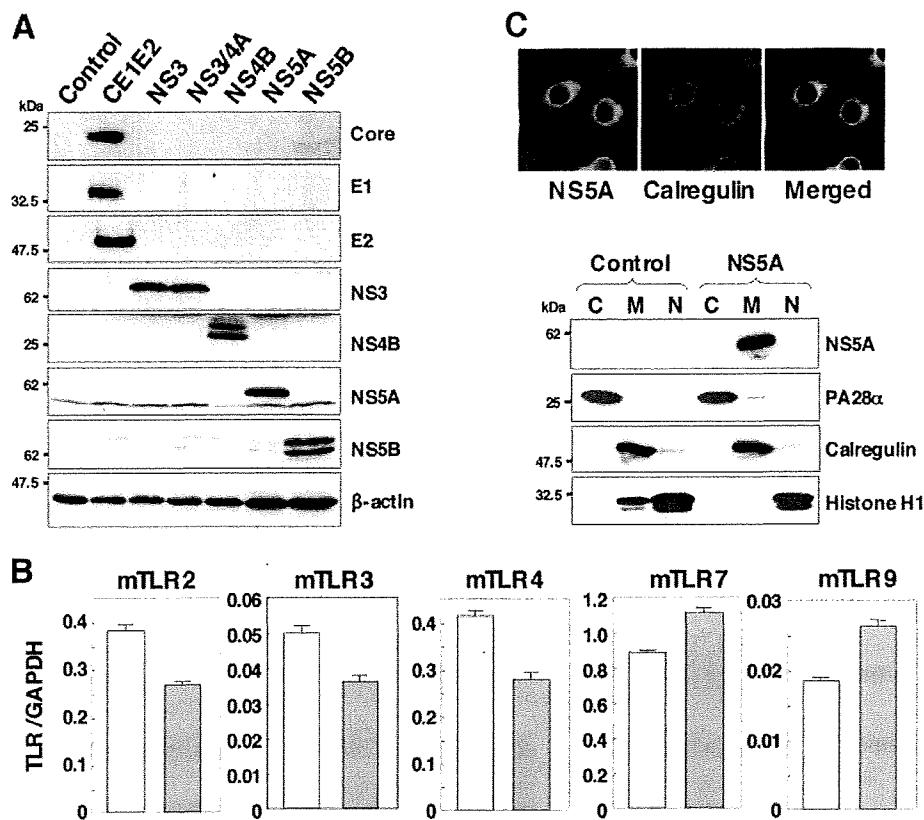


FIG. 1. Establishment of stable macrophage cell lines expressing HCV proteins. (A) Cell lysates were prepared from macrophage cell lines expressing each of the HCV proteins (4×10^6 cells) and immunoblotted with antibodies against HCV proteins or β -actin. (B) Total RNA was extracted from macrophage cell lines expressing NS5A (gray bars) or control (white bars), and the expression of mRNA of TLRs was determined by real-time PCR. (C) The subcellular localization of NS5A was examined by confocal microscopy. Cells were fixed with 4% paraformaldehyde-PBS, permeabilized with 0.5% Triton X-100, and stained with specific antibodies. Cells expressing NS5A or control cells were extracted into cytosol (C), membrane-organelle (M), and nuclear (N) fractions. Each fraction was concentrated and subjected to immunoblotting with specific antibodies. PA28 α , calregulin, and histone H1 were used as markers for cytosol, membrane-organelle, and nuclear fractions, respectively.

CGTCTGAGAATGTTGTGGCTGA-3', and 5'-ACCACAGTCCATGCCATC AC-3' and 5'-TCCACCACCCTGTTGCTGTA-3', respectively. The expression of mRNAs of each of the chemokines, cytokines, and TLR was normalized with that of GAPDH mRNA.

Immunofluorescence microscopy and subcellular localization of HCV proteins in stable macrophage cell lines. Cells were seeded onto an eight-well chamber slide at 1.5×10^4 cells per well, washed twice with PBS, fixed with PBS containing 4% paraformaldehyde at 18 h of cultivation, and permeabilized with PBS containing 0.5% Triton X-100 at 15 min. The cells were then incubated at room temperature for 1 h with 1 μ g of mouse anti-NS5A antibody (Austral Biologicals, San Ramon, CA) or rabbit polyclonal antibody against calregulin (Santa Cruz Biotechnology) in PBS containing 10% fetal calf serum (PBSF) and then incubated at room temperature for 1 h with 0.5 μ g of Alexa Fluor 488-conjugated anti-mouse IgG (Molecular Probes) or Alexa Fluor 594-conjugated anti-rabbit IgG (Molecular Probes) after three washes with PBSF. After extensive washing with PBSF, the samples were examined with a FluoView FV1000 laser scanning confocal microscope (Olympus, Japan). To confirm the subcellular localization of the HCV proteins in the macrophage cell lines, each stable cell line was fractionated with a Subcellular Proteome Extraction kit (Calbiochem, Darmstadt, Germany). Stepwise extraction resulted in four distinct fractions, which contained primarily cytosolic, membrane-organelle, nuclear, and cytoskeleton proteins, respectively. Each fraction was concentrated by Microcon (Millipore) and subjected to immunoblotting. PA28 α (Biomol International, Plymouth Meeting, PA), calregulin, and histone H1 (Santa Cruz Biotechnology) were used as cytoplasmic, membrane, and nuclear markers, respectively.

RESULTS

Establishment of macrophage cell lines stably expressing HCV proteins. To examine the effect of HCV proteins on the TLR function of immune cells, we established murine macrophage cell lines stably expressing HCV structural or nonstructural proteins. We selected mouse macrophage RAW264.7 cells due to their high level of expression of various TLRs (3) and their high sensitivity to stimulation with TLR ligands. Processed HCV structural and nonstructural proteins were detected in each of the cell lines by immunoblot analyses using specific monoclonal antibodies (Fig. 1A). To examine the effect of HCV proteins on TLR expression in macrophage cell lines, the mRNA of TLRs in cells expressing NS5A was determined by real-time PCR (Fig. 1B). Although slight reductions in TLR2, TLR3, and TLR4 or enhancement of TLR7 and TLR9 was observed, a substantial amount of mRNA of the examined TLRs was detected in the cell lines expressing NS5A and other HCV proteins (data not shown). To determine the subcellular localization of HCV proteins in macrophage cell lines, the expression of HCV proteins was examined by con-

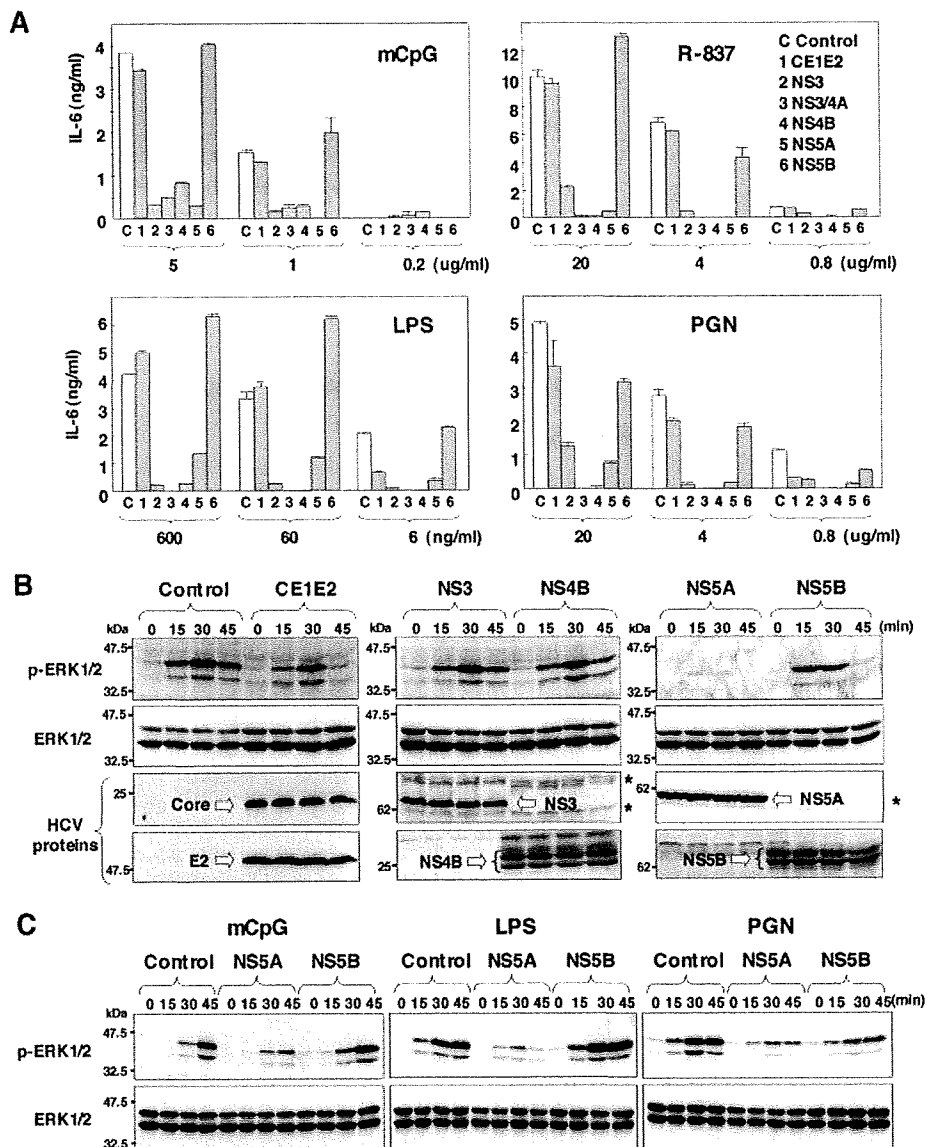


FIG. 2. Expression of HCV nonstructural proteins modulates IL-6 production and MAPK cascades through the TLR-dependent signaling pathway in macrophage cell lines. (A) Cells were seeded onto 96-well plates (1×10^5 cells/well) and stimulated with the indicated amounts of mCpG, R-837, LPS, or PGN. After 24 h of stimulation, IL-6 production in the culture supernatants was determined by sandwich ELISA. Data are shown as means \pm standard deviations (SD). (B) Cells (2×10^6 cells/well) were stimulated with $10 \mu\text{g/ml}$ of R-837 for the times indicated, and ERK1/2 phosphorylation was determined by immunoblotting with antibodies to ERK and phosphorylated ERK (p-ERK). Asterisks indicate nonspecific bands. (C) Cells (2×10^6 cells/well) were stimulated with $10 \mu\text{g/ml}$ of mCpG, 25 ng/ml of LPS, or $10 \mu\text{g/ml}$ of PGN for the times indicated, and ERK1/2 phosphorylation was determined by immunoblotting.

focal microscopy and cell fractionation (Fig. 1C). HCV NS5A was colocalized with the endoplasmic reticulum marker calnexin in the macrophage cell line as reported previously for human hepatoma cell lines (47). Other HCV proteins exhibited similar localization with NS5A (data not shown). To further confirm the subcellular localization of NS5A proteins, cytoplasmic, membrane-organelle, and nuclear fractions of the cell line expressing NS5A were analyzed by Western blotting. NS5A was detected mainly in the membrane-organelle fraction.

Expression of HCV NS3, NS3/4A, NS4B, or NS5A modulates the TLR-dependent signaling pathway in macrophage cell lines. In order to determine the effect of the expression of HCV proteins on the TLR signaling pathway in macrophage cell lines, we examined the ability of HCV proteins to inhibit NF- κ B activation via stimulation with various TLR ligands. The macrophage cell lines were stimulated with the TLR ligands, and the production of the proinflammatory cytokine IL-6 in the culture supernatants was determined by ELISA (Fig. 2A). The expression of HCV structural proteins or NS5B

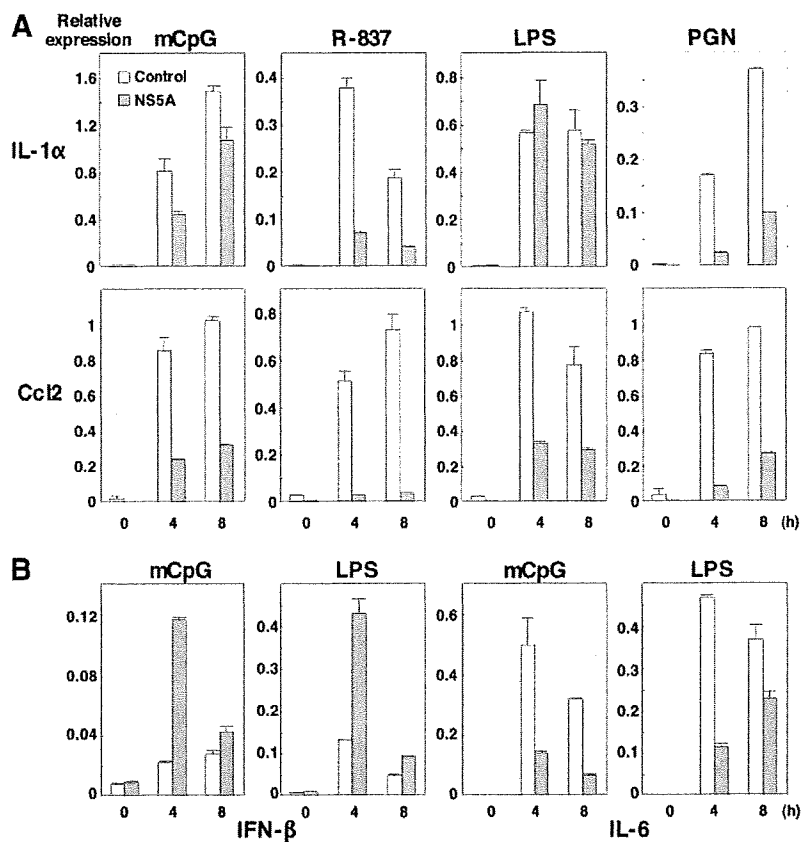


FIG. 3. Effect of NS5A expression on the production of cytokines and chemokines in response to TLR ligands in macrophage cell lines. Cells (3×10^6 cells/well) were stimulated with 10 μ g/ml of mCpG, 10 μ g/ml of R-837, 25 ng/ml of LPS, and 10 μ g/ml of PGN for the times indicated. Total RNA was extracted from macrophage cell lines expressing NS5A (gray bars) or control (white bars), and the expression of mRNA of IL-1 α and Ccl2 (A) and IFN- β and IL-6 (B) was determined by real-time PCR.

had no effect on IL-6 production after stimulation with mCpG, R-837, LPS, or PGN, which are ligands for TLR9, TLR7, TLR4, and TLR2, respectively. On the other hand, the expression of NS3, NS3/4A, NS4B, or NS5A inhibited the production of IL-6 induced by treatment with the ligands. These results indicate that the expression of NS3, NS3/4A, NS4B, and NS5A inhibits the production of IL-6 through the TLR-dependent signaling pathway in macrophage cell lines.

In addition to proinflammatory cytokine production via NF- κ B activation, stimulation of TLR also activates mitogen-activated protein kinases (MAPKs). We then examined the activation of ERK, a MAPK signaling pathway, in response to the TLR ligands in the macrophage cells expressing HCV proteins (Fig. 2B). Although the expression of the HCV structural proteins NS3, NS4B, and NS5B did not alter the phosphorylation status of ERK1/2 in response to stimulation with the TLR7 ligand R-837, the expression of NS5A exhibited a clear inhibition of the phosphorylation of ERK1/2. To further examine the effect of NS5A expression on the MAPK cascade in response to the TLR ligands, the cells were treated with mCpG, LPS, and PGN. NS5A expression was found to inhibit the phosphorylation of ERK1/2 in response to stimulation with the ligands for TLR9, TLR4, and TLR2 (Fig. 2C). In contrast, the phosphorylation of c-Jun NH₂-terminal kinase in

response to stimulation with R-837 was less impaired in the macrophage cell line expressing NS5A (data not shown). These results indicate that the expression of NS3, NS3/4A, NS4B, or NS5A inhibits the production of proinflammatory cytokines and that the expression of NS5A alone induces the inhibition of the MAPK cascade in response to stimulation by various TLR ligands in macrophage cells.

To further examine the effect of NS5A expression on the production of the other proinflammatory cytokines and chemokines in response to TLR ligands, the expression of mRNA of IL-1 α and Ccl2 in cells expressing NS5A after stimulation with TLR ligands was determined by real-time PCR (Fig. 3A). Expression of IL-1 α and Ccl2 was reduced in cells expressing NS5A by stimulation with mCpG, R-837, LPS, or PGN except for the IL-1 α expression by treatment with LPS, probably due to the TRIF-dependent activation of NF- κ B. To further confirm the specific inhibition of the MyD88-dependent signaling pathway by NS5A, we examined the effects of NS5A expression in macrophage cells on the MyD88-independent/TRIF-dependent production of IFN- β (Fig. 3B). Although the expression of IL-6 mRNA in cells expressing NS5A was impaired after stimulation with mCpG or LPS, the expression of IFN- β was enhanced. These results suggest that the expression of NS5A specifically inhibits the MyD88-dependent signaling pathway.