

may be implication of communication between mitochondria and membrane-enclosed structures of HCV RC in ATP transport through membrane-to-membrane contact. As indicated in Figure S5, putative sites of the viral RNA replication with high Venus/CFP ratios were mainly localized proximal to mitochondria. Studies are ongoing to understand the mechanism(s) underlying this phenomenon, as well as to determine if changes in ATP levels at intracellular sites supporting replication might also be observed for other RNA or DNA viruses.

In summary, we have used a FRET-based ATP indicator called ATeam to monitor ATP levels in living cells where viral RNA replicates by designing HCV replicons harboring wild-type or mutated ATeam probes inserted into the C-terminal domain of NS5A. We evaluated changes in ATP levels during HCV RNA replication and demonstrated elevated ATP levels at putative sites of replication following detection of FRET signals, which appeared as dot-like foci within the cytoplasm. The ATeam system may become a powerful tool in microbiology research by enabling determination of subcellular ATP localization in living cells infected or associated with microbes, as well as investigation of the regulation of ATP-dependent processes during the lifecycle of various pathogens.

Materials and Methods

Chemicals

PSI-6130 (β -D-2'-Deoxy-2'-fluoro-2'-C-methylcytidine) and recombinant human IFN- α 2b were obtained from Pharmasset Inc. (Princeton, NJ) [23,24] and Schering-Plough (Kenilworth, NJ), respectively. OliA and 2DG were purchased from Sigma-Aldrich (St. Louis, MO). ATP used in this study was complexed with equimolar concentrations of magnesium chloride before use in the experiments.

Plasmids

The construction of the ATeam plasmids pRSET-AT1.03, pRSET-AT1.03^{YEMK} and pRSET-AT1.03^{R122K/R126K}, which express wild-type ATeam (AT1.03), as well as a high-affinity mutant (AT1.03^{YEMK}) and a non-binding mutant (AT1.03^{RK}), has been previously described [2]. pHH/SGR-Luc (also termed SGR/luc) contains cDNA of a subgenomic replicon of HCV JFH-1 isolate (genotype 2a; [14]) with firefly luciferase flanked by the Pol I promoter and the Pol I terminator, yielding efficient RNA replication upon DNA transfection [26]. pHH/SGR-Luc/GND (also termed SGR/luc-GND), in which a point mutation of the GDD motif of the NS5B was introduced in order to abolish RNA-dependent RNA polymerase activity, was used as a negative control. pHH/SGR (also termed SGR) was created by deleting the luciferase gene in pHH/SGR-Luc. To generate a series of SGR-ATeam plasmids, wild-type or mutant ATeam genes were inserted into pHH/SGR-Luc or pHH/SGR at the Xho I site of NS5A (between amino acids 418 and 419) [25]. The ATeam genes were also inserted into the same site of pCAGNS5A, which contains the NS5A gene of JFH-1 downstream of the CAG promoter and hemagglutinin (HA) tag [26], yielding NS5A-ATeam plasmids. To generate a plasmid expressing NS3-NS5B-AT1.03 under the control of the CAG promoter, a DNA fragment containing the coding region of NS3/NS4A/NS4B/NS5A-AT1.03/NS5B of SGR/luc-ATeam was inserted into the pCAGGS vector [40]. Exact cloning strategies are available upon request.

Cell culture and plasmid transfection

Human hepatoma Huh-7 cells were propagated in Dulbecco's modified Eagle's medium (DMEM) supplemented with 10% fetal

calf serum (FCS) as well as minimal essential medium non-essential amino acid (MEM NEAA)(Invitrogen, Carlsbad, CA) in the presence of 100 units/ml of penicillin and 100 μ g/ml of streptomycin. The Huh-7-derived cell lines JFH-1/4-1 and JFH-1/4-5, which support replication of SGR RNA of HCV JFH-1 (genotype 2a) and NK5.1/0-9, which carries the SGR RNA of Con1 NK5.1 (genotype 1b), were cultured and maintained under previously described conditions [15]. DNA transfection was performed using a TransIT-LT1 transfection reagent (Takara, Shiga, Japan) in accordance with the manufacturer's instructions.

CE-TOF MS analysis

Huh-7 cells were mock-infected or infected with HCVcc derived from a wild-type JFH-1 isolate at a multiplicity of infection of 1. When most cells had become virus positive, as confirmed by immunofluorescence, with no observable cell damage at 9 days post-infection, equal amounts of cells with and without HCV infection were scraped with MeOH including 10 μ M of an internal standard after washing twice with 5% mannitol solution. Replicon cells (JFH-1/4-5) that were cultured in the absence of G418 for 2 days were harvested and prepared as above. The extracts were mixed with chloroform and water, followed by centrifugation at $2,300\times g$ for 5 min at 4°C. The upper aqueous layer was centrifugally filtered through a 5-kDa cutoff filter to remove proteins. The filtrate was lyophilized and dissolved in water, then subjected to CE-TOF MS analysis. CE-TOF MS experiments were performed using an Agilent CE-TOF MS system (Agilent Technologies, Waldbronn, Germany) as described previously [41].

ATP consumption assay

The ATP consumption assay using permeabilized replicon cells was carried out as previously described [13,22] with slight modifications, so that it was unnecessary to add either exogenous phosphocreatine or creatine phosphokinase to minimize ATP reproduction in cells. Cells (2×10^6) cultured in the presence or absence of PSI-6130 for 72 h were treated with 5 μ g Actinomycin D/ml, followed by trypsinization and 3 washes with cold buffer B (20 mM HEPES-KOH [pH 7.7], 110 mM potassium acetate, 2 mM magnesium acetate, 1 mM EGTA, and 2 mM dithiothreitol). The cells were permeabilized by incubation with buffer B containing 50 μ g/ml digitonin for 5 min on ice and the reaction was stopped by washing 3 times with cold buffer B. The permeabilized cells (1×10^7) were resuspended with 100 μ l buffer B containing 5 μ M ATP, GTP, CTP, and UTP, 20 μ M MgCl₂, and 5 μ g/ml Actinomycin D. After incubation at 27°C for 15 min, samples were centrifuged, and 20 μ l of the supernatant was then mixed with 5 μ l of 5 \times passive lysis buffer (Promega, Madison, WI). The ATP level was determined using a CellTiter-Glo Luminescent cell viability assay system (Promega). All assays were performed at least in triplicate.

Live cell microscopy

Plasmids carrying the ATP indicators were transfected at 48 h (ATeam and NS5A-ATeam) or 4 days (SGR-ATeam) before imaging of the cells. One day before imaging, the cells were seeded onto 30-mm glass-bottomed dishes (AGC Techno Glass, Chiba, Japan) at about 60% confluency. For imaging, the cells were maintained in phenol red-free DMEM containing 20 mM HEPES-KOH [pH 7.7], 10% FCS and MEM NEAA.

Two kinds of confocal microscopies were used to perform the FRET analysis in this study as follows. Since the ways of acquisition of each spectrum were quite different between the two microscopies, differences in the values of the Venus/CFP ratios in different

experiments were observed. In Figures 2, 4B and S2, cells were imaged using a confocal inverted microscope FV1000 (Olympus, Tokyo, Japan) equipped with an oil-immersion 60× Olympus UPlanSApo objective (NA = 1.35). Cells were maintained on the microscope at 37°C with a stage-top incubation system (Tokai Hit, Shizuoka, Japan). Cells were excited by a 405-nm laser diode, and CFP and Venus were detected at 480–500 nm and 515–615 nm wavelength ranges, respectively. In the analysis shown in Figures 5, 6, S3, S4 and S5, FRET images were obtained using a Zeiss LSM510 Meta confocal microscope with an oil-immersion 63× Zeiss Plan-APOCHROMAT objective (NA = 1.4)(Carl Zeiss, Jena, Germany). Cells were maintained on the microscope at 37°C with a continuous supply of a 95% air and 5% CO₂ mixture using a XL-3 incubator (Carl Zeiss). Cells were excited by a 405-nm blue diode laser, and emission spectra of 433–604 nm wavelength range were obtained using an equipped scanning module (META detector) [42,43]. Images were computationally processed by a linear unmixing algorithm using the reference spectrum of CFP and Venus, which were obtained from individual fluorescence-expressing cells. All image analyses were performed using MetaMorph (Molecular Devices, Sunnyvale, CA). Fluorescence intensities of cytoplasmic areas in NS5A-ATeam transfected cells were calculated by subtraction of the signal intensities of the nucleus from the signal intensities of the whole cell, which was standardized by the area of the corresponding cytoplasmic region. Fluorescence intensities of cytoplasmic areas and at dot-like structures corresponding to the putative viral replicating sites in SGR-ATeam-transfected cells were measured and calculated as follows. All pixels above CFP intensity levels of 100–200 were selected. The positions of dot-like structures were then determined by examining areas greater than 0.5×10^{-12} square meters and the intensity of each dot was measured. The fluorescence intensity of the cytoplasmic area, excluding that of the putative viral replicating sites in each cell, was calculated by subtraction of the signal intensities of the nucleus and the dot-like structures, as determined above, from the signal intensity of the whole cell, which was standardized by the area of the corresponding cytoplasmic region. Each Venus/CFP emission ratio was calculated by dividing pixel-by-pixel a Venus image with a CFP image.

To investigate the relationship between Venus/CFP ratios and ATP concentrations in cells, calibration procedures were performed according to previous reports [29,30]. Huh-7 cells were transfected with NS5A-AT1.03 or NS5A-AT1.03^{YEMK}. Forty-eight hours later, the cells were permeabilized by incubation with buffer B containing 50 µg/ml digitonin for 5 min at room temperature. The reaction was stopped by washing 3 times with buffer B, followed by the addition of known concentrations of ATP in warmed medium for imaging. FRET analysis, with calibration of the signal intensity in the cytoplasm of each cell, was performed as described above. Plots were fitted with Hill equations with a fixed Hill coefficient of 2; $R = (R_{\max} - R_{\min}) \times [ATP]^2 / ([ATP]^2 + K_d^2) + R_{\min}$, where R_{\max} and R_{\min} are the maximum and minimum fluorescence ratios, respectively and K_d is the apparent dissociation constant.

To analyze the effect of an inhibitor against HCV NS5B polymerase, the medium for the cells replicating SGR-ATeam was changed to medium containing various concentrations of PSI-6130. After 10-min incubation at 37°C under a continuous supply of 95% air and 5% CO₂, fluorescence intensities of cytoplasmic areas and at dot-like structures were determined as described above. Medium containing 0.01% DMSO was used as a negative control.

To visualize mitochondria, MitoTracker Red CMXRos (Molecular Probes, Eugene, OR) was added to the culture medium to a final concentration of 100 nM, incubated for 15 min at 37°C and the cells were then washed twice with phosphate buffered saline (PBS) before FRET analysis of living cells. Images were

computationally processed as described above. The reference spectrum of MitoTracker Red CMXRos was obtained from stained parental, non-transfected, Huh-7 cells.

Indirect immunofluorescence

Cells expressing SGR-ATeam were cultured in 30-mm glass-bottomed dishes with an address grid on the coverslip (AGC Techno Glass). After FRET analysis of living cells as described above, the cells were fixed with 4% paraformaldehyde at room temperature for 30 min. After washing with PBS, the cells were permeabilized with PBS containing 0.3% Triton X-100 and individually stained with a rabbit polyclonal antibody against NS3 [44], an anti-NS5A antibody [45], or a mouse monoclonal antibody against dsRNA antibody (Biocenter Ltd., Szirak, Hungary) [46]. The fluorescent secondary antibody used was Alexa Fluor 555-conjugated anti-rabbit- or anti-mouse IgG (Invitrogen). The cells were imaged using a Zeiss LSM510 Meta confocal microscope with an oil-immersion 63× Zeiss Plan-APOCHROMAT objective (NA = 1.4). For dual-color imaging, the ATeam signal was excited with the 488-nm laser line of an argon laser and Alexa Fluor 555 was excited with a 543-nm HeNe laser under MultiTrack mode. Emission filters with a 505- to 530-nm band-pass and 560-nm-long pass filter were used.

Luciferase assay

Huh-7 cells transfected with SGR/luc or SGR/luc-ATeam were harvested at different time points after transfection (Figure 4D) or at 3 days after treatment with PSI-6130 (Figure S6) and lysed in passive lysis buffer (Promega). To monitor HCV RNA replication, the luciferase activity in cells was determined using a Luciferase Assay system (Promega). All assays were performed at least in triplicate.

MTT assay

Cell viability was assessed using the Cell Proliferation Kit II (Roche, Indianapolis, IN) according to the manufacturer's instructions. The kit measures mitochondrial dehydrogenase activity, which is used as a marker of viable cells, using a colorimetric sodium 3'-[1-(phenylaminocarbonyl)-3,4-tetrazolium]-bis(4-methoxy-6-nitro)benzene sulfonic acid hydrate (MTT) assay.

Quantification of HCV RNA

HCV RNA copies in the replicon cells with or without PSI-6130 treatment were determined using the real-time detection reverse transcription polymerase chain reaction (RTD-PCR) described previously [47] with the ABI Prism 7700 sequence detector system (Applied Biosystems Japan, Tokyo, Japan).

Western blotting

The proteins were transferred onto a polyvinylidene difluoride membrane (Immobilon; Millipore, Bedford, MA) after separation by SDS-PAGE. After blocking, the membranes were probed with a rabbit polyclonal anti-NS5A antibody [44], a rabbit polyclonal anti-NS5B antibody (Chemicon, Temecula, CA), or a mouse polyclonal anti-beta-actin antibody (Sigma-Aldrich), followed by incubation with a peroxidase-conjugated secondary antibody and visualization with an ECL Plus Western blotting detection system (GE Healthcare, Buckinghamshire, UK).

Supporting Information

Figure S1 ATP Levels in HCV replicon cells and parental Huh-7 cells determined by CE-TOF MS. ATP metabolites in Huh-7 cells and JFH-1/4-5 cells were measured by

CE-TOFMS. The values of each measurement are shown at left. The right graph shows means with SD of the data at left. Open bar; Huh-7 cells, gray bar; JFH-1/4-5 cells.

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Figure S2 Cytoplasmic ATP levels in HCV replicon cells and IFN-treated cells. (Left) The HCV replicon cells JFH-1/4-1, JFH-1/4-5 (genotype 2a) and NK5.1/0-9 (genotype 1b), and parental Huh-7 cells were cultured for 72 h in the absence or presence of 1,000 IU/ml IFN- α . Forty-eight hours after transfection with AT1.03, the Venus/CFP emission ratio of each cell was calculated from fluorescent images acquired with the confocal microscope FV1000. All data are presented as means and SD for at least 10 independent cells. (Right) HCV RNA titers in cells corresponding to the left panel were determined using real-time quantitative RT-PCR. Data are presented as means and SD for three independent samples. NTD indicates not detected.

(TIF)

Figure S3 Increase in ATP-enriched dot-like structures in cells replicating SGR-ATeam. Huh-7 cells were transfected with SGR-AT1.03, and analyzed in the same way as described in the legends for Figures 5A and 5B. The lower four panels are five-fold magnifications of the boxed areas in independent cells. Scale bars, 40 μ m.

(TIF)

Figure S4 Visualization of the ATP level in cells expressing replication-defective HCV polyprotein. (A) A schematic representation of the NS3-NS5B-AT1.03 plasmid is shown. The HCV polyprotein is indicated by the open boxes. The ATeam gene was inserted into the same site as that for NS5A-ATeam and SGR-ATeam insertion as indicated in the legend for Figure 4A. CAG, CAG promoter. (B) Cells transfected with constructs encoding NS5A, NS5A-AT1.03, NS3-NS5B-AT1.03, SGR or SGR-AT1.03 were analyzed by immunoblotting with anti-NS5A, anti-NS5B or anti-beta-actin antibodies. (C) Huh-7 cells were transfected with NS3-NS5B-AT1.03, and analyzed in the same way as described in the legends for Figures 5A and 5B. The upper panel (Fluorescence) demonstrates signal intensity from a spectral channel with maximum intensity and represents the expression pattern of NS5A-ATeam processed from NS3-NS5B-AT1.03. The lower panels (Venus/CFP ratio) indicate the FRET

ratio and a five-fold magnification of the boxed area. Scale bar, 20 μ m.

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Figure S5 Relationship between ATP-enriched dot-like structures and mitochondria. Huh-7 cells replicating SGR-AT1.03 (right panels) and parental cells (left panel) were analyzed. Active mitochondria were labeled with MitoTracker Red CMXRos in living cells, and were analyzed in the same way as described in the legends for Figures 5A and 5B, using a reference for the MitoTracker spectrum. The lowest panels of SGR-ATeam cells indicate five-fold magnifications of the boxed areas. Scale bars, 20 μ m.

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Figure S6 Inhibitory effect of PSI-6130 on HCV RNA replication. (A) Replication levels of SGR/luc-AT1.03 RNA in transfected cells were determined by luciferase assay 3 days after treatment with PSI-6130 at the indicated concentrations (μ M). The values shown were normalized for transfection efficiency with luciferase activity determined 24 h post-transfection. All data are presented as means and SD for three independent samples. (B) Cell viability was assessed using the MITT assay.

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Author Contributions

Conceived and designed the experiments: T. Ando, H. Imamura, T. Wakita, T. Suzuki. Performed the experiments: T. Ando, H. Aizaki. Analyzed the data: T. Ando, H. Imamura, T. Watanabe, T. Wakita, T. Suzuki. Contributed reagents/materials/analysis tools: H. Imamura, R. Suzuki, H. Aizaki. Wrote the paper: T. Ando, T. Suzuki.

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ORIGINAL ARTICLE

Replication and infectivity of a novel genotype 1b hepatitis C virus clone

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ABSTRACT

Hepatitis C virus infection is a major public health problem because of an estimated 170 million carriers worldwide. Genotype 1b is the major subtype of HCV in many countries and is resistant to interferon therapy. Study of the viral life cycle is important for understanding the mechanisms of interferon resistance of genotype 1b HCV strains. For such studies, genotype 1b HCV strains that can replicate and produce infectious virus particles in cultured cells are required. In the present study, we isolated HCV cDNA, which we named the NC1 strain, from a patient with acute severe hepatitis. Subgenomic replicon experiments revealed that several mutations enhanced the colony-formation efficiency of the NC1 replicon. The full-length NC1 genome with these adaptive mutations could replicate in cultured cells and produce infectious virus particles. The density gradient profile and morphology of the secreted virus particles were similar to those reported for the JFH-1 virus. Further introduction of a combination of mutations of the NS3 and NS5a regions into the NC1 mutants further enhanced secreted core protein levels and infectious virus titers in the culture medium of HCV-RNA-transfected cells. However, the virus infection efficiency was not sufficient for autonomous virus propagation in cultured cells. In conclusion, we established a novel cell culture-adapted genotype 1b HCV strain, termed NC1, which can produce infectious virus when the viral RNA is transfected into cells. This system provides an important opportunity for studying the life cycle of the genotype 1b HCV.

Key words genotype 1b, hepatitis C virus (HCV), replicon, virus culture.

Hepatitis C virus infection leads to chronic liver diseases including cirrhosis and hepatocellular carcinoma, and is a major public health problem because of an estimated 170 million carriers worldwide (1–3). HCV is a plus-strand RNA virus that displays marked genetic heterogeneity and is currently classified into six major

genotypes (4). Some HCV genotypes display regional distribution, although genotypes 1 and 2 occur worldwide. Genotype 1b is the major subtype in Japan, whereas genotype 2a is the most common minor subtype (5). Infection with genotype 1b HCV is known to be resistant to interferon therapy, whereas infection with genotype 2a is

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List of Abbreviations: CFU, colony-forming units; DMEM, Dulbecco's modified Eagle's medium; EMCV, encephalomyocarditis virus; ffu, focus-forming units; HCV, hepatitis C virus; IFN, interferon; IRES, internal ribosomal entry site; PI, protease inhibitors; RTD-PCR, real-time detection RT-PCR.

usually sensitive to such intervention (6). Current standard therapy for HCV-related chronic hepatitis is based on a combination of IFN and ribavirin, although virus eradication rates are limited to approximately 50% for genotype 1b HCV infection (7–9). PI have been approved for clinical use against HCV infection in the USA, Europe and Japan, and triple combination therapy that includes PI is expected to improve treatment efficacy. However, the development of other anti-HCV drugs with different modes of action is important to achieve greater efficacy and to avoid the emergence of drug-resistant viruses. To that end, a detailed understanding of the viral replication mechanism is needed to identify novel antiviral targets.

Although HCV belongs to the *Flaviviridae* family and has a genome structure similar to the other flaviviruses, efficient virus propagation in cultured cells has been difficult ever since the discovery of the virus (10). A subgenomic HCV-RNA replicon system was developed using the genotype 1b Con1 strain (11), which enabled the assessment of HCV replication in cultured cells. Subsequently, the genotype 2a JFH-1 strain was cloned and a HCV culture system was established using this strain (12–14). However, such efficient virus production could not be reproduced using genotype 1b HCV strains, even when adaptive mutations were introduced to enhance their replication efficiency in cultured cells (15). Thus, it remains necessary to obtain genotype 1b HCV strains that can replicate and produce infectious virus particles in cultured cells.

In the present study, we isolated HCV cDNA, which we named the NC1 strain, from a patient with acute severe hepatitis. In a subgenomic replicon experiment using the NC1 clone, we found several mutations that enhanced colony-formation efficiency of the NC1 replicon. Interestingly, the full-length NC1 genome with these adaptive mutations could replicate in cultured cells and produce infectious virus particles. However, the viral infection efficiency was not sufficient for autonomous virus propagation in cultured cells even though virus production efficiency could be increased by the introduction of multiple mutations into the virus genome.

MATERIALS AND METHODS

Cell culture system

Huh7 and Huh7.5.1 cells (a generous gift from Dr Francis V. Chisari) were cultured in 5% CO₂ at 37°C in DMEM containing 10% fetal bovine serum (DMEM-10) (13, 16).

HCV clones

The genotype 1b HCV clone NC1 was isolated from a patient with acute severe hepatitis (prothrombin

time <40%). The patient was a 48-year-old woman who had no history of blood transfusions. Total RNA was extracted from the serum during the acute phase, and HCV cDNA covering the entire genome was amplified by RT-PCR using HCV-specific primers (S-Table 1). All amplified products were purified and then cloned into pGEM-T EASY™ vectors (Promega, Madison, WI, USA). PCR products and plasmids were sequenced using HCV-specific primer sets (S-Table1), a Big Dye Terminator Mix and an automated DNA sequencer (PE Biosystems, Foster City, CA, USA). Based on the consensus sequence of the NC1 strain, we then assembled pNC1 (DDBJ/EMBL/GenBank accession number: AB691953), which contained the full-length NC1 cDNA downstream of the T7 RNA polymerase promoter. An NC-1 subgenomic replicon construct, pSGR-NC1, was also assembled according to previously published methods used for Con1 replicon and pSGR-JFH1 construction (10, 17). The first 213 nucleotides at the NS3 region of pSGR-NC1 are identical with the Con1 sequence because of the restriction site used for plasmid construction. Several mutations were introduced into the pNC1 and pSGR-NC1 constructs as reported previously using specific primer sets (S-Table 2) (17). pNC1/wt contained the wild-type sequence of the NC1 strain. pNC1/SY and pNC1/SG contained S2197Y and S2204G mutations, respectively. pNC1/EGSY contained both E1202G and S2197Y mutations. pNC1/KTSY contained both K1846T and S2197Y mutations. pNC1/EGKTSY contained the three mutations, E1202G, K1846T and S2197Y.

Subgenomic replicon assay

Subgenomic replicon RNA was synthesized as reported previously (17). The synthesized replicon RNA (3 μg) was adjusted to a total RNA amount of 10 μg using cellular RNA isolated from non-transfected Huh7 cells and was then electroporated into naive Huh7 and Huh 7.5.1 cells as reported previously (17). G418 (1 mg/mL) was added to the culture medium for 3 weeks, and drug-resistant colonies were fixed with buffered formalin and stained with crystal violet or were cloned for further analysis. For the cloning analysis of the replicon cells, G418-resistant colonies were isolated by using cloning cylinders (Asahi Techno Glass Co., Tokyo, Japan) and were expanded until they reached 80% to 90% confluency in 10-cm diameter dishes. Total RNA was extracted from the cloned G418-resistant cells by using the ISOGEN reagent (Nippon Gene, Tokyo, Japan), and the replicon RNA was quantified using real-time detection RT-PCR (RTD-PCR) as reported previously (18). The cDNAs of the HCV-RNA replicon were synthesized and then amplified by PCR. The sequence of each replicon was determined (17).

Full-length HCV-RNA transfection

Full-length HCV-RNA was synthesized from pNC1 and its derivatives that contained adaptive mutations as described previously (12, 19, 20). Synthesized HCV-RNA (10 μ g) was transfected into Huh7.5.1 cells. The HCV core protein level in the culture supernatant was measured using Lumipulse Ortho HCV Ag (Ortho-Clinical Diagnostics, Tokyo, Japan) (21), and infectivity of the supernatant was determined by measurement of its focus-formation efficiency (13, 19). In some experiments, the transfected cell pellet was harvested and dissolved with RIPA buffer containing 0.1% SDS. HCV core protein levels in cell lysates were also measured using the Lumipulse Ortho HCV Ag.

Density gradient analysis of secreted virus particles

Culture medium (1 mL) derived from transfected cells was harvested for density gradient analysis 2 or 15 days after transfection of full-length NC1/SY HCV RNA. The cleared culture medium was layered onto a stepwise sucrose gradient (60% [wt/vol] to 10%) and centrifuged for 16 hrs in an SW41 rotor (Beckman, Palo Alto, CA, USA) at $200,000 \times g$ at 4°C. After centrifugation, 18 fractions were harvested from the bottom of the tubes. The core protein concentration in each fraction was determined by analysis of 100 μ L of each fraction.

Electron microscopy

Culture medium (150 mL) containing NC1/SY virus particles were collected from the cells 15 days after transfected cells. The collected culture medium was ultrafiltrated and concentrated 20-fold using a pellicon-2 filter system (Millipore, Bedford, MA, USA). The sample was layered onto a stepwise sucrose gradient (60% [wt/vol] to 10%) and centrifuged for 4 hrs in an SW28 rotor (Beckman, Palo Alto, CA, USA) at $140,000 \times g$ at 4°C. Thereafter, fractions were harvested from the bottom of the tubes. The core protein concentration in each fraction was determined and the fraction with the highest core protein level was ultrafiltrated for electron microscopic analysis. To visualize HCV particles, we adsorbed the purified virus samples onto carbon-coated grids for 1 min. The grids were then stained with 1% uranyl acetate for 1 min and examined under an H-7650 transmission electron microscope (Hitachi High-Technologies Co., Tokyo, Japan) (22).

Human hepatocyte chimeric mice experiments

Human hepatocytes were transplanted into uPA^{+/+}/SCID^{+/+} mice as described previously (23, 24). These mice

were obtained from Phoenix Bio Co., Ltd (Hiroshima, Japan). All mice received hepatocyte transplants from the same donor. Human albumin levels in the sera of the mice were monitored to evaluate the percentage replacement of mouse hepatocytes with human hepatocytes in the mouse liver. These human hepatocyte chimeric mice, in which the mouse liver cells were largely (>90%) replaced with human hepatocytes, were used to reduce the potential influence of mouse-derived mRNA on the results obtained. Two mice were each inoculated with purified NC1/SY HCV particles containing 11.6 fmol core protein. The HCV-RNA titer in inoculated mouse serum was monitored by RTD-PCR each week after inoculation.

RESULTS

Genotype 1b HCV clone isolated from a patient with acute severe hepatitis

HCV cDNA was isolated from a patient with acute severe hepatitis. This patient was a 48-year-old woman without any history of blood transfusions. She developed acute severe hepatitis as diagnosed by acute liver failure associated with stage I encephalopathy and low serum prothrombin time (<40%). In the patient's serum, no marker of cytomegalovirus, Epstein-Barr virus, herpes simplex virus, hepatitis A virus or hepatitis B virus was detected. However, only HCV-RNA was detected using RT-PCR analysis, and the virus RNA titer in her serum at admission was 16,660 KIU/mL. The genotype 1b HCV sequence was detected by sequencing analysis of the PCR fragment. The patient was therefore diagnosed as suffering from acute severe hepatitis caused by genotype 1b HCV infection. She received IFN- α treatment, which cleared the viral infection, and she subsequently recovered. The entire sequence of the amplified HCV genomic cDNA was then determined and this HCV strain was designated as NC1. The sequencing analysis indicated that this NC1 strain shared 91.2% nucleotide and 94.4% amino acid sequence homology with the Con1 strain.

Subgenomic replicon analysis of the NC1 strain

To analyze the replication efficiency of the genotype 1b NC1 strain, we constructed the subgenomic replicon, pSGR-NC1, in the form of a Con1 replicon and pSGR-JFH1 (10, 17). This synthesized NC1 replicon RNA was transfected by electroporation into Huh7 or Huh7.5.1 cells. The transfected cells were then grown for 3 weeks in a selection culture that contained 1 mg/mL G418. Several colonies survived this selection culture, as illustrated by crystal violet staining (Fig. 1). The

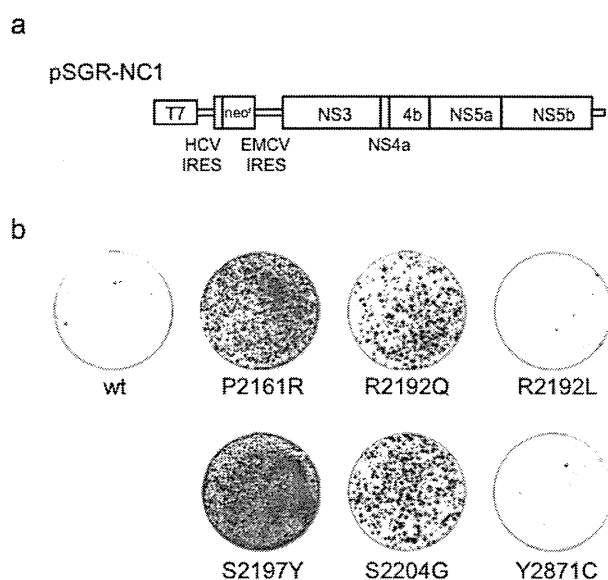


Fig. 1. NC1 subgenomic HCV replicon construct and colony formation of NC1 replicon RNA-transfected Huh7 cells. (a) Organization of the subgenomic replicon construct pSGR-NC1. Open reading frames (wide boxes) are flanked by untranslated regions (narrow boxes). The T7 RNA promoter is located upstream of the 5' end of the replicon construct. (b) Subgenomic RNAs were synthesized *in vitro* using pSGR-NC1 (wt) and replicon constructs containing one of the mutations P2161R, R2192Q, R2192L, S2197Y, S2204G and Y2871C as templates. Transcribed subgenomic replicon RNAs (3 μ g each) were electroporated into Huh7 cells and the cells were cultured with G418 for 3 weeks before staining with crystal violet. Experiments were carried out in triplicate and representative staining examples are shown.

colony-formation efficiency of the NC1 replicons was 1.77 ± 1.54 CFU/ μ g RNA, which was lower than the colony-formation efficiency of the JFH-1 subgenomic replicon that was determined in our previous study ($5.32 \pm 5.02 \times 10^4$ CFU/ μ g RNA) (17). Six colonies of the transfected Huh7 cells and 14 colonies of the transfected Huh7.5.1 cells were cloned and expanded for further analysis. Replicon RNA was isolated from each replicon cell clone, and the HCV-RNA titer and sequence of the replicon genome were determined (Table 1). The average HCV-RNA titers in the replicon cell clones derived from Huh7 and Huh7.5.1 cells were determined by RTD-PCR as $4.28 \pm 3.43 \times 10^6$ and $6.72 \pm 7.14 \times 10^6$ copies/ μ g RNA, respectively.

We next determined the sequence of the replicating replicon genome in each replicon transfected cell clone. All of the clones had at least one non-synonymous mutation and three clones also had a synonymous mutation (Table 1). We found non-synonymous mutations in all of the subgenomic non-structural regions of the replicon genome, and five of the mutations were found in more than one replicon genomic clone. Thus, of the mutations found in the NS5A region, P2161R, R2192L and

Table 1. Mutations and RNA titer of the NC1 replicon cell clones

Replicon clones†	nt mutation	nt position‡	aa mutation	aa position§	Region	Replicon RNA titer
2	G>A	5302(6916)	R>Q	2192	NS5a	3.58E+05
	T>Y	5490(7104)	S>S,P	2255	NS5a	
5	G>R	4046(5660)	none		NS4b	1.56E+07
	A>G	4088(5702)	I>M	1787	NS4b	
	C>A	5317(6931)	S>Y	2205	NS5a	
	C>S	6579(8193)	Q>Q,E	2618	NS5b	
2-1	T>C	3965(5579)	none		NS4b	3.17E+05
	T>G	5346(6960)	S>A	2207	NS5a	
2-2	C>G	5209(6823)	P>R	2161	NS5a	8.16E+06
2-3	T>C	1721	none		E-I ††	3.97E+06
	C>A	4855(6469)	S>Y	2043	NS5a	
2-5	T>C	3694(5308)	V>C	1656	NS3	1.80E+07
	C>G	5209(6823)	P>R	2161	NS5a	
2-7	G>T	5302(6916)	R>L	2192	NS5a	2.91E+06
2-8	T>C	5067(6681)	C>R	2114	NS5a	1.98E+06
	A>G	7339(8953)	Y>C	2871	NS5b	
2-9	C>A	5317(6931)	S>Y	2197	NS5a	1.58E+07
2-10	A>G	5287(6901)	K>R	2187	NS5a	1.90E+07
	A>G	5337(6951)	S>G	2204	NS5a	
	A>G	7339(8953)	Y>C	2871	NS5b	
2-11	C>A	584	D>E		NEO	2.50E+06
	A>T	3762(5376)	S>C	1679	NS4a	
	T>A	5248(6862)	M>K	2174	NS5a	
2-12	C>T	5291(6905)	none		NS5a	1.02E+06
	G>T	5302(6916)	R>L	2192	NS5a	
2-13	C>A	4850(6464)	N>K	2041	NS5a	3.65E+06
2-15	C>T	5299(6913)	A>V	2191	NS5a	8.07E+05
	A>G	5337(6951)	S>G	2204	NS5a	
	A>G	6014(7628)	none		NS5b	
	A>G	6015(7629)	I>V	2430	NS5b	
H1	C>A	5301(6915)	none		NS5a	1.01E+07
	C>A	5317(6931)	S>Y	2197	NS5a	
H3	G>A	661	G>E		NEO	4.77E+06
	C>A	5323(6937)	A>D	2199	NS5a	
H6	C>A	5265(6879)	H>N	2180	NS5a	1.21E+06
H7	C>A	5308(6922)	S>Y	2194	NS5a	4.53E+05
H10	C>A	5317(6931)	S>Y	2197	NS5a	5.12E+06
H12	A>C	5325(6939)	S>R	2200	NS5a	4.03E+06

†Replicon clones 2~2-15 were derived from Huh7.5.1 cells, and the H1~H12 replicon clones were derived from Huh7 cells. ‡Position within the subgenomic replicon and within full-length NC1 (in parentheses).

§Position within the complete open reading frame of full-length NC1.

¶Copy/ μ g RNA. ††E-I, EMCV-IRES.

S2204G mutations were independently detected in two different replicon cell clones, and the S2197Y mutation was detected in three different replicon cell clones. In addition, R2192 was not only mutated to R2192L but was also found as an R2192Q mutation in one replicon. The Y2871C mutation in NS5B was detected in two different replicon cell clones. We therefore selected P2161R, R2192L, R2192Q, S2197Y, S2204G and Y2871C mutations for further analysis to determine their adaptive effects. We inserted P2161R, R2192L, R2192Q, S2197Y, S2204G and Y2871C mutations into the pSGR-NC1 genome and tested

the colony-formation efficiency of the mutant replicons. As shown in Figure 1b, P2161R, R2192Q, S2197Y and S2204G mutations had adaptive effects for colony formation. However, R2192L and Y2871C mutations did not enhance colony-formation efficiency.

Full-length HCV replication

As shown above, some of the mutations detected in the NC1 subgenomic replicon that was transfected into cells exhibited adaptive effects that increased colony-formation efficiency. We next determined whether full-length NC1 HCV clones with these mutations were able to replicate in cultured cells and to produce infectious virus. We therefore introduced the same six mutations that we tested in the subgenomic replicon assay into the full-length NC1 HCV cDNA (Fig. 2a). Full-length viral RNA was synthesized from linearized pNC1 and its mutant derivatives and was electroporated into Huh7.5.1 cells. All of the transfected cells were serially passaged, and HCV core protein levels in the culture supernatant were monitored over time (Fig. 2b). Interestingly, only cells transfected with the NC1 HCV-RNA with an S2197Y or S2204G mutation secreted a significant amount of HCV core protein into the culture medium. Secreted HCV core protein levels reached a maximum at 5–10 days post-transfection and subsequently continuously decreased in the culture medium of the cells transfected with the viral RNA containing S2197Y or S2204G mutation until 32 days after transfection. This reduction in HCV core protein levels after a certain number of cell passages was reproducible and was confirmed in repeated experiments.

Characterization of the NC1 virus particles secreted from NC1 RNA-transfected cells

Of the six NC1 constructs with mutations that were transfected into cells, transfection of NC1/SY RNA, which had the S2197Y mutation, resulted in secretion of the highest level of HCV core protein into the culture medium (Fig. 2b). We therefore further analyzed the HCV particles produced from NC1/SY RNA-transfected cells. Synthesized NC1/SY RNA was transfected again into Huh7.5.1 cells, the transfected cells were passaged and the culture medium was harvested at cell passaging. HCV core protein levels were relatively high in the culture medium from the NC1/SY RNA-transfected cells on days 2 and 15 post-transfection (Table 2). Infectivity of the culture medium was also detected at both time points, although at very low levels (Table 2). We also analyzed HCV core protein in the culture media obtained at these two time points using a density gradient assay. Both media exhibited a high, narrow peak of HCV core protein in fraction 9, which had a density of 1.15 g/mL, as well as a broader

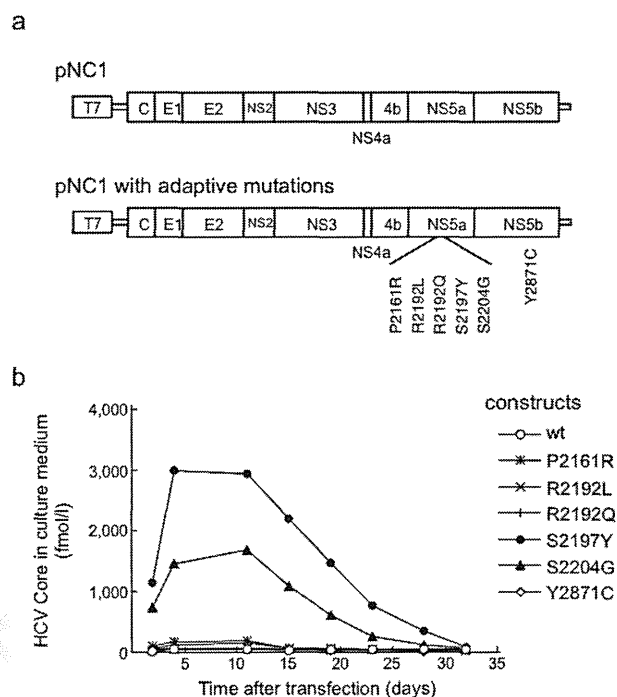


Fig. 2. Analysis of the HCV core protein released into the cell culture medium after transfection of NC1 full-length HCV-RNA. (a) Organization of the full-length NC1 construct, pNC1 (upper). Open reading frames (wide boxes) are flanked by untranslated regions (narrow boxes). A T7 RNA promoter is located upstream of the 5' end of the HCV cDNA construct. Six of the mutations identified in the replicon cell clones were independently introduced into the pNC1 construct (lower). (b) Huh7.5.1 cells were transfected with RNA transcribed from pNC1 with the wild-type HCV sequence (wt) or with RNA from one of the six constructs containing one of the mutations P2161R, R2192Q, R2192L, S2197Y, S2204G or Y2871C. Two independently transfected cell lines were passaged for each construct. At each time point after transfection, the culture medium was harvested and analyzed for the presence of HCV core protein. Average data of duplicate transfections are indicated.

Table 2. HCV core protein and infectivity levels in the culture medium of NC1/SY RNA-transfected cells

Days post-transfection	HCV Core (fmol/L)	Infectivity (ffu/mL)
2	1721	3
15	1009	16

minor peak which had a density of 1.02 to 1.04 g/mL (Fig. 3a). Interestingly, these density gradient profiles were quite similar to the previously described profile of JFH-1 (12). We further identified viral particles in the peak fraction of NC1/SY virus particles obtained following density gradient centrifugation by electron microscopic analysis (Fig. 3b). The observed particles exhibited a spherical shape with diameters of approximately 50–55 nm.

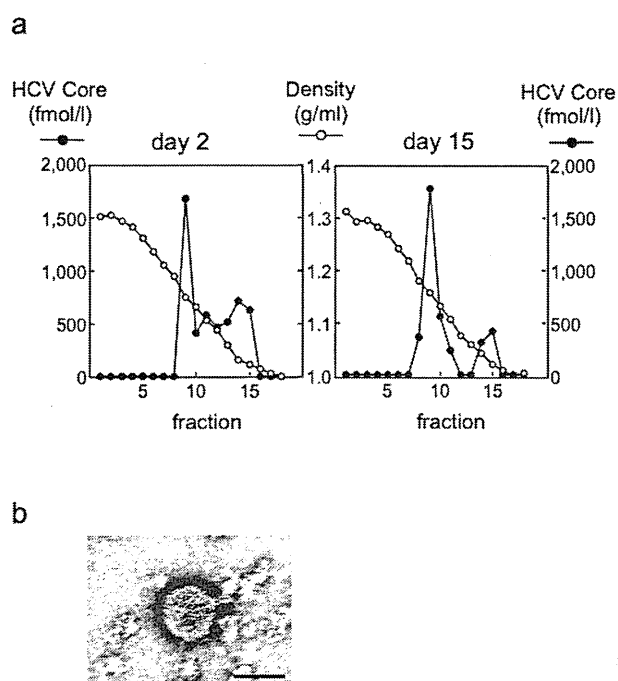


Fig. 3. Characterization of secreted HCV particles from NC1/SY RNA-transfected cells. (a) Sucrose density gradient analysis of the culture supernatant from NC1/SY RNA-transfected Huh7.5.1 cells. One ml of the culture supernatant of transfected cells that was collected on day 2 and day 15 post-transfection (Table 2) was cleared by centrifugation and filtration. Each supernatant was overlaid on a stepwise sucrose density gradient (0, 10, 20, 30, 40, 50 and 60% sucrose) and centrifuged for 16 hrs at $200,000 \times g$ at 4°C . Eighteen fractions were collected from the bottom of the tubes and the concentration of HCV core protein in each fraction was determined. Closed and open circles indicate HCV core protein levels (fmol/L) and the sucrose density (g/mL) of the fractions, respectively. (b) Negative-stained HCV particles were observed by electron microscopy. NC1/SY virus particles were purified from the culture medium at 15 days post-transfection and observed by electron microscopy using negative staining. Scale bar, 50 nm.

Infectivity of the NC1/SY virus in human hepatocyte-transplanted uPA/SCID mice

We next determined the *in vivo* infectivity of the NC1/SY virus using human hepatocyte-transplanted uPA/SCID mice, which were reported to be permissive for HCV infection (23). We harvested cell culture media containing NC1/SY virus at 6 days after RNA transfection and was concentrated approximately 20-fold. The concentrated NC1/SY virus was inoculated into two mice designated as PXB 21–39 and PXB 21–40 (Table 3). Human albumin levels in the sera of the inoculated mice were higher than 3 mg/mL during the experiment, which supported the fact that there was a high level of replacement of mouse hepatocytes with human hepatocytes in the mouse liver. Both mice were negative for HCV-RNA at 1 week after inocula-

Table 3. Serum HCV-RNA titer in human hepatocyte chimeric mice inoculated with the NC1/SY virus produced in cultured cells

Days post-infection	Mouse ID†	
	PXB 21–39	PXB 21–40
7	–	–
14	+	–
21	–	–
28	–	–
35	–	–

†Two mice were independently inoculated with 300 μL NC1/SY (38,600 fmol/L).

+, PCR positive ($<2.1 \times 10^4$ copies/mL); –, PCR negative.

tion (Table 3). The PXB 21–39 mouse became transiently HCV-RNA positive only at 2 weeks post-inoculation but thereafter remained negative from 3 to 5 weeks post-inoculation. The PXB 21–40 mouse remained HCV-RNA negative until 5 weeks post-inoculation. Thus, the cell culture-adapted NC1/SY virus in the inoculum may have possessed *in vivo* infectivity although this infectivity was at a low level.

Combinatory effects of adaptive mutations in different regions

The above experiment showed that NC1/SY RNA-transfected cells could produce infectious virus particles but at very low efficiency. To increase the replication and virus production efficiency of the NC1/SY virus, we tested the effect of introducing additional adaptive mutations into NC1. Thus, the E1202G mutation in NS3 (25) and/or the K1846T mutation in NS4B (26) were introduced into pNC1/SY (Fig. 4a) yielding pNC1/EGSY, pNC1/KTSY and pNC1/EGKTSY. RNAs transcribed from these synthesized constructs were transiently transfected into Huh7.5.1 cells. In this transient transfection experiment, NC1/EGSY and NC1/EGKTSY-RNA-transfected cells expressed higher levels of HCV core protein both in the culture medium and in the cell lysate from 48 to 96 hrs after transfection than cells transfected with RNA of the other NC1 mutants (Fig. 4b and c). However, the NC1/KTSY RNA-transfected cells expressed a similar level of HCV core protein as that expressed by NC1/SY. Interestingly, the E1202G mutation not only increased the level of the HCV core protein but also the infectivity of the culture medium. At 3 days post-transfection, HCV core protein levels reached a concentration of 8193 fmol/L in the medium of NC1/EGSY RNA-transfected cells, and, at the same time point, the infectivity titer in the culture medium of these cells reached 792 ffu/mL (Fig. 4b and Table 4). However, by 25 days post-transfection, the

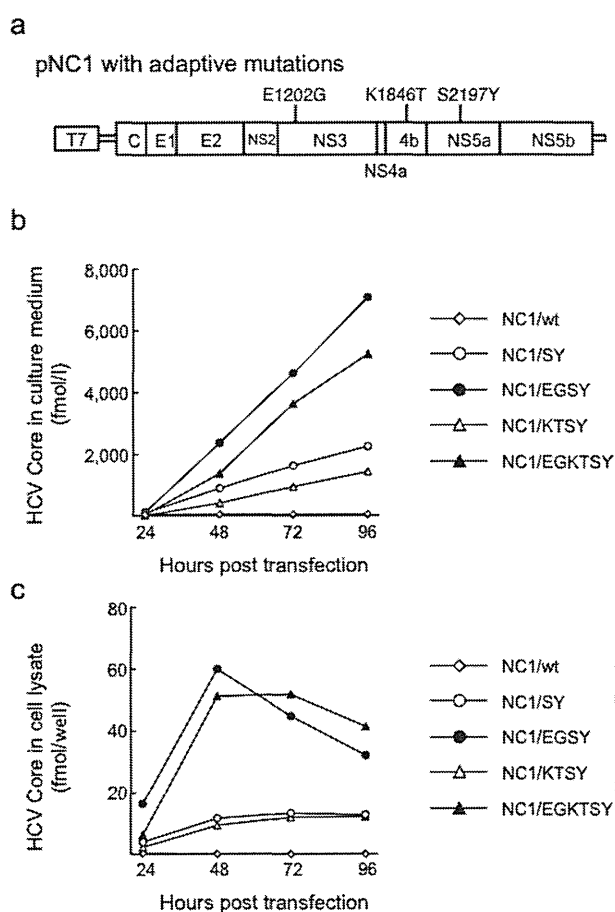


Fig. 4. Kinetics of HCV core protein release into the culture medium and cellular HCV protein expression. (a) Position of the E1202G and K1846T mutations, which were introduced alone or in combination into the full-length pNC1 containing the S2197Y mutation, is shown. Transcribed full-length HCV-RNAs from pNC1 and its mutated derivatives were transfected into Huh7 cells. At each time point, the culture medium and an aliquot of transfected cells were harvested. HCV core protein levels in the culture medium (b) and the cell lysate (c) were determined as described in Materials and Methods. Data indicate the average core protein concentration from two independent transfections. wt, wild type; EG, E1202G; KT, K1846T; SY, S2197Y.

infectivity titer in the culture medium of the NC1/EGSY RNA-transfected cells had decreased to 23.3 ffu/mL. Furthermore, reinfection of the secreted virus did not result in productive infection.

DISCUSSION

In previous studies, we isolated a cell culture infectious genotype 2a HCV strain, the JFH-1 strain, from a patient with fulminant hepatitis (12, 27). In the present study, we isolated a novel genotype 1b HCV cDNA, the NC1 strain. We tested NC1 strain replication efficiency in cultured cells using a drug-selectable subgenomic replicon

Table 4. HCV core protein levels in, and infectivity of, the culture medium of NC1 RNA-transfected cells

Days post-transfection	HCV construct	HCV core (fmol/L)	Infectivity (ffu/mL)
3	NC1/SY	2468	23.3
	NC1/EGSY	8193	792.0
	NC1/KTSY	1079	3.3
	NC1/EGKTSY	5064	467.0
25	NC1/SY	963	3.3
	NC1/EGSY	515	23.3
	NC1/KTSY	319	0.0
	NC1/EGKTSY	995	6.7

assay. Although the colony-forming efficiency of the NC1 replicon was lower than that of JFH-1, we still isolated multiple NC1 replicon cell clones. This result suggested that adaptive mutations in the replicon genome were necessary for efficient replication and that clones that expressed neomycin-resistant gene products were selected. Indeed, some mutations were identified in the NC1 replicon that enhanced colony-formation efficiency (Fig. 1). Notably, the S2197Y and S2204G mutations also increased core protein secretion from cells transfected with full-length NC1 HCV-RNA (Fig. 2). The culture medium of the NC1/SY RNA-transfected cells showed marginal infectivity for naive Huh7.5.1 cells. The *in vivo* infectivity of the NC1/SY virus was confirmed by its inoculation into human hepatocyte-transplanted uPA/SCID mice. Although the *in vivo* NC1/SY virus infectivity was very weak and transient, it was detected in one of the two inoculated mice. By introducing additional adaptive mutations into the NC1/SY virus, we found that a combination of E1202G and S2197Y mutations further enhanced HCV replication and virus production in RNA-transfected cells.

HCV was discovered as a causative agent of non-A, non-B hepatitis in 1989 (1, 2). Since then, efforts to understand the viral life cycle of HCV and to identify effective antiviral agents have been hampered by the lack of an efficient cell culture system for this virus. There have already been many attempts to develop a system for HCV infection and replication in cell culture (reviewed in ref 10). However, the viral replication efficiencies reported in these studies were modest, requiring detection by RT-PCR.

We previously isolated an HCV clone, JFH-1, from a fulminant hepatitis patient with HCV (27). A JFH-1-derived subgenomic replicon proved capable of highly efficient replication in a variety of cell lines (17), and produced infectious HCV particles in Huh7 cells (12–14). The development of an HCV infection system using the JFH-1 strain has contributed to our understanding of this important virus. A genotype 1a strain, H77S, which contained five adaptive mutations, was reported to produce infectious

virus following transfection of its synthesized RNA into Huh7 cells (28). It is thus clear that JFH-1 is not the only HCV strain that can be propagated in cultured cells. However, it is also important to understand why JFH-1 is the only strain that replicates efficiently in cultured cells in the absence of adaptive mutations. In order to understand this characteristic of JFH-1, we analyzed the mechanisms that underlie the efficient replication of the JFH-1 strain (29, 30) and identified important sequence differences in the JFH-1 strain compared to the J6CF strain. However, introduction of mutations that would abrogate such sequence differences did not enable efficient replication of genotype 1b HCV strains. These data suggested that it is necessary to identify different mutations that would increase the virus production efficiency of genotype 1b HCV. Further analysis of JFH-1 genomic replication mechanisms may help to determine other differences between the replication of JFH-1 and other strains.

Previous reports have indicated that adaptive mutations enhance viral RNA replication at the expense of virus particle formation efficiency (31). A highly cell culture-adapted Con1 strain can replicate in cultured cells, but it cannot produce infectious virus particles. In the present study, we also attempted to establish a replication-competent genotype 1b HCV strain from a patient with acute severe hepatitis. We identified several adaptive mutations in colony-forming experiments using a subgenomic replicon of this NC1 strain. Notably, S2197Y and S2204G mutations exhibited an adaptive effect for both virus replication and virus particle secretion. The adaptive mutations at amino acid positions 2197 and 2204 were previously reported in genotype 1a and 1b replicon studies (reviewed in ref 32). Although the S2197Y mutation enabled the NC1 strain to produce infectious virus, the infection efficiency of this virus was very weak. We therefore hypothesized that it may be necessary to increase replication efficiency by introducing additional mutations that would facilitate efficient virus production. For this purpose, we introduced and tested the effect of introduction of the previously reported mutations, E1202G in NS3 (25) and K1846T in NS4B (26), into the pNC1/SY construct. Interestingly, virus core protein secretion of NC1/SY was enhanced by introduction of the E1202G mutation but not by introduction of the K2864T mutation. This result suggested that the selection and combination of adaptive mutations is very important for establishment of an infectious genotype 1b HCV strain. Although NC1/EGSY RNA-transfected cells produced high levels of HCV core protein into the culture medium with infectivity, not all of the cells were infected with the virus and viral infection did not continue as the cells were passaged. After several cell passages, only a small number of the transfected cells remained infected (data not shown). This result may be

due to a low degree of infection efficiency that was not sufficient for productive infection or may be due to some other unknown mechanisms.

The *in vivo* infectivity of the NC1/SY virus was tested using the human hepatocyte-transplanted uPA/SCID mouse system. The NC1/SY virus showed only transient viremia in one out of two inoculated mice. Interestingly, a highly adapted Con1 strain was previously shown not to be infectious for chimpanzees, whereas a moderately adapted Con1 was infectious. However, the virus recovered from the infected animal was wild-type Con1 virus (33). This result clearly suggests that HCV strains with low replication efficiency are favorable for *in vivo* infection. A wild-type virus with low replication capacity is likely to evade the host immune surveillance system and thereby survive in an *in vivo* situation. However, the JFH-1 virus was infectious not only for cultured cells but also for chimpanzees and human liver-transplanted mice (12, 34, 35). It is therefore important to analyze how HCV can evade host defense mechanisms to understand the mechanism of persistent viral infection. Further detailed studies are necessary for such analysis.

In the present study, we established the cell culture-adapted genotype 1b HCV strain, NC1. Infectious virus was produced from RNA-transfected cells. However, virus infection could not be continuously passaged in Huh7.5.1 cells. Novel antiviral drugs targeting genotype 1b HCV are under development and some of these drugs will be used in a clinical setting. It is likely that such new therapy will be accompanied by the appearance of significant adverse effects and by the emergence of drug-resistant virus. It is therefore important to further develop improved genotype 1b infectious HCV culture systems for future studies so that these problems can be circumvented.

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DISCLOSURE

None of the authors have any conflicts of interest associated with this study.

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T. Date *et al.*

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

S-Table 1: Primers used to amplify and sequence the NC1 HCV strain.

S-Table 2: Primers used to introduce mutations into pNC1 and pSGR-NC1.

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Interleukin-29 Suppresses Hepatitis A and C Viral Internal Ribosomal Entry Site-Mediated Translation

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Tatsuo Miyamura,¹ Fumio Imazeki,¹ Koji Ishii,³ Takaji Wakita,³ and Osamu Yokosuka¹

Abstract

Our aim was to investigate the effects of interferons (IFNs)- λ (interleukin-29 [IL-29], IL-28A, and IL-28B) on hepatitis C virus (HCV) and hepatitis A virus (HAV) internal ribosomal entry site (IRES)-mediated translation. The effects of these IFNs on HCV/HAV translation from HAV/HCV IRES were investigated using bicistronic reporter constructs. We transfected HCV/HAV IRES constructs into these IFN-expressing cell lines. IL-29 showed stronger inhibition of their IRES-mediated translation. Combining IL-29 with IFN- α or amantadine resulted in stronger inhibition of HAV IRES activity. Our findings demonstrated a novel antiviral effect of IFNs- λ against HAV and HCV through the suppression of IRES-mediated translation.

Introduction

HEPATITIS A VIRUS (HAV), A NONENVELOPED RNA VIRUS OF THE PICORNAVIRIDAE FAMILY, is the major causative agent of acute viral hepatitis, and occasionally leads to acute liver failure including fulminant hepatitis (17,31,32). The HAV genome is approximately 7600 nt in length and consists of a 5' nontranslated region (5' NTR), a single open reading frame that encodes both structural (VP4, VP2, VP3, and VP1) and nonstructural proteins (2A, 2B, 2C, 3A, 3B, 3C, and 3D), and a 3' NTR with a polyadenylation signal (polyA) tail. The HAV genome also has an internal ribosomal entry site (IRES) that can promote 5'-end-independent initiation of RNA translation (2,11,12,15,19,20,45).

Hepatitis C virus (HCV), an enveloped RNA virus of the Flaviviridae family, causes a spectrum of diseases ranging from an asymptomatic carrier state to end-stage liver disease, including cirrhosis and hepatocellular carcinoma (HCC) (1,14,16). HCV has a 5' NTR, a long open reading frame, and a 3' NTR. The HCV genome is approximately 9600 nt in size and encodes a polyprotein precursor of about 3000 amino acids, which is cleaved by both viral and host proteases into structural (core, E1, E2, and p7) and nonstructural (NS2, NS3, NS4A, NS4B, NS5A, and NS5B) proteins. HCV also has IRES containing a 5' NTR and part of the core coding region which forms a secondary structure, and supports translation initiation of an HCV genome in a cap-independent manner (18,24).

IFNs- λ are the most recently defined members of the class III cytokine family, consisting of IL-28A (IFN- λ 2), IL-28B (IFN- λ 3), and IL-29 (IFN- λ 1), and a component of their receptor, IL28-R α . IL-28 and IL-29 represent an evolutionary link between type I IFNs and the IL-10 family (39). This receptor-ligand system might contribute to antiviral or other defenses by a mechanism similar to, but independent of, type I IFN (25). Additional study is necessary to determine whether IFN- λ can synergize with IFN- α in viral infections, or whether it plays an independent primary role in the antiviral system (41).

There are several reports that IFN- λ exerts antiviral activity against HBV (36), HCV (36), West Nile virus (WNV) (29), influenza A virus, influenza B virus, respiratory syncytial virus, human metapneumovirus, and severe acute respiratory syndrome (SARS) coronavirus (34,41). Human hepatocytes express the IFN- λ receptor complex and IFNs- λ induce signal transducer and activator of transcription 1 (STAT1) phosphorylation (5). Activation of STAT1 is an important factor for the eradication of HCV after antiviral treatments (33). In addition, cellular proteins known as IRES trans-acting factors (ITAFs) are also required for efficient IRES-mediated translation (23,26). The subset of ITAFs that regulates translation initiation appears to be specific for each IRES element (23,26). IFNs including IFNs- λ affect host factors (21,27).

We reported that HAV IRES is an attractive target of anti-HAV drugs because IRES is located in the 5' NTR, the most

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conserved region among different HAV strains (19,20,45), and is well conserved among clinical isolates (15,17). It has also been reported that HCV IRES is an attractive target of anti-HCV drugs because IRES is located in the 5' NTR, the most conserved region among different HCV strains (18,24). We focused on the IRES as an antiviral target of these viruses because IRES activity seems to be correlated with translation of viral protein, which is important for viral replication, although there are contrary opinions. Recently, several groups reported that IL-28B SNP predicts hepatitis C treatment-induced viral clearance and natural clearance (10,16,36,42). In the present study, we examined the inhibitory effects of IFN- λ against HAV and HCV IRES-mediated translation.

Materials and Methods

Cells and virus

Huh7 cells were cultured in Dulbecco's modified Eagle's medium supplemented with 10% fetal calf serum (FCS) at 37°C and 5% CO₂. The plasmids pcDNA3.1-IL28A, pcDNA3.1-IL28B, and pcDNA3.1-IL29 [kindly provided by Prof. T. Betakova, Institute of Virology, Slovak Academy of Sciences, Bratislava, Slovak Republic (41)] were plasmids expressing IL-28A, IL-28B, and IL-29, respectively. Huh7 cells were transfected with the expression plasmids pcDNA3.1-IL28A, pcDNA3.1-IL28B, pcDNA3.1-IL29, or pcDNA3.1 in Effectene transfection reagent (Qiagen, Hilden, Germany). After 48 h, G418 (Promega, Madison, WI) was added at 1000 μ g/mL for selection of Huh7-IL28A, Huh7-IL28B, Huh7-IL29, or Huh7-pcDNA3.1. After 3 wk, to avoid monoclonal selection, all cells were collected for further analysis.

Cell culture-grown HCV JFH1 (genotype 2a) was used in Huh7-derived cell lines (14,43). Tissue culture-adapted HAV strain KRM003 (genotype IIIB) was used in African green monkey kidney GL37 cells (22,37). A HAV DNA-based subgenomic replicon [kindly provided by Prof. V. Gausmuller, Institute of Virology, University of Luebeck, Luebeck, Germany (9)] was also used in HuhT7 cells that stably express T7-RNA polymerase in cytoplasm (9,38).

Reagents

The chemicals used were human recombinant IFN- α (Sigma-Aldrich, St. Louis, MO), human recombinant IL29 (IFN- λ 1; Acris Antibodies GmbH, Herford, Germany), and amantadine hydrochloride (Sigma-Aldrich).

Bicistronic reporter plasmids

The bicistronic plasmid pSV40-HAV IRES-luc, encoding *Renilla reniformis* luciferase (Rluc) and firefly luciferase (Fluc), was separated by HAV IRES derived from pHM175 (kindly provided by Prof. S.U. Emerson, U.S. National Institutes of Health) under the control of SV40 promoter, with a polyadenylation signal (polyA; Fig. 1A) (19). The bicistronic plasmid pSV40-HCV IRES-luc (kindly provided by Prof. M. Kruger, Medizinische Hochschule Hannover, Hannover, Germany), carries the Rluc gene, the HCV IRES, including the full-length HCV core, and the Fluc gene under control of the SV40 promoter, with a polyadenylation signal (polyA; Fig. 1B) (18,24).

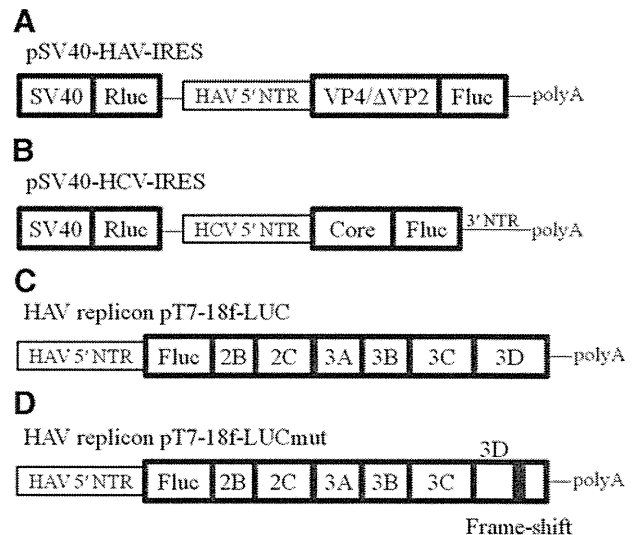


FIG. 1. Structure of HAV/HCV reporter constructs used in this study. (A) pSV40-HAV IRES-luc encodes the *Renilla reniformis* luciferase (Rluc), the internal ribosomal entry site (IRES) of HAV HM175, and firefly luciferase (Fluc) under the control of SV40 promoter, with a polyadenylation signal (polyA) (19). (B) pSV40-HCV IRES-luc encodes Rluc, the HCV IRES, including the full-length HCV core, and the Fluc gene under control of SV40 promoter, with a polyadenylation signal (polyA) (18,24). (C) Replication-competent HAV replicon pT7-18f-LUC contains an open-reading frame of Fluc flanked by the first four amino acids of HAV polyprotein, and by 12 C-terminal amino acids of VP1. This segment is followed by P2 and P3 domains of HAV strain HM175 18f (9). (D) Replication-incompetent HAV replicon pT7-18f-LUCmut contains a frameshift mutation in the polymerase 3D (9) (5' NTR, 5' nontranslated region; 3' NTR, 3' nontranslated region).

Transfection and in vitro reporter assays

Approximately 1.0×10^5 cells per well were placed in a six-well plate (Iwaki Glass, Tokyo, Japan) 24 h prior to transfection. The cells were transfected with 0.4 μ g of pSV40-HAV (HCV) IRES-luc using Effectene Transfection Reagent (Qiagen) following the manufacturer's protocol. Forty-eight or 72 h after transfection, the cells were harvested using reporter lysis buffer (Toyo Ink, Tokyo, Japan), and luciferase activity was determined by luminometer (Luminescencer-JNR II AB-2300; ATTO, Tokyo, Japan) (44). To control for variations in transcription, IRES activity was assessed by measuring the ratio of Rluc and Fluc activities. The relative ratio of Fluc activity to Rluc activity (Fluc:Rluc) was defined as 100% in the untreated condition. We accept more than 10^2 of Fluc/Rluc as being positive for IRES activity. All samples were run in triplicate.

RNA extraction, cDNA synthesis, and RT-PCR

The cells were seeded into 6-well plates, and total cellular RNA was extracted 48 h later with the RNeasy Mini Kit (Qiagen) according to the manufacturer's instructions. The RNA samples were then stored at -80°C until use. RNA quality was examined using the A₂₈₀:A₂₆₀ ratio (Pharmacia Biotech, Bedford, MA). cDNA synthesis was performed with a random hexamer using Prime Script reverse transcriptase

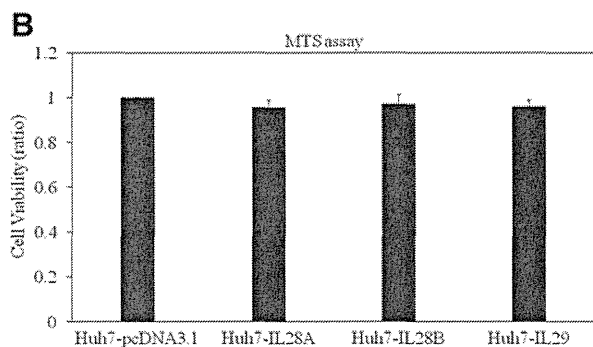
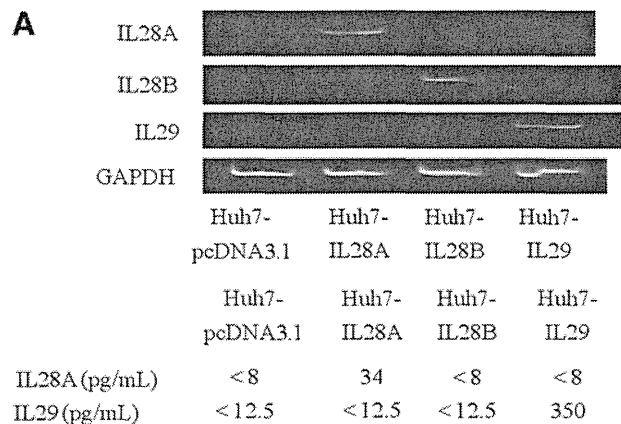


FIG. 2. Overexpression of IL-28A, IL-28B, or IL-29 in human hepatoma cell line Huh7. (A) Expression of IFNs- λ mRNA in Huh7-pcDNA3.1, Huh7-IL28A, Huh7-IL28B, and Huh7-IL29 cells (upper panel). RT-PCR was performed using each specific primer. ELISA results for IL-28A and IL-29 are shown in the lower panel. The sensitivities for human IL-28A and IL-29 by these ELISA kits were 8 pg/mL and 12.5 pg/mL, respectively. (B) IL-28A, IL-28B, or IL-29 expression does not inhibit cell growth and viability. Huh7-derived cells were plated at a density of 0.5×10^6 , and MTS assay was performed at 24 h. The value of Huh7-pcDNA3.1 was set at 1. Data are expressed as mean \pm SD of triplicate determinations from one experiment representative of four independent experiments.

(Takara Bio Inc., Otsu, Shiga, Japan). For detection of ectopic expression of IL-28A, IL-28B, and IL-29, RT-PCR was performed with a Thermal Cycler (TP3000; Takara Bio Inc.) using PrimeSTAR HS DNA polymerase (Takara Bio Inc.) with primers as previously described (41), together with primers for GAPDH (44).

Enzyme-linked immunosorbent assay (ELISA) for IL-28A and IL-29

Cell culture fluid was analyzed for human IL-28A and for IL-29 by ELISAs (R&D Systems, Minneapolis, MN and eBioscience, San Diego, CA, respectively), following the manufacturers' protocols. Briefly, cell culture fluid samples were incubated in plates at 37°C overnight, followed by incubation with biotinylated monoclonal antibodies. Avidin-conjugated peroxidase was added to the plates, and enzyme activity was detected with a Bio-Rad iMark microplate reader (Bio-Rad, Hercules, CA) (44). The sensitivities of human IL-28A and IL-29 by these ELISA kits were 8 pg/mL and 12.5 pg/mL, respectively.

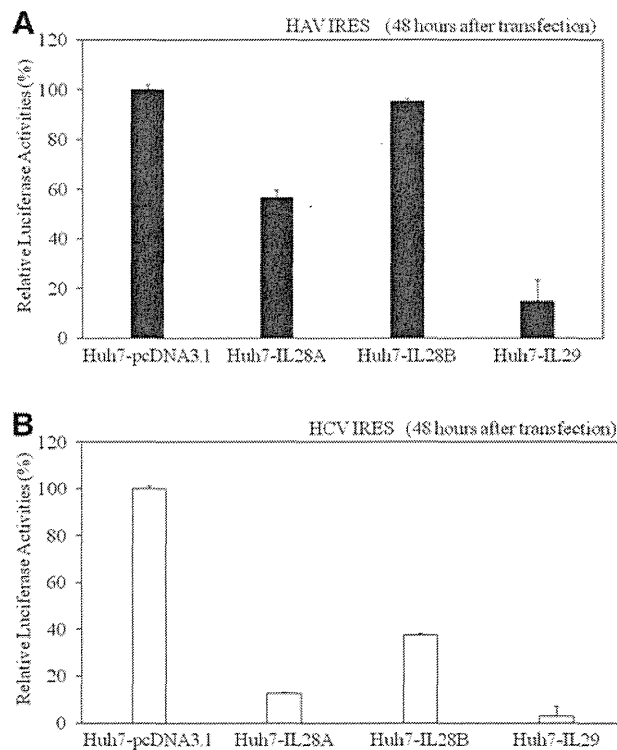


FIG. 3. Interferon- λ inhibits hepatitis A virus (HAV) (A) and HCV (B) internal ribosomal entry site (IRES)-mediated translation in human hepatoma cells. Huh7-IL28A, Huh7-IL28B, Huh7-IL29, and Huh7-pcDNA3.1, were transfected with pSV40-HAV IRES reporter vector (19) (A), and pSV40-HCV IRES reporter vector (18,24) (B), and 48 h later, luciferase activity was measured and IRES activity was determined. Relative luciferase activity (Fluc/Rluc) in Huh7-pcDNA3.1 was set at 100%. Data are expressed as mean \pm SD of triplicate determinations from one experiment representative of three independent experiments.

MTS assay

To evaluate cell growth and cell viability, dimethylthiazol carboxymethoxyphenyl sulfophenyl tetrazolium (MTS) assays were performed with the CellTiter 96 Aqueous One-Solution cell proliferation assay (Promega).

Statistical analysis

Data were expressed as mean \pm SD. Statistical analysis was done by Student's *t*-test. A value of $p < 0.05$ was considered significant.

Results

Overexpression of IL-28A, IL-28B, or IL-29, in Huh7 cells

We used three protein plasmid vectors under control of the CMV promoter: pcDNA3.1-IL28A, pcDNA3.1-IL28B, and pcDNA3.1-IL29 (41). We established three IFN- λ -overexpressing Huh7 cells, designated as Huh7-IL28A, Huh7-IL28B, and Huh7-IL29. We also used pcDNA3.1 for the establishment of a control cell, Huh7-pcDNA3.1. For the generation of stable cell lines, Huh7 cells were transfected

with these vectors and treated with G418. Antibiotic-resistant colonies were expanded for further analysis. To test the ability of these cells to express IL-28A and IL-29, we detected these mRNAs by RT-PCR and measured these cytokines by ELISA (Fig. 2A, upper and lower panels). IL-28A or IL-29 mRNAs were detected only in Huh7-IL28A or Huh7-IL29 cells, respectively. IL-28A or IL-29, respectively, could be measured in each cell culture fluid of Huh7-IL28A or Huh7-IL29. We confirmed the expression of IL-28B mRNA in the

cellular RNA of Huh7-IL28B since we could not use ELISA for IL-28B at this time (Fig. 2A, upper panel). We next examined whether overexpression of IFN- λ had any effect on cell proliferation. Equal numbers of control Huh7-pcDNA3.1 and IFN- λ -overexpressing Huh7 cells (Huh7-IL28A, Huh7-IL28B, and Huh7-IL29) were plated, and cell viability was counted at 24 h by MTS assay (Fig. 2B). There were no differences in cell viabilities among these cell lines.

HAV IRES activity in Huh7-IL28A, Huh7-IL28B, and Huh7-IL29

Next, we examined the effects of these IFNs- λ on HAV IRES-mediated translations using a luciferase reporter assay. Huh7-IL28A, Huh7-IL28B, Huh7-IL29, and Huh7-pcDNA3.1 were transfected with pSV40-HAV IRES reporter vector encoding SV40 promoter driven-Rluc and Fluc, separated by HAV IRES (19), and 48 h later, luciferase activity was measured and IRES activity was determined (Fig. 3A). HAV IRES activity was inhibited in Huh7-IL28A (56.7%; $n=3$, $p<0.0001$), Huh7-IL28B (95.3%, $n=3$, $p=0.0021$), and Huh7-IL29 (14.9%, $n=3$, $p<0.0001$), compared to that in control Huh7-pcDNA3.1 ($n=3$, 100%). IL-28A and IL-28B demonstrated inhibitory effects on HAV IRES activity, but they seemed less efficient than IL-29 (Fig. 3A).

HCV IRES activities in Huh7-IL28A, Huh7-IL28B, and Huh7-IL29

It is known that HCV also has IRES structures and plays an important role in the translation of HCV proteins (18,24). In order to compare the effects of IFNs- λ on HCV IRES-mediated translation with those on HCV, we next tested their effects on HCV IRES-mediated translation using a luciferase reporter assay. Huh7-IL28A, Huh7-IL28B, Huh7-IL29, and Huh7-pcDNA3.1 were transfected with pSV40-HCV IRES reporter vector encoding SV40 promoter driven-Rluc and Fluc, separated by HCV IRES (24), and 48 h later, luciferase activity was measured and IRES activity was determined (Fig. 3B). HCV IRES activity was inhibited in Huh7-IL28A (12.5%, $n=3$, $p<0.0001$), Huh7-IL28B (37.5%, $n=3$, $p<0.0001$), and Huh7-IL29 (2.7%, $n=3$, $p<0.0001$), compared to that in control Huh7-pcDNA3.1 ($n=3$, 100%). Similarly to HAV IRES, IL-28A and IL-28B demonstrated inhibitory effects on HCV

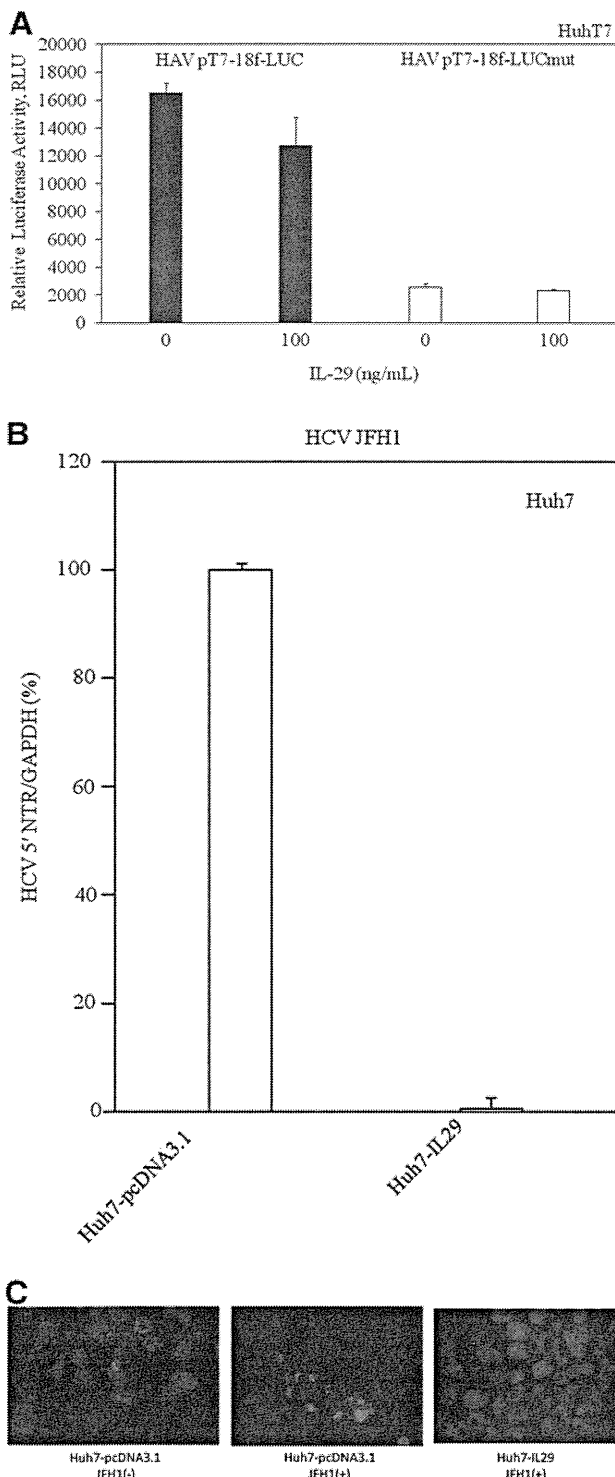


FIG. 4. IL29 suppresses hepatitis A virus (HAV) (A) and HCV (B and C) replication. (A) HuhT7 cells were transfected with replication-competent HAV replicon pT7-18f-LUC or replication-incompetent HAV replicon pT7-18f-LUCmut (9). At 60 h post-transfection, the cells were treated with 0 or 100 ng/mL IL-29. At 72 h post-transfection, reporter assays were performed to evaluate HAV subgenomic replication. (B) Huh7-IL29 and Huh7-pcDNA3.1 were infected with HCV JFH1 (genotype 2a) (14,43), and 72 h later, HCV RNA was measured by real-time RT-PCR and HCV 5'NTR/GAPDH ratios were measured by ddCt methods. (C) After 72 h of infection, HCV was detected by immunofluorescence using antibody to the core protein. Shown are representative photomicrographs of JFH1 virus production in Huh7-IL29 and Huh7-pcDNA3.1 cells. Data are expressed as mean \pm SD of triplicate determinations from one experiment representative of three independent experiments.

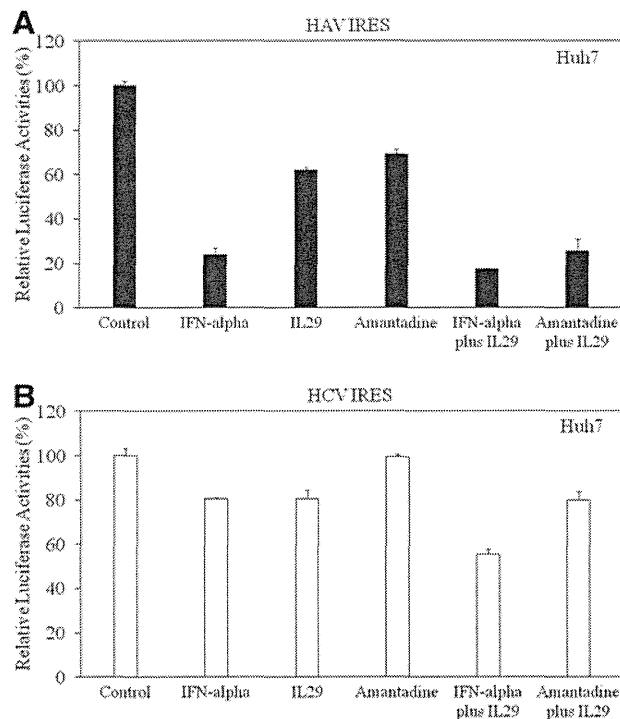


FIG. 5. Effects of IL-29 with or without interferon (IFN)- α or amantadine on hepatitis A virus (HAV) (A) and HCV (B) internal ribosomal entry site (IRES)-mediated translation in Huh7 cells. Huh7 cells were transfected with pSV40-HAV IRES reporter vector (19) (A), or pSV40-HCV IRES reporter vector (18,24) (B), and 48 h later, the cells were treated with 50 ng/mL IL-29 with or without 50 μ g/mL amantadine or 100 IU/mL IFN- α , and 24 h later luciferase activity was measured and IRES activity was determined. Relative luciferase activity (Fluc/Rluc) without treatment was set at 100%. Data are expressed as mean \pm SD of triplicate determinations from one experiment representative of three independent experiments.

IRES activity, but they seemed less efficient than IL-29 (Fig. 3B).

IL-29 inhibits both HAV and HCV replication

Next we investigated the effect of IL-29 on HAV subgenomic replication in Huh7 cells (9). IL-29 at 100 ng/mL led to 22.8% ($n=3$, $p=0.038$) inhibition of HAV replication, but we observed no reduction of HAV mutant replication (Fig. 4A). We also examined whether IL-29 inhibits HAV strain KRM003 propagation in GL37 cells, but at 50 ng/mL of IL-29 we could not observe any effect on the inhibition of HAV propagation. Two-hundred and fifty and 500 ng/mL of IL-29 showed a tendency to inhibit HAV propagation without cell damage. However, it was difficult to obtain a stable reaction. Further study will be needed.

We also examined whether IL-29 inhibits HCV replication in Huh7-derived cell lines. Huh7-IL29 and Huh7-pcDNA3.1 were infected with HCV JFH1 (genotype 2a) (14,43), and 72 h later, HCV RNA was detected less in Huh7-IL29 (0.6%; $n=3$, $p<0.0001$) than in Huh7-pcDNA3.1 (100%; $n=3$, $p<0.0001$; Fig. 4B). HCV core protein expression was also less observed in Huh7-IL29 than in Huh7-pcDNA3.1 (Fig. 4C).

Exogenous IL-29 with or without IFN- α or amantadine inhibits HAV IRES activity in Huh7

As Huh7-IL29 cells had the strongest inhibitory effect on HAV IRES-mediated translation (Fig. 3A), we investigated whether exogenous IL-29 had similar effects on HAV IRES-mediated translation using a luciferase reporter assay (Fig. 5A). Huh7 cells were transfected with pSV40-HAV IRES reporter vector (19), and 48 h later, cells were treated with IL-29 with or without amantadine or IFN- α , and 24 h after this, luciferase activity was measured and IRES activity was determined (Fig. 5A).

We previously reported that amantadine with or without IFN- α inhibits HAV IRES-mediated translation in human hepatoma cells (19,45). HAV IRES activity was significantly inhibited, to 24.1% ($n=3$, $p<0.0001$), 62.1% ($n=3$, $p<0.0001$), and 69.1% ($n=3$, $p<0.0001$), by 100 IU/mL IFN- α , 50 ng/mL IL-29, and 50 μ g/mL amantadine, respectively (Fig. 5A). The combination of IL-29 with IFN- α or amantadine led to 82.7% ($n=3$, $p<0.0001$), or 74.6% ($n=3$, $p<0.0001$) inhibition of HAV IRES activity, respectively, with these combinations demonstrating stronger effects than IL-29 alone (Fig. 5A).

In order to compare the effects of exogenous IL-29 on HAV IRES-mediated translation with those on HCV, we next tested the effects of IL-29 with or without amantadine or IFN- α on HCV IRES-mediated translation using a luciferase reporter assay. Huh7 cells were transfected with pSV40-HCV IRES reporter vector (24), and 48 h later, the cells were treated with IL-29 with or without amantadine or IFN- α , and 24 h after this, luciferase activity was measured and IRES activity was determined (Fig. 5B). HCV IRES activity demonstrated significant inhibition, to 80.6% ($n=3$, $p=0.00061$) and 80.6% ($n=3$, $p=0.00027$) by IFN- α and IL-29, respectively, but showed no inhibition by amantadine only (99.3%, $n=3$; Fig. 5B). The combination of IL-29 with IFN- α led to a 44.5% ($n=3$, $p<0.0001$) inhibition of HCV IRES activity, with this combination demonstrating stronger effects than IL-29 alone. However, the combination of IL-29 with amantadine resulted in only 20% inhibition ($n=3$, $p=0.00027$) of HCV IRES activity, similarly to the effect of IL-29 alone (Fig. 5B).

Discussion

We demonstrated that IL-29 inhibited HAV as well as HCV IRES activity in human hepatoma cell line Huh7, and that Huh7-IL29 had stronger effects than Huh7-IL28A, Huh7-IL28B, and Huh7-pcDNA3.1. The combination of IL-29 with IFN- α or amantadine seemed to have stronger inhibitory effects on HAV IRES activity than IL-29 alone.

IFNs- λ modulate innate and adaptive immune responses to environmental pathogens and protect the host against diseases such as cancer. Expression of IFNs- λ is tightly regulated by viral infection, including hepatitis viral infection (6,7). IFNs- λ utilize a receptor complex different from IFN- α , but both types of IFN induce STAT1 and STAT2, as well as STAT3 activation (33,48). Binding of IFN to the IFN receptor leads to the activation of receptor-associated Janus tyrosine protein kinase (Jak1). IFN stimulation results in tyrosine phosphorylation, dimerization, and nuclear import of STATs (3). STATs and the IFN-stimulated gene factor 3 (ISGF3) transcription factor complex move into the nucleus and bind to IFN-stimulated response elements (ISRE) in the promoters of the

IFN-stimulated genes (ISGs). ISGs inhibit viral replication and activate numerous downstream cellular responses.

In contrast to IFN- α , IFNs- λ bind to a heterodimeric receptor consisting of IL-28R α subunit and IL10R β receptor subunit, that is also shared by IL-10, IL-22, and IL-26. Because the IFN- λ receptor is different from that of IFN- α , their uses as alternative therapies for viral hepatitis need to be examined (6). Although the biological activities of IFNs- λ could overlap with IFN- α , the expression of IL-28R α receptor is limited in contrast to the ubiquitously expressed IL10R β , and IFNs- λ might have fewer adverse events than type I IFN (28). We also found that the combination of IL-29 with IFN- α or amantadine demonstrated stronger inhibitory effects on HAV IRES activity. The combination of IL-29 with amantadine may also be useful in some HAV patients.

We did not observe any differences in HAV 5' NTR or HCV 5' NTR RNA detection by RT-PCR among Huh7-pcDNA3.1, Huh7-IL28A, Huh7-IL28B, and Huh7-IL29 at 72 h after transfection of pSV40-HAV IRES-luc or pSV40-HCV IRES-luc (data not shown), although we could not completely exclude the destruction of IRES mRNAs, because IFNs- λ as well as IFN- α activate double-stranded protein kinase PKR and 2',5'-oligo A (2-5A) synthetases (21). Several noncanonical translation initiation factors such as La protein and polypyrimidine tract binding protein (PTB) have been implicated in translation from HAV and HCV IRESes (4,13,40,46). The effects of IL-29 on these proteins should be examined in future studies.

We previously demonstrated that siRNAs targeted against HAV IRES, amantadine, and IFN- α , inhibited HAV IRES-mediated translation and HAV replication (15,19,33,45). In the present study, we planned to examine the effects of IFN- λ on HAV IRES-mediated translation. IFNs are proteins induced by lymphocytes and other cells including hepatocytes in response to viruses such as HAV. Our study also supports the notion that IFNs- λ might inhibit HAV IRES-mediated translation as one of the host defense mechanisms against HAV infection.

It has been reported that genetic variations in IL-28B SNPs predict hepatitis C treatment-induced viral clearance and natural clearance (10,16,33,42). Tanaka *et al.* (42) reported that IL-28B minor SNP was associated with a null virological response in the treatment of Japanese patients infected with HCV genotype 1. Yu *et al.* (47) also reported that the IL-28B rs8099917 TT genotype is significantly independently predictive of RVR, which is the single best predictor of SVR, in Asian HCV genotype 2 patients. Pegylated IL-29 induces antiviral gene expression and represses hepatitis B and C replication *in vitro* (6), and HCV replication *in vivo* (35). Among IFNs- λ , it was reported that IL-28A inhibits HCV IRES-mediated translation and suppresses HCV replication (49). Kato *et al.* (21) reported that IFN- α , as well as IFN- β , specifically suppress the translation from HCV IRES. We also demonstrated that siRNAs targeted against HCV IRES were potent inhibitors of HCV IRES-mediated translation and HCV replication (18). In the present study, we demonstrated that IL-29, as well as IFN- α , inhibited HCV IRES-mediated translation, although amantadine did not inhibit HCV IRES-mediated translation in our experimental condition.

In conclusion, we demonstrated that IL-29 suppressed HAV as well as HCV IRES-mediated translation. Viral

IRES activity may influence the level of replication (8,15,18), although it was reported that the preponderance of host factors might determine the clinical presentation (30). To inhibit HAV or HCV IRES-mediated translation, the combination IL-29 with IFN- α or amantadine has a stronger inhibitory effect. IFNs- λ might also play an important role in host defense mechanisms and in HAV pathogenesis.

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Author Disclosure Statement

No competing financial interests exist.

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