

# Robust Production of Infectious Hepatitis C Virus (HCV) from Stably HCV cDNA-Transfected Human Hepatoma Cells

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**Hepatitis C virus (HCV) chronically infects approximately 170 million people worldwide, with an increased risk of developing cirrhosis and hepatocellular carcinoma. The study of HCV replication and pathogenesis has been hampered by the lack of an efficient stable cell culture system and small-animal models of HCV infection and propagation. In an effort to develop a robust HCV infection system, we constructed stable human hepatoma cell lines that contain a chromosomally integrated genotype 2a HCV cDNA and constitutively produce infectious virus. Transcriptional expression of the full-length HCV RNA genome is under the control of a cellular Pol II polymerase promoter at the 5' end and a hepatitis delta virus ribozyme at the 3' end. The resulting HCV RNA was expressed and replicated efficiently, as shown by the presence of high levels of HCV proteins as well as both positive- and negative-strand RNAs in the stable Huh7 cell lines. Stable cell lines robustly produce HCV virions with up to 10<sup>8</sup> copies of HCV viral RNA per milliliter (ml) of the culture medium. Subsequent infection of naïve Huh7.5 cells with HCV released from the stable cell lines resulted in high levels of HCV proteins and RNAs. Additionally, HCV infection was inhibited by monoclonal antibodies specific to CD81 and the HCV envelope glycoproteins E1 and E2, and HCV replication was suppressed by alpha interferon. Collectively, these results demonstrate the establishment of a stable HCV culture system that robustly produces infectious virus, which will allow the study of each aspect of the entire HCV life cycle.**

Discovered in 1989 by molecular cloning (10), hepatitis C virus (HCV) has been recognized as a major cause of viral hepatitis in humans. HCV infection is characterized by the establishment of chronic infection in the majority (up to 85%) of individuals exposed to HCV. It is estimated that approximately 4 million people in the United States and 170 million people worldwide are persistently infected (9, 38). The chronic HCV infection carries an increased risk of developing fatal liver diseases such as cirrhosis, liver failure, and hepatocellular carcinoma. HCV is a single-stranded positive-sense RNA virus belonging to the *Hepacivirus* genus of the family *Flaviviridae* (30). The 9.6-kb RNA genome encodes a single polyprotein that is cleaved by cellular and viral proteases into at least 10 structural (C, E1, E2, and probably p7) and nonstructural (NS2, NS3, NS4A, NS4B, NS5A, and NS5B) proteins that play important roles in virus entry, replication, assembly, and pathogenesis (24, 29). The sequence and structures of the untranslated regions (UTR) at both the 5' and 3' ends of the HCV RNA genome, which contain *cis*-acting RNA elements required for HCV RNA translation and replication, are highly conserved (7, 13, 20, 24, 25, 35, 40, 41).

A great deal of progress has been made with respect to the HCV genome organization, properties and roles of viral proteins and conserved RNA sequence/structures, virus-host

interactions, and mechanisms of HCV replication since the discovery of HCV (1, 24, 29, 36). A number of studies demonstrated that cDNA-derived HCV RNAs were infectious in chimpanzees upon intrahepatic inoculation (6, 19, 39). The chimpanzee model of HCV infection has played a central role in understanding HCV replication, disease progression, and host immune response (6, 32). A breakthrough advance was the development of a cell-based replication system in which HCV RNAs were efficiently replicated (4, 23). The HCV replicons have made it possible to determine the roles of viral proteins and RNA sequence and structures in HCV RNA replication (24). However, our ability to study the entire life cycle of HCV propagation and to perform genetic analysis and manipulation of HCV has been hampered until recently by the lack of a robust cell culture system of HCV infection and propagation. For the first time, it has recently been shown that transient transfection of a DNA vector expressing a full-length genotype 1b HCV RNA into Huh7 cells resulted in high levels of HCV virion production (15).

In an effort to develop a robust cell culture system for HCV production and infection, we have constructed stable human hepatoma cell lines that contain a chromosomally integrated cDNA of the genotype 2a HCV genome and robustly produce and secrete infectious HCV into the culture medium. The infectivity of the released HCV from the stable cell lines was demonstrated by the detection of high levels of HCV proteins and RNA in the HCV-infected Huh7.5 cells. Additionally, the HCV infectivity was efficiently neutralized by monoclonal antibodies against the HCV E1 and E2 proteins and CD81 in a

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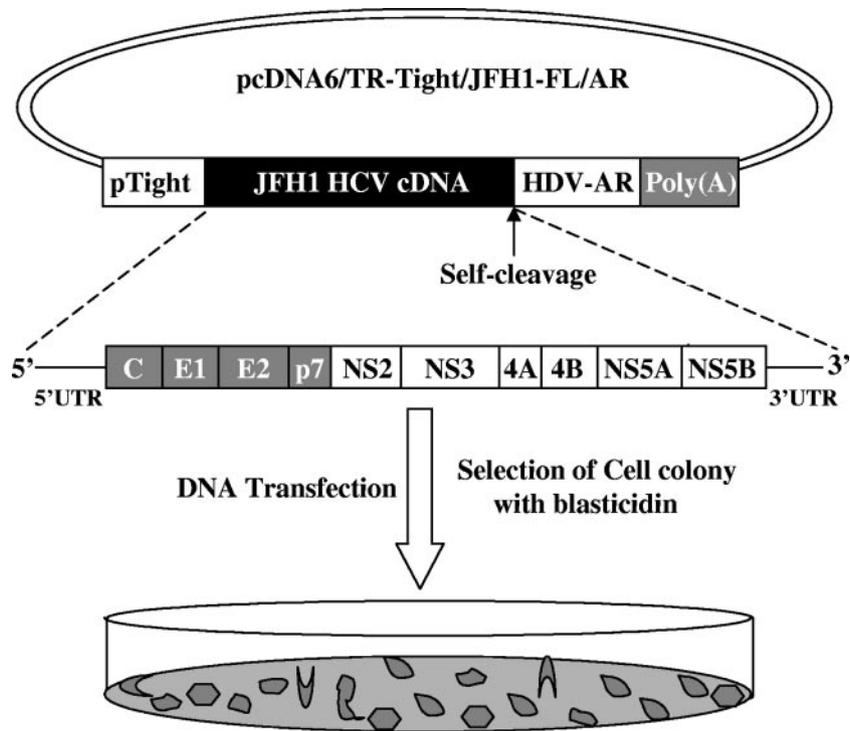


FIG. 1. Diagram of the genetic construction of stable cell lines expressing the HCV RNA genome. The transcriptional expression of the HCV RNA genome is under the control of a minimal CMV promoter (indicated by pTight) and the HDV antigenomic ribozyme (HDV-AR), followed by an SV40 poly(A) signal sequence. The JFH1 HCV genome organization and proteins are highlighted by letters and numbers. The plasmid DNA is introduced into Huh7 cells with DMRIE-C reagent, and stable cell colonies are selected by incubation with 5  $\mu$ g/ml of blasticidin.

dose-dependent manner. The HCV replication was also inhibited by treatment with alpha interferon (IFN- $\alpha$ ). Collectively, our findings demonstrate the establishment of a stable HCV culture system that robustly produces infectious virus, which will allow the study of each aspect of the entire HCV life cycle.

#### MATERIALS AND METHODS

**Cell culture and HCV infection.** A human hepatoma cell line, Huh7, was generously provided by Ralf Bartenschlager and was maintained in Dulbecco's modified Eagle's medium (DMEM) (Invitrogen) supplemented with 100 U/ml of penicillin, 100  $\mu$ g/ml of streptomycin, nonessential amino acids, and 10% fetal bovine serum (FBS) (Invitrogen) (8). Huh7.5, an Huh7 variant cell line that is highly permissive to HCV RNA replication (5), was kindly provided by Charles M. Rice. Stable Huh7 cell lines containing a chromosomally integrated HCV genotype 2a cDNA were selected, amplified, and maintained in DMEM with 10% FBS and 5  $\mu$ g/ml of blasticidin (A. G. Scientific).

**DNA construction.** The sequence of the full-length genotype 2a HCV (JFH1) cDNA was described previously (18). The vector pSGR-JFH1, which contains a subgenomic JFH1 cDNA (16), was used for construction of the full-length JFH1 HCV cDNA. The structural genes C, E1, E2, and p7 as well as the nonstructural gene NS2 were amplified by multiple rounds of PCR using synthetic oligonucleotides (Sigma-Genosys), as described previously (4, 25), based on the reported sequence (18). The synthetic C to NS2 genes were then cloned into the pBR322 vector between the EcoRI and NheI sites, and mutations that occurred during PCR were corrected by site-directed mutagenesis (Stratagene). The resulting C-NS2 genes were combined with the JFH1 subgenomic replicon cDNA, resulting in a full-length cDNA of the JFH1 HCV RNA, designated pSGR-JFH1-FL. A hepatitis delta virus (HDV) antigenomic ribozyme was placed at the immediate 3' end of the HCV RNA, followed by a simian virus 40 (SV40) poly(A) sequence, resulting in a vector designated pSGR/JFH1-FL/AR/pA. The T7 promoter at the 5' end of the pSGR/JFH1-FL/AR/pA vector was replaced with a minimal cytomegalovirus (CMV) promoter (pTight) derived from the pTRE-Tight vector (BD Biosciences) (26), resulting in a DNA construct named pSGR/Tight-JFH1-FL/AR/pA. For construction of stable cell lines, the pcDNA6/TR

containing a blasticidin resistance gene was used as a vector, which was modified by introduction of unique restriction enzyme sites EcoR I and Sbf I. A short DNA fragment formed by oligonucleotides Linker-S (5'-AATTGAATTCGG TACCGCGGCCGCACTAGTCCTGCAGGT-3') and Linker-AS (5'-CCGGAC CTGCAGGACTAGTGCGCCGCGGTACCGAATTC-3') was inserted into pcDNA6/TR between the restriction enzyme sites MfeI and AgeI. The DNA fragment containing the pTight promoter to SV40 poly(A) sequence was excised from the pSGR/Tight-JFH1-FL/AR/pA vector by EcoRI and SbfI digestion and then inserted into the modified pcDNA6/TR vector. The resulting DNA construct was designated pcDNA6/TR-Tight/JFH1-FL/AR.

**DNA transfection and stable cell line selection.** The pcDNA6/TR-Tight/JFH1-FL/AR DNA was transfected into Huh7 cells in a six-well cell culture plate by a lipofection method. Briefly, 2  $\mu$ g of DNA was mixed with 5  $\mu$ l of DMRIE-C reagent in Opti-MEM (Invitrogen) and then transferred onto Huh7 cells. At 24 h posttransfection, cells were split into 100-mm cell culture dishes at various cell densities. Cell colonies were selected by incubation with DMEM containing 10% FBS and 5  $\mu$ g/ml of blasticidin for approximately 2 weeks. Stable cell lines were picked up and amplified. The expression of HCV proteins was detected by Western blotting and immunofluorescence assays using an NS3-specific monoclonal antibody (11), while the levels of the positive- and negative-strand HCV RNAs were determined by an RNase protection assay (RPA) using HCV strand-specific and radiolabeled RNA probes (25).

**Western blot analysis.** The HCV cDNA-harboring Huh7 cells or the HCV-infected Huh7.5 cells were lysed in a radioimmunoprecipitation assay buffer (50 mM Tris-HCl, pH 7.5, 150 mM sodium chloride, 1% Nonidet P40, 0.5% sodium deoxycholate) containing a cocktail of proteinase inhibitors (Roche). The protein concentration of cell extracts was determined by using a protein assay reagent (Bio-Rad). Twenty-five micrograms of total protein for each sample was electrophoresed in a 10% sodium dodecyl sulfate-polyacrylamide gel and then transferred onto a nitrocellulose membrane. The membrane was blocked by incubation with 5% skim milk. The levels of HCV NS3 and E2 proteins were determined by using monoclonal antibodies specific to NS3 and E2 proteins. To raise NS3-specific monoclonal antibodies, the HCV NS3 helicase domain with a six-His tag (NS3H) was expressed in *Escherichia coli* and purified by a nickel column chromatograph method (42). The purified recombinant NS3H was used

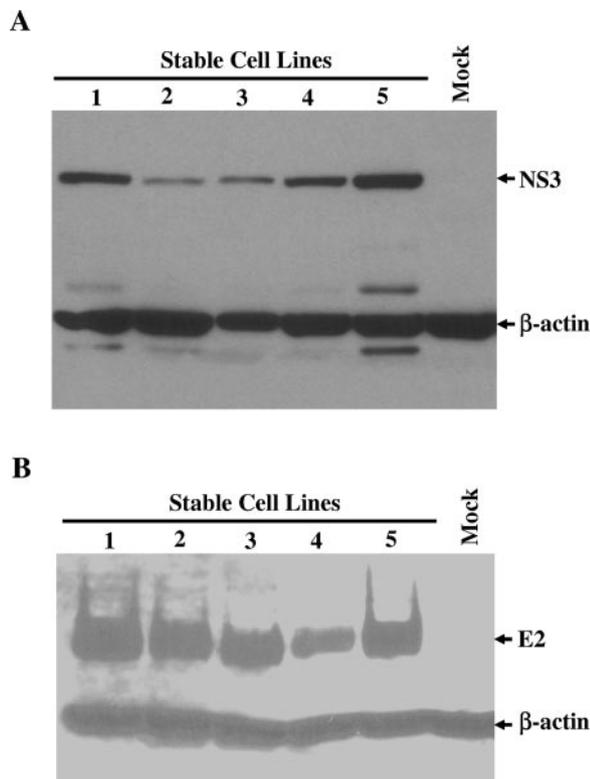


FIG. 2. Determination of the NS3 and E2 proteins in the stable cell lines by Western blotting. A total of 25  $\mu$ g of cell extract was analyzed in a 10% sodium dodecyl sulfate-polyacrylamide gel. The NS3 and E2 proteins were detected by Western blotting using monoclonal antibodies against NS3 and E2 proteins (see Materials and Methods). The stable cell lines are numbered on the top. The naïve parental cell extract (Mock) was used as a negative control, and the  $\beta$ -actin protein was used as an internal control to normalize the amounts of proteins.

as an antigen to immunize mice, and hybridoma cell lines producing NS3 monoclonal antibodies were selected and identified by screening with the recombinant NS3H protein (K. S. Chang et al., unpublished data). The E1 (E1A4) and E2 (AP33) monoclonal antibodies have been described previously (15). The HCV NS3 and E2 proteins were subsequently visualized by using a horseradish peroxidase-conjugated goat anti-mouse immunoglobulin G (IgG; Pierce) and staining with a chemiluminescence substrate (Pierce). The  $\beta$ -actin protein used as an internal control was detected by using an anti- $\beta$ -actin monoclonal antibody (Sigma).

**Immunofluorescence assay (IFA).** Stable cell lines were grown overnight on coverslips in a 24-well culture plate. Cells were washed with 1 $\times$  phosphate-buffered saline (PBS), fixed with 3% paraformaldehyde solution, and permeabilized with 0.1% Triton X-100 (Sigma), as described previously (11). Subsequently, fixed cells were blocked with 1% bovine serum albumin and 1% donkey serum in PBS. The HCV NS3 and E2 proteins in cells were then detected by incubation with NS3- and E2-specific monoclonal antibodies and visualized with the secondary donkey anti-mouse IgG conjugated with Alexa Fluor 594 fluorescein (1:1,000 dilution) (Molecular Probes) (11). As a negative control, purified normal mouse IgG1 (Santa Cruz Biotechnology) was used as a primary antibody. Coverslips were then mounted onto slides, and the HCV proteins were visualized with a Zeiss Axioplan 2 fluorescence microscope.

**RNA preparation and RPA.** The full-length genotype 2a HCV RNA was transcribed in vitro by a T7 RNA polymerase from the pSGR-JFH1-FL/AR DNA linearized with the restriction enzyme XbaI (NEB) using an RNA transcription kit (Promega). After extensive treatment with RNase-free DNase I, the T7 RNA transcripts were purified by using an RNeasy RNA purification kit (QIAGEN). Total cellular RNA was extracted from stable Huh7 cell lines using an RNeasy RNA isolation kit (QIAGEN) or from the HCV-infected Huh7.5 cells with Trizol reagent (Invitrogen). The RNA concentration was determined by spectrophotometry. The levels of positive- and negative-strand HCV RNAs in

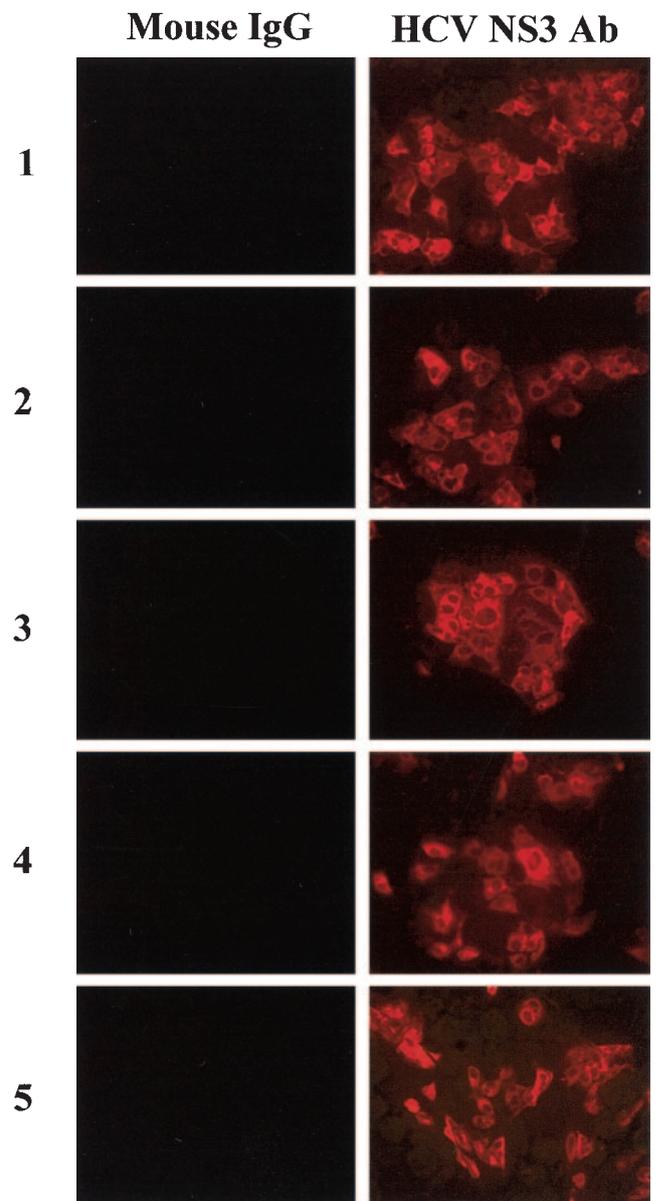


FIG. 3. IFA of the NS3 protein in stable cell lines. The stable cell lines were grown on coverslips. After a 24-h incubation, cells were fixed with 3% paraformaldehyde, permeabilized with 0.1% Triton X-100, blocked with 1% bovine serum albumin and 1% donkey serum, and incubated with an anti-NS3 monoclonal antibody. The NS3 protein in the cell was then visualized with a donkey anti-mouse IgG conjugated with the Alexa Fluor 594 fluorescein (1:1,000 dilution). Each cell line had a negative control using normal mouse IgG as primary antibody. The stable cell lines are numbered at the left.

the stable cell lines or HCV-infected Huh7.5 cells were determined by RPA using [ $\alpha$ - $^{32}$ P]UTP-labeled HCV-specific RNA probes, as described previously (8, 25). Briefly, 10  $\mu$ g of total RNA was used in the RPA for hybridization with  $4 \times 10^4$  cpm of [ $\alpha$ - $^{32}$ P]UTP-labeled  $\beta$ -actin probe and  $10^5$  cpm of either HCV (-)3' untranslated region (UTR) or (+)5' UTR RNA probe (8, 25). RPA was performed by using an RPA III kit following the manufacturer's procedures (Ambion). RNA products were analyzed by electrophoresis in a 6% polyacrylamide-7.7 M urea gel. The levels of RNAs were quantified with phosphorimager analysis.

**Virus purification and sucrose gradient sedimentation.** The culture medium (20 to 25 ml) of each stable cell line in a 162-cm $^2$  tissue culture flask was collected

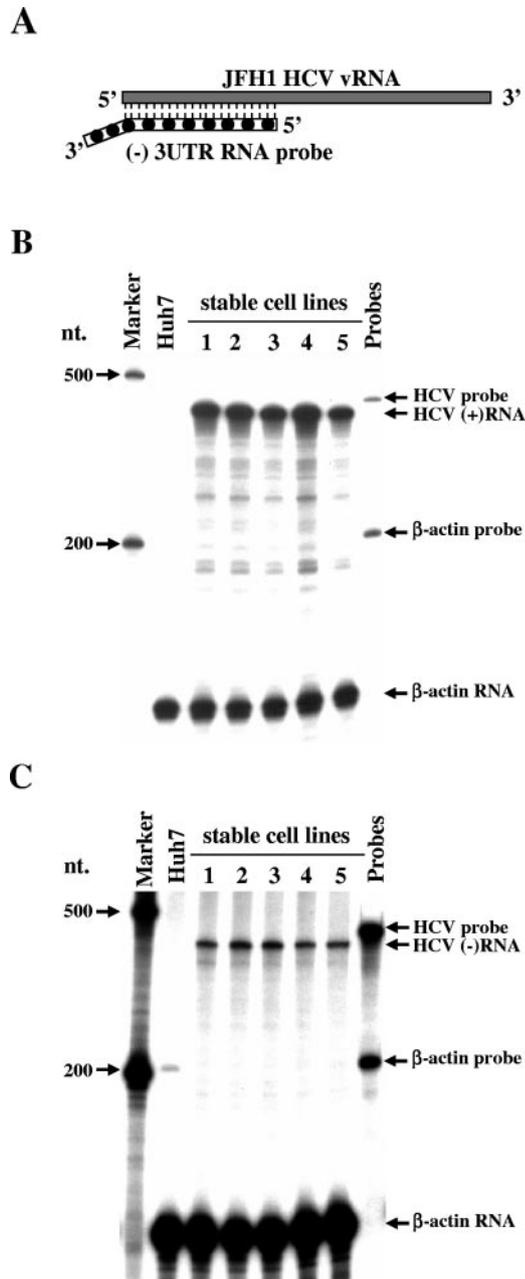


FIG. 4. (A) Schematic of the RPA. A radiolabeled RNA probe contains 377 nucleotides (nt) complementary to either the positive-strand 5' UTR or negative-strand 3' UTR of the JFH1 HCV (genotype 2a) and an additional 40 unpaired nucleotides derived from the vector. After hybridization and digestion with RNase A/T1, the region (377 nucleotides) protected from RNase digestion migrates faster than the incompletely digested RNA probe (417 nucleotides). (B) Determination of the levels of positive-strand HCV RNA present in the stable cell lines by RPA. A total of 10  $\mu$ g of total cellular RNA extracted from stable cell lines was hybridized with  $10^5$  cpm of the [ $^{32}$ P]UTP-labeled negative-strand 3' UTR RNA probe and  $4 \times 10^4$  cpm of human  $\beta$ -actin RNA probe. After RNase digestion, the RNA products were analyzed in a 6% polyacrylamide–7.7M urea gel, autoradiographed, and quantified with a phosphorimager. (C) Determination of the levels of negative-strand HCV RNA by RPA. RPA is done in the same way as described in panel B except that the HCV strand-specific RNA probe was the positive-strand 5' UTR RNA, which is complementary to the negative-strand HCV 3' UTR region (25).

and clarified by centrifugation at 2,000 rpm for 10 min in a tabletop centrifuge to remove any cell debris. The medium was then loaded onto a 20% sucrose cushion in an ultracentrifuge tube. The HCV virions were purified by centrifugation at 27,000 rpm for 4 h at 4°C in a Beckman SW28 rotor. For Western blotting to detect the envelope glycoprotein E2, the virus pellet was lysed in a radioimmunoprecipitation assay buffer. For determination of the HCV virion RNA (vRNA), the virus pellet was resuspended in 250  $\mu$ l of a TNE buffer (100 mM NaCl, 10 mM Tris-HCl, and 1 mM EDTA). The HCV vRNA was extracted with a Trizol-SP reagent (Invitrogen) following the manufacturer's instructions and collected by ethanol precipitation. The vRNA was dissolved in 50  $\mu$ l of RNase-free water. For sucrose density gradient sedimentation analysis of HCV virions, the above-concentrated HCV pellet was loaded onto the top of a continuous 20 to 60% sucrose gradient, followed by centrifugation at 40,000 rpm and 4°C for 16 h in a SW41 rotor (Beckman). Fractions of 1 ml each were collected from the top to the bottom of the sucrose gradient. The vRNA in each fraction (0.25 ml) was extracted with Trizol reagent and quantified by RPA. The infectivity of HCV virions in each fraction was determined by detection of the NS3 protein and positive-strand RNA in Huh7.5 cells infected with 0.1 ml of each fraction.

**HCV infection and infectivity inhibition and neutralization.** The naive Huh7.5 cells in a 6-well tissue culture plate or 24-well plate (IFA) were infected with 1 ml of culture medium. At 3 h postinfection (p.i.), the HCV-containing medium was replaced with 2 ml of DMEM containing 10% FBS, and the cells were incubated at 37°C for 3 days prior to protein and RNA analyses. To determine the infectious titer of HCV, the culture medium was serially diluted 10-fold and used to infect Huh7.5 cells on coverslips in a 24-well culture plate. At 3 days p.i., the HCV infectivity was determined by IFA for NS3 using an NS3-specific monoclonal antibody, as described previously (44). For infectivity neutralization experiments, monoclonal antibodies specific to HCV E1 and E2 proteins (a mixture of two antibodies in equal amounts) and CD81 (Santa Cruz Biotechnology) were diluted with the HCV-containing culture medium. As a negative control, normal mouse IgG1 (Santa Cruz Biotechnology) was used in the neutralization experiments. Huh7.5 cells were infected with the virus-containing medium in the presence of increasing concentrations of normal mouse IgG1, E1/E2 monoclonal antibodies, or monoclonal CD81 antibody. After a 3-h incubation, the virus-containing medium was removed, and the cells were washed with PBS and incubated with fresh DMEM with 10% FBS. For IFN- $\alpha$  inhibition experiments, the cells were infected with HCV at 37°C for 3 h and then incubated with DMEM containing increasing concentrations of human IFN- $\alpha$  (Sigma) for 3 days. The effects of E1/E2 and CD81 monoclonal antibodies and IFN- $\alpha$  on HCV infectivity and replication were determined by the levels of NS3 (Western blotting) protein or HCV RNAs (RPA).

**RT-PCR.** The vRNA in the culture medium at different time points after HCV infection was extracted with Trizol reagent. The vRNA was then determined by a Titan one-tube reverse-transcription PCR (RT-PCR) system using the synthetic oligonucleotides 2a/SfiI (5'-TCCTCAAATGTGTCTGTGGCGTGG-3') and 2a/3' UTR (5'-TCTAGACATGATCTGCAGAGAGACCAGT-3') as primers. The RT-PCR DNA was analyzed in 1% agarose gel and photographed.

## RESULTS

**Genetic construction of stable human hepatoma cell lines expressing HCV RNA genome.** The study of hepatitis B virus (HBV) replication and anti-HBV drug discovery have benefited enormously from the availability of a stable cell line, HepG2.2.15, which constitutively secretes infectious HBV into the culture medium (31). In this study, our goal was to genetically engineer stable human hepatoma cell lines to robustly produce infectious HCV from the chromosomally integrated HCV cDNA. To this end, we chose the JFH1 genotype 2a HCV since the JFH1 HCV RNA was isolated from a fulminant hepatitis C patient and was shown to replicate efficiently in human hepatic as well as nonhepatic cells (16–18). Additionally, we found that the JFH1 HCV RNA was able to replicate efficiently in mouse cells, which will be described elsewhere. To produce HCV RNA in the cell, we constructed a plasmid DNA in which transcription of the full-length HCV RNA genome is under the control of a 5' minimal CMV promoter, and the 3' terminus of the transcript is processed by an HDV ribozyme



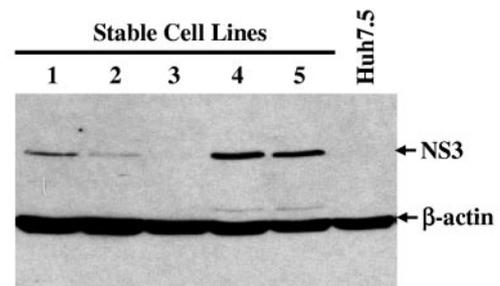
TABLE 1. vRNA copies and infectious titers of HCV virions in the culture medium of stable cell lines

Stable cell lines	vRNA copy numbers per ml	Infectious titer per ml
1	$4.5 \times 10^7$	$8 \times 10^3$
2	$3.0 \times 10^7$	$9 \times 10^3$
3	$2.4 \times 10^7$	$2 \times 10^4$
4	$7.5 \times 10^7$	$9 \times 10^4$
5	$5.4 \times 10^7$	$4 \times 10^4$

the HCV-infected Huh7.5 cells was determined by Western blot analysis, while the positive-strand RNA was detected by RPA. As shown in Fig. 6, the HCV NS3 protein was detected by Western blotting in the HCV-infected Huh7.5 cells (Fig. 6A). Consistent with the levels of the NS3 protein, the positive-strand HCV RNA was also detected by RPA (Fig. 6B). To further determine the infectious titer of HCV, the culture medium was serially diluted by 10-fold and used to infect Huh7.5 cells. The infectious titers were determined by the number of cell foci stained for NS3 by IFA at the lowest dilution point in multiplication with the dilution factor ( $n$ -fold) (44). Results are summarized in Table 1. Surprisingly, the infectious titer of HCV was lower than the vRNA copy number detected by RPA (Table 1) by approximately 1,000-fold, suggesting that a large number of HCV RNAs present in the culture are not in an infectious form. These results are consistent with those obtained from transient transfection of HCV RNA (22, 37, 44). To examine the properties of infectious versus noninfectious HCV virions, we performed a continuous 20 to 60% sucrose density gradient sedimentation analysis. HCV virions in each fraction were analyzed by the detection of vRNA and HCV infectivity. The vRNA was mainly detected in the top fractions (fractions 2 to 8), with the most abundance detected in fractions 5 and 6 (Fig. 7A). Similar to findings reported by others (22), the buoyant density of virion-containing fractions varies from 1.06 to 1.16 g/ml (Fig. 7A). By contrast, fractions 3 and 4, with a buoyant density of 1.11 and 1.12, respectively, contain most of the infectious HCV virions, as determined by NS3 expression (Fig. 7B), and positive-strand HCV RNA (Fig. 7C) in Huh7.5 cells infected with HCV of each fraction. Interestingly, fractions 5 and 6, which contain most of the vRNA, were much less infectious (fraction 5) or noninfectious (fraction 6) (Fig. 7). However, the properties of infectious and noninfectious HCV virions remain to be determined.

In an effort to examine the HCV infectious cycle, we performed a time course study of the HCV infection (Fig. 8). The HCV NS3 protein was detected at 36 h p.i. and was increasingly expressed thereafter (Fig. 8A), while the virus egresses into the culture medium as early as 24 h p.i., as shown for the presence of the HCV vRNA determined by RT-PCR (Fig. 8B). The discrepancy in timing of HCV protein and vRNA detection was most likely due to different sensitivity between Western blotting and RT-PCR analyses. Nevertheless, these findings suggest that the HCV RNA was expressed and that it replicated efficiently upon infection. Taken together, our results clearly demonstrate that the stable cell lines produced and secreted infectious HCV into the culture medium.

A



B

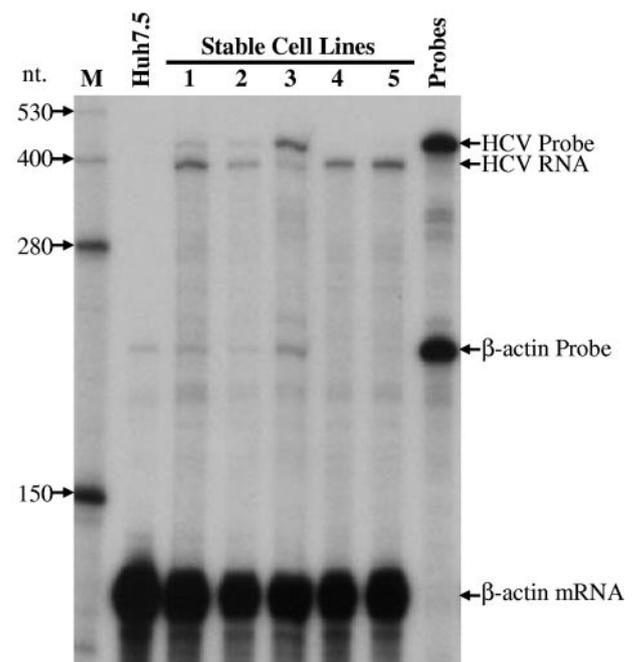


FIG. 6. Determination of the infectivity of the HCV virions secreted by the stable cell lines. The naïve Huh7.5 cells in a six-well plate were incubated with 1 ml of culture medium of each cell line. At 3 h p.i., the HCV-containing medium was replaced with 2 ml of fresh DMEM, and the cells were incubated for 3 days. One set of cells was used for Western blot analysis of the NS3 protein, and the other set was used for isolation of total cellular RNA. (A) Western blotting of the NS3 protein. (B) Determination of positive-strand HCV RNA by RPA. RPA was carried out as described in the legend of Fig. 4. The RNA sizes are indicated at the left. The culture media of the stable cell lines used for infection are numbered at the top.

**Inhibition of the HCV infectivity by monoclonal antibodies specific to the HCV envelope glycoproteins E1 and E2 and the HCV putative receptor CD81.** To further prove the infectivity of HCV virions produced by the stable cell lines, we performed infectivity neutralization and inhibition experiments using monoclonal antibodies specifically against the HCV E1 and E2 proteins and CD81. Results are shown in Fig. 9. The levels of the HCV NS3 protein were unaffected by increasing concentrations of purified normal mouse IgG1 (Fig. 9A). By contrast, the levels of the NS3 protein were proportionally reduced by treatment with increasing concentrations of the anti-E1/E2

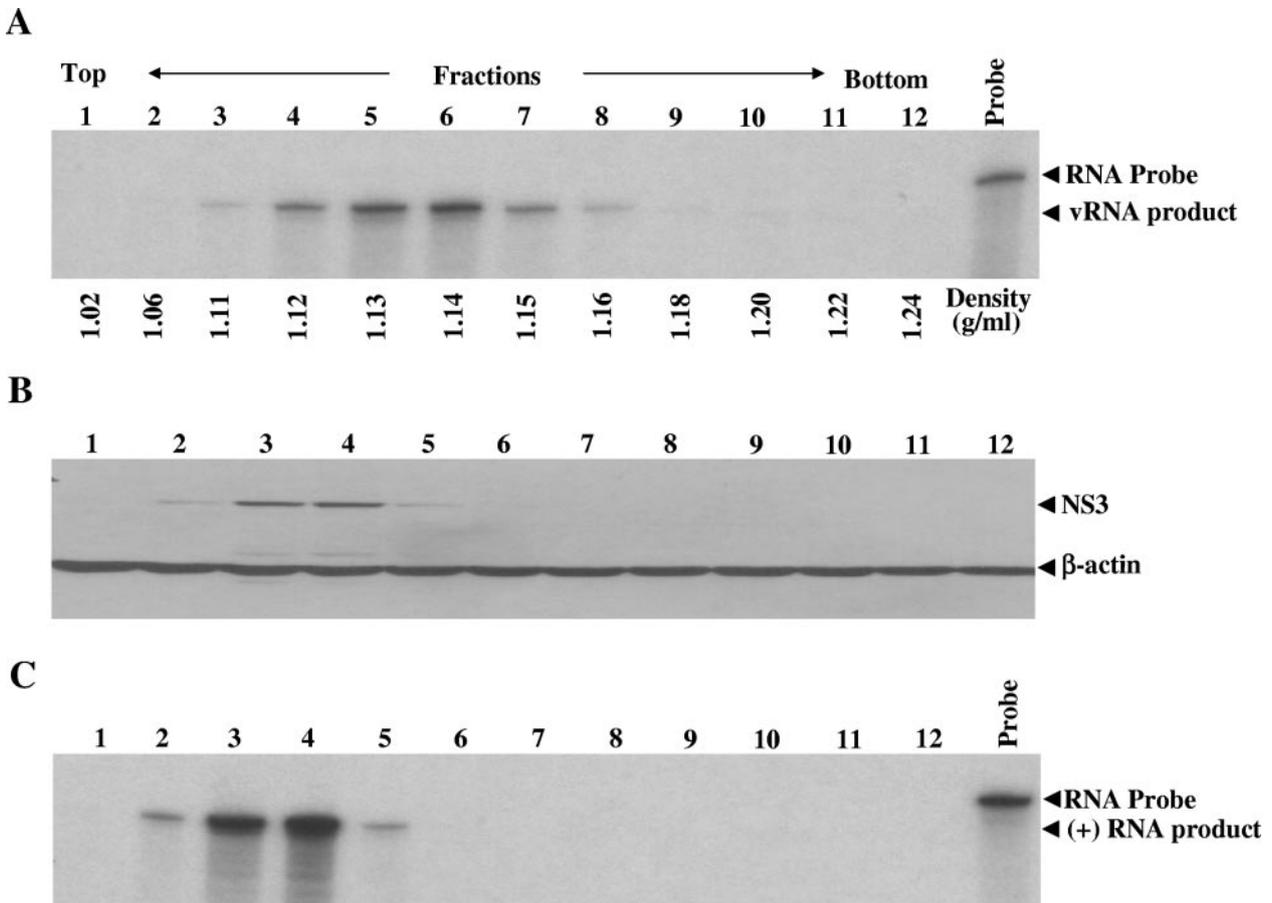


FIG. 7. (A) Sucrose gradient sedimentation analysis of HCV virions in the culture medium. HCV virions in the culture medium were concentrated by centrifugation through 20% sucrose cushion and then fractionated through 20 to 60% continuous sucrose gradient. Fractions (1 ml each) were collected from the top of the sucrose gradient. The HCV vRNA in each fraction (numbered on the top) was extracted with Trizol reagent and then determined by RPA using the [<sup>32</sup>P]UTP-labeled negative-strand 3' UTR RNA probe, as described in the legend of Fig. 4. The buoyant density (g/ml) of each fraction is indicated at the bottom. (B) Determination of HCV infectivity in different fractions by Western blotting analysis of NS3 in the infected cells. A total of 100 μl of each fraction was used to infect Huh7.5 cells in one of the six-well plates. Cells were lysed at 3 days p.i., and the NS3 protein was detected by Western blotting. (C) Determination of positive-strand HCV RNA in cells infected with different fractions by RPA. Huh7.5 cells in a six-well culture plate were infected with 100 μl of each fraction. Total RNA was extracted with Trizol reagent at 3 days p.i. The positive-strand HCV RNA was determined by RPA, as described in the legend of Fig. 4. Fraction numbers are indicated at the top.

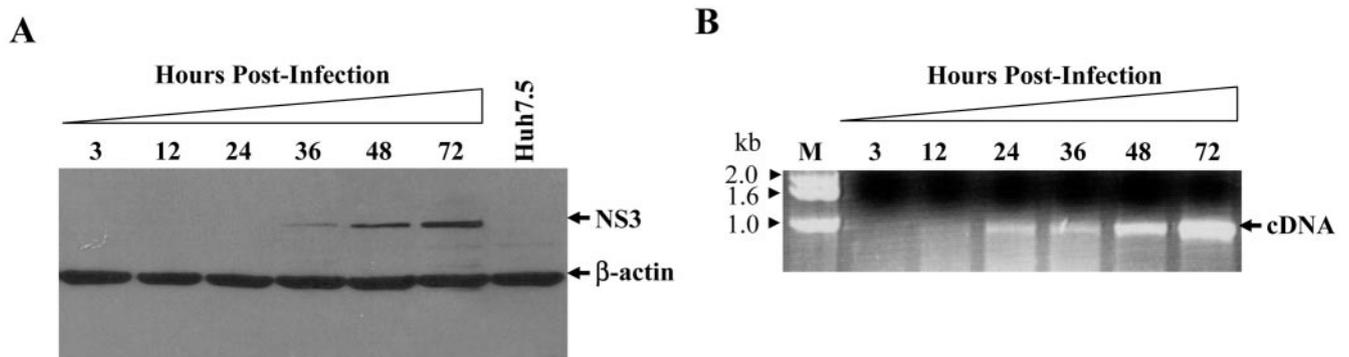


FIG. 8. Time course study of the HCV infection. Huh7.5 cells in a six-well plate were infected with 1 ml of medium of cell line 4. At 3 h p.i., the virus was removed, and cells were washed with PBS and then incubated with 2 ml of DMEM containing 10% FBS. The HCV-infected cells and culture medium were harvested at different time points (indicated at the top of each panel). (A) Detection of the NS3 protein by Western blotting. (B) Detection of the HCV vRNA in the culture medium by RT-PCR. The vRNA was extracted with Trizol reagent and was detected by using a Titan one-step RT-PCR system (Roche). The DNA products were analyzed in a 1% agarose gel and photographed.

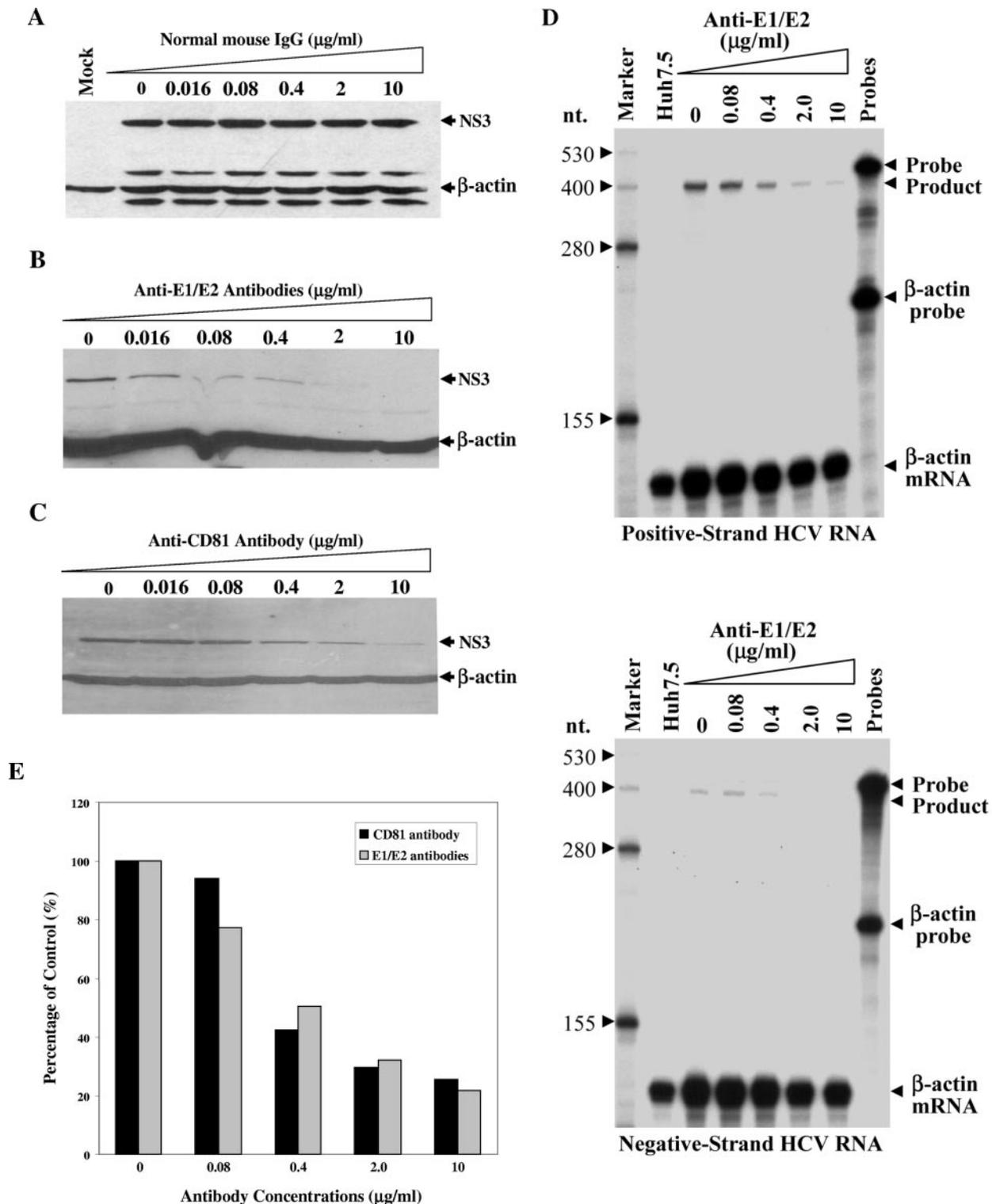


FIG. 9. (A) Effect of normal mouse IgG1 on HCV infection. Huh7.5 cells in a six-well plate were infected with 1 ml of culture medium in the presence of increasing concentrations ( $\mu$ g/ml) of normal mouse IgG1. At 3 h p.i., the HCV-containing medium was removed, and the cells were washed with PBS and incubated with DMEM containing 10% FBS for 3 days. The levels of the NS3 protein were determined by Western blotting. (B) Neutralization of HCV infectivity by anti-E1 and E2 antibodies. The HCV infection is the same as described for panel A except for the use of anti-E1 and anti-E2 antibodies (a mixture of two antibodies in equal amounts). The levels of the NS3 protein were determined by Western blotting. (C) Inhibition of HCV infectivity by CD81 monoclonal antibody. HCV infection was carried out in the presence of increasing concentrations of the CD81 monoclonal antibody; otherwise, the experiment was performed as described for panel A. (D) Determination of the positive- and negative-strand RNAs in the HCV-infected cells treated with anti-E1/E2 antibodies during infection. Half of the RNA sample was used for the determination of the positive-strand RNA, while the other half was used for detection of the negative-strand RNA, as indicated at the bottom. RPA was performed as described in the legend of Fig. 3. The concentrations of anti-E1/E2 antibodies are shown on the top. (E) Dose-dependent neutralization and suppression of the HCV infectivity by monoclonal antibodies against HCV E1/E2 proteins and CD81. The levels of positive-strand HCV RNA were quantified by phosphorimager analysis. The percentage of the RNA level relative to control cells without antibody treatment (100%) was calculated. The percentage of control is plotted against the antibody concentrations.

antibodies (Fig. 9B) or anti-CD81 antibody (Fig. 9C) during HCV infection. Likewise, the levels of both positive- and negative-strand HCV RNAs were reduced by anti-E1/E2 antibodies in a dose-dependent manner (Fig. 9D and E). At 10  $\mu$ g/ml concentration, both anti-E1/E2 antibodies and CD81 antibody neutralized or inhibited the HCV infectivity by approximately 80% (Fig. 9E). These results demonstrate that the infectivity of HCV virions secreted by the stable cell lines was potently neutralized or suppressed by anti-E1/E2 and CD81 monoclonal antibodies.

**Inhibition of HCV replication by IFN- $\alpha$ .** We next determined the inhibitory activity of IFN- $\alpha$  against HCV replication. At 3 h p.i., the HCV-infected Huh7.5 cells were incubated with increasing concentrations of IFN- $\alpha$ . At 3 days p.i., cells were harvested, and the level of the NS3 protein was determined by Western blotting. As shown in Fig. 10, IFN- $\alpha$  efficiently inhibited HCV replication in the HCV-infected Huh7.5 cells with a similar efficacy to the inhibition of a subgenomic HCV replicon replication (34).

## DISCUSSION

We have established a robust cell culture system that continuously produces and secretes infectious HCV into the culture medium by stable human hepatoma cell lines. The stable Huh7 cell lines were isolated following DNA transfection and selection with blasticidin. The transcriptional expression of the HCV RNA was under the control of a minimal CMV promoter. Upon transcription by the cellular polymerase II and self-cleavage by the HDV ribozyme at the 3' end, the resulting HCV RNA was expressed and replicated efficiently in the stable cell lines (Fig. 2, 3, and 4). High levels of HCV proteins in the stable cell lines were detected by Western blotting using anti-NS3 and anti-E2 monoclonal antibodies (Fig. 2). Additionally, the IFA experiments revealed that nearly all cells of the stable cell lines expressed HCV proteins, as shown by NS3 staining in nearly every cell (Fig. 3). Furthermore, high levels of both positive- and negative-strand HCV RNAs were detected by RPA (Fig. 4). More importantly, the stable cell lines robustly secrete HCV virions into the culture medium. The HCV virions were determined by the detection of the viral envelope glycoprotein E2 and vRNA extracted from the virus pellet (Fig. 5 and data not shown). Based on the amount of HCV vRNA determined by RPA, it is estimated that the titer of HCV virions was detected to nearly  $10^8$  copies of vRNA per milliliter of culture medium, although this value varied slightly between different cell lines (Fig. 5 and Table 1). However, the infectious titer of HCV virions in the culture medium was significantly lower than its vRNA copy numbers (Table 1) (see below). This finding indicates that many HCV virions are not infectious.

Substantial evidence derived from our studies demonstrates that infectious HCV virions were produced and secreted by the stable cell lines. Both the HCV NS3 protein and the positive-strand HCV RNA were detected by Western blotting and RPA, respectively, in the HCV-infected naive Huh7.5 cells (Fig. 6 and 7). Upon HCV infection, the HCV proteins could be detected at 36 h p.i. by Western blotting, and the virus released into the culture medium was detected as early as 24 h p.i. by RT-PCR (Fig. 8). The delayed detection of the NS3

protein in the HCV-infected cells was likely due to the differences in assay sensitivity between Western blotting and RT-PCR, as virus must replicate in order to produce progeny virions. Furthermore, the infectivity of HCV virions was potently neutralized by monoclonal antibodies against the HCV envelope glycoproteins E1 and E2 (Fig. 9), consistent with recent findings that the viral entry of recombinant pseudotype viruses was specifically inhibited by anti-E1 and anti-E2 antibodies (2, 3, 21). It is thought that the heterodimeric E1/E2 complex mediates virus entry to target cells by binding to the cell surface receptor(s) like CD81 (27, 28, 43). The infectivity of HCV virions was also inhibited by a CD81 monoclonal antibody in a dose-dependent manner (Fig. 9C and E). It is believed that CD81 serves as an HCV receptor or coreceptor for virus attachment during infection (28). Anti-CD81 antibody was shown to potently block HCV infection and the viral entry of a recombinant human immunodeficiency virus pseudotyped with the HCV E1 and E2 proteins (22, 27). Similar to the HCV replicon replication, the HCV replication in the cell was also suppressed by the treatment with IFN- $\alpha$  (14). Taken together, our findings unambiguously demonstrate the infectivity of the HCV virions produced and secreted by the stable cell lines. Recently, several other independent groups also demonstrated the infectivity of HCV virions produced in Huh7.5 cells that were transiently transfected with in vitro T7 transcripts of JFH1 HCV cDNAs (22, 37, 44).

It is puzzling that the infectious titer of HCV virions produced and secreted by the stable cell lines was about 1,000-fold lower than the vRNA copies (Table 1). This finding is not unique to HCV virions produced by our stable cell lines since it was independently observed for HCV virions generated by transient transfection of HCV RNA into Huh7.5 cells, as described by others (22, 37, 44). Findings derived from sucrose density gradient sedimentation experiments demonstrate that a lower infectious titer of HCV virions than its vRNA copies was due to the presence of a large quantity of noninfectious virions with a buoyant density of above 1.13 g/ml (Fig. 7). This finding is similar to the one reported by Lindenbach et al. (22). However, it is not clear whether the noninfectious virions are defective-interfering particles or the result of a lack of components required for infectivity. Future studies are warranted to further determine the structural properties of HCV virions important for initiating a productive infection.

The HCV replicon systems developed in the past several years have made enormous contributions to the understanding of the mechanisms of HCV replication and anti-HCV drug discovery (1, 4, 23). However, it has not been amenable to perform genetic analysis and manipulation of the infectious HCV. Our recent studies demonstrate that a cDNA-derived HCV genotype 1b RNA generated in the cell was able to produce high levels of HCV virions (15). In this study, we further demonstrate that the HCV of a genotype 2a secreted by stable cell lines is infectious and efficiently replicates in the naive Huh7.5 cells. The establishment of a stable robust culture system for HCV production and propagation opens up many new avenues to determine each aspect of the entire HCV life cycle. These include the molecular mechanisms of viral entry, assembly, and egression. The infectious virus produced by stable cell lines can be used to determine the cell tropism of infection and replication, including determination of cell re-

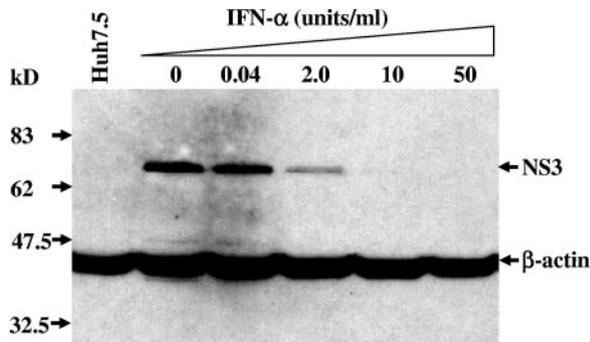


FIG. 10. Inhibition of HCV RNA replication by IFN- $\alpha$ . At 3 h p.i., cells were incubated with DMEM containing increasing concentrations of IFN- $\alpha$  for 3 days. The levels of the NS3 protein were determined by Western blotting. The concentrations of IFN- $\alpha$  are shown at the top.

ceptors and/or coreceptors. Additionally, the stable HCV culture system provides a unique source for robust production of infectious virus that can be used for anti-HCV drug discovery. The HCV infection system is superior to the HCV replicon system as to the identification of antiviral inhibitors in many ways. It covers any target of the HCV life cycle such as the viral entry, viral RNA translation, polyprotein processing and maturation, RNA replication, virus assembly and budding. In fact, the efficient inhibition of the HCV infection by anti-E1/E2 antibodies (Fig. 9) and IFN- $\alpha$  (Fig. 10) provides a proof-of-concept that such a system will be valuable for evaluation of different antiviral strategies to ultimately control HCV infection.

It was previously reported that HCV infection caused significant apoptosis (34). We have not determined whether the replication of HCV in the stable cell lines or in the infected naïve Huh7.5 cells results in any cell death, lytic infection, or cytopathic effects. Grossly, there are no significant changes in cell morphology either in the stable cell lines or in the HCV-infected naïve Huh7.5 cells. It should be noted that the stable cell lines initially grew at a slower rate than the parent cells although they are viable even after numerous (>30) passages. These observations suggest that HCV production and infection did not cause significant lytic and/or cytopathic effects. However, we do not know whether continuous passages of these stable cell lines affect HCV production. It appeared that cells grew at a much slower rate in early passages compared to later passages, suggesting that an adaptation might occur in the cell. It will be interesting to determine the effects of HCV replication on normal cell growth pathways by future investigations. Additionally, it is noteworthy that HCV appears to replicate more efficiently in Huh7.5 cells than in Huh7 cells upon infection (Z. Cai et al., unpublished data). This observation is consistent with a recent finding that the RIG-I (retinoic acid-inducible gene I) with a single amino acid mutation found in Huh7.5 cells caused a defect in the intracellular interferon response to HCV RNA replication, resulting in higher levels of HCV RNA replication (12, 33). It remains to be determined whether HCV infection was able to activate the intracellular antiviral response via a pathway independent of the RIG-I-mediated interferon response, which is specifically induced by double-strand viral RNA.

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## REFERENCES

- Bartenschlager, R., A. Kaul, and S. Sparacio. 2003. Replication of the hepatitis C virus in cell culture. *Antiviral Res.* **60**:91–102.
- Bartosch, B., J. Bukh, J. C. Meunier, C. Granier, R. E. Engle, W. C. Blackwelder, S. U. Emerson, F. L. Cosset, and R. H. Purcell. 2003. In vitro assay for neutralizing antibody to hepatitis C virus: evidence for broadly conserved neutralization epitopes. *Proc. Natl. Acad. Sci. USA* **100**:14199–14204.
- Bartosch, B., J. Dubuisson, and F. L. Cosset. 2003. Infectious hepatitis C virus pseudo-particles containing functional E1-E2 envelope protein complexes. *J. Exp. Med.* **197**:633–642.
- Blight, K. J., A. A. Kolykhalov, and C. M. Rice. 2000. Efficient initiation of HCV RNA replication in cell culture. *Science* **290**:1972–1974.
- Blight, K. J., J. A. McKeating, and C. M. Rice. 2002. Highly permissive cell lines for subgenomic and genomic hepatitis C virus RNA replication. *J. Virol.* **76**:13001–13014.
- Bukh, J. 2004. A critical role for the chimpanzee model in the study of hepatitis C. *Hepatology* **39**:1469–1475.
- Bukh, J., R. H. Purcell, and R. H. Miller. 1992. Sequence analysis of the 5' noncoding region of hepatitis C virus. *Proc. Natl. Acad. Sci. USA* **89**:4942–4946.
- Cai, Z.-H., J. Liang, and G. Luo. 2004. Effects of mutations of the initiation nucleotides on hepatitis C virus RNA replication in the cell. *J. Virol.* **78**:3633–3643.
- Centers for Disease Control and Prevention. 1998. Recommendations for prevention and control of hepatitis C virus (HCV) infection and HCV-related chronic disease. *Morb. Mortal. Wkly. Rep.* **47**:1–39.
- Choo, Q. L., G. Kuo, A. J. Weiner, L. R. Overby, D. W. Bradley, and M. Houghton. 1989. Isolation of a cDNA clone derived from a blood-borne non-A, non-B viral hepatitis genome. *Science* **244**:359–362.
- El-Hage, N., and G. Luo. 2003. Replication of hepatitis C virus RNA occurs in a membrane-bound replication complex containing nonstructural viral proteins and RNA. *J. Gen. Virol.* **84**:2761–2769.
- Foy, E., K. Li, R. Sumpter, Jr., Y. M. Loo, C. L. Johnson, C. Wang, P. M. Fish, M. Yoneyama, T. Fujita, S. M. Lemon, and M. Gale, Jr. 2005. Control of antiviral defenses through hepatitis C virus disruption of retinoic acid-inducible gene-1 signaling. *Proc. Natl. Acad. Sci. USA* **102**:2986–2991.
- Friebe, P., V. Lohmann, N. Krieger, and R. Bartenschlager. 2001. Sequences in the 5' nontranslated region of hepatitis C virus required for RNA replication. *J. Virol.* **75**:12047–12057.
- Guo, J. T., V. V. Bichko, and C. Seeger. 2001. Effect of alpha interferon on the hepatitis C virus replicon. *J. Virol.* **75**:8516–8523.
- Heller, T., S. Saito, J. Auerbach, T. Williams, T. R. Moreen, A. Jazwinski, B. Cruz, N. Jeurkar, R. Sapp, G. Luo, and T. J. Liang. 2005. An in vitro model of hepatitis C virus production. *Proc. Natl. Acad. Sci. USA* **102**:2579–2583.
- Kato, T., T. Date, M. Miyamoto, A. Furusaka, K. Tokushige, M. Mizokami, and T. Wakita. 2003. Efficient replication of the genotype 2a hepatitis C virus subgenomic replicon. *Gastroenterology* **125**:1808–1817.
- Kato, T., T. Date, M. Miyamoto, Z. Zhao, M. Mizokami, and T. Wakita. 2005. Nonhepatic cell lines HeLa and 293 support efficient replication of the hepatitis C virus genotype 2a subgenomic replicon. *J. Virol.* **79**:592–596.
- Kato, T., A. Furusaka, M. Miyamoto, T. Date, K. Yasui, J. Hiramoto, K. Nagayama, T. Tanaka, and T. Wakita. 2001. Sequence analysis of hepatitis C virus isolated from a fulminant hepatitis patient. *J. Med. Virol.* **64**:334–339.
- Kolykhalov, A. A., E. V. Agapov, K. J. Blight, K. Mihalik, S. M. Feinstone, and C. M. Rice. 1997. Transmission of hepatitis C by intrahepatic inoculation with transcribed RNA. *Science* **277**:570–574.
- Kolykhalov, A. A., S. M. Feinstone, and C. M. Rice. 1996. Identification of a highly conserved sequence element at the 3' terminus of hepatitis C virus genome RNA. *J. Virol.* **70**:3363–3371.
- Lagging, L. M., K. Meyer, R. J. Owens, and R. Ray. 1998. Functional role of hepatitis C virus chimeric glycoproteins in the infectivity of pseudotyped virus. *J. Virol.* **72**:3539–3546.

22. **Lindenhach, B. D., M. J. Evans, A. J. Syder, B. Wolk, T. L. Tellinghuisen, C. C. Liu, T. Maruyama, R. O. Hynes, D. R. Burton, J. A. McKeating, and C. M. Rice.** 2005. Complete replication of hepatitis C virus in cell culture. *Science* **309**:623–626.
23. **Lohmann, V., F. Korner, J. Koch, U. Herian, L. Theilmann, and R. Bartenschlager.** 1999. Replication of subgenomic hepatitis C virus RNAs in a hepatoma cell line. *Science* **285**:110–113.
24. **Luo, G.** 2004. *Molecular virology of hepatitis C virus.* Birkhauser, Basel, Switzerland.
25. **Luo, G., S. Xin, and Z. Cai.** 2003. Role of the 5'-proximal stem-loop structure of the 5' untranslated region in replication and translation of hepatitis C virus RNA. *J. Virol.* **77**:3312–3318.
26. **McCormick, C. J., L. Challinor, A. Macdonald, D. J. Rowlands, and M. Harris.** 2004. Introduction of replication-competent hepatitis C virus transcripts using a tetracycline-regulable baculovirus delivery system. *J. Gen. Virol.* **85**:429–439.
27. **McKeating, J. A., L. Q. Zhang, C. Logvinoff, M. Flint, J. Zhang, J. Yu, D. Butera, D. D. Ho, L. B. Dustin, C. M. Rice, and P. Balfe.** 2004. Diverse hepatitis C virus glycoproteins mediate viral infection in a CD81-dependent manner. *J. Virol.* **78**:8496–8505.
28. **Pileri, P., Y. Uematsu, S. Campagnoli, G. Galli, F. Falugi, R. Petracca, A. J. Weiner, M. Houghton, D. Rosa, G. Grandi, and S. Abrignani.** 1998. Binding of hepatitis C virus to CD81. *Science* **282**:938–941.
29. **Reed, K. E., and C. M. Rice.** 2000. Overview of hepatitis C virus genome structure, polyprotein processing, and protein properties. *Curr. Top. Microbiol. Immunol.* **242**:55–84.
30. **Robertson, B., G. Myers, C. Howard, T. Brettin, J. Bukh, B. Gaschen, T. Gojbori, G. Maertens, M. Mizokami, O. Nainan, S. Netesov, K. Nishioka, T. Shin i, P. Simmonds, D. Smith, L. Stuyver, and A. Weiner.** 1998. Classification, nomenclature, and database development for hepatitis C virus (HCV) and related viruses: proposals for standardization. *Arch. Virol.* **143**: 2493–2503.
31. **Sells, M. A., M. L. Chen, and G. Acs.** 1987. Production of hepatitis B virus particles in Hep G2 cells transfected with cloned hepatitis B virus DNA. *Proc. Natl. Acad. Sci. USA* **84**:1005–1009.
32. **Shoukry, N. H., A. G. Cawthon, and C. M. Walker.** 2004. Cell-mediated immunity and the outcome of hepatitis C virus infection. *Annu. Rev. Microbiol.* **58**:391–424.
33. **Sumpter, R., Jr., Y. M. Loo, E. Foy, K. Li, M. Yoneyama, T. Fujita, S. M. Lemon, and M. Gale, Jr.** 2005. Regulating intracellular antiviral defense and permissiveness to hepatitis C virus RNA replication through a cellular RNA helicase, RIG-I. *J. Virol.* **79**:2689–2699.
34. **Sung, V. M., S. Shimodaira, A. L. Doughty, G. R. Picchio, H. Can, T. S. Yen, K. L. Lindsay, A. M. Levine, and M. M. Lai.** 2003. Establishment of B-cell lymphoma cell lines persistently infected with hepatitis C virus in vivo and in vitro: the apoptotic effects of virus infection. *J. Virol.* **77**:2134–2146.
35. **Tanaka, T., N. Kato, M. J. Cho, K. Sugiyama, and K. Shimotohno.** 1996. Structure of the 3' terminus of the hepatitis C virus genome. *J. Virol.* **70**:3307–3312.
36. **Tellinghuisen, T. L., and C. M. Rice.** 2002. Interaction between hepatitis C virus proteins and host cell factors. *Curr. Opin. Microbiol.* **5**:419–427.
37. **Wakita, T., T. Pietschmann, T. Kato, T. Date, M. Miyamoto, Z. Zhao, K. Murthy, A. Habermann, H. G. Krausslich, M. Mizokami, R. Bartenschlager, and T. J. Liang.** 2005. Production of infectious hepatitis C virus in tissue culture from a cloned viral genome. *Nat. Med.* **11**:791–796.
38. **World Health Organization.** 1998. WHO concerns on hepatitis C. *Lancet* **351**:1415.
39. **Yanagi, M., R. H. Purcell, S. U. Emerson, and J. Bukh.** 1997. Transcripts from a single full-length cDNA clone of hepatitis C virus are infectious when directly transfected into the liver of a chimpanzee. *Proc. Natl. Acad. Sci. USA* **94**:8738–8743.
40. **Yi, M., and S. M. Lemon.** 2003. 3' nontranslated RNA signals required for replication of hepatitis C virus RNA. *J. Virol.* **77**:3557–3568.
41. **Yi, M., and S. M. Lemon.** 2003. Structure-function analysis of the 3' stem-loop of hepatitis C virus genomic RNA and its role in viral RNA replication. *RNA* **9**:331–345.
42. **Zhang, C., Z. Cai, Y. C. Kim, R. Kumar, F. Yuan, P. Y. Shi, C. Kao, and G. Luo.** 2005. Stimulation of hepatitis C virus (HCV) nonstructural protein 3 (NS3) helicase activity by the NS3 protease domain and by HCV RNA-dependent RNA polymerase. *J. Virol.* **79**:8687–8697.
43. **Zhang, J., G. Randall, A. Higginbottom, P. Monk, C. M. Rice, and J. A. McKeating.** 2004. CD81 is required for hepatitis C virus glycoprotein-mediated viral infection. *J. Virol.* **78**:1448–1455.
44. **Zhong, J., P. Gastaminza, G. Cheng, S. Kapadia, T. Kato, D. R. Burton, S. F. Wieland, S. L. Uprichard, T. Wakita, and F. V. Chisari.** 2005. Robust hepatitis C virus infection in vitro. *Proc. Natl. Acad. Sci. USA* **102**:9294–9299.