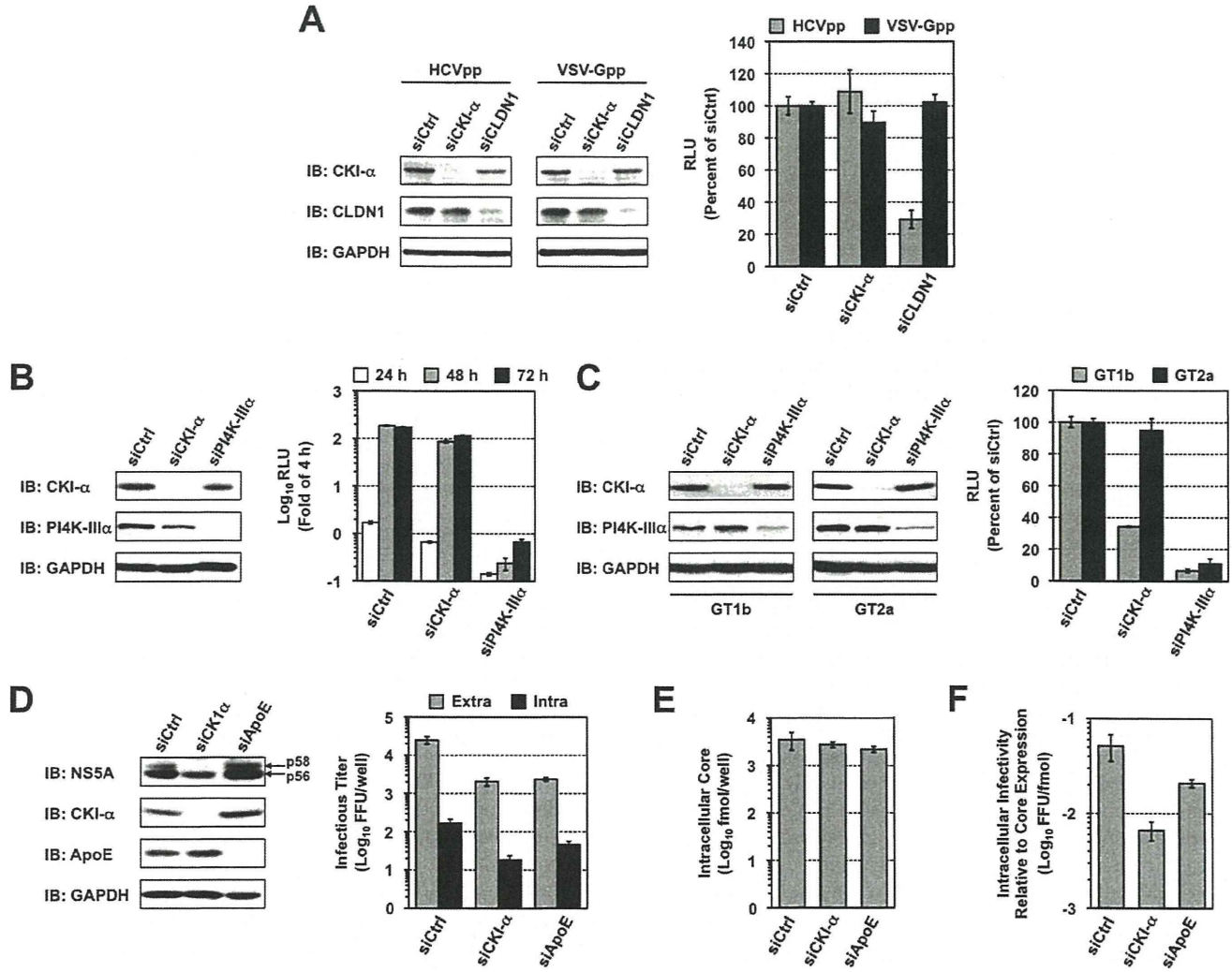


FIG 4 Virion assembly is a primary target of CKI-α. (A) Effect of CKI-α knockdown on viral entry. Huh7.5.1 cells were transfected with the indicated siRNAs. Two days later, cells were infected with HCVpp (gray bars) or VSV-Gpp (black bars) and harvested an additional 3 days later for immunoblotting (IB) and luciferase assays. Values were normalized to the value for transfection with control siRNAs (siCtrl), set at 100%. Values shown represent the means ± standard deviations from three independent transfections of siRNA. (B) Transient replication assay for the JFH-1 subgenomic replicon following CKI-α knockdown. Huh-7 cells transfected with the indicated siRNAs were coelectroporated with the identical siRNAs, and JFH-1 subgenomic luciferase reporter replicon RNA, and harvested at the indicated time points for immunoblotting (IB) and luciferase assays. The luciferase activity at each time point was corrected by the luciferase value at 4 h posttransfection to normalize transfection efficiencies. Values shown represent the means ± standard deviations from three replicate experiments. (C) Effects of CKI-α knockdown on replication in replicon cell lines derived from genotypes 1b and 2a. Two cell lines harboring an HCV subgenomic luciferase reporter replicon, LucNeo#2 (genotype 1b, GT1b) and SGR-JFH1/LucNeo (genotype 2a, GT2a), were transfected with the indicated siRNAs and harvested 3 days later for immunoblotting (IB) and luciferase assays. Luciferase activities were normalized to the luciferase values for transfection with control siRNA (siCtrl), set at 100%. Values shown represent the means ± standard deviations from three independent transfections of siRNA. (D) Effects of CKI-α knockdown on viral assembly and release. Huh7-25 cells transfected with the indicated siRNAs were coelectroporated with the identical siRNAs and JFH-1 RNA. Cells and supernatants were harvested 3 days later for immunoblotting (IB) and titrations of extracellular and intracellular infectious virus by focus-forming unit (FFU) assays. Values represent the means ± standard deviations from three replicate experiments. (E) Effect of CKI-α knockdown on the abundance of intracellular core protein. Amounts of core in cells for which results are shown in panel D were measured. Results represent the means ± standard deviations from three replicate experiments. (F) Effect of CKI-α knockdown on intracellular infectivity relative to core protein expression. Intracellular infectivity relative to core expression was determined by normalizing the yield of intracellular infectious virus (shown in panel D) with the amount of intracellular core protein shown in panel E. Results represent the means ± standard deviations from three replicate experiments.

followed by harvesting at different time points (Fig. 4B). The reporter luciferase activity at each time point was corrected with the luciferase value at 4 h posttransfection to normalize transfection efficiencies. Although efficient knockdown was achieved with siRNAs (Fig. 4B, left panel), CKI-α knockdown led to a marginal but nonnegligible decrease in the luciferase activity over the indicated time period. In contrast, PI4K-IIIα knockdown, as a positive control, resulted in a marked decrease (>200-fold) in activity (Fig. 4B, right panel). The effect of CKI-α silencing on the replication of the subgenomic replicon was further analyzed by using two cell lines derived from genotype 1b (LucNeo#2) (38, 39) and genotype 2a (SGR-JFH1/LucNeo) (Fig. 4C). Both Huh-7-based

subgenomic replicon cell lines carry a firefly luciferase reporter gene fused to the neomycin phosphotransferase gene. As shown in the right panel of Fig. 4C, knockdown of CKI-α resulted in a marked (~65%) decrease in replication of the genotype 1b replicon but only a slight (~10%) decrease in the genotype 2a replication, although knockdown efficiencies of CKI-α were sufficient and comparable in both cell lines (Fig. 4C, left panels). Our result with the genotype 1b replicon was consistent with a previous report (27). In contrast, the limited impact of CKI-α silencing on the replication of the JFH-1 subgenomic replicon suggests that the RNA replication step may not be a key role for CKI-α in the regulation of HCV JFH-1 production.

Finally, we focused on the late stages of the HCV life cycle and analyzed the involvement of CKI-α in virion assembly and release via a single-cycle virus production assay (55), in which Huh7–25 cells lacking CD81 expression were used. Three days posttransfection with siRNAs, the cells were cotransfected with the identical siRNAs and JFH-1 RNA by electroporation. The cells and culture supernatants were harvested after a further 3 days, and titrations of intra- and extracellular infectious virus were assessed (Fig. 4D to F). Reduced NS5A hyperphosphorylation was observed following CKI-α knockdown, but not following ApoE knockdown or transfection with irrelevant siRNA (Fig. 4D, left panel). Both CKI-α and ApoE knockdown led to an ~10-fold reduction in the yield of extracellular infectious virus compared to the negative control. Approximately a 9-fold reduction was found in the yield of intracellular infectious virus following CKI-α knockdown (Fig. 4D, right panel), indicating that CKI-α is not required for virus release from cells. Despite the marked decrease in intracellular virion yield, CKI-α knockdown resulted in only a 1.3-fold reduction in the abundance of intracellular core protein (Fig. 4E), supporting a limited impact for CKI-α knockdown on viral replication (Fig. 4B). Furthermore, CKI-α silencing led to approximately an 8-fold reduction in the intracellular infectivity relative to core protein expression, which represents the efficiency of viral assembly expressed as the yield of intracellular infectious virus normalized to the amount of intracellular core protein (Fig. 4F). Collectively, these observations suggest that in the HCV life cycle, CKI-α plays a key role most likely in the assembly of infectious viral particles.

NS5A hyperphosphorylation mediated by CKI-α possibly contributes to recruitment of NS5A to low-density membrane structures around LDs in infected cells. It has been demonstrated that recruitment of NS5A to cytoplasmic low-density membrane structures surrounding LDs, and the interaction of NS5A with the core protein at the site, are essential to HCV assembly (7, 8, 56). To gain mechanistic insight into the function of CKI-α in virion assembly, we performed a subcellular fractionation assay and examined whether NS5A phosphorylation by CKI-α contributed to the subcellular localization of NS5A. Lysates of cells transfected with JFH-1 RNA in the presence or absence of CKI-α silencing (Fig. 5A, left panel) were fractionated with 2.5 to 30% iodixanol gradients followed by immunoblotting of the fractions (Fig. 5A, right panels). In control cells (siCtrl), hyperphosphorylated p58 NS5A predominantly resided in low-density fractions, such as fractions 1 to 3, while hypophosphorylated p56 NS5A localized not only in the low-density fractions but also in high-density fractions, such as fractions 11 and 12. In contrast, knockdown of CKI-α (siCKI-α) decreased the abundance of hyperphosphorylated NS5A and NS5A in the low-density fractions. NS5A levels in the high-density fractions were not reduced by CKI-α knockdown. These results indicate that CKI-α is involved in the distribution of NS5A in cells as well as in its hyperphosphorylation.

We next assessed whether the intracellular localization of NS5A and its interaction with LDs or the core protein are affected by CKI-α knockdown by using laser-scanning confocal immunofluorescence microscopy. Cells were transfected either with CKI-α siRNA (siCKI-α) or with an irrelevant control siRNA (siCtrl), followed by infection with HCVcc. Efficient knockdown of CKI-α was confirmed by immunoblotting and was associated with decreased p58 expression (Fig. 5B). The delivery of siRNA into nearly 100% of the cells was observed with Cy3-labeled siRNA (Silencer Cy3-labeled GAPDH siRNA) (Fig. 5C). In siCtrl-transfected cells, NS5A was colocalized or closely associated with LDs. In contrast, its association with LDs was decreased following CKI-α depletion (Fig. 5D) ($P < 0.0001$ by two-sided Mann-Whitney test). Similarly, NS5A and the core protein were clearly colocalized in control cells, while their colocalization was reduced in CKI-α knockdown cells (Fig. 5E) ($P = 0.0110$ by two-sided Mann-Whitney test). These microscopy findings suggest that CKI-α and/or CKI-α-mediated hyperphosphorylation of NS5A is involved in the NS5A-core colocalization at or around LDs in HCV-infected cells. Taken together with the results of our subcellular fractionation assay (Fig. 5A), it is likely that CKI-α plays a role in recruiting NS5A to low-density membrane structures around LDs through hyperphosphorylation of NS5A, and it may facilitate the NS5A-core interaction at these sites.

Identification of potential phospho-acceptor regions for CKI-α. The above results prompted us to identify the phospho-acceptor sites for CKI-α by using a proteomics approach. Lysates of cells expressing the HCV JFH-1 genome, transfected with either CKI-α siRNA or an irrelevant control siRNA, were immunoprecipitated with an anti-NS5A antibody followed by SDS-PAGE (Fig. 6A). Immunoblotting showed a marked reduction of NS5A p58 following CKI-α knockdown (Fig. 6A, right panel). Silver-stained gel bands of p58 and p56 (Fig. 6A, left panel) were excised and subjected to in-gel digestion, followed by mass spectrometry analysis (Fig. 6B). A total of 629 peptides were identified from both control NS5A (siCtrl) and NS5A with CKI-α knockdown (siCKI-α) after peptide selection with a Mascot peptide score of ≥25 (see Table S3 in the supplemental material) and yielded 53% proteome coverage in total (49.4% for control NS5A and 41.8% for NS5A with CKI-α knockdown), as indicated in the upper panel of Fig. 6B (red letters). Peptides corresponding to domain III in NS5A were not obtained in this analysis. We identified three kinds of phosphopeptides (1, GSPPSEASSSVSQLSAPSLR; 2, APTPPPR; 3, TVGLSESTISEALQQLAIK [Fig. 6B, upper panel, highlighted in green, blue, and yellow, respectively]) (see also Table S3). However, fine mapping of phosphorylation sites was not completely successful in this assay, probably due to the low abundance of immunoprecipitated NS5A. We next assessed which peptide contained the potential phospho-acceptor sites for CKI-α by comparing the frequencies of phosphopeptides identified with and without CKI-α knockdown. As shown in the lower panel of Fig. 6B, the frequency of phosphopeptide 1 relative to the total number of peptide 1 identified was decreased after CKI-α knockdown (from 26.2% to 19.8%). In contrast, the relative frequencies of phosphopeptides 2 and 3 were unaffected or increased by CKI-α knockdown. We noted that the threonine residue in peptide 2 is unlikely to be a consensus phosphorylation site of CKI

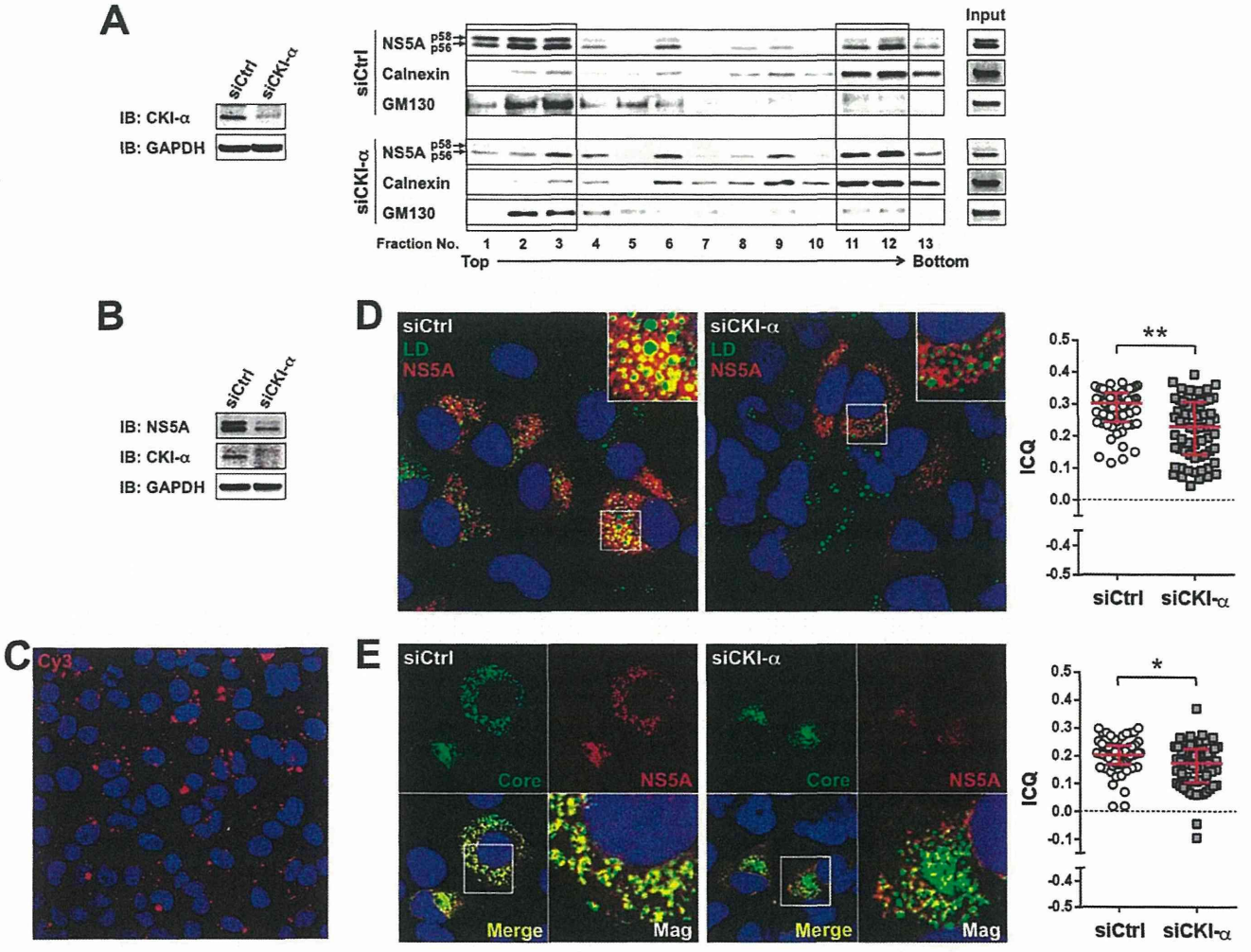
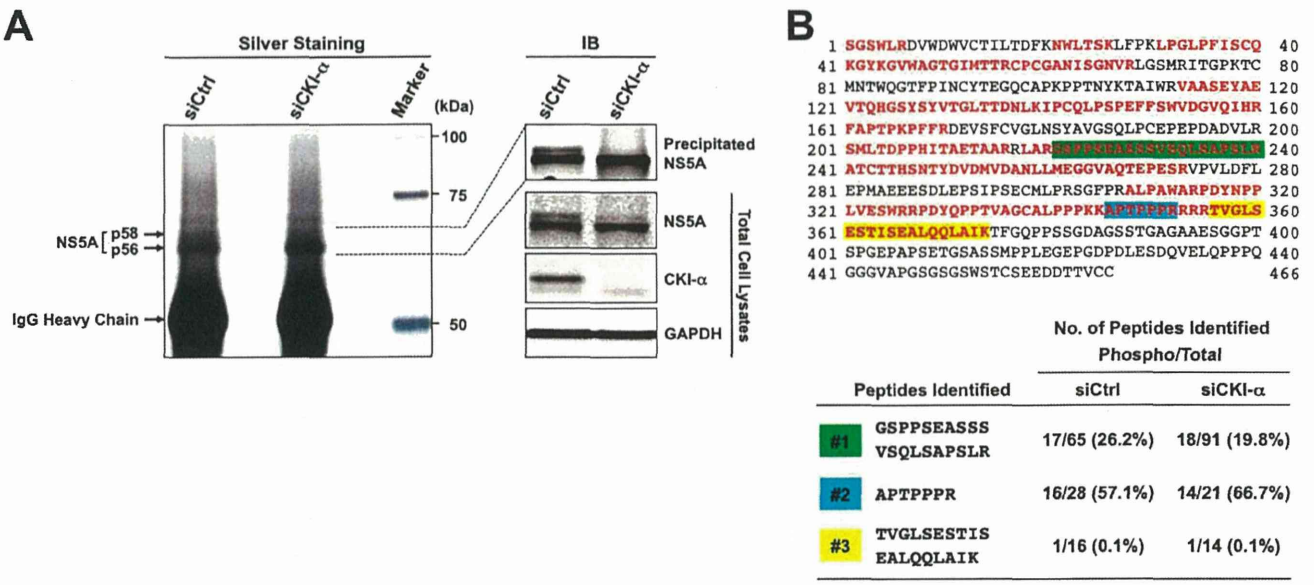


FIG 5 Effects of CKI-α knockdown on the subcellular localization of NS5A and its interaction with LDs or core protein. (A) Iodixanol density gradient analysis (right). Huh7-25 cells transfected with the indicated siRNAs were coelectroporated with the identical siRNAs and JFH-1 RNA. Cell lysates were prepared 3 days after electroporation and fractionated by iodixanol gradients of 2.5% to 30%. The gradient was collected in 0.8-ml fractions for immunoblotting. Total cell lysates before fractionation were loaded as input controls. Detected bands in fractions 1 to 3 and in fractions 11 and 12 are enclosed by squares. (Left) Immunoblotting (IB) results for CKI-α 3 days after electroporation. GAPDH was included as a loading control. (B) Immunoblot (IB) of NS5A and CKI-α 3 days after HCVcc infection. GAPDH was included as a loading control. (C) siRNA delivery efficiency. Cy3 fluorescence (red) was observed 3 days after transfection of Silencer Cy3-labeled GAPDH siRNA. Nuclei were counterstained with Hoechst 33342 (blue). (D) Colocalization of NS5A and LDs. Confocal microscopy images show cells transfected with either CKI-α siRNA (siCKI-α) or an irrelevant control siRNA (siCtrl), followed by infection with JFH-1 virus (left). Cells were fixed with paraformaldehyde 3 days after infection and labeled with an antibody specific for NS5A (red). Cells were counterstained with BODIPY 493/503 (green) to label lipid droplets and with Hoechst 33342 (blue) to label nuclei. Insets represent enlarged views of portions surrounded by squares. Colocalization of NS5A and LDs pixels were assessed quantitatively by intensity correlation analysis using ImageJ software (right). Plots shown represent the ICQ obtained from each of >60 NS5A/LD double-positive cells. Bars indicate the median ± interquartile range of the plots. **, $P < 0.01$ by two-sided Mann-Whitney test. (E) Colocalization of NS5A and core protein. Confocal microscopy images show cells transfected either with CKI-α siRNA (siCKI-α) or with a control siRNA (siCtrl), followed by infection with JFH-1 virus (left). Fixed cells were labeled with antibodies specific for NS5A (red) and core (green). Nuclei were counterstained with Hoechst 33342 (blue) in the merged images. Mag images represent enlarged views of portions surrounded by squares in the merged images. Colocalization of NS5A and core pixels was assessed quantitatively by intensity correlation analysis using ImageJ software (right). Plots shown represent ICQs obtained from each of >60 NS5A/core double-positive cells. Bars indicate the median ± interquartile range. *, $P < 0.05$ by two-sided Mann-Whitney test.

(57). Thus, the results suggest that peptide 1 (GSPPSEASSSVSQL SAPSLR) is the peptide most likely to contain the amino acids phosphorylated by CKI-α.

S225 and S232 are key residues involved in NS5A hyperphosphorylation and hyperphosphorylation-dependent regulation of infectious virus production. Peptide 1 identified above contains eight serine residues that are highly conserved among HCV isolates and are clustered within LCS I (Fig. 7A). To identify amino acids responsible for CKI-α-mediated hyperphosphorylation, we assessed the impacts of alanine or aspartic acid substitutions for these 8 serine residues on NS5A hyperphosphorylation and virus production. An HCV JFH-1 genome with the reporter luciferase, which enabled us to evaluate viral replication by measuring GLuc activity, and a series of its NS5A mutated constructs (Fig. 7A) were generated. Supernatants of cell cultures transfected with the RNA transcripts were harvested at 4, 24, 48, and 72 h posttransfection



Peptides Identified		No. of Peptides Identified Phospho/Total siCtrl	siCKI-α
#1	GSPPSEASSS VSQLSAPSLR	17/65 (26.2%)	18/91 (19.8%)
#2	APTPPPR	16/28 (57.1%)	14/21 (66.7%)
#3	TVGLSESTIS EALQQLAIK	1/16 (0.1%)	1/14 (0.1%)

FIG 6 Identification of NS5A phosphopeptides by a phospho-proteome approach. (A) Silver staining and immunoblotting of immunoprecipitated NS5A. Huh-7 cells transfected with the indicated siRNAs were coelectroporated with the identical siRNAs and JFH-1 RNA. Cell lysates were prepared 3 days after electroporation and immunoprecipitated with an anti-NS5A antibody. Immunoprecipitates were subjected to SDS-PAGE, followed by silver staining and immunoblotting (IB). (B) Phosphopeptide mapping of NS5A by LC-MS/MS analysis. p58 and p56 bands of NS5A were excised from the gel and subjected to in-gel digestion, followed by mass spectrometry analysis. Red letters represent the amino acids identified. Three kinds of phosphopeptides identified are highlighted in green (phosphopeptide 1), blue (phosphopeptide 2), and yellow (phosphopeptide 3). The numbers represent amino acid positions within NS5A.

and subjected to the GLuc assay. As shown in the left panel of Fig. 7B, serine-to-alanine substitution at either aa 229 (S229A) or at aa 235 (S235A) resulted in severe reduction in the viral replication. In contrast, the replication capacities of S222A, S228A, S230A, and S238A mutant reporter viruses were comparable to that of the wild type (WT). S225A and S232A mutations led to a slight but nonnegligible reduction in replication compared to WT. The phospho-mimetic aspartic acid substitution for aa 235 (S235D) exhibited a much higher replication capacity (~100-fold) than S235A, indicating that phosphorylation of S235 is required for efficient viral replication. In contrast, the replication capacity of S229D was still more-than-10-fold lower than that of WT, suggesting that introduction of negative charge at this position is not sufficient to enhance viral replication (Fig. 7B, right panel). S225D and S232D mutations restored viral replication capacities and exhibited the same replication phenotype as WT. Interestingly, S222D and S230D resulted in a slight reduction in viral replication compared to S222A and S230A, consistent with previous reports (23, 58) (Fig. 7B, right panel).

We next evaluated the effects of the NS5A mutations on infectious virus production by titrations of infectious virus in culture supernatants of cells transfected with RNA transcripts of JFH-1 viruses at 72 h posttransfection (Fig. 7C). S225A and S232A mutations resulted in 4- and 5-fold reductions in the virus infectious titer, respectively, compared to WT, while the abilities of S225D and S232D mutants to produce infectious virus were comparable to that of WT. Little or no virus production was observed with S229A, S229D, and S235A mutations, presumably because of their strong negative impacts on viral replication. A slight reduction in virus production observed with S230D and S235D mutations was most likely due to their replication capacities. S222A, S222D, S228A, S228D, S230A, S238A, and S238D substitutions had no significant effect on virus production (>75% of the WT level).

To determine the effect of the NS5A mutations on NS5A hyperphosphorylation, cells expressing JFH-1 viruses were subjected to immunoblotting, and the p58/p56 ratio of NS5A was estimated (Fig. 7D). The hyperphosphorylated p58 band of NS5A was clearly detected in cells transfected with WT and S222A, S228A, S230A, and S238A mutants, which had mean p58/p56 ratios of 0.42, 0.38, 0.35, 0.50, and 0.60, respectively. These p58/p56 ratios were reproducible in multiple repeated experiments but much lower than the p58/p56 ratios (e.g., 0.93 in siCtrl-transfected cells) in Fig. 3A. This difference may be attributed to the difference in the way by which HCV was introduced into cells (virus infection in Fig. 3A and transfection of viral genome in Fig. 7D and F). The p58 levels were significantly reduced in cells transfected with S225A or S232A mutants, which had mean p58/p56 ratios of 0.11 and 0.15, respectively (Fig. 7D). Since the p58/p56 ratios of the S229A and S235A mutants were not determined due to low levels of NS5A expression, we reevaluated the p58/p56 ratio of each viral muatant by using a vaccinia virus-T7 polymerase-mediated protein expression system (Fig. 7E, left panel). Cells transfected with pJFH1 or a series of its NS5A mutants were infected with vaccinia virus expressing the T7 RNA polymerase and harvested for immunoblotting. Similar to the results shown in Fig. 7D, the p58/p56 ratios of S225A and S232A mutants were significantly reduced, while S229A and S235A mutations had no effects (Fig. 7E, right panel). The hyperphosphorylated band of NS5A was observed in cells transfected with the S222D, S225D, S228D, S229D, or S230D mutant in both experimental settings. Interestingly, the S232D, S235D, and S238D mutations resulted in a slight retardation of p56 mobility (Fig. 7F and G), consistent with previous reports (58, 59).

Collectively, S225 and S232 are key residues involved in

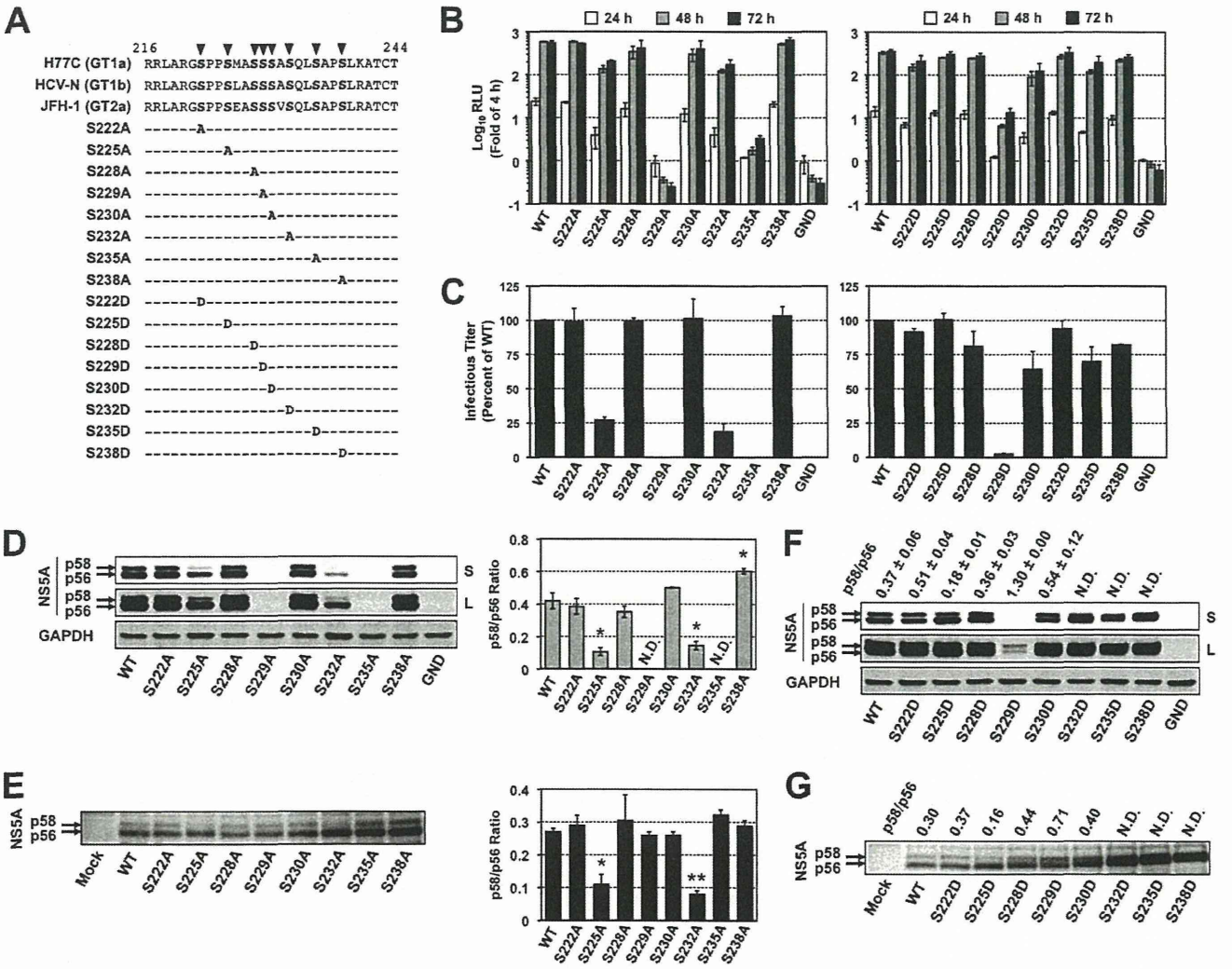


FIG 7 Effects of mutations at potential CKI-α phosphorylation sites on NS5A hyperphosphorylation, viral replication, and infectious virion production. (A) Highly conserved serine residues located within the LCS I region of NS5A and the sequences of NS5A mutants used. Arrowheads represent putative phosphorylation sites replaced with alanine or aspartic acid. The numbers represent amino acid positions within NS5A. (B) Viral replication. Huh-7 cells were transfected with the indicated JFH-1-based GLuc reporter constructs, including the WT and its replication-defective mutant (GND). Culture supernatants were harvested at the indicated time points for luciferase assays. The GLuc activity at each time point was normalized with the activity at 4 h posttransfection, and the fold chnages are shown. Results represent the means ± standard deviations from three independent experiments, each performed in triplicate. (C) Infectious virion production. Huh-7 cells were transfected with the indicated JFH-1 viral RNAs, including the WT and its replication-defective mutant (GND). Culture supernatants were harvested 3 days (72 h) later for titrations of infectious virus in a focus-forming unit (FFU) assay. The infectious virus yield of each NS5A mutant was normalized with that of JFH-1 WT, which was set at 100%. Results represent the means ± standard deviations from multiple independent experiments, each performed at least in triplicate. (D) Immunoblot of NS5A in lysates of cells transfected with JFH-1 viral RNAs carrying the indicated serine-to-alanine mutations (left). GAPDH is a loading control. The p58/p56 ratio of each virus was determined by carrying out densitometric analysis of NS5A bands (right). Results shown represent the means ± standard deviations from multiple independent experiments. *, $P < 0.05$, compared to WT. N.D., not determined, due to low levels of expression. (E) Vaccinia virus-T7 polymerase-mediated expression of NS5A in cells transfected with pJFH1 carrying the indicated serine-to-alanine mutations (left). NS5A bands were quantified by densitometric analysis, and p58/p56 ratios were calculated (right). Data shown represent the means ± standard deviations from multiple independent experiments. *, $P < 0.05$; **, $P < 0.01$ (versus WT). (F) Immunoblot of NS5A in lysates of cells transfected with JFH-1 viral RNA carrying the indicated serine-to-aspartic acid mutation. GAPDH was included as a loading control. The p58/p56 ratio of each virus was determined by carrying out densitometric analysis of NS5A bands. Results shown represent the means ± standard deviations from multiple independent experiments. N.D., not determined, due to the poor separation of p58 and p56 bands. (G) Vaccinia virus-T7 polymerase-mediated expression of NS5A in cells transfected with pJFH1 carrying the indicated serine-to-aspartic acid mutation. NS5A bands were quantified by densitometric analysis, and p58/p56 ratios were calculated. Data shown are representative of two independent experiments. N.D., not determined, due to the poor separation of p58 and p56 bands. S and L in panels D and F represent short exposure and long exposure, respectively.

NS5A hyperphosphorylation and hyperphosphorylation-dependent regulation of infectious virus production. In addition, S225A and S232A reproduced the viral phenotype following CKI-α knockdown more precisely than the other serine mutants within the peptide 1 region. It is most likely that S225 and S232 of NS5A are important for CKI-α-mediated hyperphosphorylation, which is involved in the robust production of infectious HCV.

DISCUSSION

Phosphorylation at serine and threonine residues in HCV NS5A is critical for regulation of the viral life cycle, including genome replication and infectious virus assembly (8, 9, 14, 16–18, 59–61). Several serine/threonine protein kinases have been identified as enzymes that potentially phosphorylate NS5A (9, 25, 26, 28, 50, 51). To our knowledge, however, this study is the first to identify through a kinome-wide screening protein kinases that interact with and phosphorylate NS5A. The *in vitro* AlphaScreen and phosphorylation assays, followed by RNAi screening on the HCVcc system, identified CKI-α as a major NS5A-associated kinase involved in NS5A hyperphosphorylation and the production of infectious virus.

In a previous study, CKI-α was reported to be involved in the replication of the subgenomic replicon derived from genotype 1b, with evidence that attenuation of CKI-α expression inhibited viral RNA replication up to 60% 5 days after the CKI-α knockdown (27). However, our study with the HCVcc system, as well as detailed analyses dissecting individual steps in the HCV life cycle, revealed that virion assembly is more affected by CKI-α silencing than is viral genome replication. It is highly likely that the CKI-α-mediated hyperphosphorylation of NS5A plays a role in recruiting NS5A to low-density membrane structures around LDs, leading to the acceleration of the early step(s) of virus particle formation. Mutagenesis analyses of putative CKI-α phosphorylation sites identified by a phospho-proteomic approach demonstrated that serine-to-alanine substitution at aa 225 or aa 232 in NS5A did to some extent reproduce the viral phenotype following CKI-α knockdown, indicating that S225 and S232 may be key residues for CKI-α-mediated NS5A hyperphosphorylation and regulation of virion assembly.

It is commonly held that HCV replication is regulated through the tight and delicate control of the ratio between p58 and p56 levels. Adaptive mutations or kinase inhibitors, which reduce NS5A hyperphosphorylation, enhance the HCV RNA replication of genotype 1 isolates, possibly by modulating its interaction with the host vesicle-associated membrane protein-associated protein subtype A (VAP-A), which is an essential factor for HCV replication (17–19, 24). In contrast, reduction of NS5A hyperphosphorylation by RNAi targeting protein kinases results in inhibition of the replication of genotype 1 adaptive replicons, indicating a role for p58 in efficient viral replication (25, 27). Impaired RNA replication resulting from reduced NS5A hyperphosphorylation has also been reported in the case of JFH-1 or JFH-1-based recombinant virus (25, 58–60). Consistent with a previous report (27), we found that CKI-α depletion inhibited the replication of the genotype 1b subgenomic replicon LucNeo#2, which carries the adaptive S2204R mutation in NS5A (38, 39) (Fig. 4C). Our transient-replication assay with the JFH-1 subgenomic replicon showed a slight but significant reduction in replication following CKI-α depletion (Fig. 4B). However, CKI-α silencing did not affect RNA replication in SGR-JFH1/LucNeo cells, where the JFH-1 subgenomic replicon stably replicates (Fig. 4C). Thus, the involvement of CKI-α in HCV RNA replication might be genotype or isolate dependent. We observed a difference in the replication capacity following CKI-α knockdown between transient and stable replication of JFH-1 replicons (Fig. 4B and C). A moderate reduction of replication was also detected when the JFH-1 genome carrying the S225A or S232A mutation was transiently transfected (Fig. 7B). One may infer that CKI-α is involved in the initiation of viral RNA replication rather than in its maintenance.

Our intra- and extracellular infectivity assays following CKI-α depletion suggested that CKI-α primarily targets virion assembly in the HCV life cycle (Fig. 4D to F), although a slight but nonnegligible negative effect of CKI-α knockdown on viral replication was observed (Fig. 4B). It is accepted that the assembly of HCV particles requires recruitment of NS proteins, including NS5A as well as structural proteins, to cytoplasmic membrane structures around LDs, leading to an interaction between NS5A and the core, which is important for efficient encapsidation of the viral genome (7, 8, 56). To understand how CKI-α is involved in virion assembly, we performed a subcellular fractionation assay and immunofluorescence confocal microscopy. Our subcellular fractionation assay clearly showed that hyperphosphorylated NS5A, p58, is mainly localized in low-density membrane fractions, while hypophosphorylated NS5A, p56, prefers high-density fractions. NS5A abundance in lighter fractions was decreased following CKI-α depletion (Fig. 5A). These results are supported by microscopic analyses that demonstrated that CKI-α silencing reduced colocalization of NS5A with LDs and the core (Fig. 5D and E). We tried to confirm the interaction of NS5A and core in HCVcc-infected cells that had been transfected with CKI-α siRNA or irrelevant siRNA. However, the interaction was not observed under this condition, presumably because immunoprecipitated NS5A and/or core was not abundant enough to assess their coimmunoprecipitation in siRNA-transfected cells. Alternatively, we assessed the interaction in Huh-7 cells coexpressing core and NS5A, although no p58 form (no functional NS5A) was detected in this setting. We clearly detected the interaction of NS5A and core in this experiment and found that CKI-α depletion had no significant effect on this interaction (data not shown). Taken together with the results of confocal microscopy (Fig. 5E), this finding might suggest that both (i) phosphorylation of serine residues in the C terminus of NS5A, which is involved in the generation of basally phosphorylated NS5A, as shown previously (8), and (ii) CKI-α-mediated hyperphosphorylation, in which serine residues in the LCS I region are mainly involved, are important for an efficient interaction between NS5A and core in HCV replicating cells. Collectively, CKI-α-mediated hyperphosphorylation of NS5A may contribute to an increase in the local concentration of NS5A at low-density membrane structures around LDs rather than in facilitating the physical interaction of NS5A and core. The relationship between the phosphorylation status of NS5A and its localization on cellular membranes has been previously reported. Miyanari et al. showed that mutated NS5A expressed from JFH-1 variants (JFH1^{AAA99} and JFH1^{AAA102} in their report), whose p58/p56 ratios were lower than that of wild-type virus, was not recruited to LDs (56). Qiu et al. fractionated lysates from replicon cells and demonstrated that a substantial amount of hyperphosphorylated NS5A was detected in lighter fractions. Treatment with an NS5A inhibitor, BMS-790052, reduced hyperphosphorylation of NS5A and concomitantly decreased the overall amount of NS5A in low-density membrane fractions (62). These findings raise questions about the regulatory mechanism(s) of the subcellular localization of NS5A, especially at low-density membrane structures. The above-mentioned NS5A mutants, JFH1^{AAA99} and JFH1^{AAA102}, have triple alanine substitutions for the APK sequence at aa 99 to 101 and the PPT sequence at aa 102 to 104 in NS5A, respectively, but neither is likely to be a CKI recognition site. In addition, the NS5A inhibitor

has no inhibitory effect on CKI activity (62). Thus, it appears that two or more kinds of serine/threonine-specific protein kinases, including CKI-α, participate in NS5A phosphorylation that is important for the regulation of its subcellular distribution. It is tempting to speculate that host factors involved in membrane trafficking or lipogenesis possibly interact with NS5A in a phosphorylation-dependent manner and facilitate recruitment of NS5A to low-density membrane structures surrounding LDs. Although further study is needed to validate this speculation, NS5A-interacting factors, such as VAP-A and diacylglycerol acyltransferase-1 (19, 63, 64), might be candidates for involvement in the regulation of this process.

To identify potential phospho-acceptor sites for CKI-α, a phospho-proteome analysis was carried out with NS5A isolated from HCVcc-infected cell lines with and without CKI-α knockdown (Fig. 6). Three kinds of phosphopeptides were identified out of a total of 629 peptides after peptide selection, although fine mapping of the phosphorylation sites was not completely successful. Among them, only the relative frequency of phosphopeptide 1 (GSPPSEASSSVSQLSAPSLR) was decreased after CKI-α knockdown, suggesting the possibility that peptide 1 contains amino acids phosphorylated by CKI-α. Serine residues in peptide 1, which are well conserved among HCV genotypes, matched the consensus sequences for CKI-α-mediated phosphorylation (57). In contrast, a threonine residue in peptide 2 is not conserved and does not match the consensus sequences for phosphorylation by CKI-α. The frequency of phosphopeptide 3 was unchanged with and without CKI-α knockdown (0.1% versus 0.1%). Further mutagenesis analyses targeting the peptide 1 region suggested that S225 and S232 are possible CKI-α phosphorylation sites involved in NS5A hyperphosphorylation and infectious virus production, because alanine substitution for either of these serine residues reproduced the viral phenotype after CKI-α knockdown more accurately than the other mutants within the peptide 1 region (Fig. 7B to E). The S229A and S235A mutations severely impaired viral replication, suggesting that phosphorylation at S229 and S235 is essential for efficient viral replication (Fig. 7B). However, the HCV protein expression assay using vaccinia virus expressing the T7 RNA polymerase revealed that phosphorylation of these residues is not involved in NS5A hyperphosphorylation (Fig. 7E). In the case of genotype 1 isolates, NS5A mutations that reduce hyperphosphorylation enhanced viral RNA replication (17, 18). However, this was not the case for the S225A or S232A mutation in genotype 2a. In addition, S229A and S235A mutations in genotype 1b (Con1) markedly enhance viral replication (18), but the same mutations are lethal in genotype 2a. S232 has been shown to be a potential phosphorylation site for CKI-α by a peptide-based kinase assay *in vitro* (28). However, the present study is the first to demonstrate the significance of phosphorylation at S225 and S232 in infectious virus production. The sequence coverage of NS5A by our mass spectrometry analysis was less than 60% and was especially low in domain III of NS5A (Fig. 6B). We cannot exclude the possibility of the presence of additional CKI-α phosphorylation sites in NS5A.

Recently, two cellular kinases involved in the regulation of NS5A phosphorylation have been identified. PI4K-IIIα is essential for HCV replication (65–70) and catalyzes the synthesis of phosphatidylinositol 4-phosphate accumulating in HCV replicating cells through its enzymatic activation resulting from an interaction with NS5A (71, 72). PI4K-IIIα directly interacts with the C-terminal end of NS5A domain I, and NS5A–PI4K-IIIα binding is essential for viral replication. Its depletion resulted in a relative increase of p58 abundance, while overexpression of enzymatically active PI4K-IIIα increased the relative abundance of p56 (73). Plk1 has been shown to play a role in viral replication through hyperphosphorylation of NS5A (25). Plk1 was coimmunoprecipitated with NS5A, and knockdown of Plk1 or treatment with a specific inhibitor decreased both NS5A hyperphosphorylation and HCV replication. Since the recognition sites for CKI-α, PI4K-IIIα, and Plk1 have been assumed to be spatially close to each other (25, 28, 73), it is interesting to analyze their interactive actions in regard to regulation of NS5A phosphorylation.

The exquisite balance between the two different phosphorylated forms of NS5A has been proposed to regulate the HCV life cycle; basally phosphorylated p56 abundance is hypothetically involved in viral RNA replication, and hyperphosphorylated p58 is required for virion assembly (9, 17, 18, 73, 74). However, this hypothesis has not yet been fully proven. Our results here provide strong evidence supporting the involvement of NS5A hyperphosphorylation in viral assembly and that of CKI-α in mediating this process. These results not only contribute to a better understanding of the regulatory details of the HCV life cycle but also illuminate targets for potential antiviral strategies.

ACKNOWLEDGMENTS

We are grateful to F. V. Chisari for kindly providing Huh7.5.1 cells, C. M. Rice for providing anti-NS5A mouse monoclonal antibody (9E10), K. Watashi and K. Shimotohno for providing LucNeo#2 cells, T. Pietschmann for providing the expression plasmid carrying the JFH-1 envelope glycoprotein gene, and Y. Matsuura for providing the plasmid expressing the VSV-G envelope glycoprotein. We thank D. Akazawa for help in preparing HCVpp, the Michael Hooker Microscopy Facility of the University of North Carolina for assistance with confocal microscopy, M. Sasaki, N. Sugiyama, K. Goto, and T. Date for their technical assistance, and T. Mizoguchi for secretarial assistance.

This work was supported in part by grants-in-aid from the Ministry of Health, Labor, and Welfare of Japan and the Ministry of Education, Culture, Sports, Science, and Technology, Japan, by Research on Health Sciences Focusing on Drug Innovation from the Japan Health Sciences Foundation, and by a grant (R01-AI095690) from the U.S. National Institutes of Health.

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HEPATOLOGY
Official Journal of the American Association for the Study of Liver Diseases

RAPID COMMUNICATION

Daclatasvir Plus Asunaprevir for Chronic HCV Genotype 1b Infection

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All-oral combinations of direct-acting antivirals may improve efficacy and safety outcomes for patients with hepatitis C virus (HCV) infection, particularly those who are poor candidates for current interferon/ribavirin-based regimens. In this open-label, phase 3 study, 135 interferon-ineligible/intolerant and 87 nonresponder patients with chronic HCV genotype 1b infection were enrolled at 24 centers in Japan. Patients received daclatasvir 60 mg once daily plus asunaprevir 100 mg twice daily for 24 weeks. The primary endpoint was sustained virologic response 24 weeks after treatment (SVR_{24}). This study is registered with Clinical Trials.gov (NCT01497834). SVR_{24} was achieved by 87.4% of interferon-ineligible/intolerant patients and 80.5% of nonresponder (null and partial) patients; rates were similar in cirrhosis (90.9%) and noncirrhosis (84.0%) patients, and in patients with *IL28B* CC (84.5%) or non-CC (84.8%) genotypes. Fourteen patients in each group (12.6%) discontinued dual therapy, mainly due to adverse events or lack of efficacy. Nine nonresponder patients received additional treatment with peginterferon/ribavirin per protocol-defined criteria. The rate of serious adverse events was low (5.9%) and varied among patients. The most common adverse events were nasopharyngitis, increased alanine aminotransferase (ALT) and aspartate aminotransferase (AST), headache, diarrhea, and pyrexia. *Conclusion:* Interferon-free, ribavirin-free all-oral therapy with daclatasvir and asunaprevir for 24 weeks is well tolerated and can achieve a high rate of SVR in patients with HCV genotype 1b who were ineligible, intolerant, or had not responded to prior interferon-based therapy. (HEPATOLOGY 2014;59:2083-2091)

Treatment of chronic hepatitis C virus (HCV) infection typically includes a regimen of interferon-based therapy plus ribavirin, with or without a direct-acting antiviral. The efficacy and tolerability of these regimens are not ideal, and there remains a large number of patients for whom these treatments are not acceptable or viable. The addition of direct-acting antivirals can improve treatment outcomes for patients infected with chronic HCV. When combined with peginterferon and ribavirin, the HCV protease inhibitors telaprevir, boceprevir, or simeprevir achieved overall sustained virologic response (SVR) rates ranging from 68% to 89% in treatment-naïve patients with HCV genotype 1 infection.[1-3] Patients with no response to previous peginterferon/ribavirin therapy did not respond as well to this combined regimen, with rates of SVR ranging from 34% to 52%.[3-5] In Japan, patients chronically infected with HCV are older and predominantly infected with HCV genotype 1, both factors which impact response to therapy.[6] For Japanese patients who had no prior response to treatment with peginterferon/ribavirin, telaprevir or

Abbreviations: HCV, hepatitis C virus; LLOQ, lower limit of quantitation; NS, nonstructural; SVR, sustained virologic response; TD, target detected; TND, target not detected.

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Received February 10, 2014; accepted February 28, 2014.

This study was funded by Bristol-Myers Squibb.