Interferon resistance of hepatitis C virus replicon-harbouring cells is caused by functional disruption of type I interferon receptors

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Hepatitis C virus (HCV) replicon-harbouring cell lines possessing interferon (IFN)-resistant phenotypes have recently been established. These were divided into two classes: partially IFN resistant and highly IFN resistant. Here, the viral and cellular factors contributing to the IFN resistance of HCV replicon-harbouring cells were evaluated. The results revealed that cellular factors rather than viral factors contributed to a highly IFN-resistant phenotype. The possibility of genetic abnormality of the factors involved in IFN signalling was investigated. As a result, nonsense mutations and deletions in type I IFN receptor genes (IFNAR1 and IFNAR2c) were found in replicon-harbouring cells showing a highly IFN-resistant phenotype, but rarely appeared in cells showing a partially IFN-resistant phenotype. Furthermore, similar genetic alterations were also found in IFN-resistant phenotype, replicon-harbouring cell lines obtained additionally by IFN-β treatment. Moreover, it was shown that ectopic expression of wild-type IFNAR1 in IFN-resistant phenotype, replicon-harbouring cells possessing the IFNAR1 mutant restored type I IFN signalling.

Persistent infection by hepatitis C virus (HCV) is a major cause of chronic hepatitis (Choo et al., 1989; Kuo et al., 1989), which can progress to liver cirrhosis and hepatocellular carcinoma (Saito et al., 1990). Since at least 170 million people are currently infected with HCV worldwide, this infection constitutes a global health problem (Thomas, 2000). HCV is an enveloped RNA virus belonging to the family Flaviviridae, the genome of which consists of a positive-stranded RNA encoding an approximately 3000 aa polypeptide precursor (Kato et al., 1990). This precursor protein is processed by the host and viral proteases to generate at least 10 proteins in the following order: core, envelope 1 (E1), E2, p7, non-structural protein 2 (NS2), NS3, NS4A, NS4B, NS5A and NS5B (Kato, 2001).

Since 1998, combined treatment with interferon (IFN)-α and ribavirin has been standard clinical therapy for patients with chronic hepatitis C; however, the effectiveness of IFN is limited to approximately 50% (Hadziyannis et al., 2004). This clinical result suggests that HCV directly or indirectly attenuates the antiviral actions of IFN (Pawlotsky, 2000).

Although an HCV replicon system carrying autonomously replicating HCV subgenomic RNA containing the NS3–NS5B regions (Lohmann et al., 1999) was considered to be useful in studies on the mechanism(s) of IFN resistance of HCV, all HCV replicons established to date have been highly sensitive to IFN-α, β and γ (Frese et al., 2001, 2002; Kato et al., 2003). This seems to contradict the fact that half of the patients with chronic hepatitis C are resistant to current IFN therapy. Therefore, we assumed that prolonged IFN treatment might change HCV replicons from an IFN-sensitive phenotype to an IFN-resistant phenotype.

Based on this assumption, we recently established nine HCV replicon cell lines possessing two IFN-resistant phenotypes: a partially resistant phenotype (α series: 1αR, 3αR, 4αR, 5αR and αRmix) and a highly resistant phenotype (βR series 1βR, 3βR, 4βR and 5βR) obtained by IFN-α and -β treatment, respectively (Namba et al., 2004). Genetic analysis of these replicons found one common amino acid substitution (Q1737H) in the NS4B region and several additional amino acid substitutions (such as M2174V and T2242N) in the NS4B region and several additional amino acid substitutions (such as M2174V and T2242N) in the NS5A region of the replicons (Frese et al., 2001, 2002; Kato et al., 2003). To examine which viral and cellular factors contribute to the IFN resistance of HCV replicons, we evaluated the IFN sensitivity of replicon-harbouring cells (6M.m/6Mc, 1βR/m/6Mc and 4βR/m/6Mc) established by transfection of total RNAs isolated from an IFN-sensitive clone (6M) and from highly IFN-resistant clones (1βR and 4βR) into cured 6Mc cells, from which 50-1 replicons (Kishine et al., 2002) had been eliminated by IFN-γ treatment (500 IU ml⁻¹ for
colonies survived in 1

The results revealed that few or no IFN- obtained as G418-resistant mixed colonies were treated with IFN- (Fig. 1a). Similar results were examined as described in (a) except that 6M.m/6Mc cells, respectively, pro-

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To clarify whether or not the signalling defect in these replicon-harbouring cells was restricted to type I IFN, we examined the phosphorylation status of STAT3 in 6M, 1/R and 4/R cells treated with interleukin-6 (IL6). Since it has been reported that STAT3 is also activated by IFN- (Pfeffer et al., 1997), the phosphorylation status of STAT3 in these replicon-harbouring cells after IFN- treatment was also examined. Our results revealed that STAT3 was not phosphorylated in 1/R and 4/R cells treated with IFN-, while phosphorylation of STAT3 was observed in 6M, 1/R and 4/R cells treated with IL6 and in 6M cells treated with IFN- (Fig. 2d), indicating that only type I IFN signalling was defective in 1/R and 4/R cells. These results suggested that the initial reaction following the addition of IFN- was defective in replicon-harbouring cells possessing a highly IFN-resistant phenotype.

Following up this suggestion, we examined the genetic status of tyrosine kinase 2 (TYK2) and Janus kinase 1 (JAK1). Sequence analysis of TYK2 and JAK1 cDNAs obtained from 1/R and 4/R cells was performed after cloning into the pCXbsr vector (Akagi et al., 2000), as described previously (Nozaki et al., 2003). However, the results showed no mutations in these cDNAs (data not shown). We next focused on type I IFN receptors (IFNAR1 and IFNAR2c). Our results showed that the mRNA levels of the two receptors were almost equal among all examined replicon-harbouring cells including 6M cells (see Supplementary Fig. S1a, available in JGV Online). More than three independent clones of each cDNA (1708 bp for IFNAR1 and 1582 bp for IFNAR2c) were sequenced as described above. Table 1 shows a summary of sequence analysis of IFNAR1

3 weeks). Although many colonies were found to have survived in 1/R and 4/R cells after IFN- treatment, only a few colonies survived in 1/R.m/6Mc and 4/R.m/6Mc cells or in 6M and 6M.m/6Mc cells (Fig. 1a). Similar results were obtained when these replicon-harbouring cells were treated with IFN- (400 IU ml⁻¹) (data not shown), although two colonies (named 6/R and 7/R, described below) derived from 6M.m/6Mc and 4/R.m/6Mc cells, respectively, proliferated as highly IFN-resistant clones.

We further examined the IFN sensitivity of replicon-harbouring cells (6MK1/6Mc, 1/R1/6Mc and 4/R2/6Mc) established by the transfection of in vitro-synthesized replicon RNAs (6MK1, 1/R1 and 4/R2 obtained from 6M, 1/R and 4/R cells, respectively) (Namba et al., 2004; Kato et al., 2005) into 6M cells. The results revealed that few or no colonies survived in 1/R1/6Mc and 4/R2/6Mc cells, as in 6M and 6MK1/6Mc cells, whereas many colonies survived in 1/R and 4/R cells (Fig. 1b). These results suggested that cellular factors rather than viral factors contributed to the highly IFN-resistant phenotype of HCV replicon-harbouring cells. However, the present results obtained under a high concentration of IFN do not necessarily rule out a possible role for HCV mutations in conferring low degrees of IFN resistance, because effects of HCV mutations on IFN activity are presumably weaker than those of the cellular factors.

To obtain evidence in favour of the idea that alterations in cellular factor(s) are involved in the emergence of an IFN-resistant phenotype, we attempted to prepare cured cells from the replicon-harbouring cells possessing a highly IFN-resistant phenotype. Since phosphorylation of signal transducer and activator of transcription 1 (STAT1) occurred in the 1/R and 4/R cells treated with IFN- (Fig. 2a), these replicon-harbouring cells were treated with IFN- (500 IU ml⁻¹) for 3 weeks, and cured 1/Rc and 4/Rc cells were obtained. Western blot (Fig. 2b) and RT-PCR (data not shown) analyses showed that no replicons were detected in either type of cured cells. Analysis of a luciferase reporter assay indicated that the complete defect of the IFN- signalling was not restored in the cured 1/Rc and 4/Rc cells (Fig. 2c).
and IFNAR2c mRNAs. Surprisingly, we found that nt 475 of IFNAR2c mRNA from 1/R cells had a U substituted for G in 13/13 clones, resulting in a nonsense mutation at codon 159 from glutamic acid (GAG) to the termination codon UAG (see Supplementary Fig. S1b). Furthermore, nt 319 of IFNAR1 mRNA from 4/R cells was also found to have a U substituted for G in 12/12 clones, resulting in a nonsense mutation at codon 107 from glutamic acid (GAA) to the termination codon UAA (see Supplementary Fig. S1c).

However, interestingly, IFNAR1 and IFNAR2c mRNAs obtained from 1/R and 4/R cells, which were derived from clone 1 and clone 4 and were counterparts of 1/R and 4/R cells, respectively (see Supplementary Fig. S2, available in JGV Online), did not possess the nonsense mutations found in the mRNAs from 1/R and 4/R cells. In addition, several kinds of deletion and another nonsense mutation (lysine to a termination codon at codon 458) were found in approximately half of IFNAR1 cDNA clones obtained from 3/R and 5/R cells. In contrast to the finding of frequent mutations and deletions in IFNAR mRNAs from the β/R series, such genetic abnormalities in IFN receptors were quite rare in the α/R series (Table 1).

To evaluate the possibility that genetic mutants might preexist in the cloned replicon-harbouring cells (clones 1, 3, 4 and 5 shown in supplementary Fig. S2) or that genetic mutants had appeared during the IFN-β treatment of the cloned replicon-harbouring cells, we repeated IFN-β treatment of cloned 1, 3, 4 and 5 cells following the method described previously (Namba et al., 2004). The result was almost identical to that obtained previously (Namba et al., 2004), indicating the good reproducibility of the experiment with IFN-β treatment (data not shown). In the present study, each of the three colonies showing resistance to IFN-β was isolated and proliferated (see Supplementary Fig. S2) and we then performed sequence analysis of IFNAR mRNAs.
after IFN-
observation that IFNAR mutations occurred preferentially mutation found in the 4 nonsense mutation in IFNAR1 cDNA, which was the same and IFNAR2c cDNAs as described above, the E107stop established immediately. By sequence analysis of IFNAR1

To examine whether or not additional HCV replicon cell lines possessing the IFN-resistant phenotype of 4

as described above. The results revealed that the nonsense mutations or deletions identified at this time (see Supplementary Table S1, available in JGV Online) were quite different from those obtained from the βR series (Table 1). Therefore, it is unlikely that the identified IFNAR mutants pre-existed in cloned 1, 3, 4 and 5 cells when these cells were obtained as colonies surviving IFN-α treatment.

To clarify whether or not the IFNAR mutations found in the βR series were determinants for the IFN sensitivity of HCV replicons, we prepared 4/βR cells (possessing the IFNAR1 mutant) stably expressing wild-type IFNAR1 and examined its IFN sensitivity. Analysis of a luciferase reporter assay (see Supplementary Fig. S3a, available in JGV Online) clearly showed that IFN signalling in 4/βR cells was restored by the expression of wild-type IFNAR1 in comparison with those of 4/βR cells expressing the IFNAR1 mutant (see Supplementary Fig. S3b). The quantitative RT-PCR analysis of replicon RNA in the cells treated with IFN-β clearly showed that the level of 4/βR replicon in cells expressing wild-type IFNAR1 was drastically decreased after IFN-β treatment, as was the level of 6M replicon in cells expressing wild-type IFNAR1 (see Supplementary Fig. S3c). In summary, we demonstrated that the IFNAR mutation found in 4/βR cells was a major determinant for a strongly IFN-resistant phenotype of 4/βR cells, suggesting that IFNAR mutations, which lead to the impairment of IFN signalling, convert HCV replicon-harbouring cells from an IFN-sensitive phenotype to a highly IFN-resistant phenotype.

Table 1. Genetic alterations of type I IFN receptors in HCV replicon-harbouring cell lines possessing IFN-resistant phenotypes

<table>
<thead>
<tr>
<th>Cell line</th>
<th>IFNAR1 mRNA</th>
<th>IFNAR2c mRNA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nucleotide change and position</td>
<td>Effect on protein</td>
</tr>
<tr>
<td>6M</td>
<td>NM</td>
<td>None</td>
</tr>
<tr>
<td>1βR</td>
<td>NM</td>
<td>None</td>
</tr>
<tr>
<td>3/βR</td>
<td>Deletion of 5 nt at nt 376 A to U at nt 1372</td>
<td>Truncated (135 aa)</td>
</tr>
<tr>
<td>4/βR</td>
<td>G to U at nt 319</td>
<td>E to stop at codon 107</td>
</tr>
<tr>
<td>5/βR</td>
<td>Deletion of 176 nt at nt 201 Deletion of 79 nt at nt 201</td>
<td>Truncated (78 aa) Truncated (67 aa)</td>
</tr>
<tr>
<td>1αR</td>
<td>NM</td>
<td>None</td>
</tr>
<tr>
<td>3αR</td>
<td>NM</td>
<td>None</td>
</tr>
<tr>
<td>4αR</td>
<td>Deletion of 5 nt at nt 376</td>
<td>Truncated (135 aa)</td>
</tr>
<tr>
<td>5αR</td>
<td>Deletion of 79 nt at nt 201</td>
<td>Truncated (67 aa)</td>
</tr>
<tr>
<td>2Rmix</td>
<td>NM</td>
<td>None</td>
</tr>
<tr>
<td>6Mc</td>
<td>NM</td>
<td>None</td>
</tr>
</tbody>
</table>

*Number of mutated or truncated clones/number of examined clones.

The determined nucleotide sequences were compared with those of 6M and 6Mc cells, which confirmed that the deduced amino acid sequences were identical to the human IFNAR1 (GenBank accession no. NM_000629) and IFNAR2c (GenBank accession no. L41942) sequences. NM, Not mutated.

To examine whether or not additional HCV replicon cell lines possessing the IFN-resistant phenotype could be obtained from HCV replicon-harbouring cells other than the parental replicon-harbouring cells used for the isolation of the zR and βR series, 6M.m/6Mc, 1βR.m/6Mc, 4/βR.m/6Mc and 50-1 replicon-harbouring cells were treated with IFN-β (see Supplementary Fig. S2). Finally, we obtained four replicon-harbouring cell lines (6/βR obtained from the 4/βR.m/6Mc cells, 7/βR obtained from the 6M.m/6Mc cells, and 8/βR and 9/βR obtained from the 50-1 cells) showing resistance to IFN-β. These results indicated that HCV replicon-harbouring cells showing the IFN-resistant phenotype were obtained from HCV replicon-harbouring cells established immediately. By sequence analysis of IFNAR1 and IFNAR2c cDNAs as described above, the E107stop nonsense mutation in IFNAR1 cDNA, which was the same mutation found in the 4/βR cells, was found again in the 8/βR and 9/βR cells, while no IFNAR mutations were detected in the 6/βR and 7/βR cells (see Supplementary Table S1). The observation that IFNAR mutations occurred preferentially after IFN-β treatment is interesting. Since a variety of mutations and deletions in the IFN receptors were obtained from the cloned replicon-harbouring cells surviving after IFN-β treatment, such genetic alterations might occur accidentally in order to impair the antiviral states caused after IFN-β treatment. Thereafter, only replicon-harbouring cells possessing the IFNAR mutants might be able to proliferate in the presence of G418, resulting in the βR series.
IFNAR1 and IFNAR2c belonging to the class II cytokine receptor superfamily are structurally conserved transmembrane receptors located on the cell surface (see Supplementary Fig. S4a, available in JGV Online). However, since both the IFNAR1 E107stop mutant and the IFNAR2c E159stop mutant found in 4/R and 1/R cells, respectively, were N-terminally truncated and probably soluble forms, these truncated proteins may not be functional as IFN receptors or may act as dominant-negative inhibitors, and will lead to the interception of IFN signalling (see Supplementary Fig. S4b). Thus, the cause of the IFN-resistant phenotype of 1/R or 4/R cells appeared to be the functional disruption of IFNAR. The present results suggest that the downstream JAK/STAT pathway is intact, at least in 4/R cells.

Although for the most part we could clarify the mechanism underlying a highly IFN-resistant phenotype of HCV replicon-harbouring cells, at least in the case of 4/R cells, the mechanism underlying a partially IFN-resistant phenotype remains unclear, because IFNAR mutations were rare in the zR series. Since the expression levels of IFNAR, TYK2 and JAK1 were not decreased in the zR series, a functional deficiency of other cellular factor(s) involved in the IFN signalling may contribute to the acquisition of IFN resistance. Alternatively, certain HCV mutation(s) may account for the partially IFN-resistant phenotype of the zR series.

Since Machida et al. (2004a, b) recently reported that the frequency of genetic mutation was enhanced by HCV replication in in vitro-infected B cells and that the HCV core and NS3 were involved in the induction of a mutator phenotype mediated through the activation of inducible nitric oxide synthase, we cannot exclude the possibility that persistent HCV replication induces some irreversible genetic mutations. To clarify whether or not HCV acts as a mutagen for cellular factors, further study using an HCV RNA replicating system is necessary.

The HCV replicon-harbouring cells including 1/R and 4/R, in which IFN signalling is impaired, used or obtained in the present study may be useful for future studies, not only of the mechanism(s) underlying the IFN resistance of the replicons but also of the functional characterization of IFN receptors. Furthermore, these replicon cells may also be useful for screening novel anti-HCV reagents that act by mechanisms unrelated to IFN signalling.

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References


