Core protein cleavage by signal peptide peptidase is required for hepatitis C virus-like particle assembly

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Hepatitis C virus (HCV) core protein, expressed with a Semliki Forest virus replicon, self-assembles into HCV-like particles (HCV-LP) at the endoplasmic reticulum (ER) membrane, providing an opportunity to study HCV assembly and morphogenesis by electron microscopy. This model was used to investigate whether the processing of the HCV core protein by the signal peptide peptidase (SPP) is required for the HCV-LP assembly. Several mutants were designed as there are conflicting reports concerning the cleavage of mutant proteins by SPP. Production of the only core mutant protein that escaped SPP processing led to the formation of multiple layers of electron-dense ER membrane, with no evidence of HCV-LP assembly. These data shed light on the HCV core residues involved in SPP cleavage and suggest that this cleavage is essential for HCV assembly.

Indeed, this mature form of the HCV core protein is the predominant form detected in virus particles purified from the sera of patients with chronic HCV infection (Yasui et al., 1998). However, processing of the HCV core protein by SPP has also been shown to release the core protein from the ER membrane, leading to its trafficking to zones of the ER in which lipid droplets are produced (McLauchlan et al., 2002). During its trafficking, the proline-rich, central hydrophobic domain 2 of the HCV core protein (aa 119–173) is thought to remain anchored in the cytoplasmic phospholipid monolayer of the ER and is therefore thought to be present in the membrane surrounding the lipid droplets, which consists of a single phospholipid monolayer (Hope & McLauchlan, 2000).

Thus, retention of the HCV core protein in the ER membrane by its signal sequence may play an essential role in viral particle assembly by, at least transiently, preventing trafficking to the lipid droplets. It therefore remains unclear whether HCV core protein cleavage by SPP is an essential step for virion assembly and morphogenesis. Recent advances in the establishment of cell-culture systems have made it possible to produce infectious HCV that can be efficiently propagated in cultured, naïve hepatoma cells (Lindenbach et al., 2005; Wakita et al., 2005; Zhong et al., 2005). However, it remains extremely difficult to observe virus assembly and morphogenesis in these cell cultures (P. Roingeard, unpublished observation). We have developed a model based on Semliki Forest virus (SFV) replicon vectors, in which the production of the HCV core protein in mammalian cells leads to the assembly of this protein into HCV-like...
particles (HCV-LP) (Blanchard et al., 2003). This model displays abortive HCV-LP budding, but it remains a useful tool for studies of the early events of HCV assembly in eukaryotic cells (Roingeard et al., 2004). In this study, we use this HCV capsid assembly model to characterize the role of SPP cleavage in viral morphogenesis.

Previous studies have identified various residues in the transmembrane signal sequence domain of the HCV core protein that are involved in the intramembrane cleavage of this protein by SPP. It was initially demonstrated that the ASC180/3/4VLV HCV mutant core protein, which contains helix-favouring residues in place of the helix-bending and helix-breaking residues, was not processed by SPP (Lemberg & Martoglio, 2002; McLauchlan et al., 2002). However, a recent study of the same ASC180/3/4VLV mutant demonstrated efficient cleavage of this molecule by SPP (Okamoto et al., 2004). In the same study, it was shown that an IF176/7AL core mutant protein was not processed by SPP. These discrepancies were observed for the core proteins of both the 1a and 1b genotypes of HCV. They were not due to differences in the core protein sequence or in cell type, as both studies were conducted with BHK-21 cells. We therefore designed SFV replicon vectors encoding the ASC180/3/4VLV and IF176/7AL core mutants to resolve these discrepancies and to address our own research questions. The SF173/4ML mutant core protein was found not to be processed by SPP in a third study (Yamanaka et al., 2002) and was therefore also investigated in our study. The C191 and C173 sequences were subcloned in SFV vectors from the HCV cDNA Dj 6.4 clone (genotype 1a) as described previously (Blanchard et al., 2003). Site-directed mutagenesis within the C-terminal C191 signal sequence was performed with antisense primers leading to (i) generation of the three mutants ASC180/3/4VLV, IF176/7AL and SF173/4ML (Fig. 1a) and (ii) insertion of a stop codon at the 3′ end of the core protein-coding region.

The BHK-21 cell line was cultured and electroporated as described previously (Blanchard et al., 2002). SDS-PAGE and Western blotting analysis showed that the wild-type (WT) C191 core protein was fully cleaved by SPP in these cells, as reported previously (Blanchard et al., 2003) (Fig. 1b). In cells transfected with the WT C191 construct and treated with various concentrations (60, 100 or 150 µM) of (Z-LL)2 ketone (Calbiochem), SPP cleavage was partially inhibited (Fig. 1b), as reported in previous studies using this commercially available SPP inhibitor (Weihofen et al., 2003). We used Image J gel analyser software to determine the amounts of the p23 and p21 forms of HCV core protein in the scanned blots. Uncleaved and cleaved forms were detected in equal quantities in cells treated with 60 µM (Z-LL)2 ketone. Similar quantities of uncleaved (60%) and cleaved (40%) forms were detected at concentrations of 100 and 150 µM (Z-LL)2 ketone, indicating that this protease inhibitor was most efficient at a concentration of 100 µM (Fig. 1b). This is not surprising, as this compound is very efficient in cell-free translation/translocation assays, but less efficient in cellular assays because it does not readily cross the plasma membrane (Weihofen et al., 2003).

The ASC180/3/4VLV mutant core protein was the only mutant protein studied that remained uncleaved, resulting in detection of the p23 form of the core protein alone (Fig. 1b). This confirms the results obtained by Martoglio and colleagues with this mutant (Lemberg & Martoglio, 2002; McLauchlan et al., 2002), but conflicts with the data reported by Okamoto et al. (2004). We found that the IF176/7AL mutant core protein was efficiently processed by SPP, leading to detection of the p21 core protein (Fig. 1b), despite a previous report of this protein being resistant to SPP cleavage (Okamoto et al., 2004). The SF173/4ML mutant core protein was also efficiently cleaved in our study (Fig. 1b). A total lack of processing (Yamanaka et al., 2002) or partial processing (Liu et al., 1997) has previously been reported for this protein. However, it should be pointed out that mutations in the HCV core protein have been shown to have a significant effect on the mobility of this protein in SDS-PAGE (McLauchlan et al., 2002). In addition, we cannot rule out the possibility that SPP processes the signal sequence of the core protein heterogeneously at several sites, as observed for γ-secretase, an aspartic protease closely related to SPP that cleaves the transmembrane region of the amyloid-β precursor protein at several sites (Edbauer et al., 2003). These factors may account for difficulties in interpreting SDS-PAGE results for HCV mutant core proteins and highlight the need for comparisons with relevant reference peptides. It should also be noted that the interaction of the HCV mutant core proteins with lipid droplets was not investigated in most of these previous studies. This led us to investigate the subcellular distribution of our HCV mutant core proteins.

This analysis was made with the WT and mutant constructs expressed in the human hepatoma FLC4 cell line (Aizaki et al., 2003) (Fig. 1c). Expression from SFV vectors was found to be less efficient in this cell line than in BHK-21 cells, allowing a more precise analysis of the subcellular core distribution and lipid-droplet interaction. All the core proteins except the ASC180/3/4VLV mutant were colocalized with lipid droplets (Fig. 1c). Nile red labelling in control cells transfected with β-Gal SFV RNA showed that lipids were evenly distributed throughout the cytoplasm. Transfection with the HCV WT C191 and C173 constructs induced the clustering in the perinuclear area of large lipid droplets that stained strongly for HCV core protein (Fig. 1c). The IF176/7AL and SF173/4ML mutant core proteins had a subcellular distribution similar to that of WT C191 (Fig. 1c). The ASC180/3/4VLV mutant core protein was weakly associated with some lipid droplets, but was mostly distributed in reticular patches throughout the cytoplasm (Fig. 1c). Thus, all the HCV core mutant proteins cleaved by SPP in the SDS-PAGE analysis were colocalized with lipid droplets, similar to the WT core protein. This confirmed that the ASC180/3/4VLV mutant core protein was the only mutant core protein that escaped SPP processing.
This study is the first to report the ultrastructural changes induced in cells by production of the HCV mutant core proteins ASC180/3/4VLV, IF176/7AL and SF173/4ML. BHK-21 cells transfected with the recombinant SFV RNAs encoding the two mutant HCV core proteins correctly cleaved by SPP (IF176/7AL and SF173/4ML) differed markedly in terms of ultrastructure (Fig. 2). As expected, the SF173/4ML mutant core protein gave a pattern similar to that of WT C191, with convoluted ER membranes displaying HCV-LP assembly (Fig. 2). Conversely, cells producing the IF176/7AL mutant core protein showed no sign of ER modification (Fig. 2), similar to cells transfected with \( \beta \)-Gal RNA or C173 RNA. This provides additional evidence that this mutant core protein is efficiently cleaved by SPP and does not remain anchored in the ER membrane by its transmembrane signal sequence. This finding may also suggest that aa 176 and 177 (IF in the WT core protein) are located in the mature core protein after SPP cleavage and that their replacement by other amino acids may hamper core protein multimerization.

Cells transfected with the recombinant SFV RNA encoding the ASC180/3/4VLV mutant HCV core protein, which is not processed by SPP, had a very unusual ultrastructure. Indeed, convoluted electron-dense ER membranes were found to form multiple layers in these cells (Fig. 3). No HCV-LPs or marked clustering of lipid droplets was observed in cells producing this mutant core protein. These observations confirm that the ASC180/3/4VLV core protein remains anchored in the ER membrane by its transmembrane signal sequence. This unprocessed mutant protein therefore probably displays self-interaction, inducing the formation of multi-layered ER membranes, but not assembly to give HCV-LP. These data suggest that
processing of the HCV core protein by SPP is required for assembly of the virus particle. We investigated the ultrastuctural changes induced in cells by production of the WT C191 core protein in the presence of (Z-LL)$_2$ ketone. Unfortunately, this commercially available SPP inhibitor is not very efficient in cellular assays, due to low plasma membrane permeability (Weihofen et al., 2003). We were able to achieve only 60% inhibition of SPP in cells transfected with the WT C191 core protein construct and treated with 100 µM (Z-LL)$_2$ ketone. This treatment decreased the frequency of HCV-LP, which became much harder to detect, and led to the generation of multi-layered ER membranes similar to those found in cells producing the ASC180/3/4VLV mutant core protein (data not shown).

Thus, cleavage of the transmembrane signal sequence of the HCV core protein by SPP appears to be an essential step in assembly of the viral particle. This conclusion is at odds with the recent results of analyses of WT C191 production in yeast cells (Majeau et al., 2005). The reasons for these discrepancies are unknown but may be due to differences in the HCV assembly mechanisms in yeast and mammalian cells. However, the intracellular HCV-LP assembly has not been well established by electron microscopy in yeast cell sections.

In conclusion, HCV core protein processing by SPP is required for the trafficking of the protein to the lipid droplets, but we suggest that it is also required for assembly
into virus particles at the ER membrane. Our data provide new insight into the relevance of interactions between HCV and host-cell factors and suggest that SPP inhibitors are of potential value for the treatment of HCV infection.

Acknowledgements

We thank Mario Mondelli and Yoshiharu Matsuura for providing us with the monoclonal human anti-core antibody B12F8 and the FLC4 cell line, respectively. This work was supported by a grant from the French National Agency for Research on AIDS and Viral Hepatitis (ANRS) and by the ‘Region Centre’. M. A.-G. and R. P. were supported by fellowships provided by the French Ministry of Research. M. A.-G. also received a grant from the French Foundation for Medical Research (FRM). Our data were generated with the help of the RIO Electron Microscopy Facility of the Francois Rabelais University of Tours.

Fig. 3. Electron micrographs of BHK-21 cells electroporated with the C191 ASC180/3/4VLV RNA, showing electron-dense ER membranes [delimited by arrowheads at low magnification in (a)]. At high magnification (c), these structures were found to be formed by the interaction of multiple ER membranes (arrow). (b) Immunogold labelling with anti-core antibodies demonstrated the presence of a high amount of core protein in these multi-layered ER membranes. Bars, 0·2 μm (a); 0·1 μm (b, c).

References


