Characterization of hepatitis C RNA-containing particles from human liver by density and size

Søren U. Nielsen, Margaret F. Bassendine, Caroline Martin, Daniel Lowther, Paul J. Purcell, Barnabas J. King, Dermot Neely and Geoffrey L. Toms

Hepatitis C virus (HCV) particles found in vivo are heterogeneous in density and size, but their detailed characterization has been restricted by the low titre of HCV in human serum. Previously, our group has found that HCV circulates in blood in association with very-low-density lipoprotein (VLDL). Our aim in this study was to characterize HCV RNA-containing membranes and particles in human liver by both density and size and to identify the subcellular compartment(s) where the association with VLDL occurs. HCV was purified by density using iodixanol gradients and by size using gel filtration. Both positive-strand HCV RNA (present in virus particles) and negative-strand HCV RNA (an intermediate in virus replication) were found with densities below 1.08 g ml$^{-1}$. Viral structural and non-structural proteins, host proteins ApoB, ApoE and caveolin-2, as well as cholesterol, triglyceride and phospholipids were also detected in these low density fractions. After fractionation by size with Superose gel filtration, HCV RNA and viral proteins co-fractionated with endoplasmic reticulum proteins and VLDL. Fractionation on Toyopearl, which separates particles with diameters up to 200 nm, showed that 78% of HCV RNA from liver was >100 nm in size, with a positive-/negative-strand ratio of 6:1. Also, 8% of HCV RNA was found in particles with diameters between 40 nm and 70 nm and a positive-/negative-strand ratio of 45:1. This HCV was associated with ApoB, ApoE and viral glycoprotein E2, similar to viral particles circulating in serum. Our results indicate that the association between HCV and VLDL occurs in the liver.

INTRODUCTION

Hepatitis C virus (HCV) belongs to the family Flaviviridae and is infectious in humans and chimpanzees (Lindenbach & Rice, 2001). There are some biochemical and biophysical data for HCV virus particles from infected hosts (André et al., 2002; Petit et al., 2005; Roingeard et al., 2004) but the characterization of native virus particles has been difficult due to the low titre of HCV in serum. Analysis of HCV from human serum by immunoprecipitation and Western blotting shows that the virus particle contains glycoproteins E1 and E2 (Petit et al., 2005), and that virus particles are associated with apolipoprotein B and E (ApoB and ApoE) (André et al., 2002; Nielsen et al., 2006). A more detailed structural analysis of native HCV particles from infected hosts requires higher titres of virus. However, the characterization of HCV produced in vitro has been facilitated by two scientific breakthroughs.

The first breakthrough in the characterization of HCV produced in vitro was the development of the replicon system (Lohmann et al., 1999). In this system, HCV (genotypes 1b and 2a) replicates in Huh-7 human hepatoma cells and produces all HCV structural and non-structural (NS) proteins, as well as positive- and negative-strand HCV RNA (Lohmann et al., 1999; Pietschmann et al., 2002; Quinkert et al., 2005). Although virus particles are not secreted from Huh-7 cells transfected with the replicon, the system has enabled detailed studies of subcellular structures involved in HCV replication and characterization of the HCV replication complex. The replication complex is found inside a membranous web which also contains lipid rafts (Gosert et al., 2003; Shi et al., 2003) and has a low density ($\leq 1.10$ g ml$^{-1}$) (El-Hage &
ApoB and ApoE (Andreá) is a lipid particle that contains triglyceride, phospholipid, to be associated with very-low-density lipoprotein (VLDL), biophysical properties are similar to HCV obtained from Kapadia & Chisari (2005). This study demonstrated that HCV RNA replication is increased in Huh-7 cells when the growth medium is supplemented with mono-unsaturated fatty acids, but reduced when cells are grown in the presence of polyunsaturated fatty acids.

The second breakthrough in the characterization of HCV produced in vitro was the identification of the JFH-1 strain (Kato et al., 2001). This genotype 2a virus replicates in cell culture in Huh-7 and Huh-7.5 cells to produce infectious virus (Lindenbach et al., 2005; Wakita et al., 2005). The buoyant densities of virus produced from the JFH-1 strain cover a wide range between 1.03 g ml⁻¹ and 1.16 g ml⁻¹. The peak of HCV RNA coincides with fractions of lowest infectivity that have a density around 1.14 g ml⁻¹, a sedimentation coefficient of 200 S and a diameter of approximately 55–70 nm (Gastaminza et al., 2006; Wakita et al., 2005). The buoyant density of infectious virus produced in vitro by the JFH-1 strain is below 1.10 g ml⁻¹ (Chang et al., 2007; Gastaminza et al., 2006). These biophysical properties are similar to HCV obtained from the blood of infected patients, where HCV has been shown to be associated with very-low-density lipoprotein (VLDL), a lipid particle that contains triglyceride, phosphopolipid, ApoB and ApoE (André et al., 2002; Nielsen et al., 2006; Prince et al., 1996).

The proportion of HCV circulating in blood which has low density and is associated with VLDL varies between patients (Kanto et al., 1995; Zahn & Allain, 2005). This paper aims to determine the density and size of HCV from patient's liver and suggest the subcellular location in which HCV becomes associated with VLDL, information that is currently unknown.

We have previously demonstrated the presence of viral structural proteins in the explant liver of a patient with HCV infection and common variable immunodeficiency by Western blotting and immunohistochemistry (Fenwick et al., 2006; Nielsen et al., 2004). Our present work characterizes the HCV RNA-containing particles in this patient’s liver by density and size and provides new insight into the biochemical composition and assembly of HCV in human liver.

**METHODS**

**HCV samples from patients.** Patient S6 suffered from common variable immunodeficiency and was infected with the 1a genotype of HCV from contaminated intravenous immunoglobulin (Christie et al., 1997). The viral infection progressed rapidly to cirrhosis, requiring a liver transplant. However, the transplant liver (S6b) failed and was removed at retransplant; it was found to contain a high titre of HCV (5 × 10⁹ IU per gram liver) (Pumeechochak et al., 2002). An HCV-negative liver sample was obtained from a patient with a Klatskin tumour in the hepatic bile ducts. Cubes of 1 g either of HCV-infected liver or control HCV-negative liver were immersed in ice-cold homogenization buffer (Nielsen et al., 2004) and a macerate was produced using a tight-fitting Dounce homogenizer (WVR). The collection of human serum and tissue samples was made with informed consent and the research project was approved by the Joint Ethics Committee of the Newcastle and North Tyneside Health Authority, Newcastle University and University of Northumbria.

**Iodixanol density gradients.** Preformed iodixanol (Optiprep; Axis-Shield) density gradients were prepared from two buffered solutions of iodixanol at 6% (1.7 ml 60%, w/v, iodixanol, 0.34 ml 0.5 M Tris/HCl, pH 8.0, 0.34 ml 0.1 M EDTA, pH 8.0 and 14.6 ml 0.25 M sucrose) and 56.4% (16.0 ml 60%, w/v, iodixanol, 0.34 ml 0.5 M Tris/HCl, pH 8.0, 0.34 ml 0.1 M EDTA, pH 8.0 and 0.34 ml 0.25 M sucrose). The gradient was harvested from the bottom by tube puncture using a model 184 tube piercer (Isco) and collected in 14 fractions. The density of each fraction was determined using a digital refractometer (Atago). Self-forming iodixanol gradients (Graham et al., 1994) were prepared by adding 0.2 ml 0.5 M Tris/HCl (pH 8.0), 0.34 ml 0.5 M EDTA, 4.2 ml 60% (w/v) iodixanol and 1.5 ml 0.25 M sucrose into thick-walled Ti-50 polycarbonate centrifuge tubes (Beckman). Each centrifuge tube then received 4.2 ml liver macerate and the content was thoroughly mixed to form a homogeneous solution. These gradients were centrifuged at 50,000 r.p.m. in a Beckman L8-70M ultracentrifuge using a model Ti-50 rotor for 24 h at 4 °C and harvested manually from the top, collecting 18 fractions of 0.5 ml each from each sample.

For electron microscopy (EM) analysis, iodixanol fractions were dialysed against 100 mM Tris/HCl, pH 7.4, with 2 mM EDTA at 4 °C. Samples for thin sectioning were fixed with 3% glutaraldehyde (EM grade; VWR) and embedded in LR White (London Resin). Samples for negative staining were applied to Formvar-coated and glow-discharged copper grids; these were washed with Sorenson’s buffer and stained with 1% uranyl acetate. Grids were viewed on a Phillips CM 100 transmission electron microscope equipped with an AMT CCD camera.

**Quantification of HCV RNA by real-time RT-PCR.** Real-time RT-PCR (qRT-PCR) for positive-strand HCV RNA was carried out as described previously (Mercier et al., 1999; Nielsen et al., 2004) using primers NCR-3 and NCR-5 (Mercier et al., 1999) plus a fluorescent probe (5'–FAM–ATTCCGGTGTACTCCGAGTCGGAGA–TAMRA–3'). Primers NCR-3 and -5 anneal between nucleotides 120 and 290 in the 5' non-translated region of the HCV 1a genome. The HCV positive-strand assay was calibrated against WHO international standard for HCV 96/790 from the National Institute of Biological Standards and Controls. Negative-strand HCV RNA was detected using a qRT-PCR assay with the tagged primer, NCR-9 (Komurian-Pradel et al., 2004; Nielsen et al., 2006). NCR-9 (5'–CGTCGGGC–AGTATGTTAATTCGACCCCCCTCCCCGCC–AAGGAGACAT–3'; the tag is underlined) anneals to the 3' non-translated region of the negative strand and was used for reverse transcription. Residual RNA template was removed with RNase A and RNase H (GE Healthcare). The cDNA was quantified by qRT-PCR using primer NCR-8 (5'–CGTCGCGAATTCGTCGAT–3'), which anneals to the tag sequence of NCR-9, in combination with NCR-3 and the fluorescent probe. To calibrate this assay, synthetic negative-strand HCV RNA was prepared by in vitro transcription using a T7 Megascript kit (Ambion). A 702 bp DNA fragment between nucleotides 1 and 702 of the HCV RNA genome was cloned by RT-PCR using a forward (5'–CGCCGAGCTCGTCGAG–3') and a reverse (5'–CGCAAG–CTTGCACGTAAGGATGATCAGATGACCTTAC–3'; the HindIII restriction site is underlined) primer. The BanH–HindIII–restricted DNA fragment was subcloned into plbluescript (+) (Stratagene). Negative-strand HCV RNA was synthesized from the linearized plasmid by in...
\textit{vivo} transcription and was purified by acrylamide/urea RNA gel electrophoresis. The band of negative-strand HCV RNA was eluted with SDS and the copy number was calculated from the $A_{\text{260}}$ (NanoDrop).

**SDS-PAGE and matrix-assisted laser desorption/ionization–time of flight mass spectrometry (MALDI-TOF MS) analysis.**

Proteins in iodixanol fractions were analysed on SDS-polyacrylamide gradient gels (3–18%). Proteins were stained with Coomassie brilliant blue G-250 (Sigma) and excised from the gel for MALDI-TOF MS. Peptides generated by trypsin digestion were analysed using a Voyager DE-STR mass spectrometer (Applied Biosystems). Protein bands were identified by performing searches using the peptide mass fingerprint data and the Mascot search engine program (Matrix Science), searched against the latest NCBI protein sequence database. Only proteins with Mascot scores above 64, which shows that the likelihood of a correct match is significant ($P<0.05$), were accepted as hits.

The monoclonal antibodies (mAbs) used in Western blotting were human anti-HCV E1 glycoprotein (IC4; hybridoma clone IGH398 from Dr A. Union, Innogenetics, Belgium), mouse anti-HCV E2 glycoprotein (AP33; from Dr A. Patel, MRC Virology unit, Glasgow, UK), human anti-HCV core protein (B12; from Professor M. Mondelli, University of Pavia, Italy), mouse anti-HCV NS3 protein (MMM33; LabVision) and human anti-HCV NS4A (D10; from M. Mondelli). The polyclonal antibodies used in Western blotting were rabbit anti-HCV NS5A (from Professor P. Mavromara, Hellenic Pasteur Institute, Athens, Greece) and rabbit anti-human ApoE (DakoCytonation). Western blots were developed using ECL Plus (GE Healthcare) and bands were semi-quantified using a GS-800-calibrated densitometer with Quantity One software (Bio-Rad).

**Quantification of lipids.** Lipids in iodixanol fractions were extracted with chloroform/methanol (Folch et al., 1957). Each 0.5 ml fraction was mixed with 10 ml chloroform/methanol (40:60, v/v). Extraction of lipids was performed by rotation at 11 r.p.m. for 2 h at 37°C followed by centrifugation at 2 000 g for 5 min, the lower, organic phase was separated by centrifugation at 1 000 g for 5 min. The supernatant was harvested and mixed with 1 ml 100 mM sodium phosphate, pH 7.4. After centrifugation at 2 000 g for 10 min, the lower, organic phase was evaporated to dryness with nitrogen. The pellet was resuspended in 100 μl 10 mM sodium phosphate, pH 8.0, containing 4% NP-40 (Roche). Lipids were measured with a Cobas Farah auto analyser (Roche) using phospholipid assay B and free cholesterol E kit (Wako). Triglyceride and total cholesterol were measured using kits from Horiba ABX.

**Gel filtration of lipoproteins and HCV.** Superoxide 6 prep grade was packed into one XK 16/100 column and one XK 16/40 column (GE Healthcare) and the two columns were run in series. The elution buffer contained 20 mM Tris/HCl (pH 8.0), 0.25 M sucrose, 2 mM EDTA, 2 mM MgSO4, 2 mM MgCl2 and 0.02% NaN3. The Superose column was calibrated using VLDL, low-density lipoprotein (LDL), and high-density lipoprotein (HDL) purified from normal human plasma (Mackness & Durrington, 1992; März et al., 1993). Toyopearl HW-75S (Tosoh Corporation) was packed into one XK 26/100 column. Sample (2 ml) was applied to the column; the columns were cooled to 4°C and run with a flow rate of 1 ml min⁻¹. Calibration of the Toyopearl column was performed using purified chylomicrons, VLDL, LDL and HDL as well as carboxyylated latex bead standards (Okazaki et al., 2005; MagSphere).

A standard curve was prepared by plotting $\dot{\zeta}$ against log $K_{\text{AV}}$ in nm (Anonymous, 2002), calculated using the following equation:

$$\sqrt{-\log(K_{\text{AV}})} = \sqrt{-\log(V_e-V_o)/(V_i-V_o)}$$

$V_e$ is the elution volume for each of the standards; $V_i$ is the total column volume calculated as the volume of packed beads; and $V_o$ is the void volume, which was calculated as 1/3 of the total column volume (Anonymous, 2002).

For immunoprecipitation, 20 μl from each fraction was added to 140 μl 10 mM Tris/HCl (pH 7.4), containing 0.25 M sucrose and 60 μg polyclonal antibody (ApoB, ApoAI and ApoE) or 10 μg mAb [NS3, NS4A, E1 and E2 antibody (CBH-2; from Dr S. Foung, Stanford University, USA)]. After 4 h incubation at 4°C, 25 μl from 50% Protein G Sepharose (Gammabind; GE Healthcare) was added and tubes were rotated at 1 r.p.m. for 16 h. Pellets and supernatants were separated by centrifugation at 100 g, at 4°C for 3 min. Normal rabbit IgG (DakoCytonation) was used as control. HCV RNA in pellet and supernatant was quantified by qRT-PCR.

**RESULTS**

**qRT-PCR assays for positive- and negative-strand HCV RNA**

Whilst only positive-strand HCV RNA is packaged into virus particles, both positive- and negative-strand HCV RNA are present in virus replication complexes and serve as intermediates in virus replication. With the aim of determining the specificity and sensitivity of our assays for positive and negative strand HCV RNA, dilution series with synthetic HCV RNA were prepared. The dilutions were used in qRT-PCR assays and the number of PCR cycles ($C_T$) taken to reach the fluorescence threshold was measured (Fig. 1). A linear correlation was observed between $C_T$ and positive strand HCV RNA (Fig. 1a). The sensitivity of this assay was 100 copies per tube and linearity was observed over the entire range of dilutions. In contrast, when the assay for negative strand was used with positive strand HCV RNA template (Fig. 1a), $C_T$ values were between 38 and 45, which was considered a negative result. Thus, positive strand RNA did not give a detectable signal in the assay for negative strand. When the assay for negative strand HCV RNA was used with negative strand template, a linear correlation was observed between $C_T$ values and copy number (Fig. 1b). These results confirmed the specificity of our negative strand assay, although the sensitivity was lower than that of the positive strand assay, at 1000 copies per tube.

The density distribution of positive- and negative-strand HCV RNA from liver macerate was analysed on iodixanol gradients. Five fractions with low density (fractions 14–18) contained 74% of the positive-strand RNA, with a peak in fraction 15, which had a density of 1.08 g ml⁻¹ (Fig. 1c). These fractions also contained 90% of the negative strand, with the peak at 1.05 g ml⁻¹ in fraction 17 (Fig. 1d). The ratio of positive- to negative-strand RNA was calculated for each fraction and found to be lowest in fraction 17 (6:1), suggesting that this fraction contains membranes where virus assembly takes place. In iodixanol fraction 15, the ratio was 12:1, similar to that seen in cell culture (Quinkert et al., 2005). The percentage of HCV associated with ApoB in each fraction was determined by immuno-
precipitation (Fig. 1e). This analysis showed that the association with ApoB was variable across the density gradient, with a tendency for less association to occur in the low-density fractions, where most of the HCV RNA was detected. In fraction 15, 12% of HCV RNA was associated with ApoB.

**Distribution of lipid subclasses and proteins within iodixanol density gradients**

The distribution of lipids from HCV-infected liver S6b within self-forming iodixanol gradients was compared with the lipid profile for an HCV-negative liver (Fig. 2). Cholesterol and phospholipid levels peaked in fractions 14 and 15 (Fig. 2a, b) and the distribution of these lipids was similar in the HCV-negative liver (data not shown). Most cholesterol (90%) was in the form of free cholesterol. In contrast, the largest amount of triglyceride was found in fraction 18 (Fig. 2d). The HCV-negative liver had significantly less triglyceride in fraction 18 ($P \leq 0.005$) and all other iodixanol fractions contained less triglyceride than the S6b liver (Fig. 2c). The distribution within the gradient of proteins involved in lipid metabolism was determined by Western blotting. Caveolin-2 (Cav-2), a marker for lipid rafts (Shi et al., 2003), showed a peak in fractions 14–16 (Fig. 2f). Adipocyte differentiation-related protein (ADRP), a marker for lipid droplets (Shavinskaya et al., 2007; Targett-Adams et al., 2003), showed a peak in fractions 16–17 (Fig. 2f). Microsomal transfer protein (MTP), which transfers triglyceride onto the nascent ApoB-100 molecule in the lumen of the endoplasmic reticulum (ER) (Rustaeus et al., 1999), was widely distributed within the gradient, with a peak in fraction 14 (Fig. 2g).

The distribution of host and viral proteins in iodixanol fractions was also analysed using densitometry of immunostained Western blots (Table 1). Host lipoprotein ApoB showed a peak in fraction 17 (density 1.05 g ml$^{-1}$). Smaller amounts of ApoB were detected in fractions 16 and 18 (densities 1.07 and $\leq 1.03$ g ml$^{-1}$, respectively). Similar distribution of ApoB was observed in an HCV-negative liver (data not shown) and the distribution overlaps with the distribution of triglyceride (Fig. 2c, d). Host ApoE was widely distributed within the gradient with a peak in fraction 15 (density 1.08 g ml$^{-1}$). ApoAl and ADRP, other host proteins involved in lipid metabolism, as well as lipid raft protein Cav-2 and HCV structural proteins core, E1 and E2 also showed peak intensity in fractions 13 to 17. Although NS3 was widely distributed in the gradient, this viral protein also showed a peak in fraction 15, the same fraction that contained the peak of cholesterol. In combination, these observations suggest that the
membranes involved in HCV replication fractionate with a density around 1.08 g ml\(^{-1}\) in iodixanol gradients. A third group of proteins was found at a higher density, around 1.12 g ml\(^{-1}\), and included ER protein calreticulin and NS4A. Albumin, an abundant cytosolic protein in hepatocytes, showed a peak at the bottom of the gradient, in fractions 1 and 2.

**Analysis of low-density iodixanol fractions by EM and detergent treatment**

Membranes with densities of 1.08 g ml\(^{-1}\) from HCV-positive and HCV-negative livers were analysed by thin section EM (Fig. 3a, b). Bags of particles surrounded by a lipid bilayer, some of which contained an internal structure in the form of pentagons or hexagons, were observed (Fig. 3a). Similar structures were rarely observed in the HCV-negative liver and lacked the regularly shaped internal structures that were characteristic of the structures in infected liver (Fig. 3b). Treatment with 3% NP-40 removed lipids and generated structures resembling the HCV nucleocapsid (Fig. 3c). The density of these particles was 1.20 g ml\(^{-1}\), determined by iodixanol gradient centrifugation, with a recovery of 70% (Fig. 3d). This density corresponds to that of the HCV nucleocapsid (Ishida et al., 2001).

**Separation of HCV RNA-containing membranes by gel filtration**

Gel filtration on Superose 6 was used to separate HCV RNA-containing membranes by size. The column was calibrated with purified VLDL, LDL and HDL, which eluted in three distinct peaks (Fig. 4a). The molecular mass of VLDL is between 5 \(\times\) 10\(^6\) Da for small VLDL (VLDL\(_2\)) and 10\(^7\) Da for large VLDL (VLDL\(_1\)). LDL has a molecular mass of 2.4 \(\times\) 10\(^6\) Da and that of HDL is between 200 and 400 kDa (Pownall et al., 1999). The molecular mass of VLDL\(_1\) exceeds the exclusion limit of Superose 6 (5 \(\times\) 10\(^6\) Da) and it therefore elutes with the void volume. Liver homogenate was first purified on iodixanol gradients and fractions with HCV RNA-containing membranes of less than 1.12 g ml\(^{-1}\) (peaks 13–18) were applied to the gel filtration column (Fig. 4b). All HCV RNA eluted in peak I, at the same position as VLDL. This shows that HCV in liver macerate is within membranes or particles which are greater than or equal to the size of VLDL. Peak II eluted at the same position as human serum albumin and did not contain viral RNA.

**Identification of host and viral proteins in gel-filtration peaks**

Proteins in peaks I and II from Superose gel filtration of liver macerate were analysed by SDS-PAGE (Fig. 5). Both...
peaks contained numerous different proteins (Fig. 5, lanes 1 and 2). Eight of these were excised and analysed by mass spectrometry (Table 2). This analysis identified four proteins in peak I, all ER proteins, and four proteins in peak II, all cytosolic proteins. Proteins from peaks I and II were also analysed by Western blotting, using a panel of monoclonal and polyclonal antibodies to HCV structural and NS proteins. Antibodies to HCV structural proteins core, E1 and E2 identified protein bands with expected molecular masses of 20, 31 and 62 kDa, respectively (Fig. 5, lanes 3, 5 and 7). These structural proteins were detected in peak I but not in peak II. The mAb to NS3 recognized a 69 kDa band in peak I (Fig. 5, lane 9). The human mAb to NS4A recognized a 7 kDa band in peak I (Fig. 5, lane 11), which is the expected mass for NS4A (Waris et al., 2004); this band was absent from peak II. A 56 kDa protein band was also detected in peaks I and II. This band was present in the absence of primary antibody and was identified as human IgG heavy chain. The polyclonal antibody to NS5A recognized two bands of 55 and 58 kDa in peak I but not in peak II (Fig. 5, lanes 13 and 14). These bands were also detected using a monoclonal NS5A antibody from Maine.

Table 1. Density distribution of host and HCV proteins from liver macerate

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<table>
<thead>
<tr>
<th>Protein</th>
<th>Subcellular location</th>
<th>Fraction and density (g ml⁻¹)*</th>
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<tr>
<td></td>
<td></td>
<td>7</td>
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<tr>
<td></td>
<td></td>
<td>1.15</td>
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<tr>
<td>ApoB</td>
<td>Lipoprotein</td>
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<tr>
<td>ApoE</td>
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<td>Apo Al</td>
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<tr>
<td>ADRP</td>
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<td>Cav-2</td>
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</tr>
<tr>
<td>Calreticulin</td>
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<td>5</td>
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<tr>
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<td>Albumin</td>
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<tr>
<td>HCV NS4A</td>
<td>Non-structural</td>
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*Proteins in iodixanol gradient fractions were analysed by Western blotting and semi-quantified by densitometry.

Fig. 3. Thin-section EM of fraction 15 from iodixanol gradients of HCV-positive liver (a) or a control HCV-negative liver (b). The fraction from the HCV-positive liver had a density of 1.08 g ml⁻¹. The arrow points to an isolated particle which shows internal structure in the form of a pentagon; the diameter of this is 100 nm and the width of the membrane surrounding the particle is 10 nm. (c) Iodixanol fraction 15 was treated with 3% NP-40 and analysed by negative-staining EM. The density (●) and concentration (bars) of HCV RNA following this treatment (d) indicate that it shifted the density of HCV RNA to 1.2 g ml⁻¹, corresponding to the density of the HCV nucleocapsid (Ishida et al., 2001).
Biotechnology, Inc. (Tami Pilot-Matias, personal communication). These proteins are similar in size to the 56 and 58 kDa basally phosphorylated or hyper-phosphorylated forms of NS5A that were previously observed using in vitro expression systems (Neddermann et al., 1999), suggesting that phosphorylated variants of NS5A are present in the HCV-infected human liver. A 66 kDa protein which co-migrated with human albumin was detected by the NS5A antibody (Fig. 5, lane 14), possibly as a result of cross-reactivity. The largest amount of ApoB and ApoE was found in peak I, although a small proportion of ApoE was observed in peak II (Fig. 5, lane 16).

Separation of HCV RNA-containing membranes on Toyopearl

The high exclusion limit of Toyopearl S75 enabled separation of vesicles with larger diameters, up to \(40 \times 10^6\) Da, compared with separation on Superose, and allowed the resolution of purified chylomicrons, VLDL and LDL (Fig. 6a). When serum from patient S6 was analysed on Toyopearl, HCV RNA eluted with VLDL1 (Fig. 6a). This showed that HCV in serum is similar in size to VLDL1, with a diameter in the region of 60 nm, and supports our previous determination of the HCV diameter by sedimentation analysis (Nielsen et al., 2006). HCV RNA from liver eluted in a broad peak from the Toyopearl column (Fig. 6b), indicating that most HCV in liver was within membranes with diameter \(\geq 100\) nm. However, some HCV in the liver eluted at the same position as HCV from serum, between fractions 20 and 24. Toyopearl fractions 10 to 16 from liver S6b had a low positive-/negative-strand ratio (minimum 6:1), which suggested that these fractions contain more of the replication complexes for HCV (Fig. 6c). Toyopearl fractions 20 to 24 had a high positive : negative strand ratio (maximum 45:1). These fractions had high relative association with ApoB (up to 75%, Fig. 6d) and HCV RNA was associated with ApoE, ApoAI and HCV E2 (Supplementary Table S1, available in JGV Online). In contrast, viral RNA in Toyopearl-separated fractions 10 to 16 was immunoprecipitated with the NS3 antibody but not with antibodies to HCV E1 or E2 (Supplementary Table S1).

**DISCUSSION**

Blood samples and the transplant liver from patient S6 were obtained early, during the acute phase of HCV reinfection. These circumstances provided a unique opportunity to study HCV infection in vivo and to characterize the native virus. These samples are also unique as the patient’s common variable immunodeficiency enabled us to study virus particles without the complications of host antibodies binding to the virus.

The HCV replication complex contains both positive and negative strand HCV RNA and, in *in vitro* systems, the ratio of the two falls to between 6:1 and 12:1 (Quinkert et al., 2005). Reports of the positive- to negative-strand ratio in unfractionated HCV-RNA-positive livers vary widely, from 1:1 to 1100:1 (Chang et al., 2003; Komurian-Pradel et al., 2004; Negro et al., 1998). This variability may reflect the difficulties of precise and specific RNA quantification that occur with low copy numbers of viral RNA in such a complex milieu.

HCV replication complexes have been found associated with lipid rafts and lipid droplets (Aizaki et al., 2004; El-Hage & Luo, 2003; Quinkert et al., 2005). The membranes in iodixanol fraction 15 (positive : negative strand ratio 12:1) peak at a density of 1.08 g ml\(^{-1}\) and they were enriched in HCV structural and NS proteins, Cav-2, ADRP, phospholipid and cholesterol. This density is somewhat lower than the bulk of the ER proteins, e.g. calreticulin and MTP, which are found at a density of 1.12 g ml\(^{-1}\). The low density of membranes containing positive and negative strand HCV RNA suggests that virus replication and assembly occur on structures containing
lipids, as previously suggested by Dubuisson et al. (2002), Kapadia & Chisari (2005) and Miyanari et al. (2007).

The peaks of ApoB and triglyceride were found in iodixanol fractions that had a density below 1.06 g ml\(^{-1}\); this density fraction contains Golgi-derived vesicles (Plonne et al., 1999). Phospholipid, cholesterol and ApoE peaked at slightly higher densities, corresponding with the peaks of positive and negative strand HCV RNA. Other members of the family Flaviviridae, such as Dengue virus and Kunjin virus, have been found to replicate in vesicle packets that are virus-induced membrane structures in the perinuclear region (Uchil & Satchidanandam, 2003; Westaway et al., 1997). The assembly of VLDL also occurs in the ER and Golgi, with clusters of lipoproteins accumulating in the Golgi lumen (Tran et al., 2002). Our results suggest that the assembly of HCV is linked to the assembly of VLDL, as has recently been suggested by Gastaminza et al. (2008). However, ApoB was observed in fractions of slightly lower density than the peak of positive and negative strand HCV RNA, suggesting that viral replication occurs on membranes with higher density than the Golgi clusters filled with VLDL particles.

We found that NS3, NS4A and NS5A co-fractionated with HCV RNA and host VLDL on a Superose 6 gel-filtration column and that those viral proteins had similar molecular masses in human liver as they did in recombinant in the ER and Golgi, with clusters of lipoproteins accumulating in the Golgi lumen (Tran et al., 2002). Our results suggest that the assembly of HCV is linked to the assembly of VLDL, as has recently been suggested by Gastaminza et al. (2008). However, ApoB was observed in fractions of slightly lower density than the peak of positive and negative strand HCV RNA, suggesting that viral replication occurs on membranes with higher density than the Golgi clusters filled with VLDL particles.

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Table 2. Identification of host proteins in peaks from gel filtration of human liver macerate

The protein bands were excised from SDS-PAGE gels and the letters assigned to each protein band are shown in Fig. 5, lanes 1 and 2.

<table>
<thead>
<tr>
<th>Human protein</th>
<th>Cellular location</th>
<th>Protein band</th>
<th>Observed mass (kDa)</th>
<th>Database mass (kDa)</th>
<th>Probability score*</th>
<th>Sequence coverage†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endoplasmnin</td>
<td>ER</td>
<td>A</td>
<td>100</td>
<td>92.4</td>
<td>209</td>
<td>38</td>
</tr>
<tr>
<td>NADPH cytochrome P450 reductase</td>
<td>ER</td>
<td>B</td>
<td>75</td>
<td>76.5</td>
<td>88</td>
<td>27</td>
</tr>
<tr>
<td>Annexin VI</td>
<td>ER</td>
<td>C</td>
<td>68</td>
<td>75.8</td>
<td>168</td>
<td>40</td>
</tr>
<tr>
<td>Glutathione S transferase</td>
<td>ER</td>
<td>D</td>
<td>16</td>
<td>17.5</td>
<td>86</td>
<td>74</td>
</tr>
<tr>
<td>Serum albumin</td>
<td>Cytosol</td>
<td>E</td>
<td>66</td>
<td>65.6</td>
<td>276</td>
<td>62</td>
</tr>
<tr>
<td>Superoxide dismutase (Cu-Zn)</td>
<td>Cytosol</td>
<td>F</td>
<td>19</td>
<td>15.9</td>
<td>94</td>
<td>79</td>
</tr>
<tr>
<td>Haemoglobin β chain</td>
<td>Cytosol</td>
<td>G</td>
<td>15</td>
<td>15.7</td>
<td>127</td>
<td>65</td>
</tr>
<tr>
<td>Haemoglobin α chain</td>
<td>Cytosol</td>
<td>H</td>
<td>14</td>
<td>14.9</td>
<td>92</td>
<td>49</td>
</tr>
</tbody>
</table>

*Probability score greater than 64 indicates a significant match with a protein from the NCBI database (P<0.05).
†Percentage of protein sequence covered by peptides identified in mass spectrometry analysis.
expression systems (Diaz et al., 2006; Kalamvoki et al., 2006; Nomura-Takigawa et al., 2006). The detection of 55 and 58 kDa bands with anti-NS5A suggests that the variably phosphorylated forms of this protein observed in vitro may also exist in vivo.

Gel filtration of HCV from serum in a matrix with a large exclusion limit, Toyopearl, led to separation of viral RNA from the main peak of VLDL. The diameter of HCV lipoprotein particles from plasma was determined by gel filtration on Toyopearl and found to be similar to the 55 nm determined previously by sedimentation analysis (Gastaminza et al., 2006; Nielsen et al., 2006) and by immuno-EM (Wakita et al., 2005). This diameter is similar to VLDL1 or chylomicron remnants, but is smaller than chylomicrons. Diaz et al. (2006) observed that up to 50% of HCV in plasma is associated with chylomicrons or chylomicron remnants. Toyopearl gel filtration separated differently sized fractions containing viral RNA. Most HCV RNA was in membranes >100 nm in diameter that were associated with NS3, but 8% eluted with lower diameter and high positive/-negative-strand ratio. This viral RNA was associated with ApoB, ApoE, HCV E1 and E2, and the diameter corresponded to HCV from serum.

In summary, the combination of iodixanol density gradients and gel filtration has the ability to separate HCV RNA-containing membranes by density and size. This analysis suggests that the association of HCV with lipoproteins occurs in the human liver. The association between HCV and lipoprotein has been observed by others (Gastaminza et al., 2008; Huang et al., 2007; Moradpour et al., 2007; Thomsen et al., 1993; Yao & Ye, 2008) and our techniques show that there is the potential to separate hepatitis C virions from the intracellular membranes where virus assembly occurs.

Fig. 6. Analysis of serum and liver macerate from patient S6 by gel filtration on Toyopearl. The gel filtration column was calibrated with latex beads of different sizes (indicated by arrows) as well as with purified chylomicrons, VLDL and LDL. The elution profiles of these proteins are shown as solid, dashed and dotted lines, respectively, in (a). (a) Separation of HCV RNA in serum by gel filtration. Bars show the mean ± SD HCV RNA in each fraction. (b) Elution profile of total protein (line). Bars show mean ± SD (from three determinations) of HCV RNA from liver macerate with density below 1.12 g ml⁻¹. (c) The ratio of HCV positive strand RNA and HCV negative strand RNA for each fraction. The proportion of HCV RNA within fractions enclosed by brackets is shown as a percentage. (d) Immunoprecipitation of HCV with antibody to ApoB. The total HCV RNA in the pellets and the supernatants (shaded bars) and the HCV RNA associated with ApoB (solid bars) was calculated as a percentage (given above the bars) for each fraction.

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REFERENCES


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