Hepatitis C virus triggers mitochondrial fission and attenuates apoptosis to promote viral persistence

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Mitochondrial dynamics is crucial for the regulation of cell homeostasis. Our recent findings suggest that hepatitis C virus (HCV) promotes Parkin-mediated elimination of damaged mitochondria (mitophagy). Here we show that HCV perturbs mitochondrial dynamics by promoting mitochondrial fission followed by mitophagy, which attenuates HCV-induced apoptosis. HCV infection stimulated expression of dynamin-related protein 1 (Drp1) and its mitochondrial receptor, mitochondrial fission factor. HCV further induced the phosphorylation of Drp1 (Ser616) and caused its subsequent translocation to the mitochondria, followed by mitophagy. Interference of HCV-induced mitochondrial fission and mitophagy by Drp1 silencing suppressed HCV secretion, with a concomitant decrease in cellular glycolysis and ATP levels, as well as enhanced innate immune signaling. More importantly, silencing Drp1 or Parkin caused significant increase in apoptotic signaling, evidenced by increased cytochrome C release from mitochondria, caspase 3 activity, and cleavage of poly(ADP-ribose) polymerase. These results suggest that HCV-induced mitochondrial fission and mitophagy serve to attenuate apoptosis and may contribute to persistent HCV infection.

HCV persistence | innate immunity | autophagy

Hepatitis C virus (HCV) infection often leads to chronic hepatitis that can progress to fibrosis, cirrhosis, and hepatocellular carcinoma (1). HCV is a hepatotrophic, noncytopathic (2, 3), single-stranded, positive-sense RNA virus that replicates its RNA genome on the endoplasmic reticulum (ER)-derived membranous structures (4, 5). HCV stimulates lipogenesis, leading to the accumulation of lipid droplets that facilitate virion assembly and maturation (5–8). HCV infection also induces mitochondrial dysfunction via ER and oxidative stress that results in mitochondrial Ca\textsuperscript{2+} overload, collapse of mitochondrial transmembrane potential (ΔΨ\textsubscript{m}), elevated levels of reactive oxygen species, and disruption of mitochondrial respiration (9–15). Liver tissues of patients with chronic hepatitis C frequently exhibit traits of mitochondrial injury such as swollen, ruptured, and empty mitochondria (16).

Mitochondria are dynamic organelles that constantly undergo fission, fusion, and mitophagy to facilitate mitochondrial quality control, which is crucial for maintaining cell viability and bioenergetics (17). Aberrant mitochondrial dynamics are associated with the pathogenesis of several genetic and neurological disorders, cardiac dysfunctions, cancer, and metabolic diseases such as diabetes and obesity (18). Depending on their physiological and cellular context, the balance between mitochondrial fission and fusion processes modulates the mitochondrial morphology (17). Mitochondrial fission/fusion is mediated by recruitment of cytosolic Drp1 to the mitochondria, forming spirals that constrict both the inner and outer mitochondrial membranes (19). The mitochondrial fission is modulated by mitochondrial outer membrane proteins, which include mitochondrial fission 1 (Fis1), mitochondrial fission factor (Mff), and mitochondrial dynamics proteins of 49 and 51 kDa. These proteins coordinate to recruit Drp1 to mitochondria (20, 21). Mitochondrial fusion involves mitofusin 1 and 2 proteins and the inner mitochondrial membrane protein optic atrophy 1 (19, 21). More specifically, Drp1 recruitment to mitochondria is regulated by phosphorylation and dephosphorylation of respective serine residues by putative kinases and phosphatases (19). Mitochondrial dynamics is tightly regulated in response to alterations in cellular physiology such as stress, infections, and nutrient supply, and is also shown to play a critical role in apoptosis (18, 22).

In this study, we investigated the HCV-induced modulation of mitochondrial dynamics, which plays a crucial role in attenuating apoptosis of infected cells resulting from mitochondrial injury associated with infection. We show that HCV stimulates the gene expression of Drp1 and Mff and promotes Drp1 recruitment to mitochondria by stimulating the phosphorylation of Drp1 (Ser616), leading to mitochondrial fission analyzed by confocal and electron microscopy. By using a dual-fluorescence mito-monomeric red fluorescent protein (mRFP)-EGFP reporter for monitoring complete mitophagy, we demonstrate that HCV-induced Drp1-mediated mitochondrial fission was followed by mitophagy. Interference of HCV-induced mitochondrial fission by silencing either Drp1 or Mff led to the accumulation of swollen mitochondria that resisted mitophagic degradation. Interestingly, interference of mitochondrial fission also suppressed viral secretion and glycolysis paralleled by a concomitant decline in cellular ATP levels and increased IFN synthesis in the HCV-infected cells. More importantly, inhibition of HCV-induced aberrant mitochondrial fission and mitophagy

Significance

Persistent hepatitis C virus (HCV) infection is associated with mitochondrial liver injury. Mitochondrial quality control is established as a physiological adaptation to mitochondrial injury. This study provides a new insight into how HCV disrupts mitochondrial dynamics and evades apoptosis and innate immunity to sustain persistent viral infection. HCV promotes dynamin-related protein 1-mediated mitochondrial fission, followed by mitophagy. Interference of HCV-induced mitochondrial fission and mitophagy led to the suppression of virus secretion, a decrease in glycolysis and ATP generation, an increase in interferon synthesis, and an increase in apoptotic death of infected cells via enhanced apoptotic signaling. These observations implicate the functional relevance of altered mitochondrial dynamics in the pathogenesis of chronic liver disease associated with HCV infection.

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triggered robust apoptosis evidenced by a marked increase in cytochrome C release, caspase 3 activity, and cleavage of poly(ADP-ribose) polymerase. These observations unambiguously implicate the functional relevance of mitochondrial dynamics in the maintenance of persistent HCV infection.

**Results**

**HCV Promotes Mitochondrial Fission.** HCV infection induces ER and oxidative stress and alters calcium homeostasis, which causes mitochondrial dysfunction and damage (23–25). To investigate the HCV-induced alterations of mitochondrial dynamics, metabolism, and physiology, human hepatoma (Huh7) cells were infected with cell culture-derived HCV (HCVcc) of JCI strain [genotype2a chimera of J6 and Japanese fulminant hepatitis (JFH) 1 strains]. As shown in Fig. 1A, HCV-infected cells displayed distinct fragmented mitochondria (mitochondrial fission), in contrast to uninfected cells, which displayed a typical tubular mitochondrial network indicative of normal healthy cells. We also observed similar mitochondrial fragmentation in cells infected with the HCV JFH1 strain, which replicates with lower efficiency compared with the HCV JCI strain (SI Appendix, Fig. S1). This confirms that mitochondrial fission is a consequence of HCV infection and is not selectively induced in JCI-infected cells because of its higher replication rates. Ultrastructural analysis of HCV-infected cells by transmission electron microscopy further substantiated the occurrence of fragmented mitochondria in HCV-infected cells, in contrast to uninfected cells, which displayed elongated and tubular mitochondria (Fig. 1B). Also seen in Fig. 1B are the membranous web-like structure and features of mitochondrial injury such as swollen mitochondria devoid of mitochondrial cristae. A quantitative analysis of relative mitochondrial length in uninfected versus HCV-infected Huh7 cells is presented in Fig. 1C. These analyses demonstrate that HCV infection induces mitochondrial fission.

**HCV Induces Drp1 Ser616 Phosphorylation and Mitochondrial Translocation.** Drp1 recruitment to mitochondria can be triggered by Drp1 phosphorylation at Ser616 (26) and by cyclin-dependent kinase 1 (CDK1)/cyclin B (25). HCV core protein has been previously shown to promote CDK1/cyclin B complex activity (26). To demonstrate whether HCV induces mitochondrial fission by promoting Drp1 Ser616 phosphorylation and its subsequent translocation to mitochondria, HCV-infected cells were analyzed by confocal microscopy using a specific anti-Drp1 antibody that recognizes the Ser616-phosphorylated Drp1. We observed a dramatic stimulation of Drp1 Ser616 phosphorylation in HCV-infected cells compared with uninfected cells (Fig. 2A). Confocal microscopy images also revealed that most of the Ser616 phosphorylated Drp1 localized to the mitochondria (Fig. 2A), suggesting that HCV promoted Drp1 recruitment to mitochondria by stimulating Ser616 phosphorylation. Furthermore, the siRNA-mediated interference of CDK1 also abrogated HCV-induced Drp1 Ser616 phosphorylation (SI Appendix, Fig. S2). Drp1 dephosphorylation at Ser637 acts in parallel with Drp1 Ser616 phosphorylation to promote mitochondrial fission (27). We examined the Drp1 Ser637 phosphorylation levels and noted a modest decrease in HCV-infected cells (Fig. 2C). In addition, we investigated whether any HCV proteins can independently induce Drp1 activation via Drp1 phosphorylation. The results showed that HCV envelope glycoprotein 2 (E2), core, and nonstructural protein 3/4A (NS3/4A) proteins only modestly induced Drp1 Ser616 phosphorylation (SI Appendix, Fig. S3). However, Drp1 Ser616 phosphorylation induced by HCV infection was significantly higher compared with the induction by each HCV protein (SI Appendix, Fig. S3). HCV stimulated Drp1 expression at both the transcriptional and translational levels (Fig. 2 B and C). HCV also stimulated the expression of Mff protein, which serves as a receptor for Drp1 recruitment to the mitochondria (Fig. 2C) (20, 28). We have previously shown that HCV down-regulated mitofusin 2, which is one of the mediators of mitochondrial fusion (11). To further substantiate the observation of HCV-induced Drp1 translocation to the mitochondria, we purified mitochondrial fractions from HCV-infected and uninfected Huh7 cells. Western blot analysis of subcellular fractions demonstrated that phosphorylated Drp1 is substantially enriched in the mitochondrial fraction in HCV-infected cells (Fig. 2D). To establish the clinical relevance of these observations, we also investigated the activation of Drp1 in the liver biopsies of patients with chronic hepatitis C and observed an increase in the expression levels of total Drp1 and enhanced Drp1 Ser616 phosphorylation (Fig. 2E). Together, these results demonstrate that HCV causes Drp1 translocation to mitochondria to initiate fission activities.

**HCV Induces Autophagy of Mitochondria That Undergo Drp1-Mediated Fission.** We have recently reported that HCV infection induces Parkin-dependent mitophagy (11). To examine whether Drp1-mediated mitochondrial fission facilitates mitophagy in HCV-infected cells, we used a tandem-tagged mRFP-EGFP chimeric fluorescence reporter (plasmid pAT016) encoding a mitochondrial targeting signal sequence fused in-frame with mRFP and EGFP genes (SI Appendix, Fig. S4) (29). The use of this expression scheme exploits the differential stabilities of RFP and GFP in the lysosomes (SI Appendix, Fig. S4).

**Fig. 1.** HCV infection induces mitochondrial fission. (A) Immunofluorescence analysis showing mitochondrial fission in HCV-infected cells. At 3 d postinfection, Huh7 cells infected with HCVcc (MOI, 1) were immunostained with antibodies specific to translocase of the outer mitochondrial membrane (TOM20) (red) and HCV E2 protein (green). Nuclei, DAPI (blue). Infected cells, +; uninfected cells, −. The zoomed images display the typical tubular mitochondria in uninfected cells and fragmented mitochondria in infected cells, respectively. (B) Electron microscopy of HCV-infected Huh7 cells showing the fragmented mitochondria. The ultrastructure of uninfected (naive Huh7) and infected (HCV) cells was examined by electron microscopy, as described in Materials and Methods. In the zoomed images, normal elongated tubular mitochondria in uninfected cells and fragmented mitochondria with loss of cristae in infected cells are shown. Membranous, web-like structure in infected cells is also shown. (Scale bar, uninfected, 1 μm; infected, 0.5 μm.) Organelle marker: N, nucleus. Confocal images: HCV E2, red; nuclei, blue (DAPI). (C) Quantification of mitochondrial length shown in B.
The band intensities were analyzed by ImageJ software. qRT-PCR at 1 d postinfection (mean ± SEM; n = 3; *p ≤ 0.01, by unpaired Student t test) (B) and protein expression at 5 d postinfection (C). (D) Western blot analysis of p-Drp1 (Ser616) and total Drp1 expression levels in liver biopsies of chronic hepatitis C patients. Lane 1, HCV-negative; lanes 2–3, HCV-positive. β-actin, protein-loading control. (C and E) The band intensities were analyzed by ImageJ software.

(29). The mito-mRFP-EGFP tagged mitochondria in the cytosol normally display a yellow color because of the merge of red and green fluorescence from mRFP and EGFP. However, on completion of mitophagy by fusion of autophagic vesicles containing mitochondria with lysosomes, only red fluorescence from mRFP is observed because of the higher stability of RFP over GFP in the acidic environment of lysosome. As shown in Fig. 3D, consistent with the typical tubular mitochondrial network in uninfected cells expressing mito-mRFP-EGFP, we observed predominantly a yellow color, indicating the merge of both green (EGFP) and red (mRFP) fluorescence from mitochondria in the cytosol, whereas in HCV-infected cells, most of the fragmented mitochondria predominantly displayed red fluorescence, which is indicative of the delivery of mitochondria (mitophagosomes) to lysosomes. The relative quantitative of the number of mitochondria in the cytosol and the lysosomes is shown in Fig. 3B. We also confirmed the fusion of mitophagosomes with lysosomes by staining the mito-mRFP-EGFP-transfected HCV-infected cells with lysosomal-associated membrane protein 1 antibody (SI Appendix, Fig. S5). Delivery of mitophagosomes (red) to lysosomes (blue) is shown as pink puncta (SI Appendix, Fig. S5).

Mitochondrial fission leads to mitophagy by facilitating the segregation of dysfunctional mitochondria (30). Hence, we examined whether interference of mitochondrial fission affects the HCV-induced mitophagic process. HCV-infected cells cotransfected with mito-mRFP-EGFP and Drp1-specific siRNA did not deliver display of mitochondria to lysosomes, as evidenced by the lack of distinct red puncta (Fig. 3C; see Fig. 3D for quantification), whereas cells transfected with nontargeting siRNA show red puncta, indicating mitophagy (SI Appendix, Fig. S6). In Drp1-silenced cells, both the uninfected and HCV-infected cells presented tubular mitochondria because of the absence of Drp1-dependent fission activity (Fig. 3C). In contrast, HCV-infected cells also displayed swollen mitochondria (Fig. 3C). We then examined the formation and fate of the mottled cytoplasmic Drp1-silenced HCV-infected cells expressing GFP-tagged microtubule-associated protein 1 light chain 3 (GFP-LC3). Although we observed the punctate distribution pattern of the GFP-LC3 protein, indicative of the induction of general autophagy, we did not observe colocalization of GFP-LC3 puncta (green) with mitochondria (red), barring a few regions showing overlap (SI Appendix, Fig. S7). These results suggest that inhibition of mitochondrial fission hinders HCV-induced mitophagy and support the notion that Drp1-mediated mitochondrial fission precedes the subsequent events of mitophagy (19, 21, 30).

**HCV-Induced Mitochondrial Fission Facilitates Virus Secretion and Evasion of Innate Immunity.** To characterize the functional significance of mitochondrial fission in the HCV infectious process, we determined the effect of inhibiting mitochondrial fission in HCV RNA replication and secretion. Huh7 cells transfected with nontargeting or gene-specific siRNA pools specific to Drp1 and Mff were infected with HCVcc at a multiplicity of infection (MOI) of 5 at 12 h posttransfection. HCV secretion was analyzed by determining the infectivity of culture medium by foci-forming unit assay, as described previously (31). HCV RNA replication was determined by quantitative RT-PCR (qRT-PCR). As shown in Fig. 4A, extracellular virus particle titer was decreased in Drp1- or Mff-silenced cells, indicating the functional role of mitochondrial fission in HCV secretion. Intracellular infectivity showed a notable increase, indicating the accumulation of mature HCV virions because of the inhibition of virus particle secretion/egress (Fig. 4B). Silencing Drp1 or Mff did not affect HCV replication (Fig. 4C). Drp1 silencing also did not affect HCV replication in subgenomic replicon-expressing cells, which are capable of autonomous replication (SI Appendix, Fig. S8). However, in HCV-infected cells, we observed an increase in the intracellular HCV RNA levels in the Drp1- or Mff-silenced cells, reflecting the accumulation of HCV RNA as a result of inhibition of secretion (Fig. 4C). Mitochondrial dynamics and quality control are tightly linked to cellular metabolic alterations.
and ATP levels (32). To investigate whether inhibition in HCV secretion is a result of reduction in cellular ATP levels, we determined the total ATP levels and rate of glycolysis, an alternative mode of ATP generation shown to be induced by HCV (33). As shown in Fig. 4 D and E, interference of mitochondrial fission negatively affected cellular glycolytic rates and total cellular ATP pool. We also investigated whether HCV-induced mitochondrial fission affects innate immunity, which is orchestrated at the mitochondrial level via retinoic acid-inducible gene 1–mitochondrial antiviral signaling protein (MAVS) interactions. HCV NS3/4A cleaves the MAVS protein localized to mitochondria, resulting in abrogation of the downstream signaling and IFN synthesis (34). Interestingly, interference of mitochondrial fission by Drp1 silencing significantly increased the luciferase activity under the transcriptional control of IFN-stimulated response element (ISRE), indicating that HCV-induced aberrant mitochondrial fission may also contribute in part to modulation of the innate immune response (Fig. 4F). Taken together, these results suggest that HCV-induced mitochondrial fission both affects HCV secretion and contributes in part to the evasion of the innate immune system.

Fig. 3. HCV induces mitophagy. (A) Confocal images showing HCV-induced mitophagy. HCV-infected cells transiently expressing mito-mRFP-EGFP were immunostained with anti-HCV core antibody (white). Nuclei, DAPI (blue). Infected cells, +; uninfected cells, −. In the zoomed images, fluorescence signals indicate the expression of mito-mRFP-EGFP targeting mitochondria: yellow color, no mitophagy; red color, mitophagy. (B and D) Confocal images showing the inhibition of HCV-induced mitophagy by silencing Drp1. Drp1-silenced HCV-infected cells transiently expressing mito-mRFP-EGFP were immunostained with anti-HCV E2 antibody (white). Nuclei, white dots circle. Infected cells, +; uninfected cells, −. In the zoomed images, tubular mitochondria in uninfected cells and tubular/swollen mitochondria in infected cells are shown. (B and D) Quantitative analyses of the fluorescence signal targeted to mitochondria in A and C, respectively (mean ± SEM; n ≥ 10 cells; *P ≤ 0.01, by unpaired Student t test).

Fig. 4. Inhibition of mitochondrial fission affects HCV secretion and innate immune response. (A–E) Huh7 cells transfected with nontargeting (NT) or gene-specific siRNA pools targeting Drp1 and Mff, respectively, were infected HCVcc (MOI, 5). At 3 d postinfection, culture medium and cells were used for analyses of extracellular infectivity (A) and intracellular infectivity (B) determined by Foci-forming unit assay, intracellular HCV RNA levels (C) analyzed by qRT-PCR, lactate concentration (D) determined by cell-based glycolysis assay kit, and intracellular ATP levels (E) determined by the ATP EnzyLight assay kit (mean ± SEM; n = 3; *P ≤ 0.05; **P ≤ 0.005, by unpaired Student t test). (F) Drp1 silencing increases ISRE promoter activity in HCV-infected cells. Huh7 cells cotransfected with plasmids encoding ISRE Firefly luciferase reporter and wild-type Renilla luciferase reporter were subsequently transfected with NT or Drp1-specific siRNA pools and, 12 h later, infected with HCVcc (MOI, 5). At 2 d postinfection, the relative ISRE-luciferase activity was determined as described in Materials and Methods (mean ± SD; n = 3; *P ≤ 0.01, by unpaired Student t test).

Discussion
Mitochondrial depolarization, membrane permeabilization, and swelling are common occurrences in HCV infection (36). Hence, survival of HCV-infected cells is probably dependent on their ability to clear dysfunctional mitochondria. Mitochondrial quality control maintains healthy mitochondria and cell viability. Malfunction of mitochondrial quality control results in the accumulation of mitochondrial fission and mitophagy, although serving as a quality control mechanism to eliminate damaged mitochondria, also protects virus-infected hepatocytes from apoptotic cell death, facilitating persistent viral infection.
of defective mitochondria and leads to cell death (30). Removal of damaged mitochondria via mitophagy is recognized as the primary pathway in mitochondria quality control (19, 21, 30). Aberrations in cellular mitophagy pathway are linked to varied pathophysiological conditions such as neurodegeneration and cardiac dysfunctions (19, 21, 30).

It has been proposed that asymmetric fission/fragmentation of mitochondria helps in the segregation of depolarized mitochondria that are later targeted by the mitophagy machinery. How mitochondria achieve asymmetric fission is not known, but the notion that fission is a prerequisite for mitophagy is supported by the fact that genetic manipulation of fission proteins mitochondrial fission 1 and Drp1 by siRNA or overexpression of dominant negative Drp1 reduces mitophagy (30). In addition, tubular network formation has been shown to protect mitochondria from autophagosomal degradation during nutrient starvation (37). In correlation to our previous observations of HCV-induced mitophagy (11), here we present evidence for mitochondrial fragmentation/fission activities in HCV-infected cells (Fig. 1).

Mitochondrial fission is mediated by the mitochondrial recruitment of Drp1, which drives fission by oligomerization to form spirals that constrict mitochondria (19). We observed that HCV triggered mitochondrial recruitment of Drp1 by promoting its phosphorylation at serine 616 mediated by CDK1/cyclin B (Fig. 2). siRNA-mediated interference of CDK1 subverted HCV-induced Drp1 S616 phosphorylation (SI Appendix, Fig. S2), implicating its role in this process. In addition, we observed a modest decline in Drp1 S637 phosphorylation (Fig. 2), which is also known to promote mitochondrial recruitment of Drp1 (27). We also observed that HCV enhanced the expression levels of the fission proteins Drp1 and Mff (Fig. 2C). We have previously shown that mitofusin 2, one of the mediators of mitochondrial fusion, is ubiquitinated by Parkin and degraded in HCV-infected cells (11). Collectively, these findings suggest that HCV also selectively manipulates the expression levels of fission and fusion proteins to shift the balance of mitochondrial dynamics toward fission.

It has been proposed that asymmetric mitochondrial fission generates a segregated pool of depolarized mitochondria that are later subjected to mitophagy (30). We observed a higher number of mitochondria in lysosomes in HCV-infected cells (Fig. 3). Depletion of Drp1 during HCV infection compromises mitophagy. We did not observe colocalization between GFP-LC3 puncta and swollen mitochondria (SI Appendix, Fig. S7B), suggesting that efficient engulfment of these swollen mitochondria by phagophore is impaired, probably because of their larger size (38). The tubular mitochondrial network has also been shown to resist autophagic degradation during nutrient stress, probably because of nonproductive engulfment of continuous mitochondrial network (37).

Mitochondrial fission and mitophagy are the key determinants of mitochondrial quality control, and HCV modulates these key processes in the adaptation to cellular physiological perturbations associated with infection to promote viral persistence. Mitochondrial fission is not invariably associated with cell death because it also protect cells from death induced by oxidative stress and Ca²⁺-dependent apoptotic stimuli (18, 22, 38). In this study, we observed that despite high levels of mitochondrial fission in HCV-infected cells, there was no upregulation of apoptotic signaling. However, interference of mitochondrial fission and mitophagy led to a dramatic increase in apoptotic signaling (Fig. 5), suggesting that mitochondrial fission during HCV infection promotes cell survival (see model in SI Appendix, Fig. S10). Interestingly, we also observed that inhibition of mitochondrial fission resulted in the inhibition of HCV secretion with a concomitant accumulation of infectious intracellular viral particles (Fig. 4). HCV infection has been previously shown to promote glycolysis (33). Hence, we investigated whether perturbing mitochondrial dynamics affects mitochondrial functions and metabolic reprogramming. Inhibition of mitochondrial fission led to a decline in glycolysis and total cellular ATP levels, which may directly affect HCV secretion (Fig. 4). Alternatively, reactive oxygen species emanating from accumulated dysfunctional mitochondria can damage lipids and proteins that could play a crucial role in HCV secretion. However, the precise molecular mechanisms underlying the role of mitochondrial dynamics in HCV secretion still remain to be fully characterized.

Viral persistence is a primary determinant of chronic viral infection and pathogenesis of associated diseases. The occurrence of immunologically distinct viral variants (quasispecies) and the intrinsic ability of HCV to abrogate cellular immunity helps to evade the immune attack and facilitate viral persistence (2). Mitochondrial dynamics have been shown to regulate innate immunity (39). Mitochondrial fusion may serve to increase the interaction of key molecules such as MAVS in downstream signaling of IFN synthesis, and mitochondrial fission may prevent these interactions (39, 40). Consistent with this idea, we observed an increase in IFN synthesis on depletion of Drp1 (Fig. 4F), suggesting that mitochondrial fission may also participate in some way in evading innate immune response, in addition to the cleavage of MAVS by HCV NS3/4A protease (34). In the case of HCV, we observed that Huh7.5 cells, which are devoid of retinoic acid-inducible gene 1 (34), maintained mitochondrial fission, suggesting that mitochondrial fission is independent of the retinoic acid-inducible gene 1 signaling pathway (SI Appendix, Fig. S11). The molecular details about how HCV-induced mitochondrial fission may affect innate immunity remains to be characterized. Apart from the immune escape, the viability of the infected cells is a primary requirement for viral persistence. Despite the infection-associated stresses and mitochondrial injury, HCV does not produce any notable cytopathic effects (2, 41). Perhaps the physiological and metabolic alterations triggered by HCV in the
infected hepatocyte play a role in abating the stress associated with viral infection and prevent the manifestation of viral cytotoxic effects to sustain persistent infection. The present study highlights the physiological adaptation involving up-regulation of mitochondrial quality control in HCV-infected hepatocytes to sustain cellular viability and promote viral persistence. The primary cause of persistent HCV infection is a result of the failure to mount an efficient immune response to eliminate infected hepatocytes (2). However, HCV-induced aberrant mitochondrial dynamics may also contribute to the viral persistence by attenuating apoptosis of infected cells. A similar strategy of perturbation of mitochondrial dynamics and attenuation of apoptosis is also used by hepatitis B virus (29). Our findings implicate the mitochondrial quality control pathway as a potential therapeutic target against HCV infection and associated liver disease pathogenesis.

Materials and Methods

Additional information is provided in SI Appendix, Materials and Methods.

Cell Culture and Virus. The human hepatoma cell line HuH7 was cultured as described previously (11). Cell culture-derived HCV (HCVcc) of JCI and JFH1 strains were used in this study and prepared as described previously (11, 42).

DNA Constructs. The pEGBP-LC3 plasmid DNA was a kind gift from Tamotsu Yoshimori (National Institute of Genetics, Japan). The p-mito-mRFP-EGBP plasmid DNA (pAT016) was described previously (29).

Immunofluorescence. HCV-infected cells and those transfected with siRNA were grown on coverslips and used for immunofluorescence assay, as described previously (11). Images were visualized under a 60x or 100x oil objectives, using an Olympus Fluoview 1000 confocal microscope.

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SI Materials and Methods

Reagents and Antibodies

Primary antibodies used in this study include the following: rabbit monoclonal anti-Drp1, anti-phospho-Drp1 (S637), and anti-phospho-Drp1 (S616) (Cell Signaling); rabbit monoclonal anti-Mff (Sigma); rabbit polyclonal and mouse monoclonal anti-Parkin (Abcam); rabbit polyclonal anti-GAPDH (Santa Cruz); rabbit polyclonal anti-β-actin (Cell Signaling); mouse monoclonal anti-TOM20 (BD); rabbit polyclonal anti-TOM20 (Abcam); rabbit monoclonal anti-cleaved PARP and anti-cleaved caspase-3 (Cell Signaling); rabbit polyclonal anti-cytochrome c (Cell Signaling); HCV Core (Thermo Scientific); HCV NS5A (gift from Dr. Charles Rice, Rockefeller University, NY); HCV E2 (gift from Dr. Mansun Law, The Scripps Research Institute, CA). The secondary antibodies used for immunofluorescence were Alexa Fluor 405, 488, 594 or 647 donkey anti-mouse, rabbit, or goat IgG (Molecular Probe) and Alexa Fluor 555 goat anti-human IgG (Molecular Probe). The HRP-conjugated secondary antibodies used for Western blot analysis were from Cell Signaling Technologies and Jackson Laboratories.

siRNA Transfection

Small interfering RNA (siRNA) pools used in this study were siGENOME SMARTpool for Drp1, Parkin, CDK1, and non-targeting #1 control (Dharmacon). The cells were transfected with siRNA (30 nM) for the indicated times using DharmaFECT 4 transfection reagent according to the manufacturer’s instructions (Dharmacon).

Real-time qRT-PCR

Quantitative real-time PCR analysis of HCV RNA levels was performed as described previously (1). The mRNA level of Drp1 was quantified by real-time qRT-PCR using DyNAmo HS SYBR Green qPCR kit (Finnzymes). The primers used were: Drp1 forward, 5’-TGGGCGCGACATCA; Drp1 reverse, 5’-GCTCTGCGTTCCACACTACGA; GAPDH forward, 5’-GCCATCAATGACCCCTTCATT; and GAPDH reverse, 5’-TTGACGGTGCCATGGAATTT.
HCV RNA Replication and Foci-forming Unit (FFU) Assay

HCV RNA replication was determined by estimating the levels of HCV RNA in total cellular RNA by quantitative real-time PCR as described previously (2). Virus titer in the culture medium and cells was determined by FFU assay as described previously (2). Briefly, log-fold dilutions of the infectious cell culture medium were used to infect naïve Huh7.5.1 cells. 72 h post-infection the cells are fixed, immunostained for HCV NS5A and number of HCV positive foci counted. For intracellular infectivity, the cells were subjected to repeated freeze-thaw cycles and clarified cell lysate was used to perform FFU assay (2).

Glycolysis and ATP Estimation

Huh7 cells were transfected with non-targeting or gene-specific siRNAs against Drp1 or Mff. At 12 hours post-transfection, cells were infected with high titer (MOI ~5) of HCVcc. At 72 hours post-infection, cells and culture medium were collected. Glycolysis rate was estimated by determining the lactate levels in culture medium using the glycolysis cell-based assay kit according to the manufacturer’s instructions (Cayman Chemicals). Total ATP levels were determined by luciferase-based ATP Enzylight kit according to manufacturer’s instructions (BioAssay System).

Western Blot Analysis

For Western blot analysis, whole lysates were extracted from cells and homogenized liver biopsy tissues subjected to SDS-PAGE, transferred to nitrocellulose membrane (Thermo Scientific), and Western blot analyzed with antibodies against the indicated proteins as described previously (1).

Subcellular Fractionation

To isolate pure cytosolic and mitochondrial fraction, HCV-infected Huh7 cells were homogenized and isolated as described previously (1, 3).
Electron Microscopy

Huh7 cells infected with HCVcc at an MOI of 5 were prepared for electron microscopy. At 5 days post-infection, cells were fixed and embedded as described previously (1). Ultrathin sections were examined using a JEOL 1200 EX II transmission electron microscope at 80 kV.

ISRE-luciferase Reporter Assay

Briefly, Huh7 cells were cotransfected with a pISRE-Luc (a gift from Dr. Michael David, University of California, San Diego), expressing firefly luciferase under the transcriptional control of IFN-stimulated response element (ISRE), and pRL-CMV plasmids (Promega), expressing Renilla luciferase. Subsequently, these cells were transfected with non-targeting (NT) or gene specific siRNA pools targeting Drp1 and infected with HCVcc (MOI of 5) 12 h later. At 2 days post-infection, the relative ISRE-luciferase activity was determined by using the dual-luciferase reporter assay system according to the manufacturer’s instructions (Promega). Firefly luciferase activity was normalized against Renilla luciferase activity to normalize the transfection efficiency.

Caspase-3/7 and TUNEL assay

The activity of caspase-3/7 in HCV-infected cells transfected with siRNA pools specific to Drp1 and Parkin, respectively, was measured by using Caspase-Glo 3/7 assay kit according to the manufacturer’s instructions (Promega). Apoptotic cell death in these cells was measured by using Click-iT TUNEL Alexa Fluor 488 imaging assay kit according to the manufacturer’s instructions (Invitrogen). For quantitative analysis, at least 1,000 cells on immunofluorescence image were counted.

Human liver biopsy specimens

The frozen human liver biopsy specimens ($n = 3$) were obtained from UCSD medical center. The liver biopsy specimens used in this study include the following: anti-HCV negative normal patient, $n = 1$; anti-HCV positive patients with chronic HCV, $n = 2$. The biopsy material was collected on
consent of the patients following the institution ethical guidelines.

**Statistical Analysis**

Statistical analysis using the unpaired Student t test was performed by using Sigma Plot software (Systat Software Inc., San Jose, CA).

**References**

**Fig. S1.** HCV infection promotes mitochondrial fission. Confocal image of HCV-infected cells showing mitochondrial fission. Huh7 cells infected with JFH1 HCVcc were immunostained with antibodies specific to TOM20 (white) and HCV core protein (green). Nuclei were stained with DAPI (blue). Infected (+) and uninfected (-) cells are marked. In the zoomed images, fragmented mitochondria in HCV-infected cells and typical tubular mitochondria in uninfected cells are shown.

**Fig. S2.** Silencing CDK1 suppresses HCV-induced Drp1 Ser616 phosphorylation. Huh7 cells infected with HCVcc were transfected with non-targeting (NT) or CDK1-specific siRNA pools. At 3 days post-transfection, whole cell lysates were analyzed by immunoblotting with antibodies specific to the indicated proteins. β-actin, internal loading control.
Fig. S3. HCV proteins-mediated Drp1 Ser616 phosphorylation. The intensity ratio of p-Drp1(S616)/total Drp1 analyzed by ImageJ software. The expression levels of p-Drp1 (S616) and total Drp1 were analyzed by immunoblotting of whole cell lysates extracted from Huh7 cells transiently expressing HCV E2, core, NS3/4A, NS4B, NS5A, and NS5B, respectively. Mock, empty vector.

Fig. S4. A novel system for monitoring mitophagy. A novel system for monitoring the maturation process by which mitophagosomes are converted into mitophagolysosome (mitophagy) using a dual fluorescence p-mito-mRFP-EGFP reporter. Lysosomal delivery of the tandem fusion protein mito-mRFP-EGFP along with entire mitochondria results in differential quenching and degradation of the two individual fluorochromes, thereby allowing for visual analysis of mitophagic flux.
**Fig. S5. HCV induces complete mitophagy.** Confocal images showing the fusion between mito-mRFP-EGFP and lysosome (mitophagolysosome formation) in HCV-infected cells. Uninfected and infected cells transiently expressing mito-mRFP-EGFP were immunostained with antibodies specific to LAMP1 (blue) and HCV E2 protein (cyan). Nuclei, white dot circles. Uninfected cells, (-); infected cells (+). In the zoomed images, the arrows indicate merged of red fluorescence of mito-mRFP-EGFP targeted to mitochondria with lysosome (pink puncta).
Fig. S6. Confocal images showing mitophagy in HCV-infected cells in the presence of non-targeting siRNA. At 2 days post-infection, HCV-infected cells transiently expressing mito-mRFP-EGFP were immunostained with anti-HCV core antibody (white). Nuclei, white dot circles. Infected cells, (+); uninfected cells, (-). The zoomed images display tubular mitochondrial network in uninfected cells and fragmented mitochondria in infected cells.
**Fig. S7. Drp1 silencing interferes with mitophagosome formation in HCV-infected cells.** (A) Western blot analysis of whole cell lysates extracted from Huh7 cells transfected with siRNA pools specific to Drp1 and Mff, respectively. Non-targeting (NT) siRNA pools, a negative control. (B) Confocal microscopy showing inhibition of mitophagosome formation by silencing Drp1 in HCV-infected cells. Drp1-silencing Huh7 cells transfected with GFP-LC3 construct were infected with HCVcc. At 2 days post-infection, cells prestained with MitoTracker (Mito, red) were immunostained with anti-HCV E2 antibody (white). Infected cells, (+); uninfected cells, (-). Nuclei, white dot circles. The zoomed image indicates that GFP-LC3 puncta (green) does not colocalize with mitochondria in HCV-infected cells.
**Fig. S8. Drp1 silencing does not affect HCV replication.** SGR-Feo subgenomic replicon cells were transfected with non-targeting (NT) or Drp1-specific siRNA pools (30 nM) and assayed at 2 days post-transfection. Values are mean ± SD (n = 3). *P ≤ 0.05, by unpaired Student t test.

**Fig. S9. Drp1 and Mff silencing enhances HCV-induced mitochondrial swelling.** (A and B) Confocal microscopy showing mitochondria shape with enhanced swelling morphology in Drp1 (A) or Mff (B) silencing HCV-infected cells. Huh7 cells transfected with Drp1 and Mff siRNA, respectively were infected with HCVcc (MOI of 1). At 2 days post-infection, cells pre-stained with MitoTracker (Mito, white) were immunostained with antibodies specific to Drp1 (green, panel A), Mff (green, panel B), and HCV E2 protein (orange). In the zoomed images, uninfected cells display tubular mitochondria, whereas infected cells show tubular and enhanced mitochondrial swelling. Infected cells, (+); uninfected cells, (-). Nuclei, white dot circles.
Fig. S10. A model elucidating the role of HCV-induced mitochondrial fission in mitochondrial apoptosis and viral life cycle. HCV infection disrupts mitochondrial dynamics: Induces mitochondrial fission via Drp1 translocation to mitochondria subsequent mitophagy. Interference of mitochondrial fission can lead to apoptotic cell death in infected cells via upregulation of apoptotic signaling as shown in Fig. 5.
Fig. S11. HCV induces mitochondrial fission in Huh7.5 cells. Confocal microscopy showing mitochondrial fission in HCV-infected Huh7.5 cells. At 2 days post-infection, Huh7.5 cells infected with HCVcc (MOI of 1) were immunostained with antibodies specific to TOM20 (green) and HCV E2 protein (white). Nuclei, DAPI (blue). Infected cells, (+); uninfected cells, (-). The zoomed images display tubular mitochondrial network in uninfected cells and fragmented mitochondria in infected cells.