nucleus [37]. They further screened a human liver cDNA library using NS2 with deletion of the N-terminal TM domain, and CIDE-B protein, a member of the CIDE family of apoptosis-inducing factors, was identified. However, whether CIDE-B is involved in the HCV lifecycle and/or viral pathogenesis is unclear. de Chassey et al. reported several cellular proteins as potential NS2 binding proteins using NS2 with N-terminal deletion as a bait [38]. Involvement of these proteins in the HCV lifecycle is also unclear. In our study, to screen for NS2-binding partners using full-length NS2 as a bait, we utilized a split-ubiquitin yeast two-hybrid system that allows for the identification of interactions between full-length integral membrane proteins or between a full-length membrane-associated protein and a soluble protein [39]. SPCS1 was identified as a positive clone of an NS2-binding protein, but proteins that have been reported to interact with NS2 were not selected from our screening.

SPCS1 is a component of the signal peptidase complex that processes membrane-associated and secreted proteins in cells. The mammalian signal peptidase complex consists of five subunits, SPCS1, SPCS2, SPCS3, SEC11A, and SEC11C [27]. Among them, the functional role of SPCS1 is still unclear, and SPCS1 is considered unlikely to function as a catalytic subunit according to membrane topology [40]. The yeast homolog of SPCS1, Spc1p, is also known to be nonessential for cell growth and enzyme activity [28,41]. Interestingly, these findings are consistent with the results obtained in this study. Knockdown of SPCS1 did not impair processing of HCV structural proteins (Fig. 4A) or secretion of apoE and albumin (Fig. 4B and C), which are regulated by ER membrane-associated signal peptidase activity. The propagation of JEV, whose structural protein regions are cleaved by signal peptidase, was also not affected by the knockdown of SPCS1 (Fig. 3B). SPCS1, SPCS2, and SPCS3 are among the host factors that function in HCV production identified from genome-wide siRNA screening [42]. It seemed that knockdown of SPCS1 had a higher impact on the later stage of viral infection compared to either SPCS2 or SPCS3, which are possibly involved in the catalytic activity of the signal peptidase.

Further analyses to address the mechanistic implication of SPCS1 on the HCV lifecycle revealed that SPCS1 knockdown impaired the assembly of infectious viruses in the cells, but not cell entry, RNA replication, or release from the cells (Fig. 5). We thus considered the possibility that the SPCS1-NS2 interaction is important for the role of NS2 in viral assembly. Several studies have reported that HCV NS2 is associated biochemically or genetically with viral structural proteins as well as NS proteins [10,18–25]. As an intriguing model, it has been proposed that NS2 functions as a key organizer of HCV assembly and plays a key role in recruiting viral envelope proteins and NS protein(s) such as NS3 to the assembly sites in close proximity to lipid droplets [21]. The interaction of NS2 with E2 has been shown by use of an HCV genome encoding tagged-NS2 protein in virion-producing cells. Furthermore, the selection of an assembly-deficient NS2 mutation located within its TM3 for pseudoreversion leads to a rescue mutation in the TM domain of E2, suggesting an in-membrane interaction between NS2 and E2 [21]. Another study identified two classes of NS2 mutations with defects in virus assembly; one class leads to reduced interaction with NS3, and the other, located in the TM3 domain, maintains its interaction with NS3 but shows impaired interaction between NS2 and E1-E2 [20]. However, the precise details of the NS2-E2 interaction, such as direct protein-protein binding or participating host factors, are unknown. Our results provide evidence that SPCS1 has an important role in the formation of the NS2-E2 complex by its interaction with both NS2 and E2, most likely via their transmembrane domains, including TM3 of NS2. As knockdown of SPCS1 reduced the interaction of NS2 and E2 as shown in Fig. 6D and E, it may be that SPCS1 contributes to NS2-E2 complex formation or to stabilizing the complex. Based on data obtained in this study, we propose a model of the formation of an E2-SPCS1-NS2 complex at the ER membrane (Fig. 7).

In summary, we identified SPCS1 as a novel NS2-binding host factor required for HCV assembly by split-ubiquitin membrane yeast two-hybrid screening. Our data demonstrate that SPCS1 plays a key role in the E2-NS2 interaction via formation of an E2-SPCS1-NS2 complex. These findings provide clues for understanding the molecular mechanism of assembly and formation of infectious HCV particles.

## Materials and Methods

### Split ubiquitin-based yeast two-hybrid screen

A split-ubiquitin membrane yeast two-hybrid screen was performed to identify possible NS2 binding partners. This screening system (DUALmembrane system; Dualsystems Biotech, Schlieren, Switzerland) is based on an adaptation of the ubiquitin-based split protein sensor [26]. The full-length HCV NS2 gene derived from the JFH-1 strain [29] was cloned into pBT3-SUC bait vector to obtain bait protein fused to the C-terminal half of ubiquitin (NS2-Cub) along with a transcription factor. Prey proteins generated from a human liver cDNA library (Dualsystems Biotech) were expressed as a fusion to the N-terminal half of ubiquitin (NubG). Complex formation between NS2-Cub and NubG-protein from the library leads to cleavage at the C-terminus of reconstituted ubiquitin by ubiquitin-specific protease(s) with consequent translocation of the transcription factor into the nucleus. Library plasmids were recovered from positive transformants, followed by determining the nucleotide sequences of inserted cDNAs, which were identified using the BLAST algorithm with the GenBank database.

### Cell culture

Human embryonic kidney 293T cells, and human hepatoma Huh-7 cells and its derivative cell lines Huh7.5.1 [43] and Huh7-25 [36], were maintained in Dulbecco's modified Eagle medium supplemented with nonessential amino acids, 100 U of penicillin/ml, 100 μg of streptomycin/ml, and 10% fetal bovine serum (FBS) at 37°C in a 5% $CO_2$ incubator.

### Plasmids

Plasmids pCAGC-NS2/JFH1am and pHHJFH1am were previously described [33]. The plasmid pCAGC-p7/JFHam, having

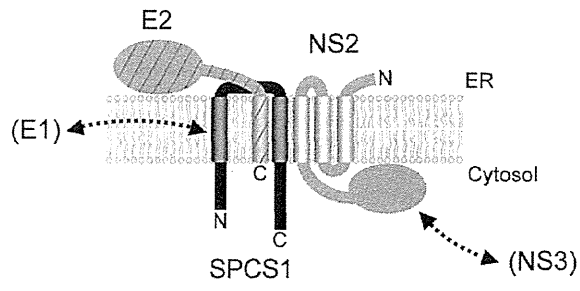


**Figure 7. A proposed model for a complex consisting of NS2, SPCS1 and E2 associated with ER membranes.**
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adaptive mutations in E2 (N417S) and p7 (N765D) in pCAG/C-p7 [44], was constructed by oligonucleotide-directed mutagenesis.

To generate the NS2 expression plasmid pCAG F-NS2 and the NS2-deletion mutants, cDNAs encoding the full-length or parts of NS2 possessing the FLAG-tag and spacer sequences (MDYKDDDDKGGGGS) were amplified from pCAGC-NS2/JFH1am by PCR. The resultant fragments were cloned into pCAGGS. For the NS2-NS3 expression plasmid pEF F-NS2-3, a cDNA encoding the entire NS2 and the N-terminal 226 amino acids of NS3 with the N-terminal FLAG-tag sequence as above was amplified by PCR and was inserted into pEF1/myc-His (Invitrogen, Carlsbad, CA). The plasmid pEF F-NS2-3 H956A, having a defective mutation in the protease active site within NS2, was constructed by oligonucleotide-directed mutagenesis.

To generate the NS3 expression plasmid pCAGN-HANS3JFH1, a cDNA encoding NS3 with an HA tag at the N terminus, which was amplified by PCR with pHHJFHam as a template, was inserted downstream of the CAG promoter of pCAGGS.

To generate the SPCS1-expressing plasmid pCAG-SPCS1-myc and its deletion mutants, cDNAs encoding all of or parts of SPCS1 with the Myc tag sequence (EQKLISEEDL) at the C-terminus, which was amplified by PCR, was inserted into pCAGGS. pSilencer-shSPCS1 carrying a shRNA targeted to SPCS1 under the control of the U6 promoter was constructed by cloning the oligonucleotide pair 5′- GATCCGCAATAGTTGGATTTATCT TTCAAGAGAAGATAAATCCAACTATTGCTTTTTTGGA AA-3′ and 5′- AGCTTTTCCAAAAAAGCAATAGTTGGATT-TATCTTCTCTTGAAAGATAAATCCAACTATTGCG-3′ between the BamHI and HindIII sites of pSilencer 2.1-U6 hygro (Ambion, Austin, TX). To generate a construct expressing shRNA-resistant SPCS1 pSPCS1-sh$^r$, a cDNA fragment coding for SPCS1, in which the 6 bp within the shRNA targeting region (5′-GCAATAGTTGGATTTATCT-3′) was replaced with GCT ATTGTCGGCTTCATAT that causes no aa change, was amplified by PCR. The resulting fragment was confirmed by sequencing and then cloned into pCAGGS.

Full-length SPCS1 and N-terminal region of NS2 (aa 1–94) were amplified by PCR and cloned onto EcoRI and HindIII sites of phmKGN-MN and phmKGC-MN, which encode the mKG fragments (CoralHue Fluo-chase Kit; MBL, Nagoya, Japan), designated as pSPCS1-mKG(N) and pNS2-mKG(C), respectively. Transmembrane domain of the E1 to E2 was also amplified by PCR and cloned onto EcoRI and HindIII sites of phmKGC-MN. To avoid the cleavage of E2-mKG(C) fusion protein in the cells, last alanine of the E2 protein was deleted. Positive control plasmids for mKG system, pCONT-1 and pCONT-2, which encode p65 partial domain from NF-κB complex fused to mKG(N) and p50 partial domain from NF-κB complex fused to mKG(C) respectively, were supplied from MBL. For PLA experiments, cDNA for SPCS1 d2-myc with the V5 tag at the N-terminus was amplified by PCR, and inserted into pCAGGS. For expression of HCV E2, cDNA from E1 signal to the last codon of the transmembrane domain of the E2, in which part of the hypervariable region-1 (aa 394–400) were replaced with FLAG-tag and spacer sequences (DYKDDDDKGGG), was amplified by PCR, and inserted into pCAGGS. For expression of FLAG-core, cDNAs encoding Core (aa 1–152) possessing the FLAG-tag and spacer sequences (MDYKDDDDKGGGGS) were amplified from pCAGC191 [45] by PCR. The resultant fragments were cloned into pCAGGS.

## DNA transfection

Monolayers of 293T cells were transfected with plasmid DNA using FuGENE 6 transfection reagent (Roche, Basel, Switzerland) in accordance with the manufacturer's instructions. Huh-7, Huh7.5.1, and Huh7-25 cells were transfected with plasmid DNA using TransIT LT1 transfection reagent (Mirus, Madison, WI).

## PLA

The assay was performed in a humid chamber at 37°C according to the manufacturer's instructions (Olink Bioscience, Uppsala, Sweden). Transfected 293T cells were grown on glass coverslips. Two days after transfection, cells were fixed with 4% paraformaldehyde in phosphate-buffered saline (PBS) for 20 min, then blocked and permeabilized with 0.3% Triton X-100 in a nonfat milk solution (Block Ace; Snow Brand Milk Products Co., Sapporo, Japan) for 60 min at room temperature. Then the samples were incubated with a mixture of mouse anti-FLAG monoclonal antibody M2 and rabbit anti-V5 polyclonal antibody for 60 min, washed three times, and incubated with plus and minus PLA probes. After washing, the ligation mixture containing connector oligonucleotide was added for 30 min. The washing step was repeated, and amplification mixture containing fluorescently labeled DNA probe was added for 100 min. Finally, the samples were washed and mounted with DAPI mounting medium. The signal representing interaction was analyzed by Leica TCS SPE confocal microscope.

## mKG system

The assay was performed according to the manufacturer's instructions (CoralHue Fluo-chase Kit; MBL). 293T cells were transfected by a pair of mKG fusion constructs. Twenty-four hours after transfection, cell were fixed and stained with DAPI. The signal representing interaction was analyzed by Leica TCS SPE confocal microscope.

## Gene silencing by siRNA

The siRNAs were purchased from Sigma-Aldrich (St. Louis, MO) and were introduced into the cells at a final concentration of 10 to 30 nM using Lipofectamine RNAiMAX (Invitrogen). Target sequences of the siRNAs were as follows: SPCS1 #1 (5′-CAGUUCGGGUGGACUGUCU-3′), SPCS1 #2 (5′-GCAAUA GUUGGAUUUAUCU-3′), SPCS1 #3 (5′-GAUGUUUCAGG-GAAUUAUU-3′), SPCS1 #4 (5′-GUUAUGGCCGGAUUUG-CUU-3′), claudin-1 (5′-CAGUCAAUGCCAGGUACGA-3′), PI4K (5′-GCAAUGUGCUUCGCGAGAA-3′) and scrambled negative control (5′-GCAAGGGAAACCGUGUAAU-3′). Additional control siRNAs for SPCS1 were as follows: C911-#2 (5′-GCAAUAGUaccAUUUAUCU-3′), C911-#3 (5′-GAUGUUU-CuccGAAUUAUU-3′) and C911-#4 (5′-GUUAUGGCgccAUU UGCUU-3′). Bases 9 through 11 of the siRNAs replaced with their complements were shown in lower cases.

## Establishment of a stable cell line expressing the shRNA

Huh-7 cells were transfected with pSilencer-SPCS1, and drug-resistant clones were selected by treatment with hygromycin B (Wako, Tokyo, Japan) at a final concentration of 500 μg/ml for 4 weeks.

## Virus

HCVtcp and HCVcc derived from JFH-1 having adaptive mutations in E2 (N417S), p7 (N765D), and NS2 (Q1012R) were generated as described previously [33]. The rAT strain of JEV [46] was used to generate virus stock.

## Antibodies

Mouse monoclonal antibodies against actin (AC-15) and FLAG (M2) were obtained from Sigma-Aldrich (St. Louis, MO). Mouse

monoclonal antibodies against flavivirus group antigen (D1-4G2) were obtained from Millipore (Billerica, MA). Rabbit polyclonal antibodies against FLAG and V5 were obtained from Sigma-Aldrich. Rabbit polyclonal antibodies against SPCS1, claudin-1, PI4K and myc were obtained from Proteintech (Chicago, IL), Life Technologies (Carlsbad, CA), Cell Signaling (Danvers, MA) and Santa Cruz Biotechnology (Santa Cruz, CA), respectively. An anti-apoE goat polyclonal antibody was obtained from Millipore. Rabbit polyclonal antibodies against NS2 and NS3 were generated with synthetic peptides as antigens. Mouse monoclonal antibodies against HCV Core (2H9) and E2 (8D10-3) and rabbit polyclonal antibodies against NS5A and JEV are described elsewhere [47].

### Titration

To determine the titers of HCVcc, Huh7.5.1 cells in 96-well plates were incubated with serially-diluted virus samples and then replaced with media containing 10% FBS and 0.8% carboxymethyl cellulose. Following incubation for 72 h, the monolayers were fixed and immunostained with the anti-NS5A antibody, followed by an Alexa Fluor 488-conjugated anti-rabbit secondary antibody (Invitrogen). Stained foci were counted and used to calculate the titers of focus-forming units (FFU)/ml. For intracellular infectivity of HCVcc, the pellets of infected cells were resuspended in culture medium and were lysed by four freeze-thaw cycles. After centrifugation for 5 min at 4,000 rpm, supernatants were collected and used for virus titration as above. For titration of JEV, Huh7.5.1 cells were incubated with serially-diluted virus samples and then replaced with media containing 10% FBS and 0.8% carboxymethyl cellulose. After a 24 h incubation, the monolayers were fixed and immunostained with a mouse monoclonal anti-flavivirus group antibody (D1-4G2), followed by an Alexa Fluor 488-conjugated anti-mouse secondary antibody (Invitrogen).

### Immunoprecipitation

Transfected cells were washed with ice-cold PBS, and suspended in lysis buffer (20 mM Tris-HCl [pH 7.4] containing 135 mM NaCl, 1% TritonX-100, and 10% glycerol) supplemented with 50 mM NaF, 5 mM $Na_3VO_4$, and complete protease inhibitor cocktail, EDTA free (Roche). Cell lysates were sonicated for 10 min and then incubated for 30 min at 4°C, followed by centrifugation at 14,000× *g* for 10 min. The supernatants were immunoprecipitated with anti-Myc-agarose beads (sc-40, Santa Cruz Biotechnology) or anti-FLAG antibody in the presence of Dynabeads Protein G (Invitrogen). The immunocomplexes were precipitated with the beads by centrifugation at 800× *g* for 30 s, or by applying a magnetic field, and then were washed four times with the lysis buffer. The proteins binding to the beads were boiled with SDS sample buffer and then subjected to SDS–polyacrylamide gel electrophoresis (PAGE).

### Immunoblotting

Transfected cells were washed with PBS and lysed with 50 mM Tris-HCl, pH 7.4, 300 mM NaCl, 1% Triton X-100. Lysates were then sonicated for 10 min and added to the same volume of SDS sample buffer. The protein samples were boiled for 10 min, separated by SDS-PAGE, and transferred to polyvinylidene difluoride membranes (Millipore). After blocking, the membranes were probed with the primary antibodies, followed by incubation with peroxidase-conjugated secondary antibody. Antigen-antibody complexes were visualized by an enhanced chemiluminescence detection system (Super Signal West Pico Chemiluminescent Substrate; PIERCE, Rockford, IL) according to the manufacturer's protocol and were detected by an LAS-3000 image analyzer system (Fujifilm, Tokyo, Japan).

### Albumin measurement

To determine the human albumin level secreted from cells, culture supernatants were collected and passed through a 0.45-μm pore filter to remove cellular debris. The amounts of human albumin were quantified using a human albumin ELISA kit (Bethyl Laboratories, Montgomery, TX) according to the manufacturer's protocol.

## Supporting Information

**Figure S1** Effects of SPCS1-siRNAs and the C911 mismatch control siRNAs on the expression of SPCS1 and production of HCV. (A) Huh7.5.1 cells were transfected with either siRNAs targeted for SPCS1 (SPCS1-#2, -#3, and -#4), scrambled control siRNA (Scrambled) or C911 siRNA in which bases 9 through 11 of each SPCS1 siRNA were replaced with their complements (C911-#2, -#3, and -#4) at a final concentration of 15 nM, and were infected with HCVcc at a multiplicity of infection (MOI) of 0.05 at 24 h post-transfection. Expression levels of endogenous SPCS1 and actin in the cells were examined by immunoblotting using anti-SPCS1 and anti-actin antibodies at 3 days post-infection. (B) Infectious titers of HCVcc in the supernatant of the infected cells were determined at 3 days postinfection.
(TIF)

**Figure S2** 293T cells were transfected with E2 expression plasmid in the presence or absence of SPCS1-myc expression plasmid. The cell lysates of the transfected cells were immunoprecipitated with anti-myc antibody. The resulting precipitates and whole cell lysates used in IP were examined by immunoblotting using anti-E2 or anti-myc antibody. An empty plasmid was used as a negative control.
(TIF)

**Figure S3** Interaction of HCV E2 with SPCS1 in mammalian cells. (A) 293T cells were transfected with indicated plasmids. 2 days posttransfection, cells were fixed and permeabilized with Triton X-100, then subjected to in situ PLA (Upper) or immunofluorescence staining (Lower) using anti-FLAG and anti-V5 antibodies. (B) Detection of the SPCS1-E2 interaction in transfected cells using the mKG system. 293T cells were transfected by indicated pair of mKG fusion constructs. Twenty-four hours after transfection, cell were fixed and stained with DAPI, and observed under a confocal microscope.
(TIF)

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## Author Contributions

Conceived and designed the experiments: RS TS. Performed the experiments: RS MM. Analyzed the data: RS KW HA TS. Contributed reagents/materials/analysis tools: YM TW. Wrote the paper: RS TS.

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# Zinc-finger antiviral protein mediates retinoic acid inducible gene I–like receptor-independent antiviral response to murine leukemia virus

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**When host cells are infected by an RNA virus, pattern-recognition receptors (PRRs) recognize the viral RNA and induce the antiviral innate immunity. Toll-like receptor 7 (TLR7) detects the genomic RNA of incoming murine leukemia virus (MLV) in endosomes and mediates the antiviral response. However, the RNA-sensing PRR that recognizes the MLV in the cytosol is not fully understood. Here, we definitively demonstrate that zinc-finger antiviral protein (ZAP) acts as a cytosolic RNA sensor, inducing the degradation of the MLV transcripts by the exosome, an RNA degradation system, on RNA granules. Although the retinoic acid inducible gene I (RIG-I)–like receptors (RLRs) RIG-I and melanoma differentiation-associated protein 5 detect various RNA viruses in the cytosol and induce the type I IFN-dependent antiviral response, RLR loss does not alter the replication efficiency of MLV. In sharp contrast, the loss of ZAP greatly enhances the replication efficiency of MLV. ZAP localizes to RNA granules, where the processing-body and stress-granule proteins assemble. ZAP induces the recruitment of the MLV transcripts and exosome components to the RNA granules. The CCCH-type zinc-finger domains of ZAP, which are RNA-binding motifs, mediate its localization to RNA granules and MLV transcripts degradation by the exosome. Although ZAP was known as a regulator of RIG-I signaling in a human cell line, ZAP deficiency does not affect the RIG-I–dependent production of type I IFN in mouse cells. Thus, ZAP is a unique member of the cytosolic RNA-sensing PRR family that targets and eliminates intracellular RNA viruses independently of TLR and RLR family members.**

host defense | retrovirus | ZC3HAV1

Innate immunity is induced after the recognition of viral RNAs by pattern-recognition receptors (PRRs) and is the first line of the host defenses against a variety of RNA viruses (1, 2). Among the PRRs, the Toll-like receptor (TLR) and retinoic acid-inducible gene I (RIG-I)-like receptor (RLR) families play major roles in the recognition of viral RNAs. The RLR's RIG-I [also called DEAD (Asp-Glu-Ala-Asp) box polypeptide 58 (DDX58)] and melanoma differentiation-associated protein 5 [MDA5, also called interferon induced with helicase C domain 1 (IFIH1)] are RNA helicases that sense the ds form of viral RNAs in the cytosol (3, 4). After sensing dsRNA, the RLRs trigger a signaling pathway that activates interferon (IFN) regulatory factor 3 (IRF3) and IRF7, transcription factors that induce IFN stimulation-responsive, element-dependent transcription (5, 6). This results in the production of type I IFN and the expression of IFN-inducible antiviral proteins. The sensing of viral RNAs by TLR family members also induces the IRF3- and IRF7-dependent type I IFN response (1, 2). In epithelial cells, TLR3, a sensor of dsRNA, detects the incoming RNA virus genomes in endosomes and induces the activation of IRF3, leading to the production of type I IFN (7, 8). In plasmacytoid dendritic cells, TLR7, a sensor of single-stranded (ss) RNA, detects incoming RNA virus genomes in endo-lysosomes and triggers the activation of IRF7, leading to the robust production of type I IFN (9–13). Thus, TLRs and RLRs play major roles in the establishment of an antiviral state by mediating the production of type I IFN.

Murine leukemia virus (MLV), a retrovirus belonging to the gammaretroviral genus of the family *Retroviridae*, is a causative agent of cancer in murine hosts (14, 15). Although type I IFN is essential for the protection of hosts from lethal infection with a variety of RNA viruses, such as influenza A virus (IAV) and vesicular stomatitis virus (VSV), type I IFN is not essential for induction of the antiviral state against MLV (16–18). Therefore, a different type of innate immune system has been proposed to protect hosts from MLV infection. Although TLR7 has been shown to induce virus-neutralizing immunity after MLV genomic RNA is detected in endosomes (16), the RNA sensor responsible for the elimination of MLV in the cytosol has not been fully understood. RLRs are candidate RNA sensors of intracellular MLV. RLRs might mediate the antiviral response to MLV after the viral RNA is detected, independently of type I IFN because RLRs stimulate not only IRF3/IRF7, but also other transcription factors, such as NF-κB and activator protein 1, which are responsible for the production of inflammatory cytokines and chemokines (19). Another candidate sensor is zinc-finger antiviral protein [ZAP, also called zinc finger CCCH-type, antiviral 1 (ZC3HAV1)]. ZAP was originally identified with an expression cloning method as one of the antiviral proteins directed against MLV (20). ZAP reduces the level of MLV transcripts in the cytosol to suppress MLV infection at the posttranscriptional stage, whereas ZAP does not inhibit the early stage of the MLV infection. ZAP recognizes the MLV transcripts via its CCCH-type zinc-finger domains and binds with RNA helicases and the components of the exosome (an RNA degradation system) to induce the degradation of the MLV transcripts (21–25). However, it is unclear whether endogenous ZAP is involved in the antiviral response to replication-competent MLV in primary cells. In the present study, we examined the roles of these two types of cytosolic RNA sensors and demonstrated the spatial regulation of the innate immune response directed against intracellular MLV.

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## Results

**RLRs Do Not Regulate the Antiviral Response to MLV in Primary Mouse Embryonic Fibroblasts.** We first examined the involvement of RLRs in the antiviral response to MLV in mouse embryonic fibroblasts (MEFs). The replication efficiency of MLV in *Ddx58*$^{-/-}$/*Ifih1*$^{-/-}$ MEFs was similar to that in *Ddx58*$^{+/+}$/*Ifih1*$^{+/+}$ MEFs (Fig. 1*A*). Furthermore, the replication efficiency of MLV in *Irf3*$^{-/-}$/*Irf7*$^{-/-}$ MEFs was similar to that in *Irf3*$^{+/-}$/*Irf7*$^{+/-}$ MEFs (Fig. 1*B*). Consistent with this, the levels of *Ifnb1* and *chemokine (C-X-C motif) ligand 10* (*Cxcl10*) mRNAs did not change during MLV infection (Fig. 1 *C–F*). The RLR–IRF3/7 signaling axis is essential for the up-regulation of *Ifnb1* and *Cxcl10* mRNAs during VSV infection. R848, a ligand of TLR7, failed to stimulate MEFs isolated from C57BL/6 mice (Fig. S1), indicating that no RNA-sensing TLR family member recognizes MLV in the extracellular space of MEFs. Therefore, MLV evades the RLR and TLR systems and does not induce the type I IFN response in MEFs.

**Endogenous ZAP Limits the Replication of MLV in Primary MEFs.** We next investigated the role of ZAP, another cytosolic sensor of viral RNA, in the antiviral response to MLV. Previous studies have demonstrated that the ectopic expression of ZAP potently inhibits replication-incompetent MLV in the cytoplasm of various types of cell lines (20). Therefore, we generated *Zc3hav1*$^{-/-}$ mice to examine whether endogenous ZAP controls the replication of MLV in primary cells (Fig. S2). Detectable levels of ZAP protein were expressed in *Zc3hav1*$^{+/+}$ MEFs before and after MLV infection (Fig. S2*D*). Whereas ZAP deficiency did not alter the replication efficiency of VSV in MEFs (Fig. S3), ZAP deficiency greatly enhanced the replication efficiency of MLV (Fig. 2 *A* and *B*). These findings indicate that endogenous ZAP is responsible for the antiviral response to replication-competent MLV in primary mouse cells.

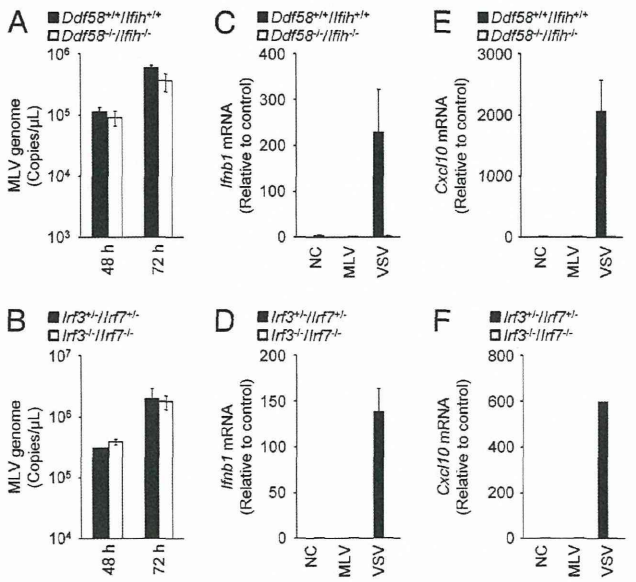


**Fig. 1.** RIG-I–like receptors are not essential for the antiviral response to MLV in primary MEFs. (*A* and *B*) *Ddx58*$^{+/+}$/*Ifih1*$^{+/+}$ and *Ddx5*$^{-/-}$/*Ifih1*$^{-/-}$ MEFs (*A*) or *Irf3*$^{-/-}$/*Irf7*$^{+/-}$ and *Irf*$^{-/-}$/*Irf7*$^{-/-}$ MEFs (*B*) were infected with MLV ($2 \times 10^{10}$ copies per μL) for 48 or 72 h. The copy numbers of the MLV genome in the culture supernatants were measured by quantitative RT-PCR. (*C–F*) *Ddx58*$^{+/+}$/*Ifih1*$^{+/+}$ and *Ddx58*$^{-/-}$/*Ifih1*$^{-/-}$ MEFs (*C* and *E*) or *Irf3*$^{+/-}$/*Irf7*$^{+/-}$ and *Irf3*$^{-/-}$/*Irf7*$^{-/-}$ MEFs (*D* and *F*) were infected with MLV ($2 \times 10^{10}$ copies per μL) or VSV [multiplicity of infection (MOI) = 1] for 12 h. The levels of *Ifnb1* (*C* and *D*) and *Cxcl10* (*E* and *F*) mRNAs were measured by quantitative RT-PCR. The results shown are means ± SD ($n = 3$).

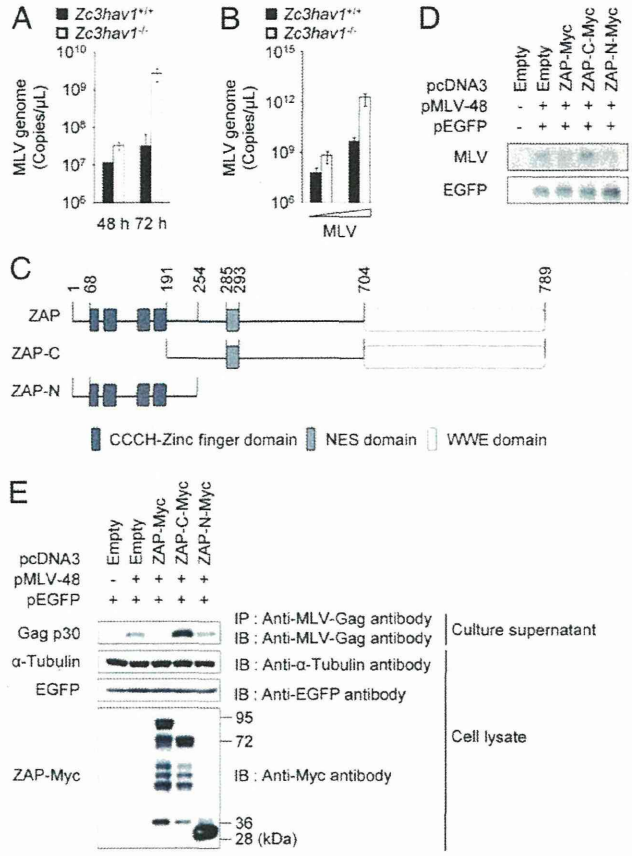


**Fig. 2.** ZAP inhibits MLV replication in primary MEFs. (*A*) *Zc3hav1*$^{+/+}$ and *Zc3hav1*$^{-/-}$ MEFs were infected with MLV ($2 \times 10^{10}$ copies per μL). Viral RNA was isolated at the indicated time points. The copy numbers of the MLV genome in the culture supernatants were measured by quantitative RT-PCR. (*B*) *Zc3hav1*$^{+/+}$ and *Zc3hav1*$^{-/-}$ MEFs were infected with increasing doses of MLV ($2 \times 10^{8}$ and $2 \times 10^{9}$ copies per μL) for 96 h. The copy numbers of the MLV genome in the culture supernatants were measured by quantitative RT-PCR. (*C*) Domain architecture of ZAP. (*D* and *E*) 293T cells were transfected with pMLV-48 and pEGFP-N1 together with the indicated ZAP expression plasmids for 48 h. Cytoplasmic RNA was subjected to Northern blotting analysis of the indicated RNAs (*D*). The culture supernatants were subjected to immunoprecipitation coupled to immunoblotting to detect the indicated proteins (*E*). The results shown are means ± SD ($n = 3$). NES, nuclear export signal.

The CCCH-type zinc-finger domains of ZAP are known to recognize the MLV transcripts and to induce its degradation (21, 25). Consistent with this, the ectopic expression of the N-terminal portion of ZAP, which contains the CCCH-type zinc-finger domains, but not the ectopic expression of the C-terminal portion of ZAP, which lacks CCCH-type zinc-finger domains, reduced the level of MLV transcripts in the cytosol (Fig. 2 *C* and *D*). The ectopic expression of the CCCH-type zinc-finger domains of ZAP also suppressed the expression of the Gag protein of MLV (Fig. 2*E*). Therefore, the CCCH-type zinc-finger domains of ZAP are essential for its antiviral action against MLV.

**CCCH-Type Zinc-Finger Domains of ZAP Mediate Its Localization to the RNA Granules.** The involvement of ZAP in the antiviral response to MLV prompted us to determine the mechanism underlying the ZAP-dependent degradation of the MLV transcripts. Although a previous study showed that ZAP acts in the cytosol (20), it was still unclear where in the cytosol ZAP eliminates the MLV transcripts. Therefore, we examined whether ZAP localizes to a cytosolic compartment, such as in the processing bodies

(P-bodies) (26). When it was ectopically expressed, ZAP localized to cytoplasmic dot-like structures in a manner that was dependent on its CCCH-type zinc-finger domains (Fig. 3*A*). The ZAP-positive dot-like structures colocalized with marker proteins for P-bodies, such as DCP1 decapping enzyme homolog A (*Saccharomyces cerevisiae*; DCP1A) and DDX6 (Fig. 3*B*). ZAP induced the enlargement of the DCP1A- and DDX6-positive dot-like structures, suggesting that the ZAP-positive dot-like structures are not conventional P-bodies. ZAP also colocalized with marker proteins for stress granules, such as GTPase-activating protein (SH3 domain) binding protein 1 (G3BP1) and cytotoxic granule-associated RNA binding protein (TIA-1) (Fig. S4). Furthermore, the RNA helicase DEAH (Asp-Glu-Ala-His) box polypeptide 30 (DHX30), which binds to ZAP to facilitate its antiviral action against MLV (24), colocalized with ZAP to the DCP1A-positive dot-like structures (Fig. S5). By contrast, ZAP did not colocalize with mitochondrial preprotein translocases of the outer membrane 20 (TOM20), 70-kDa peroxisomal membrane protein (PMP70), early endosome antigen 1 (EEA1), or lysosomal-associated membrane protein 1 (LAMP1), marker proteins for the mitochondria, peroxisomes, endosomes, and lysosomes, respectively (Fig. 3*C*). These findings indicate that ZAP localizes to the RNA granules, where the marker proteins for P-bodies and stress granules assemble.

**ZAP Recruits the MLV Transcripts and Exosome Components to RNA Granules.** The localization of the MLV transcripts has been poorly understood. We used an improved RNA FISH method to visualize the subcellular localization of viral RNA and identified the cytosolic compartments in which ZAP acts on the MLV transcripts. The MLV transcripts mainly localize in the cytosol and colocalize with DCP1A-positive RNA granules at low frequency (Fig. 4). However, the ectopic expression of ZAP reduced the level of MLV transcripts in the cytosol and dramatically altered its localization from the cytosol to ZAP- and DCP1A-positive RNA granules (Fig. 4 and Fig. S6). Therefore, ZAP tethers the MLV transcripts and transfers it to the RNA granules.

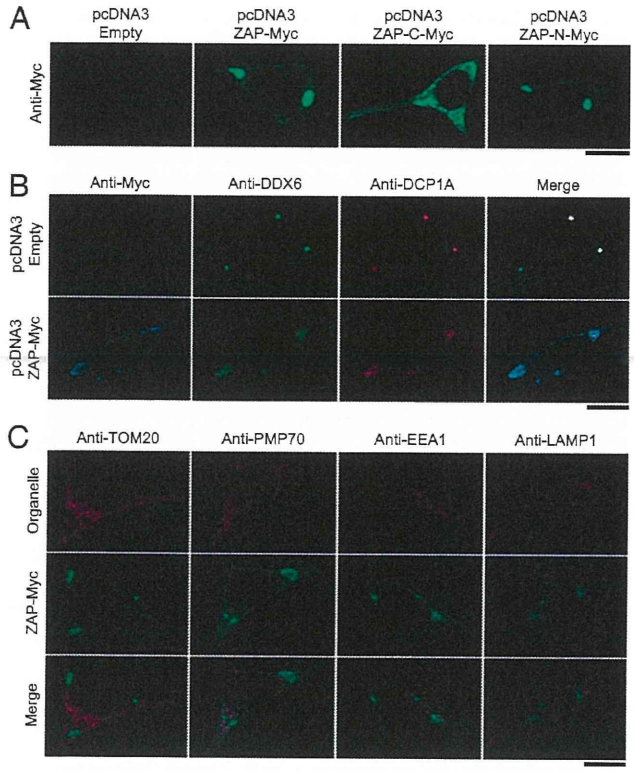


**Fig. 3.** ZAP localizes to DCP1A- and DDX6-positive RNA granules. (*A–C*) 293T cells were transfected with the indicated vectors for 48 h and then fixed. The samples were immunostained with the indicated antibodies and then observed by confocal laser scanning microscopy. The data are representative of three independent experiments. (Scale bars, 10 μm.)

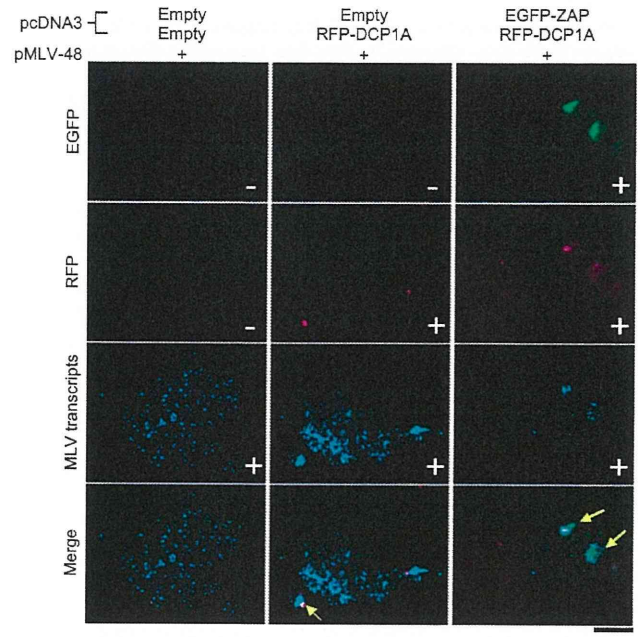


**Fig. 4.** ZAP recruits the MLV transcripts to RNA granules. 293T cells were transfected with the indicated plasmids for 48 h and then fixed. The samples were subjected to in situ hybridization analysis with a fluorescent probe for MLV transcripts and then observed by confocal laser scanning microscopy. (Scale bar, 10 μm.)

Because ZAP is not a ribonuclease, it requires the support of an RNA degradation system to destabilize the MLV transcripts. Consistent with this, previous studies have shown that exosome components and RNA helicases interact with ZAP to mediate the antiviral response to MLV (22–24). Therefore, we focused on the localization of exosome component 5 (EXOSC5, also known as RRP46) (27). The ectopic expression of EXOSC5 reduced the level of MLV transcripts in the cytosol (Fig. 5*A*). Under normal conditions, EXOSC5 localized in the cytosol and nuclei, and colocalized with the DCP1A-positive RNA granules at low frequency (Fig. 5*B*). However, when ZAP was ectopically expressed, EXOSC5 moved from the cytosol to the ZAP- and DCP1A-positive RNA granules (Fig. 5*B*). These findings indicate that ZAP recruits the exosome component to the RNA granules to induce the degradation of MLV transcripts.

**ZAP Does Not Regulate the RIG-I–Dependent Type I IFN Response in Primary Mouse Cells.** A recent study showed that ZAP positively regulated RIG-I signaling during RNA virus infection in a human cell line (28). Therefore, we examined the involvement of ZAP in the RIG-I–dependent type I IFN response in primary mouse cells. In *Zc3hav1*$^{-/-}$ primary MEFs, the IFN-β and Cxcl10 proteins were produced normally in response to VSV, an RNA virus recognized by RIG-I (Fig. 6 *A* and *B*). Although ZAP deficiency greatly enhanced the replication of MLV (Fig. 2 *A* and *B*), no IFN-β or Cxcl10 protein was produced in *Zc3hav1*$^{-/-}$ MEFs infected with MLV. In *Zc3hav1*$^{-/-}$ mouse primary dendritic cells, IFN-β and Cxcl10 were also normally produced in response to

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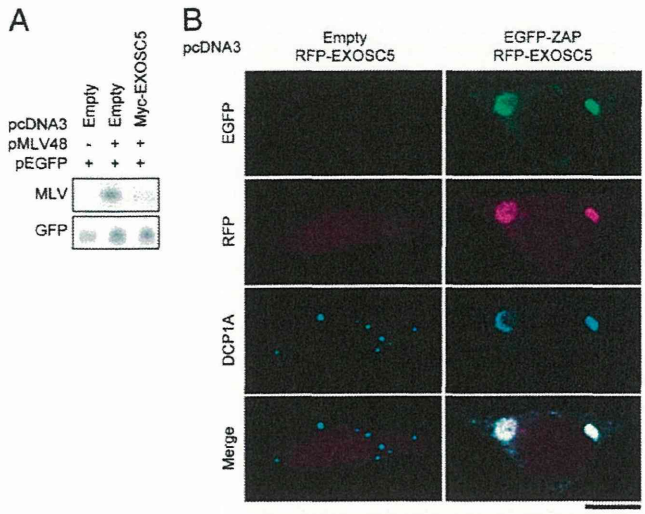


**Fig. 5.** EXOSC5 colocalizes with ZAP on RNA granules. (*A*) 293T cells were transfected with pMLV-48 and pEGFP-N1 together with the indicated ZAP expression plasmids for 48 h. Cytoplasmic RNA was subjected to Northern blotting analysis to detect the indicated RNAs. (*B*) 293T cells were transfected with the indicated plasmids and then fixed. The samples were immunostained with anti-DCP1A antibody and then observed by confocal laser scanning microscopy. The data are representative of three independent experiments. (Scale bar, 10 μm.)

Newcastle disease virus (NDV) and IAV, RNA viruses recognized by RIG-I (Fig. 6 *C* and *D*). Furthermore, ZAP deficiency did not affect the production of IFN-β in MEFs stimulated with the RIG-I ligand, 5′ triphosphate dsRNA (3pRNA) (Fig. S7 *A* and *B*), the MDA5 ligand poly(rI–rC), and a synthetic dsDNA poly(dA–dT) (Fig. S7*C*). These findings indicate that ZAP is not a regulator of the RIG-I–dependent type I IFN response in primary mouse cells and strengthen our conclusion that ZAP eliminates MLV independently of the RLR–IRF3/7 signaling axis.

## Discussion

In this study, we showed that endogenous ZAP suppresses the replication of MLV in MEFs. This raises the issue of whether endogenous ZAP suppresses the replication of other types of RNA viruses, including human retroviruses. The RNAi-mediated knockdown of *ZC3HAV1* mRNA enhanced the replication of xenotropic MLV-related virus, an artificial retrovirus belonging to the gammaretroviral genus of the family *Retroviridae* (29), in 293T cells (Fig. S8 *A* and *B*), whereas the knockdown of *ZC3HAV1* mRNA did not enhance the replication of human T-cell leukemia virus type I, a retrovirus belonging to the deltaretroviral genus of the family *Retroviridae* (30), in MT-2 cells (Fig. S8 *C* and *D*). In a previous study, the knockdown of *ZC3HAV1* mRNA enhanced the replication of HIV-1, a retrovirus belonging to the lentiviral genus of the family *Retroviridae* (31), in HOS-CD4 cells expressing chemokine (C-C motif) receptor 5 (32). Therefore, ZAP functions in human cells to target not all but certain types of retroviruses. ZAP is also known to suppress the replication of RNA viruses belonging to the families *Filoviridae* and *Togaviridae* (33, 34). Although ZAP has been shown to recognize the viral RNA of RNA viruses belonging to the families *Filoviridae*, *Togaviridae*, and *Retroviridae via*, its CCCH-type zinc-finger domains, the common features that are recognized by these domains, such as specific sequences or structural characteristics, have not been determined. Further studies are required to identify the RNA ligand of ZAP that induces the destabilization of the viral RNA by the RNA degradation machinery.

Although accumulating evidence indicates that ZAP counters a variety of RNA viruses under in vitro experimental conditions (20, 33, 34), it is still unclear whether ZAP protects hosts from RNA viral infections in vivo. RNA-sensing TLRs and the ssDNA cytosine deaminase apolipoprotein B mRNA-editing, enzyme-catalytic, polypeptide-like 3 are other antiviral systems that affect mouse retroviruses, and also control the replication of endogenous retroviruses (ERVs) (16, 35–37). Therefore, ZAP might also contribute to the antiviral response to ERVs and prevent the ERV-induced generation of tumors in vivo. To assess this, we are now establishing a colony of *Zc3hav1*$^{-/-}$ mice in the C57BL/6 genetic background. In a future study, we will attempt to determine the in vivo role of ZAP in the host defense responses to endogenous and exogenous microbes.

The CCCH-type zinc-finger–domain-containing protein family regulates RNA synthesis, splicing, and degradation, and is involved in a variety of cellular events, including cell growth, cell death, the inflammatory response, and the antimicrobial response (38, 39). To date, more than 50 CCCH-type zinc-finger-domain–containing proteins have been identified (40). Although various CCCH-type zinc-finger-domain-containing proteins, including tristetraprolin, roquin, and regnase-1, have been shown to be regulators of cytokine mRNA stability, ZAP is the only CCCH-type zinc-finger–domain-containing protein known to promote the destabilization of viral RNA (20, 41–43). Therefore, it will be interesting to identify a CCCH-type zinc-finger–domain-containing protein capable of mediating an antiviral response to RNA viruses that have evaded ZAP and the other RNA-sensing PRRs.

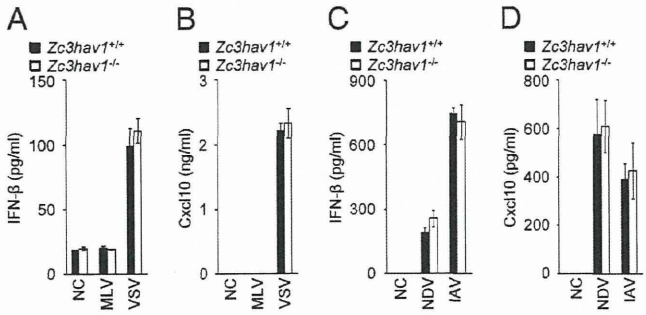


**Fig. 6.** ZAP is not essential for the RIG-I–mediated type I IFN response. (*A* and *B*) *Zc3hav1*$^{+/+}$ and *Zc3hav1*$^{-/-}$ MEFs were infected with MLV ($2 \times 10^{10}$ copies per μL) or VSV (MOI = 1) for 12 h. The levels of IFN-β (*A*) and Cxcl10 (*B*) proteins in the culture supernatants were measured with ELISAs. (*C* and *D*) *Zc3hav1*$^{+/+}$ and *Zc3hav1*$^{-/-}$ bone marrow-derived dendritic cells were infected with NDV ($2.5 \times 10^5$ pfu/mL) or IAV (PR8, 100 Hematoglutinin) for 24 h. The levels of IFN-β (*C*) and Cxcl10 (*D*) proteins in the culture supernatants were measured with ELISAs. The results shown are means ± SD ($n = 3$).

## Materials and Methods

**Reagents.** Anti-MLV-Gag antibody (ABIN457547) was purchased from Antibodies-online. Anti–α-tubulin antibody (T6199) was purchased from Sigma. Anti-GFP antibody (598) was purchased from MBL. Chicken anti–avian myelocytomatosis viral oncogene homolog (Myc) antibody (A190-103A) for the immunostaining assay was purchased from Bethyl Laboratories. Mouse anti–Myc-tag antibody (2276S) for immunoblotting was purchased from Cell Signaling. Anti-DDX6 (ab40684), anti-PMP70 (ab3421), and anti-LAMP1 (ab24170) antibodies were purchased from Abcam. Anti-DCP1A antibody (H00055802-M06) was purchased from Abnova. Anti-TOM20 antibody (SC-11415) was purchased from Santa Cruz Biotechnology. Anti-EEA1 antibody (610456) was purchased from BD Biosciences. The ELISA kit for mouse IFN-β was purchased from Pestka Biomedical Laboratories Interferon Source. The ELISA kit for mouse Cxcl10 was purchased from R&D Systems.

**Plasmids.** pMLV-48 (GenBank accession no. J02255.1) was previously described (44) and kindly donated by H. Fan (University of California, Irvine, CA). pcDNA3.1(+) was purchased from Invitrogen. To generate the ZAP

expression constructs, NheI/NotI cDNA fragments encoding full-length mouse ZAP (GenBank accession no. NM_028864.2) and the C-terminal portion of ZAP and a BamHI/NotI cDNA fragment encoding the N-terminal portion of ZAP were amplified from pCMV-SPORT6-Zc3hav1 (MMM1013-7511214, Open Biosystems) by PCR and cloned into the corresponding restriction sites of pcDNA3 to produce pcDNA3-ZAP, pcDNA3-ZAP-C, and pcDNA3-ZAP-N, respectively. To generate the expression construct for the EGFP-ZAP fusion protein, an NheI/SpeI cDNA fragment encoding EGFP was amplified from pEGFP-N1 (Clontech) by PCR and cloned into the NheI site of pcDNA3-ZAP to produce pcDNA3-EGFP-ZAP. To generate the red fluorescent protein (RFP) expression construct, a BamHI/EcoRI cDNA fragment of RFP was amplified from pTagRFP-N1 (Evrogen) by PCR and cloned into the BamHI/EcoRI sites of pcDNA3 to produce pcDNA3-RFP. To generate the expression constructs for the RFP-DCP1A and RFP-EXOSC5 fusion proteins, EcoRI/NotI cDNA fragments of human DCP1A and human EXOSC5 were amplified from a 293T cDNA library by PCR, and cloned into the EcoRI/NotI sites of pcDNA3-RFP to produce pcDNA3-RFP-DCP1A and pcDNA3-RFP-EXOSC5.

**Mice, Cells, and Viruses.** C57BL/6 mice were purchased from CLEA Japan, Inc. *Irf3*$^{-/-}$*Irf7*$^{-/-}$ mice were kindly donated by T. Taniguchi (The University of Tokyo, Tokyo, Japan). The *Ddx58*$^{-/-}$*Ifih1*$^{-/-}$ mice have been described previously (45). The mice were maintained in our animal facility and treated in accordance with the guidelines of Osaka University. Primary MEFs were prepared from pregnant female mice on embryonic day 13.5, as described previously (4). To prepare bone marrow-derived dendritic cells, mouse bone marrow cells were cultured in the presence of 10 ng/mL GM-CSF (PeproTech) for 6 d, during which time the culture medium was replaced with medium containing GM-CSF every 2 d. The 293T cells have been described previously (46). Replication-competent MLV was produced by 293T cells transfected with pMLV-48. To induce infection, MLV was incubated with MEFs for 2 h in the presence of 10 μg/mL Polybrene (Millipore). VSV, IAV (A/Puerto Rico/8/34, H1N1 strain), and NDV have been described elsewhere (3, 4).

**Quantitative RT-PCR.** Total RNA was isolated using the ZR RNA MicroPrep kit (Zymo Research), according the manufacturer's instructions. Viral RNA was isolated from the culture supernatants using the ZR Viral RNA kit (Zymo Research), according the manufacturer's instructions. RT was performed using random primers and Verso reverse transcriptase (Thermo Scientific) according to the manufacturer's instructions. For quantitative PCR, the cDNA fragments were amplified from the RT products with Real-Time PCR Master Mix (Toyobo) according to the manufacturer's instructions. The fluorescence from the TaqMan probe for each cytokine was detected with a 7500 Real-Time PCR System (Applied Biosystems). To determine the relative induction of cytokine mRNAs, the level of mRNA expressed from each gene was normalized to the expression of 18S RNA. The copy number of the MLV genomic RNA was determined with the dsDNA copy number calculator program. The experiments were repeated at least three times, with reproducible results.

**ELISAs.** The levels of IFN-β and Cxcl10 in the culture supernatants were measured with ELISAs in accordance with the manufacturer's instructions. The experiments were repeated at least three times, with reproducible results.

**Northern Blotting.** Cytoplasmic RNA was extracted using the Cytoplasmic and Nuclear RNA Purification Kit (Norgen) according the manufacturer's instructions. The RNA obtained was separated electrophoretically, transferred to nylon membranes, and hybridized with the indicated probes. An RNA probe was designed to hybridize specifically to the Gag region from nucleotide 1291 to nucleotide 1472 of the MLV transcripts. The experiments were repeated at least three times, with reproducible results.

**Immunoblotting.** Immunoblotting was performed as described previously (47). The experiments were repeated at least three times, with reproducible results.

**Immunostaining Assay.** Cells cultured in microscopy chambers (ibidi) were fixed with 3% (wt/vol) paraformaldehyde and then processed for immunostaining as described previously (47). The samples were examined under an LSM 780 confocal laser scanning microscope (Carl Zeiss). The experiments were repeated at least three times, with reproducible results.

**Detection of the MLV Transcripts with FISH.** The cells were fixed with 4% paraformaldehyde. FISH was performed using the QuantiGene ViewRNA ISH Cell Assay kit (Veritas) according to the manufacturer's instructions. A Cy5-labeled FISH probe was designed to hybridize specifically to the Gag region from nucleotide 607 to nucleotide 1833 of the MLV transcripts. The samples were examined under an LSM780 confocal laser scanning microscope. The experiments were repeated at least three times, with reproducible results.

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