



Title	Viroporin activity of the JC polyomavirus is regulated by interactions with the adaptor protein complex 3
Author(s)	Suzuki, Tadaki; Orba, Yasuko; Makino, Yoshinori; Okada, Yuki; Sunden, Yuji; Hasegawa, Hideki; Hall, William W.; Sawa, Hirofumi
Citation	Proceedings of the National Academy of Sciences of the United States of America, 110(46), 18668-18673 https://doi.org/10.1073/pnas.1311457110
Issue Date	2013-11-12
Doc URL	http://hdl.handle.net/2115/55727
Type	article (author version)
Additional Information	There are other files related to this item in HUSCAP. Check the above URL.
File Information	Supporting Information_SuzukiT2013PNAS46.pdf (Supporting Information)



[Instructions for use](#)

Supporting Information

SI Materials and Methods

Construction of Plasmids

For expression of JCV agnoprotein in mammalian cells, the cDNA of JCV agnoprotein was amplified by polymerase chain reaction (PCR) using a plasmid encoding the complete JCV genome, pJC1->4pJCV [VG015, Health Science Research Resources Bank (HSRRB)] and subcloned into a pCXS N plasmid (1) which was constructed by removing myc-tag from pCMV-myc (Clontech) and adding Xho I, Sal I, and Not I recognition sites; pCXS N-FlagN (1) which was constructed by adding Flag-tag to the pCXS N plasmid at the 5' region of the Xho I site; pCXS N-MycN (1) was constructed by adding Myc-tag to the pCXS N plasmid at the 5' region of the Xho I site; pERedNLS (kindly provided by Dr. M. Matsuda) (1); pCFPNLS (1) which was constructed by replacing DsRedExpress with sECFP (kindly provided by Dr. A. Miyawaki). pERedNLS or pCFPNLS contains the internal ribosome entry site (IRES) of the encephalomyocarditis virus (ECMV) between the multiple cloning sites (MCS) and the ERedNLS [DsRed-Express with nuclear localization signal (NLS) of simian virus 40 (SV40) large T-antigen fused to its C-terminus] or CFPNLS (sECFP with NLS of SV40 large T-antigen fused to its C-terminus). This plasmid permits both the inserted gene in the MCS and the ERedNLS gene or the CFPNLS gene to be translated from a single bicistronic mRNA. These plasmid-transfected cells were thus labeled by expression of DsRed-Express or sECFP in the nucleus. The gene in MCS is not fused with ERedNLS or CFPNLS, but tagged with a Flag-epitope at the NH₂-terminus. The substitution mutants of agnoprotein were constructed as described

previously (1). The plasmid containing the genome of JCV Mad1-SVE Δ (pUC19-Mad1SVE Δ) was kindly provided by Dr. W. J. Atwood (2, 3). Agnoprotein with mutated viral genomes (Δ Agno and RK8AA) were generated by site-directed mutagenesis as described previously (1). The cDNA of AP3D1 isoform 2 was amplified from the HEK293-derived cDNA library, and subcloned into pCMV-myc (Clontech). Successful cloning was confirmed by sequencing. Myc-tagged AP3D-Y27, AP3D-Y27N and AP3D-Y27C were amplified with pCMV-myc-AP3D1 and subcloned into the pIRESneo3 vector (Clontech). AP3D-Y27, AP3D-Y27N and AP3D-Y27C were amplified with pIRESneo3-AP3D-Y27 and subcloned into pGEX6P1 vector (GE). Successful cloning was confirmed by sequencing. The plasmid encoding ts045-VSVG-GFP (pVSVG-GFP) was a kind gift from Dr. I. Wada (4). The ts045-VSVG protein is a type I transmembrane protein that has been widely used for studying secretory membrane trafficking because it contains a mutation that leads to its reversible misfolding and retention in the ER at 40°C. The entire coding sequences of VP1 (pET15b-VP1) (5) and RK8AA mutant of agnoprotein (pET15b-His-RK8AA) were amplified by PCR and subcloned into the pET15b expression vector (Novagen) for bacterial expression. The integrities of plasmids were verified by sequencing.

Primary Antibodies and Reagents

Rabbit anti-JCV agnoprotein, anti-JCV VP1, and anti-JCV Large T polyclonal antibodies were produced as described previously (6-8). Alexa Flour 488-labeled or Alexa Flour 647 anti-agnoprotein antibodies were prepared using APEX Antibody Labeling Kits (Invitrogen)

according to manufacturer's instructions. Mouse anti-GM130, anti-EEA1 and anti-AP3 δ subunit (AP3D) monoclonal antibodies were purchased from BD Transduction Laboratories. Mouse anti-Lamp1 and anti-CD71 monoclonal antibodies were purchased from BD Pharmingen. Mouse anti-Lamp2 (H4B4), MHC-Class I (HLA-ABC, W6/32) and anti-actin (MAB1501R) monoclonal antibodies were purchased from Santa Cruz, eBioscience, and Chemicon International, respectively. Mouse anti-Flag (M2) monoclonal antibodies were purchased from Sigma. Mouse anti-Myc tag (9E10) monoclonal antibodies were purchased from Calbiochem. Goat anti-GFP polyclonal antibody was purchased from Rockland. Mouse anti-His-tag (OGHis) monoclonal antibodies were purchased from MBL. The vATPase inhibitor bafilomycin A1 was obtained from WAKO. Leupeptin, pepstatin A and E64d were obtained from the Peptide Institute.

***In vitro* synthesized agnoprotein**

In vitro transcription and *in vitro* translation were performed using the cell-free expression system, the MembraneMax HN Protein Expression Kit (Invitrogen), according to the manufacturer's instructions. The plasmid, such as pURE2-Agnoprotein, -RK8AA mutant, -K9Q mutant and pURE2 plasmids encoding agnoprotein deletion mutants(C6, C18, and C25), which contains T7 promoter, ribosomal binding site, and terminator sequence were used as a template DNA. The entire coding sequences of wild type, K9Q mutant of JCV agnoprotein and WT BKV agnoprotein (Dunlop strain) were also subcloned into the pEXP5-CT/TOPO expression vector (Invitrogen) and used as a template DNA for expression of the C-terminal hexahistidine (6 x His) tagged agnoprotein. After

synthesis of recombinant proteins, the reaction mixture was subjected to SDS-PAGE analysis and immunoblotting using anti-agnoprotein antibody to confirm the expression of proteins.

GST Pull-down assay

GST fusion proteins of AP3D-Y27 or its deletion mutants were expressed in *E. coli* (BL21DE3, Novagen) and purified with the use of glutathione–sepharose 4B beads (GE Healthcare). For *in vitro* GST precipitation assays, GST or GST fusion proteins were mixed with 10 μ l of 50% (v/v) glutathione–sepharose 4B for 2 h at 4°C. After addition of cell lysates from 293T cells transfected with pCMV-Agno or *in vitro* synthesized agnoprotein in TN-TNE buffer [20 mM Tris-HCl (pH 7.4), 150 mM NaCl, 5 mM EDTA, 1% Nonidet P-40, 1% Triton X-100, 10% glycerol, and 0.5 mM phenylmethylsulfonyl fluoride (PMSF)] and complete protease inhibitor cocktail, the mixture was incubated for another 30 min at 4°C. The beads were separated by centrifugation and washed with TN-TNE buffer, and the bound proteins were subjected to immunoblot analysis.

Preparation and Infection of Recombinant Lentiviruses

The following constructs were kindly provided by Dr. H. Miyoshi: CSII-CMV-MCS-IRES2-Bsd, a self-inactivating lentiviral construct (9); pCAG-HIVgp, a packaging construct expressing Gag and Pol proteins; and pCMV-VSV-G-RSV-Rev, a construct expressing the vesicular stomatitis virus G glycoprotein (VSV-G) and Rev. This lentiviral system is designed to express a desired gene under the direction of the CMV promoter, and the Blastcidin resistance gene as a marker for selection of

infected cells. Recombinant lentiviruses constitutively expressing agnoprotein were produced as follows: cDNAs encoding agnoprotein were inserted into the multicloning site of the lentiviral expression vector. The lentiviruses were prepared as previously described (10). Briefly, 293T cells were co-transfected with three plasmids: CSII-CMV-MCS-IRES2-Bsd with or without agnoprotein cDNA insert, pCAG-HIVgp and pCMV-VSV-G-RSV-Rev using LipofectAmine 2000 (Invitrogen). The culture supernatants containing the recombinant lentiviruses were collected at 48 h after transfection, passed through a 0.45 μm filter, and used for infection experiments. SVG-A cells or 293T cells seeded in the 35-mm dishes were infected at 10% confluence with each recombinant virus. Virus-infected cells were selected by culturing with blastcidin (10 $\mu\text{g}/\text{ml}$) containing media.

Flow Cytometry

Cells were detached using an enzyme-free/phosphate buffered saline (PBS)-based cell dissociation buffer (Invitrogen) according to the manufacturer's instruction. Aliquots of 10^6 cells were washed in PBS/2% FBS and suspended in 100 μl of PBS/2% FBS. Cells were then incubated with 200 ng of primary antibody or control IgG (BD Pharmingen) as a negative control for 30 min at 4°C. After washing, bound antibodies were visualized by addition of phycoerythrin (PE)-conjugated anti-mouse or -rabbit Ig antibody (Beckman Coulter). After washing, cells were suspended in 250 μl of PBS/2% FBS. Cell surface fluorescence was analyzed with a Becton Dickinson FACScanto (BD Bioscience). The data were analyzed by using FlowJo software (Tree Star). For quantification of amount of agnoprotein or MHC-class I, the cells were stained Alexa Flour 647 or 488 labeled primary

antibodies and subjected to the analysis with FACScanto. Experiments performed three times independently. The data were analyzed by using FlowJo software.

Transfection, Immunoblot Analysis, and Immunoprecipitation

Cell transfections were performed with LipofectAmine 2000 for 293T cells or Fugene HD for HeLa and SVG-A cells. For immunoblot analysis, cells were harvested at the indicated time points after transfection, lysed in TNE buffer [10 mM Tris-HCl (pH 7.5), 150 mM NaCl, 5 mM EDTA, 10% glycerol, 1% Triton X-100, and 0.5 mM PMSF], and mixed with Complete protease inhibitor cocktail. The cell lysates were fractionated by SDS-PAGE, and the separated proteins were transferred to a polyvinylidene difluoride filter (Millipore). The filter was incubated with primary antibodies, and immune complexes were then detected with horseradish peroxidase–conjugated secondary antibodies and ECL reagents (GE Healthcare). The Flag epitope was detected directly with horseradish peroxidase–conjugated primary antibodies. For detection of the homo-interaction of RK8AA mutant of agnoproteins, 293T cells transfected with Myc-tagged RK8AA / Flag-tagged RK8AA or Myc-tagged RK8AA alone were incubated for 72 h and then lysed in TNE buffer and subjected to immunoprecipitation. For detection of the interactions between WT or RK8AA mutant agnoproteins and AP3D, 293AG or 293RK8AA cells were treated for 72 h with or without DOX and then lysed in 0.1% Tx lysis buffer [10 mM Tris-HCl (pH 7.5), 150 mM NaCl, 0.5 mM MgCl₂, 1 mM EGTA, 0.1 mM EDTA, 1 mM DTT, 0.1% Triton X-100, and 50 µg/ml DNase I] mixed with Complete protease inhibitor cocktail, and subjected to immunoprecipitation. Immunoprecipitation was

performed by incubation of cell lysates at 4°C initially for 4 h with antibody-coupled protein G-Sepharose FF beads (GE Healthcare). After washing with cell lysis buffer, the bead-bound proteins were subjected to immunoblot analysis.

siRNA preparation

The following stealth RNA duplexes were synthesized by Invitrogen: siRNA-AP3-481 sense 5'-AAAUACGUCAGCUUGCAGACCGCGU-3' and antisense 5'-ACGCGGUCUGCAAGCUGACGUAUUU -3'; siRNA-AP3-564 sense 5'-UUCGCUUGAAGGUGAACUUGGAGGC-3' and antisense 5'-GCCUCCAAGUUCACCUUCAAGCGAA -3'; siRNA-AP3-1122 sense 5'-AUUCAUAGAGGAGAGACAUGGCAGA -3' and antisense 5'-UCUGCCAUGUCUCUCCUCUAUGAAU -3'; Negative control (siRNA-NC1) sense 5'-GCAUCGUACAGACAAUCUUCAGUUU -3' and antisense 5'-AAACUGAAGA UUGUCUGUACGAUGC -3'; Negative control (siRNA-NC2) sense 5'-GGAUCUUAUAGGUUAGGAGUCGGUU -3' and antisense 5'-AACCGACUCCUAACCUAUAAGA UCC -3'. The negative control siRNAs were previously used (11, 12). We also used medium GC duplex siRNA (siRNA-NC3), which does not have homology to any vertebrate transcriptome (Invitrogen). The stealth RNA duplexes against AP2M, AP2M1 Stealth Select 3 RNAi (HSS101953; HSS101954; HSS101955) were obtained from Invitrogen. The siRNA

duplexes against AP1B1, AP2M2, AP3B2, AP3D1 and AP4M1 used in Figure S5C were from a siPerfect Membrane transporter Library (Sigma Genosys).

Yeast Two-Hybrid Screening

The Matchmaker System 3 and HEK293–derived cDNA library were purchased from Clontech. The cDNA of the N-terminal fragment (a.a. 1-24) of wild type (Agno-N24) or RK8AA mutant (RK8AA-N24) of agnoprotein was subcloned into the pGBKT7 yeast shuttle vector (Clontech). AH109 yeast cells were cotransformed with pGBKT7-Agno-N24 (WT) or pGBKT7-RK8AA-N24 and cDNAs from the HEK293 library, and the procedures for yeast growth were according to the manufacturers' protocols. Plasmids were isolated from positive colonies following transformation of *E. coli*, DH5 alpha and sequenced. The sequence data were analyzed by BLAST in NCBI.

Immunofluorescence

For analysis of the colocalization of agnoprotein with AP3D, EEA-1, or Lamp-2, JCV infected SVG-A cells or DOX-treated SVG-AG / SVG-RK8AA cells were fixed for 3 min in 100% methanol at -80°C. After blocking with 1% BSA, cells were incubated with anti-agnoprotein / anti-AP3D, anti-agnoprotein / anti-EEA-1 or anti-agnoprotein / anti-Lamp-2 antibodies overnight at 4°C, and stained with Alexa Fluor 488-conjugated anti-mouse immunoglobulin antibody and Alexa Fluor 594-conjugated anti-rabbit immunoglobulin antibodies (Molecular Probes) for 1 h at room temperature. Nuclei were labeled with 4',6-diamidino-2-phenylindole (DAPI) simultaneously with secondary antibody. The cells

were observed with a confocal laser-scanning microscope (Olympus). For analysis of colocalization of VSVG-GFP and GM130, 293T cells were transfected with pVSVG-GFP and pERedNLS-Agno for evaluation of VSVG-GFP transport to the plasma membrane. The cells were cultured first at non-permissive temperature (39.5°C) for the ts045- VSVG-GFP transport for 20 h, followed by a permissive temperature (32°C). After 3 h incubation, the cells were fixed for 20 min in 4% paraformaldehyde (PFA) / PBS, permeabilized with 0.5% Triton X-100 in PBS, and incubated at room temperature with 1% BSA in PBS. The cells were then incubated with anti-GM130 antibody followed by staining with Alexa Fluor 647-conjugated anti-mouse immunoglobulin antibody and analyzed by confocal microscopy. For analysis of the localization of agnoprotein, SVG-AG or SVG-RK8AA cells were fixed for 20 min in 4% PFA / PBS, permeabilized with 0.5% Triton X-100 in PBS, and incubated at room temperature with 1% BSA in PBS. The cells were then incubated with anti-agnoprotein antibody followed by staining with Alexa Fluor 488-conjugated anti-rabbit immunoglobulin antibody. Actin filaments and nuclei were labeled with Alexa Fluor 647-conjugated phalloidin and DAPI simultaneously with secondary antibody. The cells were imaged with an inverted fluorescence/phase-contrast microscopy (Olympus) equipped with cooled CCD camera (Olympus). The levels of protein expression in single cell were analyzed by Multi Wavelength Cell Scoring Application Modules of MetaMorph software. The number of agnoprotein-positive punctuate objects was analyzed by Granularity Application Module of MetaMorph software (Molecular device).

Statistical Analysis

All data were expressed as mean \pm S.D. Student's t-test was used to analyze differences between two groups. A value of $p < 0.05$ was considered as statistically significant.

References

1. Suzuki T, *et al.* (2010) The human polyoma JC virus agnoprotein acts as a viroporin. *PLoS Pathog* 6(3):e1000801.
2. Gasparovic ML, Gee GV, & Atwood WJ (2006) JC virus minor capsid proteins Vp2 and Vp3 are essential for virus propagation. *J Virol* 80(21):10858-10861.
3. Gee GV, Tsomaia N, Mierke DF, & Atwood WJ (2004) Modeling a sialic acid binding pocket in the external loops of JC virus VP1. *J Biol Chem* 279(47):49172-49176.
4. Nagaya H, Wada I, Jia YJ, & Kanoh H (2002) Diacylglycerol kinase delta suppresses ER-to-Golgi traffic via its SAM and PH domains. *Mol Biol Cell* 13(1):302-316.
5. Komagome R, *et al.* (2002) Oligosaccharides as receptors for JC virus. *J Virol* 76(24):12992-13000.
6. Okada Y, *et al.* (2002) Expression of JC virus agnoprotein in progressive multifocal leukoencephalopathy brain. *Acta Neuropathol (Berl)* 104(2):130-136.
7. Sunden Y, *et al.* (2006) Characterization and application of polyclonal antibodies that specifically recognize JC virus large T antigen. *Acta Neuropathol* 111(4):379-387.
8. Suzuki S, *et al.* (2001) Broad distribution of the JC virus receptor contrasts with a marked cellular restriction of virus replication. *Virology* 286(1):100-112.
9. Miyoshi H, Blomer U, Takahashi M, Gage FH, & Verma IM (1998) Development of a self-inactivating lentivirus vector. *J Virol* 72(10):8150-8157.
10. Katayama K, *et al.* (2004) RNA interfering approach for clarifying the PPARgamma pathway using lentiviral vector expressing short hairpin RNA. *FEBS Lett* 560(1-3):178-182.
11. Sunden Y, *et al.* (2007) DDX1 promotes proliferation of the JC virus through transactivation of its promoter. *Microbiol Immunol* 51(3):339-347.
12. Suzuki T, *et al.* (2005) Identification of FEZ1 as a protein that interacts with JC virus agnoprotein and microtubules: role of agnoprotein-induced dissociation of FEZ1 from microtubules in viral propagation. *J Biol Chem* 280(26):24948-24956.

Figure legends

Fig. S1. Identification of AP3D as an Agnoprotein Interacting Protein.

(A) GST pull-down assay with the GST-AP3D-Y27, GST-AP3D-Y27N, or GST-AP3D-Y27C. After incubation with cellular lysates transfected with pCMV-Agno, the GST fusion proteins were precipitated with glutathione-sepharose and bound proteins were subjected to immunoblot analysis with anti-agnoprotein Ab (upper panel). GST fusion proteins of AP3D-Y27, AP3D-Y27N, and AP3D-Y27C were subjected to CBB staining (lower panel). Asterisks indicate the recombinant proteins. (B) Schematic representation of the constructs of WT and mutants of agnoprotein. The yellow boxes indicate the amino acids, which are necessary for targeting the ER (Suzuki et al., 2010). The green boxes indicate the basic amino acid cluster, which is important for viroporin activity. The gray boxes indicate a hydrophobic amino acid stretch. Arg-8 and Lys-9 of agnoprotein were substituted by Ala in the RK8AA mutant, indicated as a red box. (C) Comparison of the N-terminal regions of agnoproteins of JCV and BKV. The differences of amino acids are indicated with red colored characters. Lys-9 of JCV agnoprotein was substituted by Gln in the K9Q mutant (JCV Agno K9Q). (D) GST pull-down assay with the GST-fused proteins (GST-AP3D-Y27N or GST-AP3D-Y27C) and *in vitro* synthesized JCV agnoproteins (WT, K9Q). After incubation with *in vitro* synthesized JCV agnoproteins, the GST fusion proteins were precipitated with glutathione-sepharose and beads-bound proteins were subjected to immunoblot analysis with anti-agnoprotein Ab. The aliquots from mixtures before a pull-down experiment were also subjected to immunoblot analysis as 10% input. (E) GST pull-down assay with the GST-AP3D-Y27C and *in vitro* synthesized the C-terminal hexahistidine (6 x His) tagged agnoproteins of JCV or BKV. After incubation with *in vitro* synthesized agnoproteins, the GST fusion proteins were precipitated with glutathione-sepharose and beads-bound proteins were subjected to immunoblot analysis with anti-His tag Ab. The aliquots from mixtures before pull-down experiment were also subjected to immunoblot analysis as 10% input.

Fig. S2. Agnoprotein Blocks Intracellular Trafficking of Vesicular Stomatitis Virus G Protein (VSVG).

(A and B) 293AG cells in the absence or presence of DOX were transfected with pVSVG-GFP. The cells were incubated for 20 h at 39.5°C. The temperature was then shifted to 20°C for 3 h to accumulate VSVG-GFP in the perinuclear region, and then to 32°C in the presence of

cycloheximide to permit VSVG-GFP transport from the perinuclear region. The cells were fixed at the indicated time points. The localization of VSVG-GFP protein was analyzed by confocal microscopy. The graph indicates the average proportion of cells with the TGN of VSVG-GFP in 200 cells. Results are the average of three independent experiments, and the significance of changes was analyzed by Student's *t*-test ($*p < 0.05$). Scale bars, 20 μm . (C) 293AG cells in the absence (-) or presence (Agno) of DOX were transfected with pVSVG-GFP. The cells were incubated for 20 h at 39.5°C to accumulate VSVG-GFP in the ER. The temperature was then shifted to 32°C in the presence of cycloheximide to permit VSVG-GFP transport from the ER. Brefeldin A (BFA, 5 $\mu\text{g/ml}$) was added to the cells in the absence of DOX as a control VSVG-GFP transport inhibition from the ER to the Golgi. The cells were fixed at the indicated time points. The localization of VSVG-GFP protein was analyzed by confocal microscopy. In the presence of BFA the VSVG-GFP signal was still clearly present in the ER at 180 min. In contrast, almost all the VSVG-GFP was transported to the perinuclear region in the presence of agnoprotein, suggesting that the transport of VSVG-GFP between the ER and Golgi apparatus, which is independent of AP3D, was disrupted by BFA but not by agnoprotein. Results are representative of three independent experiments. Scale bars, 20 μm .

Fig. S3. Agnoprotein Impairs AP-3–Mediated Vesicular Trafficking.

(A, B and C) 293T cells were transfected with pVSVG-GFP, pERedNLS-Agno (Agno), or pERedNLS (DsRed) and pCMV-Myc-AP3D (AP3D) or pCMV-Myc (Mock) for measurement of VSVG-GFP transport to the plasma membrane. The cells were cultured first at non-permissive temperature (39.5°C) for 20 h, followed by 20°C for 3 h to accumulate VSVG-GFP in the TGN, and were subsequently shifted to 32°C to permit VSVG-GFP transport from the TGN. Thereafter, the cells were fixed and analyzed by confocal microscopy. The cell lysates corresponding to the imaging analysis were subjected to immunoblot analysis with anti-AP3D (AP3D) and anti-agnoprotein (Agno) antibodies. The levels of AP3D expression in cells transfected with pCMV-Myc-AP3D (AP3D) were significantly higher than that with pCMV-Myc empty vector (Mock). The graph indicates the average proportion of cells with the TGN of VSVG-GFP in 200 cells. Results are the average of three independent experiments, and the significance of changes was analyzed by Student's *t*-test ($*p < 0.05$). Green color represents VSVG-GFP signal, and Red color represents DsRed expression in nuclei as a marker of transfection. (D) 293T cells were transfected with pERedNLS-Agno (Agno) or

pERedNLS (DsRed) and siAP3D or siNC. The cells were lysed and subjected to immunoblotting. The levels of AP3D expression in cells transfected with siAP3D were significantly lower than that with siNC. (E) 293T cells were transfected with siAP3D or siNC and incubated for 48 h. Then, the cells were transfected with pVSVG-GFP and pERedNLS-Agno (Agno) or pERedNLS (DsRed) for measurement of VSVG-GFP transport to the plasma membrane. The cells were cultured at 39.5°C for 20 h, followed by incubation at 32°C. Thereafter, the cells were fixed at indicated time points and analyzed by confocal microscopy. The bar graph indicates the average proportion of cells with TGN localization of VSVG-GFP in 200 cells. Results are representative of three independent experiments, and the significance of changes was analyzed by Student's *t*-test ($*p < 0.05$).

Fig. S4. Establishment of DOX-Inducible agnoprotein expressing cells, SVG-AG cells.

(A and B) The levels of agnoprotein expression in SVG-AG cells was similar to that in JCV-infected parent SVG-A cells. SVG-AG cells were incubated with 1 µg/ml of DOX for 72 h, and SVG-A cells were infected with JCV and incubated for 96 h. These cells were fixed and subjected to immunofluorescence analysis using anti-agnoprotein and anti-actin Abs followed by Alexa Fluor 488-conjugated anti-rabbit IgG and Alexa Fluor 647-conjugated anti-mouse IgG Abs, respectively. The cell images were acquired by fluorescence microscopy and analyzed using MetaMorph software. The bar graph indicates the ratio of total fluorescence intensity of agnoprotein in single cell which is normalized by total fluorescence intensity of actin. No significant differences between SVG-AG cells and JCV-infected SVG-A cells was observed ($p = 0.985$). Scale bars, 50 µm.

Fig. S5. Association of Agnoprotein with AP3D is Fundamental to Membrane Permeabilization.

(A) DOX-inducible agnoprotein expressing cells, SVG-AG cells (WT) or SVG-RK8AA cells (RK8AA), were incubated with or without 1 µg/ml DOX for 72 h. Nascent protein syntheses in these cells with or without 500 µg/ml HygB were labeled using the Click-iT AHA Alexa Fluor 488 Protein Synthesis Kit and observed by fluorescence microscopy. The cell images were analyzed using MetaMorph software. The bar graph indicates the proportion of mean signal intensity of Alexa Fluor 488 of the cells in the presence of HygB compared to those in the absence of HygB. Results are average of three independent experiments, and the significance of changes was analyzed by Student's *t*-test ($*p < 0.05$). (B) SVG-AG cells stably expressing partial fragments of AP3D (Y27N or Y27C) or

empty vector (Mock) were incubated with or without 1 $\mu\text{g/ml}$ DOX for 72 h. Nascent protein syntheses in these cells were similarly observed. The cell images were analyzed using MetaMorph software. The bar graph indicates the proportion of mean signal intensity of Alexa Fluor 488 of the cells in the presence of HygB against without those in the absence of HygB. Results are average of three independent experiments, and the significance of changes was analyzed by Student's *t*-test ($*p < 0.05$). (C) SVG-AG cells were incubated with or without 1 $\mu\text{g/ml}$ DOX for 72 h. Then the cells were stained with FM1-43FX dye in HBSS without magnesium or calcium on ice, for 1 min and fixed with 4% PFA. The cells were analyzed by fluorescence microscopy. Scale bars, 100 μm . Phase: Phase contrast images. Inset: high magnification of cells stained by FM1-43FX (Bar = 20 μm). (D) SVG-AG cells (WT), SVG-RK8AA (RK8AA) cells or SVG-Mock cells, in which DsRed as induction marker proteins are expressed with DOX treatment, were incubated with or without 1 $\mu\text{g/ml}$ DOX for 72 h. Thereafter, the cells were stained with FM1-43FX dye in HBSS without magnesium or calcium on ice for 1 min and fixed with 4% PFA. The intensities of FM1-43FX were analyzed by flow cytometry. (E) SVG-AG cells stably expressing partial fragments of AP3D (Y27N or Y27C) were incubated with or without 1 $\mu\text{g/ml}$ DOX for 72 h, stained with FM1-43FX, fixed with 4% PFA, and analyzed by flow cytometry.

Fig. S6. Disruption of AP-3–Mediated Vesicular Trafficking is Necessary for the Viroporin Activity of Agnoprotein.

(A and B) SVG-RK8AA (RK8AA) cells were transfected with siAP3D or siNC and incubated with or without 1 $\mu\text{g/ml}$ DOX for 72 h. Nascent protein syntheses in these cells in the presence or absence of 500 $\mu\text{g/ml}$ of HygB was labeled using Click-iT AHA Alexa Fluor 488 and analyzed by fluorescence microscopy. The cell images were analyzed using MetaMorph software. Scale bars, 100 μm . The bar graph indicates the average proportion of total fluorescence intensity of the cells in the presence of HygB against those in the absence of HygB. Results are average of three independent experiments, and the significance of changes was analyzed by Student's *t*-test ($*p < 0.05$). (C) HeLa cells, which were transfected with siAP3Ds or siNCs and incubated for 24 h, were transfected with pCFPNLS-RK8AA (RK8AA) or control vector and incubated for another 72 h. The cells were pretreated with or without HygB (400 $\mu\text{g/ml}$), radiolabeled with [^{35}S] Met-Cys, and incubated in the presence (+) or absence (-) of HygB for 2 h. The cell extracts were harvested, and the CFPNLS

protein as a transfection marker protein was immunoprecipitated with an anti-GFP antibody and analyzed by SDS-PAGE. The membrane permeability for HygB by suppression of AP3D was confirmed by the ^{35}S metabolic assay. (D) SVG-A cells were transfected with RK8AAJCV mutant genome. After 24 h, cells were transfected with siRNAs indicated in the Figure. Cells were incubated another 96 h, and then harvested whole cell lysates (WCL) and supernatants (SUP) simultaneously. The collected samples were applied to SDS-PAGE and immunoblotting with the indicated antibodies. Culture supernatants were concentrated 25 times by centrifugation.

Fig. S7. RK8AA Mutant is Poorly Expressed on the Cellular Surface.

(A, B) SVG-AG cells (WT) or SVG-RK8AA cells (RK8AA) were incubated with 1 $\mu\text{g}/\text{ml}$ DOX for 72 h and subjected to immunofluorescence analysis using anti-agnoprotein antibody followed by Alexa Fluor 488-conjugated anti-rabbit IgG antibody (green). Actin filaments and nuclei were labeled with Alexa Fluor 647 phalloidin (red) and DAPI (blue) simultaneously. The cells in which agnoprotein was predominantly localized in the perinuclear region (perinuclear pattern) are indicated by arrowheads. An arrow indicated the cells in which agnoprotein localized diffusely (diffuse pattern) in the cytoplasm. The bar graph indicates the average proportion of cells with the diffuse pattern of localization compared with total agnoprotein-expressing cells (B, $*p < 0.05$). Scale bars, 50 μm . (C) SVG-AG cells (WT) or SVG-RK8AA cells (RK8AA) were incubated with or without 1 $\mu\text{g}/\text{ml}$ DOX for indicated time points. The cells were subjected to cell surface-staining using anti-agnoprotein antibody followed by Alexa Fluor 488-conjugated anti-rabbit IgG antibody, and then analyzed by flow cytometry. The fluorescence of DsRed was used as marker for induction of proteins by DOX treatment. (D) SVG-AG cells (WT), SVG-RK8AA cells (RK8AA) or SVG-Mock cells (Mock) were incubated with 1 $\mu\text{g}/\text{ml}$ DOX for 72 h. The levels of agnoprotein expression on cell surface were measured by flow cytometry using Alexa Fluor 647 labeled anti-agnoprotein antibody. The bar graph indicates the relative mean fluorescence intensity of agnoprotein ($**p < 0.01$).

Fig. S8. RK8AA Mutant of Agnoprotein Localized in the Lysosome.

(A) Confocal microscopy analysis of SVG-A cells transfected with WTJCV genome showed the colocalization of WT agnoprotein (WT) with EEA1, an early endosome marker, but not with Lamp-2, the lysosome marker. In contrast, SVG-A cells transfected with RK8AAJCV genome showed the

colocalization of RK8AA mutant of agnoprotein with both EEA1 and Lamp-2. Scale bars, 10 μm . The boxed areas in the upper panels are shown at higher magnification in the lower panels. Scales bars 5 μm . Arrowheads indicate the colocalization of agnoprotein with marker proteins. (B) SVG-AG cells (WT) or SVG-RK8AA cells (RK8AA) transfected with siAP3D or siNC were incubated with 1 $\mu\text{g/ml}$ DOX for 72 h and thereafter subjected to immunofluorescence analysis. The bar graph indicates the average proportion of cells with the diffuse pattern of agnoprotein expression. Results are average of three independent experiments, and the significance of changes was analyzed by Student's *t*-test ($*p < 0.05$). (C) SVG-RK8AA cells (RK8AA) were transfected with siAP3D or siNC and incubated with 1 $\mu\text{g/ml}$ DOX for 72 h. The cells were subjected to immunofluorescence analysis using anti-agnoprotein antibody followed by Alexa Fluor 488-conjugated anti-rabbit IgG antibody, and observed by fluorescence microscopy. The granules localizations of agnoprotein were quantified by MetaMorph software. The bar graph indicates the average number of granular localization of agnoprotein in a single cell. Results are average of three independent experiments, and the significance of changes was analyzed by Student's *t*-test ($*p < 0.05$).

Fig. S9. Agnoprotein was Degraded by AP-3 Dependent Pathway.

(A) SVG-AG cells were transfected with siAP3D or siNC and incubated with or without 1 $\mu\text{g/ml}$ DOX for the indicated time and subjected to immunoblotting using anti-AP3D, anti-actin or anti-agnoprotein antibodies. (B) DOX-treated SVG-RK8AA cells were cultured in the presence of lysosomal protease inhibitor (LPI) for 48 h, and processed for immunofluorescence staining. Confocal microscopy analysis of the cells showed prominent colocalization of RK8AA mutant with Lamp-2. Scale bars, 10 μm .