Characterization of Virus-Encoded RNA Interference Suppressors in *Caenorhabditis elegans*

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In fungi, plants, and invertebrates, antiviral RNA interference (RNAi) directed by virus-derived small interfering RNAs (siRNAs) represents a major antiviral defense that the invading viruses have to overcome in order to establish infection. As a counterdefense mechanism, viruses of these hosts produce diverse classes of proteins capable of suppressing the biogenesis and/or function of viral siRNAs. This RNA-directed viral immunity (RDVI) in the nematode *Caenorhabditis elegans* is known to exhibit some unique features. Currently, little is known about viral suppression of RNAi in *C. elegans*. Here, we show that ectopic expression of the B2 protein encoded by Flock House virus (FHV) suppresses RNAi induced by either long double-stranded RNA (dsRNA) or an FHV-based replicon and facilitates the natural infection of *C. elegans* by Orsay virus but is not active against RNA silencing mediated by microRNAs. We report the development of an assay for the identification of viral suppressor of RNAi (VSR) in *C. elegans* based on the suppression of a viral replicon-triggered RDVI by ectopic expression of candidate proteins. No VSR activity was detected for either of the two Orsay viral proteins proposed previously as VSRs. We detected, among the known heterologous VSRs, VSR activity for B2 of Nodamura virus but not for 2b of tomato aspermy virus, p29 of fungus-infecting hypovirus, or p19 of tomato bushy stunt virus. We further show that, unlike that in plants and insects, FHV B2 suppressors work RDVI mainly by interfering with the function of virus-derived primary siRNAs.

Viral suppressors of RNA silencing (VSRs) are a group of virus-encoded proteins that facilitate virus infection by suppressing the antiviral immunity mediated by RNA interference (RNAi) (1). Small interfering RNAs (siRNAs) derived from replicating viruses guide sequence-specific antiviral RNAi in fungi, plants, and invertebrates (2). Accumulating evidence suggested that most of virus-derived siRNAs are processed from viral replication intermediates, in the form of double-stranded RNAs (dsRNAs), by Dicer proteins, a class of RNase III RNases (3). siRNA-mediated silencing of invading viruses culminates with the cleavage of viral transcripts by Argonaute (AGO) proteins which recruit siRNAs as a sequence guide for target RNA selection and slice the matching RNA molecules with their RNAS H-like activity (2). In plants and the nematode worm *Caenorhabditis elegans*, RNA-dependent RNA polymerases (RdRPs) are essential for this RNA-directed viral immunity (RDVI) by amplifying siRNAs (4–6).

Since RDVI is mediated by siRNAs processed from replicating viral genomes, the chance for the targeted viruses to evade RDVI through generating genome variants is low. Therefore, one of the major strategies for the targeted viruses to establish successful infection is to produce VSRs. VSRs are diverse, in term of sequence and structure, classes of proteins encoded by fungus, plant, and animal viruses with DNA or RNA genome and target viral or host factors to suppress the biogenesis and/or function of siRNAs (7). For example, the B2 proteins produced by Flock House virus (FHV) or Nodamura virus (NoV) have been shown to bind long dsRNAs, thereby suppressing the processing of dsRNAs into siRNAs by Dicer, whereas the p19 protein of tomato bushy stunt virus (TBSV) and the 2b protein of tomato aspermy virus (TAV) specifically bind and inhibit the function of 21-nucleotide (nt) siRNAs (8–14). The fact that TBSV p19 is an active suppressor of RNAi in both insect and mammalian cells suggests that its function does not require host factors (15–17). In plants, VSRs are capable of interfering with the function of microRNAs (miRNAs), a class of endogenous small noncoding RNAs with important functions in development and stress response (18–20). miRNAs are encoded by nuclear genes and their biogenesis requires Dicer proteins and cofactors. Accumulating evidence suggests that suppression of miRNA function by VSRs is responsible for the developmental defects induced by plant virus infection (21, 22).

Development of RDVI suppression assays has played an important role in the discovery and characterization of VSRs and the study of VSR-mediated virus-host interaction (1). The early assays surveyed suppression of transgene RNA silencing in plants by a candidate viral protein expressed from either an infectious recombinant virus or a transgene (23–25). RNAi targeting a cellular gene induced by synthetic long dsRNAs or siRNAs in animal cells was similarly used for the identification of VSRs (17). Subsequently, experimental systems were developed to directly assay for the suppression of RNA silencing that is induced by and specifically targets a replicating virus in a host cell (26). Development of these experimental systems was made possible by the detailed characterization of mutant viruses or virus-based replicons from which a cognate VSR was deleted. These VSR-deficient viruses and replicons exhibit no defect in replication but accumulate to only low levels in host cells because of robust and specific antiviral RNAi induced by virus replication. However, abundant accumulation of VSR-deficient viruses is restored in host cells defective in RDVI. Therefore, a candidate viral protein is identified as a VSR when its expression rescues the accumulation of a VSR-deficient mutant virus or replicon after replication in a host cell.

*C. elegans* has recently emerged as an important animal model
for the study of virus-host interaction, especially the antiviral immunity, in single-Dicer invertebrates (11, 27–31). RDVI in C. elegans exhibits several distinct features. Current studies on C. elegans RDVI suggest that the worm RDVI is initiated upon the processing of viral dsRNAs into primary siRNAs by the single worm Dicer, DCR-1, with the aid of a dsRNA binding protein termed RDE-4 (30–32). Subsequently, RDE-1, an AGO protein, recruits primary siRNAs as sequence reference for the target viral transcript selection (33–35). As found in plants, the worm RDVI also requires an RdRP termed RRF-1 (27, 30, 32). However, unlike the plant RdRPs that produce secondary siRNAs with the help from Dicer, RRF-1 functions downstream of RDE-1 and directs unprimed synthesis of 22-nt single-stranded siRNAs with triphosphate group at the 5’ end in a Dicer-independent manner (36–38). In addition to AGO and RdRP proteins, the worm RDVI also requires some components, such as RSD-2 and DRH-1, that are not conserved in plants or insects. RSD-2 is a novel protein known to contribute to chromosomal functions possibly through facilitating the accumulation of secondary siRNAs (39, 40). DRH-1 is a putative DEAD box RNA helicase that shares significant sequence homology with RIG-1, a mammalian cytosolic virus sensor in interferon-mediated antiviral immunity (32, 41). Interestingly, DRH-1 appears to be a dedicated factor of RDVI in C. elegans since RNA silencing targeting cellular transcripts occurs in a DRH-1-independent manner (32). Besides, worm RDVI seems to be negatively regulated by a mechanism that involves the degradation of siRNAs (42).

Little is known about viral suppression of RDVI in C. elegans. Recent studies have discovered naturally occurring virus that infects and induces RDVI in C. elegans (27). However, it is unknown whether the virus encodes VSR or VSR expression enhances virus infection in C. elegans. Previously, B2 of FHV has been shown to be required for efficient viral replication in wild-type worms but not in worm mutants defective in RDVI (11), suggesting a function for FHV B2 in worm RDVI suppression. However, it remains unknown whether ectopic expression of FHV B2 suppresses RNAi induced by synthetic dsRNA or worm RDVI induced by FHV or heterologous viruses. Here, using FHV B2 as a reference VSR, we developed a robust RDVI suppression assay that allows for the identification of VSRs with RDVI suppression activity in C. elegans. Using this assay, we not only demonstrated that the Orsay virus RNA2 encodes no RDVI suppression activity but also identified NoV B2 as a VSR that retained the RDVI suppression activity in worm. It was also clear from our study that FHV B2 mainly inhibits the function, rather than the biogenesis, of virus-derived primary siRNAs in C. elegans but is unable to suppress the function of worm miRNAs which use the same Dicer for biogenesis. Intriguingly, we found that TBSV p19 is not an active RDVI suppressor in C. elegans. Since TBSV p19 is known to specifically bind and inhibit the function of 21-nt siRNAs, our observations suggested 21-nt primary siRNAs may not make major contribution to worm RDVI.

**MATERIALS AND METHODS**

**Worm genetics.** The Bristol isolate of C. elegans, N2, was used as the reference strain in the present study. Other N2-derived mutants used in the present study include rde-1 (mc490) and rrf-1 (pk1417). The genotype of rde-1 worms was confirmed using skn-1 feeding RNAi combined with genomic DNA sequencing. The genotype for rrf-1 allele pk1417 was identified using PCR as described previously (29). All worm strains were maintained using NGM plates seeded with Escherichia coli strain OP50 except otherwise indicated. Standard genetic cross was used to deliver various transgenes into different genetic backgrounds.

**Plasmid constructs and transgenic worms.** All constructs utilizing the heat-inducible promoter were developed by inserting the target gene into pPD49.83 utilizing the XmaI and SacI site. All constructs utilizing the sur-5 promoter were developed by inserting the target gene into LR50 described previously (29). The coding sequences for TBSV p19 and TAV 2b were PCR amplified from corresponding T-DNA expression binary constructs described previously (43, 44). The point mutations in p19m and 2bm were introduced through PCR amplification of wild-type genes using primers containing desired mutations. All resulting constructs were confirmed through DNA sequencing. The construct used to drive gfp dsRNA expression in E. coli was described previously (29).

Transgenic animals were generated through gonadal microinjection of the target constructs. Briefly, the target plasmid constructs, each at a final concentration of 10 ng/μl, were mixed with the 2-log DNA ladder (New England BioLabs, Inc.) at final concentration of 100 ng/μl and the reporter plasmid Pmyo-2:zCherry at final concentration 40 ng/μl and injected into the gonads of target worms. Generation of corresponding chromosomal integrants and assay for viral replication were as described previously (29).

**Infectious filtrate preparation and Orsay virus inoculation.** Orsay virus was maintained using the JU1580 isolate at room temperature following a protocol described previously (27). To prepare Orsay virus inoculum, JU1580 worms infected with Orsay virus were washed off, using M9 buffer, from slightly starved 10-cm plates, 5 ml per plate. The virus-containing liquid was then filtered through a 0.22-μm-pore-size filter unit (Millipore), and the filtrate was used to resuspend purified OP50 E. coli for NGM plate seeding.

**RNAi experiments.** The skin-1 and gfp feeding RNAi assay was performed using a bacterial feeding protocol described previously (45). Briefly, NGM agar plates containing 5 mM IPTG and 100 mg of carbenicillin/ml were seeded with E. coli. HT115 expressing skin-1 or gfp dsRNAs.

**Assay for mirRNA biogenesis/function suppression activity.** Worms used in this assay contain a let-7 function reporter transgene, which contains a green fluorescent protein (GFP) coding sequence fused with the let-7 target sequence, namely, the 3’ end untranslated region of lin-41, and a transgene expressing the let-7 miRNAs. Both transgenes are driven by the myo-2 promoter, and thus enhanced green fluorescence can be observed in the pharynx tissue in worms defective in mirRNA biogenesis and/or function (46). The assay began with microinjection of plasmid constructs containing candidate VSR targeting constructs driven by the myo-2 promoter into the reporter worm strain XX335 (obtained from the Caenorhabditis Genetics Center). The PRF4 construct was co injected to produce the roller phenotype as a visual mark for the VSR transgene. After microinjection, transgenic lines carrying translatable extrachromosomal arrays were picked up and maintained at room temperature. For each transgenic line, the green fluorescence in the pharynx tissue was compared, at different developmental stages, in between worms that carry the extrachromosomal array and worms that do not.

**Protein and RNA gel blot analysis.** Total proteins were extracted from worms of mixed stages treated with or without heat induction and were resolved on an 8% SDS-PAGE gel, electrobblotted, and subjected to protein gel blot analysis using either anti-HA (Cell Signaling Technology) or anti-actin primary antibody (Sigma-Aldrich) and goat anti-rabbit secondary antibody (Cell Signaling Technology). Total RNA extraction, small RNA enrichment, viral genomic and subgenomic RNA detection, and siRNA and miRNA detection were performed using protocols described previously (29). The detection of viral high molecular transcripts used probe derived from the full-length of gfp CDNA. For FR1gfp siRNA detection, the probes were prepared using 32 DNA oligonucleotides covering the entire GFP region of FR1gfp. The detection of mir-385DNA used digoxigenin (DIG)-labeled oligonucleotide ATTTGCAGTACCTGACCAGTCTCA as a probe. Four DNA oligonucleotides of 19, 21, 23, or 25 nt were detected.
using DIG-labeled cDNA oligonucleotides and, together with miR-58, served as a size reference.

**Terminator treatment of small RNA samples.** The terminator treatment was carried out by mixing 20 μg of small RNA sample with 4 U of terminator exonuclease (Epicentre, Inc.) in 50-μl reaction mix containing 1× buffer and 1 U of RNase inhibitor. The reaction mix was then incubated at 30°C for 60 min. For both treatments, the treated small RNA samples were cleaned through extracting with phenol-chloroform and then precipitated with ethanol.

**Imaging microscopy.** The green and red fluorescence images were recorded using a Nikon digital camera p7000 mounted on a Nikon SMZ1500 microscope.

**RESULTS**

FHV B2 suppresses dsRNA-triggered RNAi and RDVI targeting a natural viral pathogen of *C. elegans*. Thus far, no VSR has been shown to suppress classical RNAi triggered by long dsRNA in *C. elegans*. FHV B2 retains its RNAi suppression activity when expressed in *C. elegans*. Despite its insect origin, FHV B2 was shown to be required for efficient replication of the cognate virus in the wild-type *C. elegans* but became dispensable in worm mutants defective in RDVI (11), suggesting that FHV B2 retains its RDVI suppression activity in worms. To find out whether FHV B2 suppresses classical RNAi in *C. elegans*, we assayed the silencing of a *gfp* transgene triggered by ingestion of *gfp* dsRNA in worms carrying constitutively active nuclear transgene corresponding to FHV B1 and FHV B2 (Fig. 1A). The B1 protein of FHV, which is translated from the same subgenomic RNA as B2, is known to be inactive in RNAi suppression (47) and thus served as control to FHV B2 in our test. As shown in Fig. 1B, silencing of the *gfp* transgene was suppressed in transgenic worms expressing FHV B2 but not in wild-type N2 worms or worms expressing FHV B1, confirming that FHV B2 indeed suppresses long dsRNA-triggered RNAi in worms.

Orsay virus is a naturally occurring viral pathogen of *C. elegans* that was originally isolated from a worm mutant defective in RDVI (27). Interestingly, the replication of Orsay virus in wild-type N2 worms is significantly weaker compared to that in RDVI-defective mutants. The fact that Orsay virus is still sensitive to RDVI suggested that its replication would be further enhanced in worms expressing a functional VSR. To test this hypothesis, we checked the Orsay virus infection in transgenic worms constitutively expressing FHV B2. As shown in Fig. 1C, compared to that in nontransgenic N2 worms and N2 worms expressing FHV B1, the replication of Orsay virus was significantly enhanced in transgenic N2 worms expressing FHV B2. These results together suggested that FHV B2 is able to suppress both long dsRNA-triggered RNAi and RNAi triggered by natural viral infection in *C. elegans*.

**Development of an assay for the identification of VSRs in *C. elegans***. To facilitate the discovery and characterization of VSRs in *C. elegans*, we developed an RDVI suppression assay based on the induction of RDVI by the self-replication of the genomic RNA1 of FHV. The construction of FR1gfp, an FHV RNA1-based replicon that contains a GFP coding sequence in the place of B2 coding sequence (Fig. 2A), was described previously (32). As shown previously, the replication of FR1gfp launched from a chromosomally integrated transgene is suppressed by RDVI in wild-type worms but is restored to yield green fluorescence expressed from the subgenomic RNA produced after RNA1 replication in RNAi-defective mutant worms such as *rde-1* and *drh-1* mutants. We determined whether the FR1gfp-induced RDVI was suppressed and whether the expression of GFP was activated following ectopic expression of a functional VSR. We chose the FHV B2 as the VSR since it exhibits RNAi suppression activity following ectopic expression in both plant and insect cells and suppresses FHV RNA1-induced RDVI when encoded in cis (26, 47). In our experimental system, two plasmid constructs were comicroinjected into the gonads of young adult worms containing the FR1gfp replicon (32), and GFP expression was monitored in the next generation of worms. The first constructs directed expression of the FHV B2 driven by the same heat-inducible promoter used to initiate FR1gfp replication (Fig. 2A). The second construct directed mcherry expression in the pharynx tissue and was used to generate a visible marker for transgene transformation. Most of the extrachromosomal transgenic arrays generated through gonad injection are randomly passed on to the next generations so that there are always some worms within each generation of the transgenic lines that are free of the transgene, marked by the absence of mcherry expression. Therefore, progenies from a transformed parent often include individuals that do not inherit the transgene, and thus can serve as an internal negative control.

As shown in Fig. 1B, we found that all transgenic progenies carrying the HIP::B2 extrachromosomal arrays, marked by red fluorescent in head, produced bright full body green fluorescence in response to induction of FR1gfp replication through heat treatment. However, no full body green fluorescence was observed in the progenies carrying the transgenic arrays that directed expression of FHV B1, which was encoded by the same subgenomic RNA as B2 but showed no VSR activity (47). To further verify these findings, we generated chromosomal integrants for the FHV B1 and B2 transgenes and checked the accumulation of FR1gfp transcripts in response to heat induction in respective transgenic...
Suppression of RNAi in C. elegans

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**FIG 2** Ectopic expression of FHV B2 suppresses worm RDVI targeting FR1gfp replicon. (A) Schematic structure of the FR1gfp replicon, the Pmyo-2::mcherry reporter construct, and the FHV B1 and B2 transgenes utilizing the heat-inducible promoter. HIP, heat-inducible promoter; protein A, replicase of FHV; Rz, self-cleaving ribozyme sequence from hepatitis delta virus; UTR, 3’ end untranslated sequence of the worm gene unc-54; Pmyo-2, promoter for the worm gene myo-2, which directs target gene expression in the pharynx tissue. (B) Visualization of green fluorescence in worms carrying the FR1gfp nuclear transgene and extrachromosomal array corresponding to FHV B1 or FHV B2, as indicated, at 48 h after heat induction. Shown here are merged images recorded using the same exposure under white light, red fluorescence, and green fluorescence. Worms showing red or orange (merged from red and green) color are transgenic for FHV B1 or FHV B2. (C) Accumulation of FR1gfp genomic and subgenomic RNAs in wild-type N2 worms expressing the Rde-1 null allele (ne300) or integrated transgene corresponding to FHV B1 or B2 as indicated. Total RNA was prepared at 48 h after heat induction. The total RNA was hybridized with probes prepared from full-length gfp cDNA. Methylene blue-stained rRNA serves as an equal loading control. (D) Accumulation of FR1gfp transcripts in N2 worms expressing FHV B1 or B2 utilizing the sur-5 promoter or the heat-inducible promoter (indicated with asterisks).

wprms using Northern blot hybridization. As shown in Fig. 2C, enhanced FR1gfp replication was detected in FHV B2 chromosomal integrants as found in the rde-1 mutant worms defective in RDVI, but not in the integrants containing FHV B1 transgene. These results together showed that ectopic expression of FHV B2 suppressed the replicon-induced RDVI in adult worms, indicating that the rescue of the VSR-deficient FR1gfp replicon could serve as an RDVI suppression assay to identify VSRs in C. elegans following heat-inducible expression.

We next determined whether RDVI was suppressed by FHV B2 driven by a constitutive promoter. We found that the replication of FR1gfp was also significantly enhanced in worms constitutively expressing FHV B2 compared to that in worms constitutively expressing the B1. However, in comparison, the expression of FHV B2 utilizing the heat-inducible promoter achieved a stronger rescue on FR1gfp replication (Fig. 2D).

The genomic RNA2 of Orsay virus encodes no detectable RDVI suppression activity. The fact that the replication of Orsay virus in wild-type N2 worms is suppressed by RDVI and can be rescued by FHV B2 suggested that Orsay virus encodes weak or no RDVI suppression activity. To test this hypothesis, we subjected the putative coat protein and the delta protein encoded by Orsay virus genomic RNA2 to the RDVI suppression assay described in Fig. 2. Our assay also included NoV B2 which, despite sharing limited sequence identity with FHV B2, adopts a mechanism similar to that of FHV B2 to suppress RNAi (12), was thus expected to retain the function of 21-nt siRNA duplexes (9, 13, 14, 17). In particular, TBSV p19 is known to be functional in heterologous systems such as insect and mammalian (15–17) and, owing to its target specificity, has been used as a genetic tool to explore the molecular mechanism of 21 siRNAs or miRNAs (17,48). The p29 protein encoded by fungus-infecting hypovirus is another VSR known to be able to suppress RNAi in heterologous system such as plants (49). Currently, how P29 suppresses RDVI remains largely unknown. To find out whether these three VSRs retain their RDVI suppression activity in worm, we subjected all of them to the RDVI suppression assay described in Fig. 2. Our assay also included NoV B2 which, despite sharing limited sequence identity with FHV B2, adopts a mechanism similar to that of FHV B2 to suppress RNAi (12), was thus expected to retain the RDVI suppression activity in worms. Indeed, as shown in Fig. 4A and B, ectopic expression of NoV B2 utilizing the heat-inducible promoter led to successful rescue of FR1gfp replication, manifested as significantly enhanced GFP fluorescence, in wild-type N2 worms. Surprisingly, such a rescue was not observed for ectopic expression of...
TBSV p19, TAV 2b, a p19 loss-of-function mutant termed p19m, that contains the R72G point mutation (50), or hypovirus p29. Consistent with this observation, enhanced FR1gfp replication was detected by Northern blotting only in chromosomal integrants containing the heat-inducible NoV B2 transgene (Fig. 4C).

A previous study suggested that TBSV p19 can be tagged with an hemagglutinin (HA) epitope tag to the carboxyl terminus (C terminus) without losing its RNAi suppression activity (17). To rule out the possibility that the failure of TBSV p19 in suppressing worm RDVI is a result of instability of this suppressor when produced in worm, we checked the accumulation of HA-tagged p19 produced in wild-type N2 worms and worms containing the heat-inducible transgene shown in the upper left panel. In the right panel, the HA-tagged TBSV p19 is deficient in RDVI suppression. Shown here is the accumulation of FR1gfp transcripts detected in wild-type N2 worms and worms containing the heat-inducible transgene corresponding to HA-tagged p19. Asterisks denote samples prepared using heat-induced worms. (E) NoV B2, but not TBSV p19 or TAV 2b, suppresses dsRNA-triggered RNAi targeting a gfp transgene. Asterisks denote total RNA samples extracted from worms fed on E. coli food expressing gfp dsRNA. (F) NoV B2, but not TBSV p19 or TAV 2b, enhances the replication of Orsay virus. Shown here is the accumulation of Orsay virus RNA1 in worms containing NoV B2, TBSV p19, and TAV 2b transgenes, as indicated, utilizing the constitutively active promoter of the sur-5 gene.

TBSV p19, TAV 2b, a p19 loss-of-function mutant termed p19m, that contains the R72G point mutation (50), or hypovirus p29. Consistent with this observation, enhanced FR1gfp replication was detected by Northern blotting only in chromosomal integrants containing the heat-inducible transgene (Fig. 4C).

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To find out whether TBSV p19, TAV 2b, and NoV B2 are able to suppress dsRNA-triggered RNAi and RDVI targeting Orsay virus, we checked the gfp transgene silencing triggered by gfp dsRNA ingestion (see Fig. 1 for details) and Orsay virus replication in wild-type N2 worms constitutively expressing each of these suppressors. As shown in Fig. 4E, the suppression on dsRNA-triggered gfp transgene silencing was only observed in NoV B2-expressing worms. Consistent with this observation, enhanced Orsay virus replication, compared to that in wild-type N2 worms, only occurred in worms transgenic for NoV B2 (Fig. 4F). These observations together suggested that NoV B2, but not TBSV p19 or TAV 2b, suppresses dsRNA-triggered RNAi and RDVI triggered during natural viral infection in C. elegans.

**FIG 4** NoV B2, but not TBSV p19 or TAV 2b, suppresses long dsRNA-triggered RNAi and RDVI targeting Orsay virus. (A) Schematic structure of heat-inducible transgenes corresponding to NoV B2 (nB2), TBSV p19 (p19), TBSV p19m (p19m), TAV 2b (2b), and p29. (B) Visualization of green fluorescence in worms carrying the FR1gfp replicon transgene and extrachromosomal arrays generated through gonad injection of constructs shown in panel A. Shown here are merged images recorded under white light, red fluorescence and green fluorescence with the same exposure 48 h after heat induction. (C) Accumulation of FR1gfp transcripts in transgenic N2 worms carrying the integrated transgenes corresponding to NoV B2, TBSV p19, TBSV p19m, and TAV 2b, p19m, a p19 variant that contains the R72G point mutation and is known to be deficient in RNAi suppression. (D) HA-tagged TBSV p19 is deficient in RDVI suppression. The upper left panel shows the structure of a heat-inducible transgene expressing TBSV p19 tagged with HA at the C terminus. The lower left panel shows Western blot detection of HA-tagged p19 produced in wild-type N2 worms and worms containing the heat-inducible transgene shown in the upper left panel. In the right panel, the HA-tagged TBSV p19 is deficient in RDVI suppression. Shown here is the accumulation of FR1gfp transcripts detected in wild-type N2 worms and worms containing the heat-inducible transgene corresponding to HA-tagged p19. Asterisks denote samples prepared using heat-induced worms. (E) NoV B2, but not TBSV p19 or TAV 2b, suppresses dsRNA-triggered RNAi targeting a gfp transgene. Asterisks denote total RNA samples extracted from worms fed on E. coli food expressing gfp dsRNA. (F) NoV B2, but not TBSV p19 or TAV 2b, enhances the replication of Orsay virus. Shown here is the accumulation of Orsay virus RNA1 in worms containing NoV B2, TBSV p19, and TAV 2b transgenes, as indicated, utilizing the constitutively active promoter of the sur-5 gene.
p19, and TAV 2b in worm RDVI suppression, we examined the accumulation of FR1gfp-derived siRNAs in worms containing heat-inducible transgene corresponding to each of these VSRs. Consistent with previous deep-sequencing analysis (51), our Northern blotting analyses detected discrete primary siRNA bands, with the major one showing up at the position corresponding to 23 nt in the rde-1 mutants which are known to accumulate only primary siRNAs (Fig. 5A) (32, 35, 52). As indicated by arrows in Fig. 5A, our Northern blot analyses also detected an siRNA band with a size falling between 21 and 22 nt in wild-type N2 worms and worms containing heat-inducible transgene corresponding to FHV B1. However, such an siRNA band was not detected in single or double mutants containing the rrf-1-null allele. In the light of the fact that rrf-1 functions downstream of rde-1 to produce 22-nt secondary siRNAs in a Dicer-independent manner (36–38, 52), we believed that this band represents the rrf-1-dependent secondary siRNAs. The faster migration rate of this band compared to the 22-nt primary siRNAs may be a manifestation of the fact that the rrf-1-dependent siRNAs carry a triphosphate group at the 5′ end. FR1gfp-derived siRNAs were also detected in FHV B2 and NoV B2 transgenic worms with a pattern similar to that detected in rde-1 mutants (Fig. 5A and B), suggesting that FHV B2 and NoV B2 inhibit the function, rather than the biogenesis of, primary siRNAs to suppress RDVI. In agreement with this notion, the rrf-1-dependent secondary siRNAs were not detected in the presence of FHV B2 (Fig. 5A and B).

As shown in Fig. 5A, the accumulation of miR-58 was not reduced in response to FHV B2 expression compared to that in wild-type N2 worms or worms expressing FHV B1, suggesting that FHV B2 does not suppress the biogenesis of worm miRNAs.

As shown in Fig. 5C, the rrf-1-dependent siRNAs were also detected in worms expressing TBSV p19, TAV 2b or their loss-of-function mutants with a pattern similar to that detected in wild-type N2 worms. However, it is interesting that despite of the fact that none of TBSV p19, TAV 2b and their loss-of-function mutants exhibited RDVI suppression activity in our FR1gfp replication rescue assays (Fig. 4), a slightly enhanced accumulation of 22-nt primary siRNAs was detected in worms expressing wild-type TBSV p19 or TAV 2b compared to worms expressing respective loss-of-function mutants (Fig. 5C).

To find out whether FR1gfp-derived siRNAs detected in the presence of FHV B2 are bona fide primary siRNA duplexes produced by worm Dicer, we treated our small RNA samples with Terminator exonuclease, which destroys single-stranded RNAs carrying a monophosphate group at the 5′ end but is much less efficient in digesting siRNA duplexes carrying monophosphate at the 5′ end (53). As expected, our Terminator treatment destroyed siRNAs in rrf-1 mutants and worms containing heat-inducible transgenes corresponding to, as indicated, TBSV p19, TAV 2b, or their loss-of-function mutants. 2bm, a loss-of-function mutant of TAV 2b that contains the P41A point mutation (9). To obtain a size reference and equal loading control, we treated our small RNA samples with Terminator exonuclease, which destroys single-stranded RNAs carrying a monophosphate group at the 5′ end but is much less efficient in digesting siRNA duplexes carrying monophosphate at the 5′ end (53). As expected, our Terminator treatment destroyed

FIG 5 FHV B2 targets a step downstream of the primary siRNA biogenesis to suppress RDVI. (A) Accumulation of FR1gfp-derived siRNAs, detected by Northern blotting, in worms containing heat-inducible transgene corresponding to FHV B1 or FHV B2 and wild-type N2 worms and single and double mutants defective in rde-1 and/or rrf-1 function as indicated. After the detection of the virus-derived siRNAs, the same filter membrane was reused, after stripping, for the detection of miR-58 miRNAs. M, four DNA oligonucleotides with different sizes as indicated. They were detected using DIG-labeled cDNA oligonucleotides and, together with miR-58, served as size references. The accumulation of miR-58 in each sample also served as an equal loading control. Arrows indicate the rrf-1-dependent siRNAs. (B) Accumulation of FR1gfp-derived siRNAs in rde-1 mutants and worms containing heat-inducible FHV B2 or NoV B2 transgenes. (C) Accumulation of FR1gfp-derived siRNAs in rrf-1 mutants and worms containing heat-inducible transgenes corresponding to, as indicated, TBSV p19, TAV 2b, or their loss-of-function mutants. 2bm, a loss-of-function mutant of TAV 2b that contains the P41A point mutation (9). To obtain a size reference and equal loading control, the same filter membrane was reprobed for the detection of miR-58 miRNAs. (D) Northern blot detection of FR1gfp-derived siRNAs in transgenic N2 worms containing heat-inducible transgenes corresponding to various VSRs, as indicated, after treatment with the Terminator exonuclease. After the detection of the virus-derived siRNAs, the same filter membrane was reused for the detection of miR-58 miRNAs to generate size reference and equal loading control and Terminator treatment effectiveness control. Asterisk denotes samples not treated with the Terminator exonuclease.
the miR-58 miRNAs in all small RNA samples (compare the treated samples to the untreated fB1 and fB2 small RNA samples) (Fig. 5D). However, such a treatment generated no detectable impact to the abundance of siRNAs detected in rde-1 mutants or worms expressing the FHV B2. This result thus suggested that the siRNAs detected in the presence of FHV B2 are bona fide primary siRNA duplexes.

**FHV B2 does not inhibit the function of worm miRNAs.** In plants, VSRs are capable of interfering with the function of miRNAs, leading to development defects (19, 21, 22). The C. elegans genome encodes a single Dicer that is required for the biogenesis of both siRNAs and miRNAs (54, 55). The fact that the accumulation of miR-58 is not affected in worms expressing FHV B2 (Fig. 5A and B) suggested that FHV B2 does not suppress the biogenesis of worm miRNAs. However, the fact that heat-inducible expression of FHV B2 exhibited stronger suppression on RDVI, compared to constitutive expression (Fig. 2D), suggested that a hypothesis that constitutive expression of FHV B2 leads to the suppression on miRNA function such that worms constitutively expressing FHV B2 at high level failed to develop and thus were selected out. To test this hypothesis, we checked the suppression activity of FHV B2 on miRNA function using an assay system developed previously (46). This assay system features a myo-2 promoter driven gfp transgene containing the let-7 target sequences within the 3′-end untranslated region. Thus, suppression of miRNA function will result in enhanced green fluorescence in the pharynx tissue which can be easily identified.

We used the myo-2 promoter to drive the expression of FHV B2 and the control protein FHV B1 in our assay to ensure that both transgenes will have the same tissue-specific expression pattern as the gfp reporter gene (Fig. 6A). To ensure that functional FHV B2 proteins are produced in the pharynx tissue, we checked the suppression activity of FHV B2 on RNAi triggered by two transgenes that produce complementary transcripts within the pharynx tissue. As shown in Fig. 6A, the Pmyo-2::GFP construct contains a GFP coding sequence under the control of myo-2 promoter, whereas the Pmyo-2::PFG construct contains a sequence complementary to the GFP coding sequence under the control of the same myo-2 promoter. Thus, codelivery of Pmyo-2::GFP and Pmyo-2::PFG constructs is expected to trigger gfp silencing in wild-type N2 worms. Indeed, as shown in Fig. 6B, a transgenic locus containing both Pmyo-2::GFP and Pmyo-2::PFG transgenes produced weak green fluorescence in wild-type N2 worms but bright green fluorescence in rde-4 mutants. Enhanced green fluorescence produced by the same transgenic locus was also observed in wild-type N2 worms containing the Pmyo-2::PFG transgene. However, such an enhancement in green fluorescence was not observed in the presence of the Pmyo-2::fB1 transgene, confirming that the Pmyo-2::fB2 transgene produces functional FHV B2 in the pharynx tissue.

To find out whether FHV B2 suppresses the function of miRNAs, we injected the wild-type N2 worms carrying the gfp reporter transgene with Pmyo-2::fB1 or Pmyo-2::fB2 constructs. Subsequently, we checked the production of green fluorescence in worms containing extrachromosomal arrays corresponding to Pmyo-2::fB1 or Pmyo-2::fB2. As shown in Fig. 6C, no enhanced green fluorescence was observed in response to ectopic expression of either FHV B1 or FHV B2, suggesting that FHV B2 does not interfere with the function of miRNAs in C. elegans.

**DISCUSSION**

RDVI represents a major antiviral mechanism in fungi, plants, and insects (2). To survive, many viruses produce diverse classes, in terms of sequence and structure, of VSRs that suppress RDVI through distinct mechanisms (1, 7). Since VSRs can target and suppress RNAi directed by endogenous siRNAs and miRNAs studies on the VSR-mediated virus-host interactions have not only significantly improved our understanding of the evolutionary arm race between viruses and their natural hosts but also allowed us to gain insight into the mechanistic basis underlying disease induction by virus infection in the aforementioned systems (7, 15, 22). The nematode worm C. elegans has recently emerged as an important animal model for the study of virus-host interaction in single-Dicer invertebrates. Thus far, the study on VSR-mediated virus-nematode host interaction, especially the interaction that leads to disease development, has remained to be an unexplored field mainly owing to the fact that a robust RDVI suppression assay has yet to be developed for the identification of VSRs with worm RDVI suppression activity. Here, we reported a worm RDVI suppression assay system developed using FHV B2 as a reference VSR. Because a viral replicon is used as both trigger and target of RDVI, our assay system is expected to identify VSRs with true function in RDVI suppression. Using this assay we have successfully identified NoV B2, which shares limited sequence homology with FHV B2 but uses similar mechanism in RDVI sup-

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**FIG 6 FHV B2 does not inhibit miRNA function.** (A) Schematic structure of the myo-2 promoter-based constructs. PFG, antisense of GFP coding sequence. (B) FHV B2 suppresses RNAi in the pharynx tissue. Shown here is the green fluorescence in pharynx tissue in wild-type N2 worms, rde-4 mutants, and worms containing Pmyo-2::fB1 or Pmyo-2::fB2 transgene as indicated. All worms used in this test contain a nuclear transgene generated by coinjection of Pmyo-2::GFP and Pmyo-2::PFG. The images were produced by merging images recorded using the same exposure under white light, red fluorescence, or green fluorescence. (C) FHV B2 does not suppress miRNA function in C. elegans. Shown here is the green fluorescence in the pharynx tissue in wild-type N2 worms and worms containing extrachromosomal array corresponding to Pmyo-2::fB1 or Pmyo-2::fB2 as indicated. The images were produced by merging images recorded under white light or green fluorescence with the same exposure. The insets are images recorded under white light.
pression, as another VSR that retains RDVI suppression activity in the worm system, confirming the robustness of our assay system. Thus, our assay system for the first time makes it possible to identify VSRs with worm RDVI suppression activity. It can be expected that functional and mechanistic characterization of VSRs identified using our assay will help unravel some unique features of VSR-mediated virus-nematode worm interaction.

Unlike plants and insects, the nematode worm *C. elegans* uses a single Dicer to initiate both RDVI and other RNAi-related pathways. Moreover, the worm RDVI pathway features some unique components, such as RSD-2 and DRH-1 (32), and is known to require RRF-1, an RdRP that produces 22-nt single-stranded secondary siRNAs in a Dicer-independent manner (32, 37, 38, 52). These observations make it interesting to ask whether the worm RDVI responds differently to VSRs identified in heterologous systems. To address this question, we assayed the RDVI suppression activity for VSRs encoded by fungus, plant, and insect viruses in *C. elegans*. Our results clearly showed that, in addition to FHV B2, secondary siRNA, biogenesis to suppress RNAi (Fig. 5A and D). Interestingly, however, unlike that in plants and insects, FHV B2 appears to target a step downstream of primary siRNA, but upstream of secondary siRNA, biogenesis to suppress RNAi (Fig. 5A and D). These results together not only confirmed that worm RDVI indeed responds differently to heterologous VSRs but also shed light on some unique mechanistic features of worm RDVI as discussed below.

Probably due to an siRNA degradation mechanism (42), the abundance of virus-derived siRNAs is extremely low in *C. elegans*. Using a newly developed Northern blotting protocol (29), we managed to detect virus-derived siRNAs at an unprecedented resolution. Consistent with previous deep-sequencing analysis (51), our Northern blotting analyses detected several viral siRNA bands, with the major one detected with a size of 23 nt, in *rde-1* mutants (Fig. 5A). We believed that these viral siRNAs are bona fide primary siRNA duplexes produced by the worm Dicer, considering the facts that the primary siRNAs produced by worm Dicer are predominantly 23 nt in size (56), *rde-1* mutants are known to accumulate only primary siRNAs (35), and the detected viral siRNAs are resistant to Terminator exonuclease, which destroys single-stranded RNA molecules with 5′ end monophosphate group, such as miRNAs, but is much less efficient in digesting siRNA duplexes (Fig. 5D). Our Northern blotting analyses also detected an *rff-1*-dependent siRNA band with a size falling between 21 and 22 nt (Fig. 5A and C). The unique migration pattern of these *rff-1*-dependent siRNAs may simply reflect the fact that, although 22 nt in size (36–38), *rff-1*-dependent siRNAs carry a triphosphate, instead of a monophosphate, group at the 5′ end and thus are expected to migrate faster than the 22-nt primary siRNAs which carry monophosphate group at the 5′ end.

FHV B2 is a versatile VSR that suppresses RNAi in diverse organisms (16, 26, 47). Previous biochemical and structural studies suggested that FHV B2 forms homodimers and binds to dsRNA without a length preference (8, 10, 11). These observations suggested that FHV B2 could have dual modes of action in RDVI suppression: inhibiting Dicer-processing of dsRNAs or interfering with the function of siRNAs (8). Previously, it has been shown that the major mode of action of B2 in plants and insects is to suppress the biogenesis of siRNAs (47, 57). Currently, it remains unclear whether FHV B2 actively suppresses RDVI by inhibiting the function of siRNAs. Here, we show that FR1gfp-derived siRNAs in worms expressing FHV B2 can be detected at a comparable amount and with a similar pattern as that in *rde-1* mutants (Fig. 5A). Since *rde-1* mutant is known to be defective in the biogenesis, but not the function, of primary siRNAs (35), this observation suggests that the major mechanism of FHV B2 in worm RDVI suppression is to inhibit the function, thus the biogenesis of secondary siRNAs, of primary siRNAs. In supporting this notion, the *rff-1*-dependent secondary siRNAs became undetectable in worms expressing FHV B2 (Fig. 5A and B). Worm RDVI pathway contains some unique components such as DRH-1. Considering the fact that the mammalian counterparts of DRH-1 function as cytosolic virus sensors, it is possible that DRH-1 functions as a virus sensor to facilitate the viral dsRNA acquisition by worm Dicer. As a result, the biogenesis of viral primary siRNAs can be significantly enhanced even in the presence of FHV B2. However, since FHV B2 can inhibit the function of primary siRNAs and the biogenesis of secondary siRNAs, the targeted viruses will still be able to replicate efficiently in the presence of FHV B2, as revealed here.

TBSV p19 is a well-characterized VSR of plant origin that can suppress RNAi in heterologous systems such as insects and mammals (17, 26). Previous studies suggested that both TBSV p19 and TAV 2b specifically bind and inhibit the function of 21-nt siRNAs to suppress RNAi. Although siRNA duplexes of other sizes can also be bound by these two VSRs, the binding affinity diminishes rapidly with increasing size differences (9, 13, 14). In fact, because of its target specificity TBSV p19 has been used as a universal RNAi suppressor to explore the molecular mechanism of 21-nt siRNAs to suppress RNAi. We show here that, although successfully expressed in *C. elegans*, TBSV p19 failed to suppress long dsRNA-triggered RNAi, RDVI triggered by two unrelated viruses, and the biogenesis of RRF-1-dependent secondary siRNAs. This finding suggests that virus-derived 21-nt primary siRNAs, which, unlike the 22- and 23-nt primary siRNAs, can only be detected in some RDVI mutants (Fig. 5A and C), do not make major contribution to RDVI in *C. elegans*.

In plants, VSRs can interfere with the function of miRNAs, which usually form near-perfect sequence matches with their passenger strands, resulting in developmental defects or diseases (19, 22). Animal miRNAs and their passenger strands often do not form near-perfect sequence matches and thus have been shown to be resistant to the inhibitory effect of VSRs produced in drosophila (15, 16). Currently, it remains unclear whether VSRs are able to interfere with the biogenesis and/or function of miRNAs in the nematode kingdom, which uses a single Dicer to initiate both siRNA and miRNA pathways. In this report, we show that FHV B2 is unable to suppress the biogenesis and function of miRNAs in *C. elegans* (Fig. 5 and 6). This is the first demonstration that VSRs selectively suppress siRNA, but not miRNA, function in organisms that use single Dicer to produce both siRNAs and miRNAs.

Previously, endogenous siRNAs that function in transposon control in drosophila have been shown to be susceptible to the inhibitory effect of VSRs (15). Recently, worm endogenous siRNAs have been shown to contribute to normal cellular function by maintaining wide-spread gene silencing, together with piRNAs, a class of endogenous small RNAs whose biogenesis does not require Dicer (58). Thus, it was expected that functional inhibition of these endogenous siRNAs by nodavirus B2 proteins,
which appears to inhibit the function of virus-derived siRNAs as shown in Fig. 5, will induce developmental defects in worms. Thus far, we have not observed any developmental defects associated with constitutive expression of the B2 VSRs. However, it remains possible that the inhibitory effect of the B2 proteins on worm endogenous siRNAs takes much longer time to develop or needs a specific bioassay to identify. Alternatively, strong inhibition of endogenous siRNA function may have resulted in lethal embryos and, as a result, only transgenic animals expressing the B2 proteins can retain their functional specificity in the worm system, making it possible to use these VSRs as genetic tools to study the biogenesis and function of worm endogenous siRNAs.

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REFERENCES


