Influence of Host Chloroplast Proteins on *Tobacco mosaic virus* Accumulation and Intercellular Movement

Sumana Bhat, Svetlana Y. Folimonova, Anthony B. Cole, Kimberly D. Ballard, Zhentian Lei, Bonnie S. Watson, Lloyd W. Sumner, and Richard S. Nelson*

Plant Biology Division, The Samuel Roberts Noble Foundation, Inc., Ardmore, Oklahoma 73401

*Tobacco mosaic virus* (TMV) forms dense cytoplasmic bodies containing replication-associated proteins (virus replication complexes [VRCs]) upon infection. To identify host proteins that interact with individual viral components of VRCs or VRCs in toto, we isolated viral replicate- and VRC-enriched fractions from TMV-infected *Nicotiana tabacum* plants. Two host proteins in enriched fractions, ATP-synthase γ-subunit (AtpC) and Rubisco activase (RCA) were identified by matrix-assisted laser-desorption ionization time-of-flight mass spectrometry or liquid chromatography-tandem mass spectrometry. Through pull-down analysis, RCA bound predominantly to the region between the methyltransferase and helicase domains of the TMV replicase. Tobamovirus, but not *Cucumber mosaic virus* or *Potato virus X*, infection of *N. tabacum* plants resulted in 50% reductions in Rca and AtpC messenger RNA levels. To investigate the role of these host proteins in TMV accumulation and plant defense, we used a *Tobacco rattle virus* vector to silence these genes in *Nicotiana benthamiana* plants prior to challenge with TMV expressing green fluorescent protein. TMV-induced fluorescent lesions on Rca- or AtpC-silenced leaves were, respectively, similar or twice the size of those on leaves expressing these genes. Silencing Rca and AtpC did not influence the spread of *Tomato bushy stunt virus* and *Potato virus X*. In AtpC- and Rca-silenced leaves TMV accumulation and pathogenicity were greatly enhanced, suggesting a role of both host-encoded proteins in a defense response against TMV. In addition, silencing these host genes altered the phenotype of the TMV infection foci and VRCs, yielding foci with concentric fluorescent rings and dramatically more but smaller VRCs. The concentric rings occurred through renewed virus accumulation internal to the infection front.

As obligate intracellular organisms, plant viruses must interact with various host factors essential for their accumulation and intercellular movement. These virus-host interactions are often complex and difficult to understand mechanistically, but for some of them considerable progress has been made in recent years (Ahlquist et al., 2003; Boevink and Oparka, 2005; Benitez-Alfonso et al., 2010; Harries et al., 2010; Ishibashi et al., 2010; Laliberté and Sanfaçon, 2010; Verchot-Lubicz et al., 2010; Le Gall et al., 2011; Nagy and Pogany, 2011; Niehl and Heinlein, 2011; Schoelz et al., 2011). Progress also has been made toward understanding virus-host interactions involved in the plant immune response (Kang et al., 2005; Padmanabhan and Dinesh-Kumar, 2010; Cournoyer and Dinesh-Kumar, 2011). There are other interactions that are not essential for virus accumulation and movement and that do not function in the immune response, but which also can significantly disrupt host and virus physiology and cause disease (Culver and Padmanabhan, 2007). Those involved in defense are often referred to as nonhost resistance and are not cultivar specific (Mysore and Ryu 2004; Maule et al., 2007). These interactions, whether to inhibit or aid virus accumulation, and the mechanism(s) by which they influence host physiology and disease induction are less understood than those involving essential or immune response interactions. Considering the serious effect these nonessential interactions can have on host development and disease, they require further study to devise new strategies to limit virus-mediated economic damage (Culver and Padmanabhan, 2007).

We have used the model *Nicotiana* spp.-*Tobacco mosaic virus* (TMV) system to further identify host factors that may participate in virus replication and elucidate their role in the accumulation, movement, and disease-invoking ability of a virus. TMV is a positive-sense single-stranded RNA virus that is the type member of the well-studied genus, *Tobamovirus*. The full-length RNA encodes the 126- and 183-kD replication-associated proteins, the latter translated by a read through of an amber termination codon at the end of the 126-kD protein open reading frame (Pelham, 1978). Together

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2 Present address: University of Florida, Citrus Research and Education Center, 700 Experiment Station Road, Lake Alfred, FL 33850.

3 Present address: Dakota Wesleyan University, Mitchell, SD 57301.

* Corresponding author; e-mail rnselson@noble.org.

The author responsible for distribution of materials integral to the findings presented in this article in accordance with the policy described in the Instructions for Authors (www.plantphysiol.org) is: Richard S. Nelson (rnselson@noble.org).

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they are often referred to as components of the TMV replicase. The 30-kD movement protein (MP) and the 17.5-kD coat protein (CP) are translated from the subgenomic mRNAs (Zaitlin, 1999). The 126- and 183-kD proteins are of central interest in this study. These proteins contain domains with sequences or activities similar to those of methyltransferases (MTs), helicases (HELs), and RNA-dependent RNA polymerases (POLs; Evans et al., 1985; Dunigan and Zaitlin, 1990; Koonin, 1991). In addition to their enhancement of, or necessity for, virus accumulation, respectively, the 126- and 183-kD proteins of TMV and related viruses are involved in other aspects of the viral infection. These include inducing mosaic symptoms in Nicotiana tabacum (Bao et al., 1996; Shintaku et al., 1996), mediating a necrotic resistance response through interaction with a specific host resistance gene in N. tabacum (Padgett and Beachy, 1993; Whitham et al., 1994; Abbink et al., 1998; Erickson et al., 1999), supporting intercellular virus movement in N. tabacum (Goregaoker et al., 2001; Hirashima and Watanabe, 2001, 2003), and suppressing gene silencing in N. tabacum and Nicotiana benthamiana (Ding et al., 2004). The determinants of some of these activities have been mapped to various regions within these viral proteins: chlorosis and gene silencing suppression determinants to the MT, HEL, and nonconserved domain between the MT and HEL domains, necrosis determinants to the HEL domain, and intercellular movement determinants to both the nonconserved and HEL domains (Bao et al., 1996; Padgett et al., 1997; Abbink et al., 1998; Hirashima and Watanabe, 2003; Ding et al., 2004; Wang et al., 2012).

Plant proteins associate with the 126- and/or 183-kD proteins and some of these interactions influence virus accumulation and disease development. The RNA binding subunit of host translation initiation factor eIF-3 was shown to associate with the RNA-dependent RNA POL complex of a TMV that infects tomato (Solanum lycopersicum); Osman and Buck, 1997). Another translation factor, elongation factor 1A (EF1a), interacts directly with the MT domain of the TMV 126-/183-kD proteins and is necessary for normal virus accumulation (Yamaji et al., 2006, 2010). Other host factors such as membrane proteins encoded by the Tobamovirus multiplication (TOM) genes that interact with the 126-kD protein or its ortholog and an associated host GTP-binding protein, ARL8, are essential for tobamovirus replication in Arabidopsis (Arabidopsis thaliana) and N. tabacum (Yamanaka et al., 2000; Yamanaka et al., 2002; Asano et al., 2005; Nishikiori et al., 2011). Also, the tomato resistance gene, Tm-1, was shown to interact with the homologs of the 126- and 183-kD proteins from the tobamovirus Tomato mosaic virus to prevent its replication (Ishibashi et al., 2007). The allelic gene of Tm-1, tm-1, which fails to interact with the replication proteins from or provide resistance to Tomato mosaic virus, does bind the replication proteins from and inhibit the replication of Tobacco mild green mosaic virus and Pepper mild mottle virus in vitro (Ishibashi et al., 2009). In regard to disease development, the plant P58IPK, an inhibitor of a double-stranded RNA-activated protein kinase, mediates interaction between the HEL domain of TMV replicase and the N. tabacum N protein for the normal development of disease symptoms (Bilgin et al., 2003). The HEL domain of the TMV 126-kD protein also interacts with a subset of the auxin/indole-3-acetic acid protein family, and this interaction is correlated with the disruption of auxin/indole-3-acetic acid targeting, increased virus accumulation in mature tissue, and the production of a disease phenotype (Padmanabhan et al., 2005, 2006, 2008). Lastly, through a direct or indirect interaction, microfilaments were determined to be necessary for the intracellular trafficking of the TMV 126-kD protein fused with GFP and sustained intercellular movement of TMV (Liu et al., 2005; Harries et al., 2009).

In addition to interacting with host proteins, the 126- and 183-kD proteins are present in dense cytoplasmic bodies (also referred to as VRCs for TMV) within the host cell during infection. These VRCs contain other virus-encoded proteins and associate with various host cell components such as ribosomes, endoplasmic reticulum, and cytoskeleton (Shalla, 1964; Hills et al., 1987; Heinlein et al., 1998; Mås and Beachy, 1999). The VRCs also are very dynamic, changing location and content over time (Szécsi et al., 1999). However, the full composition of the VRCs and their function during infection is still not understood. Also, considering that most plant viruses induce the formation of cytoplasmic bodies and the increasing experimental support that they are correlated with disease induction (Shalla et al., 1980; Liu et al., 2005; Liu et al., 2006), it is important to understand their composition and function during virus infection for practical purposes.

Here we describe the isolation and purification of complexes containing the TMV 126-/183-kD proteins from TMV-infected N. tabacum leaves and the use of proteomics to identify host proteins associated with them. Two nuclear-encoded chloroplast proteins, ATP synthase-ψ subunit (AtpC, encoded by AtpC) and Rubisco activase (RCA) copurified with enriched VRCs and/or viral POL. Their influence on virus accumulation, virus spread, and disease induction was investigated through gene knockdown in N. benthamiana plants. In addition, the influence of virus infection on their transcript accumulation and presence in VRCs was assessed. These proteins were found to specifically inhibit tobamovirus spread and/or accumulation, possibly through transient interaction with the 126-/183-kD proteins or indirectly through an unknown mechanism.

RESULTS

Identification of Host Proteins Enriched in the TMV Replicase Complex

The TMV replication-associated proteins associate with different plant factors during virus replication and movement within the host. To identify more host
proteins, TMV replicase complexes were isolated from *N. tabacum* leaves 4 d post inoculation (dpi) with the U1 strain of TMV (Shintaku et al., 1996). The fractions containing the highest TMV 126-/183-kD protein levels and RNA POL activities (Supplemental Fig. S1) were profiled by SDS-PAGE and compared with the healthy controls processed in parallel (Fig. 1A). The proteins that were present in higher levels in the extracts from TMV-infected leaves when compared with healthy control extracts were subjected to in-gel trypsin digestions and matrix-assisted laser-desorption ionization time-of-flight mass spectrometry (MALDI-ToFMS) or nano-liquid chromatography-tandem mass spectrometry (LC-MS/MS) analyses. Resultant mass spectral data were used in Mascot (Perkins et al., 1999) to search against the National Center for Biotechnology Information nonredundant database with a restriction to the Viridiplantae. The protein identifications were based upon significant molecular weight search (MOWSE) scores and at least two peptide matches. In addition to the 183- and 126-kD replication-associated proteins and 17-kD TMV CP, we identified two host chloroplast proteins, AtpC (GenBank accession no. X63606) and RCA (EMBL accession no. Z14980). AtpC is one of the subunits of the chloroplast ATP synthase and is encoded by a nuclear gene (*AtpC*) as a precursor protein (41 kD) that is transported from the cytoplasm into the chloroplast stroma where it is processed into its mature form (36 kD; Larsson et al., 1992). RCA is encoded by a nuclear gene (*Rca*) as an immature protein (approximately 49 kD) that also is transported from the cytoplasm into the chloroplast where it is processed into its mature form (approximately 42 kD) to activate Rubisco by releasing the bound sugar and phosphates from the active site in an ATP-dependent manner (Portis and Salvucci, 2002; Spreitzer and Salvucci, 2002). RCA is also a member of the AAA+ protein family (ATPases associated with diverse cellular activities; Portis et al., 2008). For AtpC and RCA, respectively, we obtained six peptide matches covering 16% of the apparent precursor protein (*M*, estimate from gel approximately 41 kD) and five peptide matches covering 19% of the apparent precursor protein (*M*, estimate from gel approximately 47 kD). To further investigate the presence of host factors in TMV VRCs, we performed a crude purification of the VRCs from *N. tabacum* using a virus expressing an MP-GFP fusion (TMV-MP-GFP-CP). The MP-GFP fusion is present in VRCs at early stages of infection (Heinlein et al., 1998; Liu et al., 2005). It is important to note that these fractions enriched for MP-GFP and 183- and 126-kD protein were also enriched with both precursor (49 kD) and mature (42 kD) forms of RCA (six peptide matches with a MOWSE score of 422 covering 21% of the precursor protein, and thirteen peptide matches with a MOWSE score of 1,402 covering 33% of the mature protein; Fig. 1B). Amino acid composition of the peptide fragments also matched those of the predicted RCA fragments. Although by position during SDS-PAGE migration both the POL-enriched and VRC-enriched fractions contained the precursor forms of AtpC and RCA (Fig. 1, A and B), no expected transit peptide fragments were identified through MALDI-ToFMS or LC-MS/MS analysis.

Because RCA was found in fractions enriched in both TMV POL activity and VRCs, we further analyzed the specific domains of the TMV replicase proteins required for the interaction with RCA by in vitro pull-down assays using glutathione-S-transferase (GST). The domains of 126-/183-kD proteins were fused to the C-terminal end of GST. Equal amounts of fusion proteins bound to glutathione sepharose beads were incubated with the S30 fraction of *N. tabacum* leaves and the pulled-down extracts were assayed by immunoblotting with anti-RCA. RCA bound to the GST-I, II nonconserved domain, located between the MT and HEL domains, and, to a lesser extent, the GST-MT and GST-POL domains (Fig. 1C), indicating that RCA interacts most specifically with the I, II domain of the TMV-encoded replicase proteins.

![Figure 1](https://plantphysiol.org)
Considering these results, experiments were initiated to determine if the AtpC and RCA proteins would colocalize extensively in vivo with the TMV 126-kD GFP fusion protein during ectopic expression or VRC of TMV during infection. After agroinfiltration of N. benthamiana epidermal leaves with fusions of AtpC or RCA with the mCherry reporter gene, we did not observe significant colocalization of these proteins to the VRCs induced by TMV.MP-GFP or to the inclusions induced during ectopic expression of the 126-kD GFP protein fusion (Supplemental Figs. S2 and S3).

Tobamovirus Infection Alters the Expression Levels of AtpC and Rca mRNAs

Because AtpC and RCA were enriched in replicase and/or VRC-enriched fractions from TMV-inoculated leaves when compared with the uninfected controls, we wanted to determine the effect of virus infection on the accumulation of their respective encoding mRNAs. To this end, N. tabacum leaves were challenged with TMV-U1, and the levels of AtpC and Rca mRNAs were determined by quantitative reverse transcription-PCR (RT-PCR) in the infected leaves. Both AtpC (Fig. 2A) and Rca (Fig. 2B) mRNAs were reduced by 50% in TMV-infected leaves compared with mock-inoculated leaves at 4 dpi. RCA levels in chloroplasts were also reduced by 70% after TMV infection (data not shown). In addition to TMV, N. tabacum leaves were challenged with Turnip vein clearing virus (TVCV), Cucumber mosaic virus (CMV), or Potato virus X (PVX). Infection by TVCV, a member of the Tobamovirus genus, like TMV, also reduced the levels of AtpC and Rca mRNA by 50% compared with mock-inoculated leaves (Fig. 2, A and B, respectively). It is important to note that infections with viruses belonging to different genera, the Cucumovirus CMV, and the Potexvirus PVX, modestly reduced AtpC mRNA levels and had no effect on Rca mRNA levels. The influence of tobamoviruses on AtpC and Rca mRNA levels was not due to a general down-regulation of host mRNA levels as EF1α and ubiquitin mRNA levels were induced equally by TMV, TVCV, PVX, and CMV (Supplemental Fig. S4). In addition, the influence of the tobamoviruses on AtpC and Rca mRNA levels was not due to a greater titer of these viruses compared with PVX and CMV because there was no correlation between virus titer and down-regulation of the targeted host mRNAs (compare results shown in Supplemental Fig. S5 and Fig. 2).

AtpC and RCA Influence Accumulation and/or Spread of TMV, But Not PVX or Tomato bushy stunt virus

To investigate the possible roles of AtpC and Rca during TMV infection, we used Tobacco rattle virus (TRV)-mediated virus-induced gene silencing (VIGS; Liu et al., 2002) to silence these genes in N. benthamiana. By 10 dpi, the plants infiltrated with TRV expressing a fragment of the AtpC or Rca genes (TRV-AtpC or TRV-Rca) showed stunted growth with light-green areas on systemically silenced leaves compared with the plants infiltrated with TRV vector alone (Supplemental Fig. S6, A and B). Quantitative RT-PCR analyses confirmed the silencing of AtpC and Rca genes (greater than 90% decrease in mRNA levels; Fig. 3, A and B). Fourteen days after infiltration with the VIGS vectors we inoculated silenced leaves with TMV.MP.GFP.CP, PVX-GFP, and Tomato bushy stunt virus (TBSV)-GFP infectious transcripts, all expressing unfused GFP. Virus intercellular movement on the TRV-AtpC/Rca, mock, and TRV controls was quantified by imaging GFP fluorescence at 4 dpi (Fig. 4A; Supplemental Fig. S7A). TMV.MP.GFP.CP-induced lesions on AtpC-silenced leaves were twice as large as those on mock-infiltrated and mock-silenced leaves (Fig. 4B). It is surprising that AtpC silencing had the opposite effect on TBSV-GFP and PVX-GFP intercellular spread, resulting in generally smaller lesions compared with those on mock-
and TRV-infiltrated leaves (Supplemental Fig. S7, B and C). Silencing Rca did not significantly alter the intercellular movement of TMV.MP.GFP.CP (Fig. 4B). However, lesions induced by TBSV-GFP (Supplemental Fig. S7B) and PVX-GFP (Supplemental Fig. S7C) were generally smaller on Rca-silenced leaves than on the mock- or TRV-inoculated leaves.

In an effort to determine the effect of AtpC and Rca silencing on the accumulation of TMV.MP.GFP.CP at 4 dpi, we utilized an ELISA to quantify TMV CP levels per lesion. The ELISA data showed that silencing Rca caused a 7-fold increase in TMV.MP.GFP.CP accumulation per cell and silencing AtpC caused a 4-fold increase in TMV accumulation, a portion of which could be accounted for by the increased intercellular spread (Fig. 4C, and for AtpC, compare with value in Fig. 4B). It is important to note that silencing of Rca and AtpC enhanced the TMV U1 pathogenicity in N. benthamiana plants with symptoms progressing more quickly in Rca- and AtpC-silenced plants (Fig. 5). By 14 dpi, TMV U1 infection resulted in stem necrosis and apical death in plants infiltrated with TRV-Rca (Fig. 5, A and C) and TRV-AtpC (Fig. 5, B and D) compared with mock-infiltrated or TRV-inoculated plants (Fig. 5, C and D).

Silencing of AtpC and Rca Alters the TMV.MP-GFP Infection Foci and VRC Phenotypes

To further study the effect of silencing AtpC and Rca on TMV accumulation and movement, we used TMV.MP-GFP (Heinlein et al., 1995), where GFP was fused with MP and the fusion was driven by the MP subgenomic promoter. N. benthamiana leaves silenced for AtpC and Rca expression were inoculated with TMV.MP-GFP, and the spread of GFP fluorescence was monitored at 4 dpi. As observed with TMV.

![Image](https://plantphysiol.org)
MP.GFP.CP, which expressed an unfused GFP (Fig. 4), lesions induced by TMV.MP-GFP on leaves silenced for AtpC were significantly larger than those on control plants (Fig. 6A). Also, for both the AtpC- and Rca-silenced leaves, we observed infection foci consisting of concentric fluorescent rings with alternating dark areas unlike those on mock-infiltrated and TRV-infiltrated controls (Fig. 6B). At least 90% of the total number of the TMV.MP-GFP foci present on AtpC-silenced leaves and 50% of those on Rca-silenced leaves had these concentric fluorescent rings.

We proposed two models to explain the formation of concentric fluorescent rings within infection foci. In the first model, we hypothesized that a reinitiation of MP-GFP accumulation either from the center of the infection foci or from the internal edge of the spreading infection occurs over time, resulting in successive rings as fluorescence spreads (Fig. 7A1). In the second model, we hypothesized that the initial infection ring spreads radially, inducing a defense response that inhibits virus accumulation as it spreads with time (through RNA interference or other inducible defense mechanisms). As the defense response proceeds, the virus, which is the inducer of the response, decreases in accumulation resulting in a dark area. At some point, the induction of the defense response becomes so low that virus again is able to accumulate, creating a second fluorescent ring outside the first. This ripple effect would continue over time radiating outward from the infection center (Fig. 7A2). To determine which of these hypotheses was correct, we compared the size of the single lesion ring at 2 dpi to those of the internal infection ring at 4 dpi with TMV.MP-GFP on AtpC-silenced leaves (compare size of ring at 2 dpi with those of internal ring at 4 dpi in Fig. 7, A and B). If the internal ring at 4 dpi was smaller than the ring at 2 dpi, the first model was supported. The internal infection rings at 4 dpi were significantly smaller than those of TMV.MP-GFP accumulation from the center of the infection site or the internal edge of the spreading infection (Fig. 7B and model 1 in Fig. 7A).

To examine the VRC phenotype in the concentrically ringed infection foci, the MP-GFP fluorescence at 4 dpi was observed under a higher magnification. The morphology of the TMV VRCs at the front of the infection ring induced in the AtpC- (Fig. 8C) and Rca-silenced (Fig. 8D) leaves were much smaller compared with those in tissue where these genes were not silenced (Fig. 8, A and B). In addition, a significant increase in the number and decrease in size of VRCs in the AtpC- and Rca-silenced leaves was observed compared with the controls (Fig. 8E). The huge increase in the number of VRCs in AtpC- and Rca-silenced leaves correlated with the increase in GFP accumulation in the individual lesions at 4 dpi (Fig. 8F).

**Intercellular Movement of TVCV Is Facilitated by Silencing AtpC and Rca**

Because silencing of AtpC and Rca did not facilitate the spread of TBSV and PVX, both members of different genera from TMV, we wanted to know the effect of silencing these genes on the intercellular movement of a virus in the same genus as TMV. Using TVCV expressing an unfused GFP (TVCV-GFP), we determined that similar to TMV, its spread at 4 dpi was significantly enhanced in N. benthamiana leaves silenced for AtpC (Fig. 9A). TVCV-GFP spread in leaves silenced for Rca expression resulted in, at most, a modest increase in lesion size compared with the mock-inoculated and TRV-inoculated controls (Fig. 9A). This result was more similar to those observed after TMV infection than those observed after TBSV or PVX infection (compare Fig. 4 and Supplemental Fig. S7 with Fig. 9). Taken together, these data indicate that silencing AtpC in N. benthamiana increases the spread of tobamoviruses specifically.

**DISCUSSION**

Host proteins play a critical role in the life cycle of an invading virus. However, host proteins that influence virus accumulation and symptoms, but are not essential
for virus accumulation or identified as participants in an active defense response, are poorly understood. Identifying these proteins and determining the mechanism by which these interactions translate to less virus or host transcript accumulation could lead to novel methods to achieve virus-resistant plants.

Nuclear-Encoded Chloroplast Proteins Associated with TMV Complexes Are Influenced by Tobamovirus Infection and, in Turn, Influence Tobamovirus Accumulation

We have identified two chloroplast proteins, AtpC and RCA, which are enriched in the TMV replicase complex fractions and for RCA, also in VRC fractions, upon extraction (Fig. 1). It is interesting to note that tobamovirus infections and not those of viruses from other genera inhibited the steady-state levels of mRNAs encoding these proteins (Fig. 2). In what may be a related finding, silencing AtpC and Rca released tobamoviruses to accumulate to high levels and in AtpC-silenced tissue, to spread more quickly (Fig. 4, 6, and 8). This high accumulation (Rca- and AtpC-silenced tissue) and more rapid spread (AtpC-silenced tissue) was associated with severe disease symptoms (Fig. 5). These nuclear-encoded chloroplast proteins (Larsson et al., 1992; Portis and Salvucci, 2002) therefore appear to have a function in defending against tobamovirus infections and tobamoviruses possibly evolved to specifically inhibit the expression of these genes to enhance their own accumulation.

Considering that tobamoviruses replicate in the cytoplasm of infected cells, it may seem surprising that two nuclear-encoded chloroplast proteins would be influenced by tobamovirus accumulation and themselves influence virus accumulation. However, infections with TMV and other viruses are known to alter the transcript levels of nuclear genes encoding chloroplast-localized proteins (Itaya et al., 2002). In addition, modifying levels of particular host chloroplast proteins alters the accumulation of some viruses. The chloroplast protein, phosphoglycerate kinase, is required for the accumulation of Bamboo mosaic virus, a virus related to PVX (Lin et al., 2007). Also, chloroplast proteins are implicated in defending against infections. NRIP1, a chloroplast-targeted host protein, is important for pathogen recognition through its ability to interact with both the plant N immune receptor and TMV 126-kD replicase protein (Caplan et al., 2008). Increased accumulation of TMV was observed upon silencing the genes encoding ferredoxin I and the 33K subunit of the oxygen-evolving complex (OEC) of PSII and increased

Figure 6. AtpC and Rca silencing influences the intercellular movement and/or visual phenotype of TMV-MP-GFP infection foci in N. benthamiana. A, Relative lesion areas were determined at 4 dpi with TMV-MP-GFP on silenced leaves from TRV-AtpC- or TRV-Rca-infiltrated plants with the percentages standardized against those from buffer-infiltrated (Mock) samples. Plants infiltrated with buffer or TRV without insert (TRV) were controls. Each bar represents a grand mean ± s.e of three experimental means. No deviation is shown for the mock treatment grand mean because each mock treatment experimental mean was normalized to 100% for comparison with other treatment values. Each experimental mean contained at least 12 replicates. The standard deviations for the experimental mock treatment means averaged 31%. Different letters above bars for each treatment indicate significant differences between those grand means at the P = 0.05 level as determined by ANOVA and LSD. B, Representative images of TMV-MP-GFP-induced infection foci at 4 dpi on mock-, TRV-, TRV-AtpC-, or TRV-Rca-infiltrated N. benthamiana plants. Bars = 1 mm.

Figure 7. Analysis of the mechanism by which concentric rings form in AtpC-silenced leaves after TMV-MP-GFP inoculation. A, Models to explain the visual phenotype of TMV-MP-GFP lesions on AtpC-silenced N. benthamiana leaves. The first involves reinitiation of infection either from the center of the infection locus or from the internal edge of the spreading infection, and the second involves repeated lowering and increasing over time of virus accumulation at the spreading front. B, Standardized lesion areas of virus-induced single rings at 2 dpi and middle rings at 4 dpi on AtpC-silenced N. benthamiana leaves. Each bar represents the mean of 24 replicates ± s.e.
accumulation of *Plum pox virus* (PPV) was observed upon silencing the gene encoding PSI subunit K (PSI-K) protein (Abbink et al., 2002; Jiménez et al., 2006; Ma et al., 2008). All of these proteins therefore appear to have a role in defending the host against infection. It is interesting to note that for both the 33K subunit and PSI-K proteins, infection by TMV or PPV inhibits their respective mRNA levels (Abbink et al., 2002; Jiménez et al., 2006). Both the 33K subunit and the PSI-K proteins were identified through yeast (*Saccharomyces cerevisiae*) two-hybrid screens with the helicase domain of the 126-kD protein of TMV and the cylindrical inclusion protein of PPV, respectively, as bait (Abbink et al., 2002; Jiménez et al., 2006). Thus, our findings with AtpC and RCA have striking similarities to findings by others for nuclear-encoded chloroplast proteins unrelated to AtpC or RCA. The challenge from all of these studies is to further understand mechanistically how these interactions influence virus accumulation.

**Toward a Mechanistic Understanding of AtpC and RCA Influence on Virus Accumulation**

One way to begin a mechanistic understanding is to consider the specificity of the interaction for a particular virus. This would provide some indication of the required protein structures to elicit the response. Abbink and associates (2002) determined that silencing the 33K OEC subunit mRNA, in addition to allowing TMV overaccumulation, resulted in a significant severalfold increase in accumulation of viruses from different genera, PVX and *Alfalfa mosaic virus*. Although the possibility exists that proteins encoded by these disparate viruses have similar motifs that also interact with the 33K OEC subunit, it seems more likely that the down-regulation of the 33K OEC subunit accumulation, either by silencing or TMV infection, results in a general nonspecific plant response that supports accumulation of multiple viruses. Perhaps supporting this conclusion is the finding that infection of *N. tabacum* with *Alfalfa mosaic virus* did not decrease the mRNA levels of the 33K OEC subunit (Abbink et al., 2002). In our study, we determined that silencing AtpC and RCA caused a significant increase in the spread (in AtpC-silenced tissue) and accumulation (in AtpC and RCA-silenced tissue) of the tobamoviruses, TMV and TVCV, but not viruses of other genera, TBSV and PVX. These findings suggest that the modified activities of these host proteins caused by the tobamoviruses do not cause a general plant metabolic response that would aid the accumulation of all viruses. Further support for this conclusion comes from our finding that the levels of virus accumulation in infected tissues for each virus...
were not correlated with the level of AtpC and Rca transcript levels in these tissues (Fig. 2; Supplemental Fig. S5).

The different infection phenotypes displayed in plants silenced for AtpC and RCA indicates a further specificity in the effect of these proteins on tobamovirus physiology. That silencing of Rca mRNA resulted in only an increase in TMV accumulation, whereas silencing of AtpC resulted in predominantly an increase in virus spread indicated that different aspects of the TMV life cycle were influenced by silencing these respective genes. The main known function of RCA in plants is to activate Rubisco by releasing the bound sugar and phosphates from the active site in an ATP-dependent manner (Portis and Salvucci, 2002). Possibly of more interest, RCA is a member of the AAA family of proteins (Portis and Salvucci, 2002; Portis, 2003). These proteins often assemble as hexameric ring complexes and utilize a conserved ATPase domain as an energy generator to remodel macromolecules during divergent processes such as protein unfolding and degradation, organelle biogenesis, and DNA recombination and repair (Ogura and Wilkinson, 2001; Snider et al., 2008). In the study by Abbink and colleagues (2002), in addition to the previously described 33K OEC subunit, a protein belonging to the AAA family but with unknown function was identified that also interacted with a portion of the TMV replicase-associated proteins (Abbink et al., 2002). Unlike our findings with RCA, however, they found that TMV infection did not modify the transcript levels of this protein and silencing this AAA gene resulted in a decrease in TMV accumulation (Abbink et al., 2002). Additionally, we found that RCA had its strongest interaction with domain I, II between the MT and HEL domains of the TMV replicase-associated proteins whereas the AAA with unknown function interacted with the helicase domain (Fig. 1C; Abbink et al., 2002).

AAA family members have a conserved domain necessary for ATPase activity that is within the core of the multimer complex, with less conserved domains which undertake the distinct activities for each family member often to the perimeter of this core region. It may be that the common domain of the AAA proteins interacts with the TMV replicase-associated domains because multiple AAA proteins have been identified that interact with the TMV 126-/183-kD proteins (Fig. 1; Abbink et al., 2002; a plant representative of the FtsH gene family [S. Bhat and R.S. Nelson, unpublished data]). However, the common domain in these AAA proteins is not sufficient to explain the opposite effects observed for RCA and the unknown AAA protein on virus accumulation: one limiting and one aiding virus accumulation. The unique domains on these AAA proteins or the unique binding sites for these proteins within the 126-/183-kD proteins may control these responses.

Regarding the response of TMV to RCA specifically, we hypothesized that RCA was retargeted to VRCs in the cytoplasm instead of chloroplasts by the 126-/183-kD proteins because putative precursor protein identified by size was present in SDS-PAGE (Fig. 1, A and B), possibly leading to the premature degradation of the replication complex. Our finding that RCA interacts in vitro with domains of 126- and 183-kD replicase, particularly with the domain I, II, is consistent with this hypothesis (Fig. 1C). An example of a relocation of another host protein by a viral protein is the observation that the TBSV P19 protein interacts in vitro with the Arabidopsis ALY2 protein involved in RNA transport and relocates ALY2 from its normal nuclear location to the cytoplasm (Uhrig et al., 2004). However, in our study, after agroinfiltration with fusions of AtpC or RCA with the mCherry reporter gene, we did not observe significant relocation of these proteins to the VRCs induced by TMV MP-GFP or to...
the inclusions induced during ectopic expression of the 126-GFP protein fusion (Supplemental Figs. S2 and S3). Also, no relocalization of RCA to VRCs was observed by immunofluorescence microscopy on fixed tissue incubated with rhodamine-conjugated secondary antibodies (data not shown). The interactions between host proteins and TMV VRCs may be transient and in immunofluorescence studies, disrupted during cell fixation. Another possibility is that only a small percentage of the total RCA protein and/or replicase have the correct structure(s) to bind one another and thus not at a level that could be detected by fluorescence colocalization studies. Support for this hypothesis comes from the pull-down results where only a small percentage of the input RCA was bound by the various replicase domains (Fig. 1C). However, we cannot be certain whether what was bound reflected a structure in minor amounts or was limited by the absence of the virus holoprotein or the binding capacity of the assay. It is also possible that the interaction between AtpC or RCA with the 126-kD protein is present only on extraction. The influence of these host proteins on virus accumulation then would be necessarily indirect, for example by supporting host activities whose products then inhibit virus accumulation. Assuming lower photosynthesis rates in the absence of RCA and AtpC (in particular under normal CO₂ levels; Somerville et al., 1982; Rott et al., 2011), it is interesting that the tobramoviruses would overaccumulate under these conditions because previous studies indicate that TMV accumulation is indirectly supported when photosynthesis is unimpeded (Kano, 1985). Thus, it likely would be other functions of these proteins, beyond supporting photosynthesis, responsible for inhibiting tobramovirus accumulation.

AtpC and RCA host proteins could have a role in plant defense against TMV infection by manipulating signaling pathways. It is intriguing to note that the proteolytic fragments of Atpcs referred to as inceptors play an important role in defending legume plants against insect attack by inducing various phytohormone signaling pathways including salicylic acid, jasmonic acid, and ethylene (Schmelz et al., 2006, 2007). Applying this information to our findings, perhaps the reduction in AtpC mRNA induced by TMV or free AtpC due to an interaction with the 126-/183-kD protein(s) results in fewer proteolytic fragments of AtpC. This would result in less salicylic acid, and lower salicylic acid accumulation allows greater spread and accumulation of TMV (Chivasa et al., 1997; Murphy and Carr, 2002). Further work is necessary to test the efficacy of this model.

Two characteristics of the tobramovirus infection phenotypes in both Rca- and AtpC-silenced plants is the appearance of concentric fluorescent rings and the overproduction of multiple small VRCs (Figs. 6B and 8, C and D). It is likely that the increased accumulation of TMV in the AtpC-silenced plants rather than its increased spread in these plants is represented by these phenotypes because they are displayed to varying degrees during virus infection in Rca-silenced plants where only increased virus accumulation was observed (Fig. 6, B and D). Under normal conditions with no gene silencing, TMV MP-GFP produces a single fluorescent ring due to completion of the virus life cycle and the degradation of MP-GFP in the center of the infection foci (Szekcsi et al., 1999). In an effort to further understand the cause of the concentric fluorescent rings in Rca- and AtpC-silenced plants, we determined that the additional ring of fluorescence initiated either from the center of the infection foci or from the internal edge of the spreading infection rather than through waves of increased and decreased virus accumulation at the infection front (Fig. 7). This finding is consistent with a model where there is renewing of virus accumulation in tissue normally finished with this activity (Fig. 7A, model 1). It is possible that the formation of the smaller and more numerous VRCs and viruses in plants silenced for AtpC and RCA accumulation is mechanistically related to the concentric ring phenotype (Figs. 8 and 6). The appearance of these numerous and bright granules may reflect overaccumulation of virus or virus products that would lead over time to an inducible host defense (e.g. RNA interference) at the center of the lesion.

The concentric fluorescent ring phenotype displayed by TMV in the AtpC- and RCA-silenced plants resembles the concentric necrotic rings observed during infections with ringspot viruses. The development of concentric ring spots of Tomato ringspot virus in N. benthamiana induced the accumulation of hydrogen peroxide in the ring spots (Jovel et al., 2007). However, there was no correlation in virus accumulation levels between necrotic and nonnecrotic tissue in systemically infected leaves (Jovel et al., 2007). Although it is necessary to verify this finding within necrotic and nonnecrotic tissue from necrotic ringspots themselves (the more closely related system to our work), this result is different from our findings where the presence of alternating fluorescence intensities is a direct measure of alternating levels of accumulation of a virally encoded protein. In addition, the cause of the concentric rings themselves requires further study. We have indicated that the fluorescent rings may be due to a loss of a defense response internal to the infection front that in some manner is associated with AtpC or RCA silencing. Both these genes are more active in light (e.g. Kusnetsov et al., 1999; Wang et al., 2003) and thus ring formation may be due to a diurnal decrease in the efficiency in silencing in this tissue. Impaired silencing, however, would likely influence accumulation at the infection front, in addition to an influence internal to the front, leading to multiple rings appearing externally and internally as the infection spreads (i.e. model 2). Our results do not support this mechanism of ring formation. In addition, if silencing efficiency was the cause of the ring pattern, similar rings might be observed even in nonsilenced tissue due to the diurnal pattern of AtpC and RCA expression. Such a ring pattern is absent in nonsilenced tissue.
(Fig. 6; Szécsi et al., 1999). Although our results support the conclusion that a weakened defense response, related to AtPC and Rca silencing, allows reinitiation of infection internal to the spreading infection, the intracellular mechanism responsible for the concentric fluorescent ring phenomenon and its relationship to necrotic ringspot formation requires more study.

CONCLUSION

Taken together, our results demonstrate that the host chloroplast proteins AtPC and Rca interact with TMV replication-associated proteins and VRCs in vitro and play a role in plant defense specifically against tobamoviruses. Although both proteins limit tobamovirus infections, they have different effects on TMV spread, indicating that although they interact with similar TMV complexes, their influences are not always on the same stage of the virus life cycle. A practical outcome of this work is that overexpression of these proteins in plants may result in an increased resistance to tobamoviruses. Further studies of these host proteins during TMV infection will tell much about how host factors involved in “passive” resistance to virus infection function.

MATERIALS AND METHODS

Plant Materials, Virus Strains, and Virus Inoculations

Nicotiana tabacum and Nicotiana benthamiana were grown as described (Harries et al., 2008). Purified virus (TMV) U1 strain, (Shintaku et al., 1996) or virus from plant extracts TVCV, CMV, and PVX (Yang et al., 2004) were used in some studies. Plant extracts containing TVCV, CMV, or PVX were obtained by grinding infected leaf tissue in liquid nitrogen followed by addition of approximately 2 volumes of 0.1 M sodium phosphate buffer (pH 7). Crude extracts or purified TMV U1 strain diluted with phosphate buffer, then were inoculated directly to plants dusted with carborundum (330 grit, Fisher), as described (Ding et al., 2004). Gene silencing was conducted by standard RNA interference (RNAi) and cloned into pCR-Blunt II-TOPO as instructed (Invitrogen). A 425-bp fragment from N. benthamiana leaves as described (Ding et al., 2004). Gene silencing was confirmed by standard RNA extraction and quantitative RT-PCR analysis.

Total RNA Extraction and Quantitative RT-PCR Analysis

Total RNA from leaf tissues were extracted using an RNeasy plant mini kit (Qiagen) and treated with DNase I. First-strand cDNA was synthesized using a 20-fold diluted cDNA, gene specific primers, and the Power SYBR Green master mix (Applied Biosystems) were used for quantitative RT-PCR analyses of AtPC and Rca mRNA levels with an ABI Prism 7900 HT sequence detection system (Applied Biosystems). To normalize the mRNA levels of target genes between samples, relative EF1-α and ubiquitin mRNA levels also was determined through this method. Additionally, virus levels in tissues were determined through reverse transcription and quantitative PCR with virus-specific primers. To create standard curves used to quantify virus levels, virus RNA was isolated from infected tissue through virus-specific procedures: TMV and TVCV (Bruning and Bhat et al., 2001).
et al., 1976; Gooding and Hebert, 1967), PVX (AboulHaidar et al., 1998; Franki and McLean, 1968), and CMV (Roossinck and White, 1998). The viral RNA was quantified by spectrophotometry. Viral RNA levels from treatment tissue were quantified by comparing their cycle threshold values obtained during quantitative RT-PCR with cycle threshold values obtained from mock-inoculated tissue spiked with known amounts of viral RNA. Reverse-strand synthesis utilized SRT III (Invitrogen). Primers for all quantitative RT-PCR reactions are provided (Supplemental Table S1).

Statistical analysis of VRC numbers and sizes in Atpc- and Rca-silenced compared with mock- and TRV-infected control plants utilized generalized linear or linear mixed models (number: GENMOD procedure, size: MIXED procedure) with repeated measurements in SAS 9.3 (SAS Institute, Inc.). As necessary, the data were transformed to meet assumptions for equal variances between means. Individual treatment mean comparisons utilized the Tukey-Kramer adjustment of P values.

ELISAs

For ELISA analyses, discs of equal size containing tissue from outside the perimeter of the largest green fluorescent lesion were harvested at a particular dpi, as described in the results, and frozen in liquid nitrogen. Frozen tissue was homogenized in 100 μL of phosphate-buffered saline (PBS) buffer (0.14 M NaCl, 3 mM KCl, 10 mM phosphate buffer, pH 7.0), and ELISAs were performed for TMV CP accumulation as described (Derrick et al., 1997).

GST Constructs and Pull-Down Assay

The cDNA fragments of MT (nucleotides 69–999), I, II (nucleotides 956–2487), HEL (nucleotides 2463–3416), and POL (nucleotides 421–4916) domains of 126-/183-kD proteins were cloned into pGEX-5X-2 (GE Lifesciences) and expressed in Escherichia coli. Expressed GST or GST-fused MT, I-II, HEL, and POL domains were bound to 50 μl of glutathione sepharose 4B as instructed (GE Lifesciences). Supernatant fraction (S30) from N. tabacum was prepared as described previously (Yamaji et al., 2006). Tubes containing approximately equal amounts of GST or GST virus genes fusion bound to sepharose beads, as determined through SDS-PAGE analysis of the bound beads, were incubated with 200 μL of S30 fraction in protein interaction buffer (PBS containing 1% Triton X-100, 0.5% NP-40, 0.1% SDS, and 1mM phenylmethylsulfonyl fluoride) for 1 h at 4°C. The beads were washed three times, twice with PBS containing 1% Triton X-100 and once in PBS. Unbound fractions were removed and the bound beads were heated in SDS-PAGE sample buffer at 100°C for 10 min and centrifuged at 18,000g for 5 min. The supernatant was resolved on 10% SDS-PAGE and subjected to immunoblotting.

Total Protein Extraction and Western-Blot Assays

Plant tissue frozen in liquid nitrogen was ground to fine powder and thawed in protein extraction buffer (5 mM Tris-HCl, pH 8.0, 130 mM NaCl, 2 mM MgCl2, 50 mM KCl, 1% Triton X-100, 0.5 mM dithiothreitol) containing protease inhibitor (Complete EDTA-free, Roche; 1 tablet/50 mL). Samples were placed on ice for 30 min and centrifuged at 18,000g for 10 min. Fifteen micrograms of each protein sample was boiled in SDS-PAGE sample buffer at 100°C for 10 min and centrifuged at 18,000g for 5 min. The supernatant was resolved on 4% to 10% SDS-PAGE and subjected to immunoblotting.

Microscopy

Fluorescent viral lesion images were captured with an Olympus SZX-12 fluorescent stereomicroscope (Olympus). Lesion areas (pixels) were measured using the MetaMorph 4.5 program (Universal Imaging). TMV-MP-GFP VRCs were imaged on a Bio-Rad model 1024ES. Images were processed using Adobe Photoshop. GFP was excited using a 488-nm line from a krypton/argon laser and emissions were captured at 522 nm.

Subcellular Localization of AtpC and RCA

Full length Atpc and Rca open reading frames were cloned into 5G-mCherry plasmid obtained from Dr. Elison Blancafor (Noble Foundation) and introduced into A. tumefaciens GV2260 by electroporation. For studies on the interaction of Atpc and RCA with ectopically expressed 126-kD protein-GFP fusion, A. tumefaciens containing the 126-kD protein-GFP fusion was co-cultivated with A. tumefaciens containing Atpc-mCherry or Rca-mCherry using a needleless syringe and observed 2 dpi. For studies involving later challenge with the virus, N. benthamiana leaves were syringe-infiltrated with A. tumefaciens containing Atpc-mCherry or Rca-mCherry and placed in the growth chamber for 2 d. Leaves expressing Atpc-mCherry or RCA-mCherry then were inoculated with TMV-MP-GFP, and 4 dpi, the infected cells were imaged using a Perkin-Elmer UltraView ERS spinning-disc confocal system coupled to a Zeiss Observer D1 inverted microscope. The cells were observed with a 63× water-immersion objective. GFP was excited at 488 nm, and emission was detected at 510 nm. Chloroplast autofluorescence was detected by excitation at 467 nm, and emission was detected at 680 nm. mCherry was excited at 587 nm, and emission was detected at 610 nm. Sequence data from this article can be found in the GenBank/EMBL data libraries under accession numbers X63606 and Z14980.

Supplemental Data

The following materials are available in the online version of this article.

Supplemental Figure S1. Fraction analysis for TMV 126- and 183-kD proteins and RNA POL activity.

Supplemental Figure S2. Lack of Atpc- or RCA-mCherry colocalization with TMV.MP-GFP in epidermal cells of N. benthamiana.

Supplemental Figure S3. Lack of Atpc- or RCA-mCherry colocalization with a 126-kD protein-GFP fusion in epidermal cells of N. benthamiana.

Supplemental Figure S4. Host EF1α and ubiquitin mRNA levels in N. tabacum challenged with TVCV, CMV, and PVX.

Supplemental Figure S5. Virus accumulation in extracts from challenged plants analyzed for Atpc and Rca mRNA levels in Figure 2.

Supplemental Figure S6. Atpc and Rca mRNA silencing phenotypes in N. benthamiana plants.

Supplemental Figure S7. Influence of Atpc or Rca silencing on intercellular movement of TBV-GFP and PVX-GFP.

Supplemental Table S1. Primers for VIGS constructs and quantitative RT-PCR analyses.

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