Matching NLR Immune Receptors to Autoimmunity in camta3 Mutants Using Antimorphic NLR Alleles

Highlights

- Dominant-negative NLR forms (DN-NLR) disrupt the function of wild-type NLR alleles
- DN-NLRs can be used to screen for suppression of autoimmunity in autoimmune mutants
- Two NLRs (DSC1 and DSC2) are responsible for autoimmunity in Arabidopsis camta3 mutants
- Immunity triggered by DSC1 or DSC2 in tobacco is suppressed by CAMTA3 co-expression

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In Brief

NLRs detect pathogen-induced modifications in plant proteins, triggering immunity. Lolle et al. express dominant-negative NLRs (DN-NLRs) and screen for suppressed autoimmunity in various mutants. DN-NLRs for DSC1 and DSC2 suppress autoimmunity in a camta3 mutant, a putative negative regulator of immunity, suggesting that autoimmunity results from detection of modified self.
Matching NLR Immune Receptors to Autoimmunity in camta3 Mutants Using Antimorphic NLR Alleles

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SUMMARY

To establish infection, pathogens deploy effectors to modify or remove host proteins. Plant immune receptors with nucleotide-binding, leucine-rich repeat domains (NLRs) detect these modifications and trigger immunity. Plant NLRs thus guard host “guardees.” A corollary is that autoimmunity may result from inappropriate NLR activation because mutations in plant guardees could trigger corresponding NLR guards. To explore these hypotheses, we expressed 108 dominant-negative (DN) Arabidopsis NLRs in various lesion mimic mutants, including camta3, which exhibits autoimmunity. CAMTA3 was previously described as a negative regulator of immunity, and we find that autoimmunity in camta3 is fully suppressed by expressing DN of two NLRs, DSC1 and DSC2. Additionally, expression of either NLR triggers cell death that can be suppressed by CAMTA3 expression. These findings support a model in which DSC1 and DSC2 guard CAMTA3, and they suggest that other negative regulators of immunity may similarly represent guardees.

INTRODUCTION

The innate immune system includes receptors that recognize pathogen-associated molecular patterns (PAMPs). Thus, plants and animals have bacterial flagellin receptors that trigger immunity (Gómez-Gómez and Boller, 2002). Successful pathogens deliver effectors into host cells to suppress this layer of immunity (Jones and Dangl, 2006). In a next layer, cytoplasmic nucleotide-binding leucine-rich-repeat domain (NLR) receptors, which are similar to animal NOD-like receptors, directly or indirectly recognize the activities of pathogen effectors. NLRs activate effector triggered immunity (ETI) that is often associated with local host cell death known as the hypersensitive response (HR) (Dangl et al., 2013). Two subfamilies of plant NLRs can be defined by the presence of either an N-terminal Toll/interleukin-1 receptor (TIR) or a coiled-coil (CC) domain (Jones and Dangl, 2006).

Signaling by TIR-NLRs generally requires ENHANCED DISEASE SUSCEPTIBILITY1 (EDS1), whereas NON-RACE SPECIFIC DISEASE RESISTANCE1 (NDR1) is important for CC-NLR-triggered HR (Aarts et al., 1998). So while bacterial effectors possess diverse activities to manipulate host responses (Speth et al., 2007), NLRs with diverse recognition specificities and downstream signaling are found in single plant species (DeYoung and Innes, 2006). An example of this complexity is the bacterial pathogen Pseudomonas syringae (Pst), which injects effectors via a type III secretion system to establish infection in Arabidopsis (Buell et al., 2003). These effectors include AvrRpm1 and AvrRpt2, which target the host protein RIN4 by phosphorylation or degradation, respectively. These changes in RIN4 are detected by two NLRs, RPM1 and RPS2, which both trigger ETI (Axtell and Staskawicz, 2003; Belkhadir et al., 2004). Importantly, loss of RIN4 results in RPS2-dependent autoimmunity, indicating that RPS2 guards RIN4 (Axtell and Staskawicz, 2003; Spoel and Dong, 2012).

Numerous autoimmune or lesion mimic mutants are caused by gain-of-function mutations in NLRs (Shirano et al., 2002; Zhang et al., 2003) or by loss of function in diverse genes thought to act as negative regulators of immunity and the HR (Dietrich et al., 1994; Greenberg and Ausubel, 1993; Greenberg et al., 1994; Lu et al., 2011; Petersen et al., 2000; Shirano et al., 2002; Zhang et al., 2003). Interestingly, the autoimmune phenotypes of these mutants are largely the same as those for ETI, including EDS1/PAD4 or NDR1 dependency, stunted growth, accumulation of reactive oxygen species, and elevated defense gene expression (Brodersen et al., 2002, 2006; Grant et al., 2000; Sohn et al., 2014; Zhang et al., 2003). In addition, like ETI, autoimmunity can often be suppressed by high growth temperature (Zhang et al., 2012). Importantly, some 40% of Arabidopsis autoimmune mutants are suppressed by mutations in NLRs and other immune signaling components (Bruggeman et al., 2015; Rodriguez et al., 2016).

Other evidence linking autoimmunity and NLRs may be hybrid necrosis. Some 2% of intraspecific Arabidopsis crosses yield F1 progeny with hybrid necrosis or autoimmunity, which can be suppressed at higher growth temperatures (Bomblies and Weigel, 2007). These incompatibility loci often map to rapidly evolving NLR genes or gene clusters. Such hybrid necrosis may be due to the activation of NLR-dependent defense responses due to a failure in guard-guardee interactions (Chae et al., 2014).
In some instances, NLR-dependent autoimmunity is well described. ACCELERATED CELL DEATH11 (ACD11) is a ceramide-1-phosphate transfer protein (Simanshu et al., 2014), and acd11 mutants exhibit autoimmunity dependent on the NLR LAZ5. Thus, acd11 is rescued by laz5 knockout and by a dominant-negative laz5-D2 allele, indicating that ACD11 or its complexes/pathways are likely effector target(s) guarded by LAZ5 (Palma et al., 2010). The laz5-D2 allele has a mutation in the P loop (Leu→Asn) of its nucleotide-binding domain (Palma et al., 2010). This is similar to the DN mutation (Val→Asn) of the tobacco NLR N, which also abolishes its function (Mestre and Baulcombe, 2006). Clearly, the P loop is important for NLR function.

Knockout of MAP kinase 4 (MPK4) or double knockouts of the two upstream kinases MKK1 and 2 also lead to autoimmunity, which is suppressed by mutations in the NLR SUMM2. Since the MPK4 pathway is a target of the HopAI1 effector and HopAI1 activity triggers SUMM2, loss of MKK1/2 mimics the presence of HopAI1 and triggers SUMM2-dependent autoimmunity (Zhang et al., 2012). It is, therefore, likely that NLRs cause autoimmunity in plants with mutations in genes encoding effector targets.

An example of such NLR-induced autoimmunity might be the CALMODULIN BINDING TRANSCRIPTION ACTIVATOR 3 (CAMTA3) with five homologs in Arabidopsis (CAMTA1–6) (Bouché et al., 2002), CAMTA1, 2, and 3 appear to coordinately regulate gene expression (Kim et al., 2013), but loss of CAMTA3 is sufficient to cause autoimmunity (Galon et al., 2008). Since CAMTA3 can bind to the promoter of EDS1 and mutations in EDS1 rescue camta3 mutants, CAMTA3 was proposed to function as a negative regulator of immunity and EDS1 transcription (Du et al., 2009). In contrast, CAMTAs may positively regulate early stress response genes via a core CAMTA-binding sequence present in their promoters (Benn et al., 2014).

We describe here a collection of 108 Arabidopsis NLRs mutated in their P loops to potentially create their corresponding dominant-negative NLR-DN alleles. We transform this collection into various lesion mimic mutants, including camta3, to screen for suppression of autoimmunity. As proof of principle, we first show that transgenic lines expressing RPM1-DN are indistinguishable from RPM1–3 knockout mutants in terms of ETI and gene-for-gene resistance. Importantly, RPM1-DN does not interfere with common CC-NLR or TIR-NLR signaling pathways. In addition, we find that DN mutants of two NLRs we name DSC1 and DSC2 fully suppress autoimmune in the camta3 mutant. Since DSC1- and DSC2-triggered cell death in N. benthamiana is prevented specifically by CAMTA3 expression and as DSC1 appears to interact with both CAMTA3 and DSC2, autoimmunity in camta3 is probably not caused by a lack of its proposed function as a negative regulator of genes required for immunity. Instead, the camta3 phenotype is triggered by the NLRs DSC1 and DSC2.

RESULTS

Function and Specificity of P Loop Mutations

Screens for suppression of one or more autoimmune mutants by NLR loss-of-function mutations are time consuming and potentially uninformative for NLRs with redundant functions. We therefore took an alternative, transgenic approach with a screen for suppression in T2 transformants. Since specific mutations in the P loop domain of NLRs can have dominant-negative effects (Dinesh-Kumar et al., 2000; Palma et al., 2010; Roberts et al., 2013), we examined the consequences of a P loop mutation in the well-studied CC-NLR RPM1 (GK, 221, 222, AA; here named RPM1-DN). RPM1 triggers cell death in plants infected with Pst DC3000 (AvrRpm1) (Grant et al., 1995). We compared cell death responses in 4-week-old Col-0, rpm1–3 knockout mutant, and two independent RPM1-DN transformants (RPM1-DN1 and RPM1-DN2), using an electrolyte leakage assay (Mackey et al., 2003). As expected, cell death measured as conductance increased in Col-0 already after 3 hr (Figure 1A). However, this increase was suppressed in RPM1-DN1 and RPM1-DN2 plants to the same extent as in rpm1–3 (Figure 1A). We also tested resistance responses in 4-week-old, short-day-grown rosette leaves syringe infiltrated with Pst DC3000 (AvrRpm1), by measuring bacterial growth at 0 and 3 days. After 3 days, bacterial growth was almost 100-fold higher in RPM1-DN1, RPM1-DN2, and rpm1–3 compared to Col-0 (Figure 1B). Moreover, we did not observe any difference in growth of virulent Pst DC3000 among Col-0, rpm1–3 mutants, and plants expressing RPM1-DN (Figure 1C). Thus, expression of RPM1-DN in wild-type plants compromises the function of RPM1.

We then tested the specificity of this dominant suppression by examining if resistance to bacteria expressing AvrRps4 and AvrRpt2 was affected by the expression of RPM1-DN. AvrRps4 is recognized by the TIR-NLR pairs RPS4/RPS1 and RPS4B/RPS1B (Narusaka et al., 2009; Saucet et al., 2015), whereas resistance against AvrRpt2 is conferred by the CC-NLR RPS2 (Tsuchida et al., 2013). This revealed that two RPM1-DN lines suppressed similar levels of growth of Pst DC3000 (AvrRps4) as Col-0 and rpm1–3, while the susceptible control eds1–2 supported significantly higher growth (Figure 2A). Similarly, expression of RPM1-DN did not interfere with recognition of AvrRpt2, as the RPM1-DN lines did not support more bacterial growth than Col-0 (Figure 2B). As expected, the susceptible control ndr1 supported significantly higher bacterial growth than the other genotypes (Figure 2B). Thus, plants expressing dominant-negative versions of RPM1 are indistinguishable from rpm1–3 mutants and the function of other NLRs is unaffected. Lastly, to confirm that mutations in specific NLRs can suppress single autoimmune mutants, we mutated the P loop in SUMM2. Loss-of-function mutations in the de-capping activator PAT1 (PROTEIN ASSOCIATED WITH TOPOISOMERASE II NUMBER 1) lead to SUMM2-dependent autoimmunity, including dwarfism and elevated levels of the defense marker PATHOGENESIS RELATED 1 (PR1) transcripts (Roux et al., 2015). Similar to pat1 summ2 double homozygotes, expression of SUMM2-DN in pat1 suppressed dwarfism, enhanced resistance, and elevated PR1 transcript levels (Figure S1). Thus, as in pat1 summ2 plants, autoimmunity is suppressed in pat1 mutants expressing SUMM2-DN.

Introducing a P Loop Mutation in Multiple Arabidopsis NLRs

The proof of concept with DN mutant forms of RPM1 and SUMM2 prompted us to introduce such mutations into an additional 106 Arabidopsis NLRs (Table S1). These NLRs were used because they were readily cloned/mutated and because they...
encode typical TIR- (72 genes) or CC-NLRs (34 genes) without truncations or additional domains. With RPM1 and SUMM2, this allele collection represents 89% (73/82) of Arabidopsis TIR-NLRs and 73% (35/48) of CC-NLRs (Meyers et al., 2003). More specifically, the conserved P loop motif GXXXXGK(T/S) in these genes was mutated to GXXXXAA(T/S) using mismatch primers and a multi-fragment USER cloning approach (Geu-Flores et al., 2007). Sequenced clones were introduced into Agrobacterium GV3101 and then transformed into wild-type plants and a collection of autoimmune mutants, including camt3. Independent T1 plants (T2 seeds) were collected after BASTA selection and screened for suppression of stunted growth, chlorosis, or early flowering phenotypes exhibited by the autoimmune mutants. In a screen of /C24 NLR-DN-expressing lines, we identified one line exhibiting suppression of the camt3 phenotype (Figure 3A). We named this line, which

Figure 1. Expression of RPM1-DN Compromises RPM1 Function and Attenuates Resistance
(A) AvrRpm1-dependent cell death is inhibited by RPM1-DN expression. Ion leakage assay after inoculation of Pst DC3000 (AvrRpm1) into Col-0, rpm1–3, or two transgenic lines overexpressing RPM1-DN (line RPM1-DN1 and 2) is shown. Error bars represent ±SD. Groups with statistically different means are indicated by different letters.
(B and C) Col-0 resistance to Pst DC3000 (AvrRpm1, B) is compromised by RPM1-DN expression. No effect is seen in resistance to Pst DC3000 carrying an empty vector (C). Growth of Pst DC3000 (AvrRpm1 or empty vector) at days 0 (gray) and 3 (black) as log10-transformed colony-forming units per square centimeter leaf tissue (CFU/cm²) is shown. Error bars represent ±SD (n = 4). Means not sharing the same letter are significantly different.

Figure 2. RPM1-DN Expression Specifically Inhibits RPM1 Function and Does Not Compromise Resistance to AvrRps4 or AvrRpt2
(A and B) Wild-type resistance to Pst DC3000 (AvrRps4 and AvrRpt2) is retained in transgenic RPM1-DN plants. Col-0, rpm1–3, RPM1-DN1, RPM1-DN2, and eds1-2 or ndr1-1 were inoculated with Pst DC3000 (AvrRps4, A, and AvrRpt2, B). Bacterial growth was measured on days 0 (gray) and 3 (black). Mean ± SD (n = 4) is shown and means not sharing the same letter are significantly different.

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expresses the DN form of the NLR encoded by At4g12010, DSC1-DN for DOMINANT SUPPRESSOR OF camta3 NUMBER 1-DOMINANT NEGATIVE. DSC1 encodes a typical TIR-NLR proposed to be part of an NLR pair together with the TIR-NLR At4g12020 (Narusaka et al., 2009). This head-to-head pair may share a small promoter region of 273 bp and both genes are lowly expressed (AtGenExpress). However, Meyers et al. (2003) found that DSC1 is one of only 38 NLRs for which mRNA expression levels are affected by SA or flg22, while At4g12020 is not. Although At4g12020 is the closest homolog of DSC1, it contains WRKY and MAPx kinase domains and was, therefore, not included in our NLR-DN collection.

There are six CAMTA proteins in Arabidopsis, and null alleles of CAMTA1 or CAMTA2 in camta3 mutants enhance the latter’s dwarfism and chlorosis (Kim et al., 2013). However, expression of DSC1-DN in camta1 camta3 double mutants did not suppress this growth defect. This indicates that DSC1-DN suppression is specific to CAMTA3 (Figure S2).

NLR-Dependent Autoimmunity in camta3
T3 lines homozygous for DSC1-DN were examined for suppression in more detail. The 6-week-old camta3 mutants grown in short days exhibited stunted growth, necrotic lesions in older leaves (Figure 3A), and clusters of dead mesophyll cells (Figure 3B) (Du et al., 2009). In contrast, camta3 DSC1-DN appeared wild-type (Figures 3A and 3B). Expression of DSC1-DN in Col-0 did not affect its wild-type growth and did not induce cell death (Figures 3A and 3B).
The camta3 mutants also exhibit increased resistance toward virulent Pst DC3000 (Galon et al., 2008). To evaluate if this trait was also abrogated by expression of DSC1-DN, we syringe inoculated 5-week-old plants with Pst DC3000 and measured bacterial growth after 3 days. While bacterial growth in camta3 mutants was significantly lower than in Col-0, bacterial growth was restored to wild-type levels in camta3 DSC1-DN (Figure 3C). Importantly, expression of DSC1-DN in Col-0 did not affect susceptibility (Figure 3C).

The camta3 mutants constitutively express defense genes, including PR1 (Du et al., 2009). However, PR1 mRNA levels were restored to Col-0 levels in camta3 DSC1-DN lines, and the expression of DSC1-DN in Col-0 did not affect PR1 mRNA levels (Figure 3D).

Since CAMTA3 was found to bind the EDS1 promoter and was reported to be a negative regulator of EDS1 expression, elevated levels of EDS1 and other CAMTA3-regulated transcripts were thought to cause autoimmunity in camta3 (Du et al., 2009). While autoimmunity in camta3 mutants may be suppressed by DSC1-DN, expression of EDS1 should remain elevated in camta3 DSC1-DN. In agreement with previous reports, we found that EDS1 mRNA levels were significantly higher in 5-week-old camta3 compared to Col-0 plants (Figure 3E). However, the levels of EDS1 transcripts in camta3 DSC1-DN were not significantly different from those in Col-0 or DSC1-DN single mutants (Figure 3E). These results indicate that autoimmunity in camta3 mutants is triggered by DSC1 and not by the loss of negative regulation of EDS1 and other regulatory transcripts.

CAMTA3 Interacts with DSC1 and Inhibits DSC1-Triggered HR in N. benthamiana
To further investigate the relationship between DSC1 and CAMTA3, we expressed them in N. benthamiana as transient overexpression of NLRs can trigger HR cell death in this system (Césari et al., 2014). In line with this, expression of DSC1 alone triggered strong and rapid HR-like cell death (Figure 4A). This DSC1-triggered HR was suppressed by co-expression with CAMTA3 (Figure 4A), while co-expression of CAMTA1 or CAMTA2 had no influence on DSC1-triggered HR (Figure 4A). Expression of the three CAMTA3 alone did not induce a reaction. DSC1, therefore, acts as an HR trigger specifically in the absence of CAMTA3.

The above results suggest that DSC1 and CAMTA3 represent a guard/guardian pair. We therefore speculated that DSC1 and CAMTA3 may be found together in subcellular complexes. To assess this, we examined the localization of CAMTA3 fused to CFP (Figure 3A) and DSC1 fused to yellow fluorescent protein (YFP) (Figure 3B). Since both showed cytoplasmic and nuclear localization when transiently expressed in N. benthamiana, we tested their interaction in vivo by Förster resonance energy transfer acceptor bleaching (FRET-AB). Using CFP_CAMTA as donor and YFP_DSC1 as acceptor, we observed a clear increase in donor fluorescence (FRET efficiency) after photobleaching of YFP (Figure 4B). The same FRET efficiency was not seen with donor/acceptor pairs of CFP_CAMTA and YFP_SUMM2 or CFP_MPK4 and YFP_DSC1, included as negative controls (Figure 4C). To confirm the positive FRET, we transiently expressed HA_DSC1 with CAMTA3_CFP or GFP_MYC in N. benthamiana and immunoprecipitated DSC1 with HA-trap beads. Only CAMTA3_CFP was detected in HA_DSC1 precipitates (Figure 4D), confirming that DSC1 and CAMTA3 can exist in complexes in planta.

Autoimmunity in camta3 Depends on Two NLRs
To further probe connections between DSC1 and CAMTA3, we generated camta3 dsc1 double loss-of-function mutants. Surprisingly, these double mutants appeared indistinguishable from camta3 single mutants (Figure 5A), and, upon inoculation with Pst DC3000, they showed camta3-like enhanced resistance (Figure 5B). In addition, like camta3, camta3 dsc1 had elevated levels of PR1 and EDS1 expression (Figures 5C and 5D). This suggests that DSC1-DN interferes with more than just DSC1 function. As two or more NLRs may guard the same guardee (Belkhadir et al., 2004; Eitas et al., 2008) and as NLRs may dimerize (Eitas and Dangl, 2010; Narusaka et al., 2009, 2013), we speculated that DSC1 might function together with another NLR. If so, DSC1-DN might poison their cooperativity while the absence of DSC1 in the dsc1 mutant would not. We therefore screened our remaining NLR-DN alleles for suppression of camta3 autoimmune, and we found an NLR-DN allele of At5g18370, here called DSC2-DN, whose expression also fully suppressed the camta3 phenotypes (Figure 6A). The closest DSC2 homolog (At5g18350), separated from it by ~10 kb encoding both a TIR-NLR (At5g18360) and another gene (At5g18362), was included in the NLR-DN screen, but it did not exhibit suppression of camta3.

As for DSC1-DN, expression of DSC2-DN in camta3 abrogated resistance to Pst DC3000 (Figure 6B) and restored PR1 expression almost to wild-type levels (Figure 6C). Expression of DSC2-DN in Col-0 did not affect resistance or PR1 expression levels. Importantly EDS1 mRNA levels in camta3 DSC2-DN were similar to those in Col-0 and DSC2-DN (Figure 6D). We also found that, as for DSC1, transient expression of DSC2 in N. benthamiana triggered HR-like cell death, which was suppressed by co-expression with CAMTA3 (Figure 6E). This again indicates that autoimmunity in camta3 mutants is triggered by NLRs and is not due to the loss of CAMTA3 as a negative regulator of EDS1.

We generated camta3 dsc2 double mutants to further examine the connection between CAMTA3 and DSC2. Unlike camta3, camta3 dsc2 did not exhibit dwarfism, but leaf development was not restored to wild-type (Figure S4A). The camta3 dsc2 mutants also had only partial suppression of resistance toward Pst DC3000 (Figure S4B), and they showed higher expression of PR1 and EDS1 compared to wild-type (Figures S4C and S4D).

Since camta3 dsc1 showed no suppression and camta3 dsc2 showed only partial suppression of the camta3 autoimmune phenotypes, we generated triple camta3 dsc1 dsc2 mutants. These triple mutants appeared wild-type and developed like Col-0 (Figure 7A), while camta3 growth defects were restored in the triple mutant complemented with genomic clones of either DSC1 or DSC2 (Figure 5S). Although the triple mutants did not develop visible autoimmune phenotypes, it was possible that they retained increased pathogen resistance. To test this, we inoculated leaves of Col-0, camta3, and camta3 dsc1 dsc2 with Pst DC3000. This demonstrated that camta3 dsc1 dsc2 resistance
Figure 4. CAMTA3 Is Associated with DSC1 in *N. benthamiana*

(A) Expression of CAMTA3 rescues DSC1-induced cell death in *N. benthamiana*. Inoculation with *Agrobacterium* expressing DSC1 resulted in HR induction. Co-inoculation with CAMTA3 inhibited this DSC1-induced cell death. Co-inoculation with CAMTA1 or CAMTA2 failed to inhibit the induction of HR. Dashed lines mark infiltrated areas.

(B and C) Detection of in vivo interaction between CAMTA3 and DSC1 by FRET in *N. benthamiana*. CFP_CAMTA3 and YFP_DSC1 were co-expressed in *N. benthamiana* and analyzed for FRET-AB. CFP_MPK4 and YFP_PAT1 were included as positive controls. Negative controls are CFP_CAMTA with YFP_SUMM2 and CFP_MPK4 with YFP_DSC1. Error bars represent ± SD (n = 4). Means not sharing the same letter are significantly different. See also Figure S3.

(D) CAMTA3 is associated with DSC1 in *N. benthamiana*. HA_DSC1 and CAMTA3_CFP or GFP_MYC were co-expressed in *N. benthamiana* and tissue was harvested at 24 hpi. Immunoblots of input and anti-HA immunoprecipitates (IPs) probed with anti-HA and anti-GFP antibodies are shown. Left panel, anti-HA IP; right panel, input; black arrow, HA_DSC1; gray arrow, CAMTA3_CFP; white arrow, GFP_MYC.

was restored to wild-type levels (Figure 7B). While increased resistance was seen in camta3 and in camta3 dsc1 and camta3 dsc2 3 days post-inoculation (Figures 5B and S4B), bacterial growth in camta3 dsc1 dsc2 reached the same levels seen in Col-0 and in camta3 DSC1-DN and camta3 DSC2-DN (Figures 7B, 3B, and 6B). In addition, *PR1* levels were restored to
wild-type levels in the camta3 dsc1 dsc2 triple mutant (Figure 7C), in contrast to the higher levels in camta3 dsc1 and camta3 dsc2 (Figures 5C and S4C). Furthermore, EDS1 mRNA levels in camta3 dsc1 dsc2 plants were similar to those in Col-0 (Figure 7D).

In summary, DSC1 and DSC2 contribute to autoimmunity in camta3. Although they seem to operate independently, the fact that the dominant-negative version of either one influences the other suggests that DSC1 and DSC2 interact directly or indirectly. To test this, we transiently expressed HA_DSC1 with DSC2_YFP, YFP_DSC2, or GFP_MYC in N. benthamiana, and we immunoprecipitated DSC2 with GFP-trap beads. As a specificity control, we also expressed DSC2-YFP, YFP-DSC2, and GFP-MYC with HA-RPS4 (Zhang et al., 2004), as DCS1 and RPS4 share 61% amino acid identity. HA_DSC1 could only be detected in DSC2 precipitates and not in GFP_MYC precipitates (Figure 7E). In contrast, RPS4 was not detected in the DSC2_YFP precipitates, although a faint RPS4 band was observed in the YFP_DSC2 precipitates when expressed at similar levels to DSC1 at 24 hr post-inoculation (hpi) (Figure 7E). In line with this, expression of RPS4 alone triggered strong and rapid HR-like cell death only a few days after infiltration, which was not suppressed by co-expression with CAMTA3 (Figure 7F).

These data show that DSC2 preferentially co-immunoprecipitates with DSC1, indicating that they may be found in complexes in planta.

**DISCUSSION**

*Arabidopsis* autoimmune mutants have been intensively studied for more than 20 years (Dietrich et al., 1994; Greenberg and Ausubel, 1993; Greenberg et al., 1994). Many reports link autoimmune phenotypes to NLR-signaling pathways and recently also directly to NLR genes (Bonardi et al., 2011; Bruggeman et al., 2015; Palma et al., 2010; Roux et al., 2015; Zhang et al., 2012). We hypothesized that numerous phenotypes related to autoimmunity may be caused by NLR activation. This implies that specific mutations in host plant guardees mimic pathogen effector activities and trigger the corresponding NLR guards.

To examine this possibility, we introduced specific mutations into the P loops of a large collection of NLRs. This approach was supported by (1) the conservation of the P loop in the STAND and closely related NLR families (Leipe et al., 2004); (2) the dominant-negative effects of such mutations on the *Arabidopsis* LAZ5 and tobacco N NLRs (Dinesh-Kumar et al., 2000; Mestre and Baulcombe, 2006; Palma et al., 2010); and (3) the possibility that numerous NLRs form dimers or directly or indirectly associate in complexes (Mestre and Baulcombe, 2006), leading to dominant-negative subunit poisoning.

As proof of concept, we compromised the function of RPM1 by expressing its dominant-negative version, and we showed that this suppression was specific and did not affect general NLR function (Figures 1 and 2). Abolition of RPM1 function by...
P loop mutation was shown previously (Chung et al., 2011; Tornero et al., 2002), but not the dominant-negative effect described here. In addition, we found that expression of SUMM2-DN suppressed autoimmunity in pat1 mutants (Figure S1). Thus, NLR-DN alleles can be made via simple P loop mutagenesis.

We then conducted a screen to identify other NLR-DN alleles that suppress the autoimmune phenotype of the camta3 mutant (Galon et al., 2008). This screen identified DSC1-DN and DSC2-DN. CAMTA3 was described as a negative regulator of immunity due to the ectopic accumulation of defense-related transcripts, including EDS1 in camta3 mutants, and to the suppression of camta3 phenotypes in camta3 eds1 double mutants (Du et al., 2009). However, EDS1 is ectopically expressed in many autoimmune mutants, and EDS1 mutations suppress autoimmunity in many of them (Bruggeman et al., 2015; Rodriguez et al., 2016). We show here that EDS1 mRNA levels are similar to those in wild-type when DSC1-DN or DSC2-DN is expressed in camta3 (Figures 3E and 6D). Importantly, the increased resistance to virulent Pst DC3000 in camta3 was also reduced to wild-type (WT) levels in camta3 expressing either DSC1-DN or DSC2-DN (Figures 3C and 6B). These findings do not support a function for CAMTA3 as a negative regulator of immunity.

Figure 6. DSC2-DN Transgene Suppresses the camta3 Autoimmune Phenotypes

(A) camta3 growth and chlorosis phenotypes are rescued by the expression of DSC2-DN. Pictures are representative for several individual lines.

(B) Expression of DSC2-DN suppresses resistance in camta3 mutants. Plants were syringe inoculated with Pst DC3000 and colony-forming units per square centimeter counted on days 0 (gray bars) and 3 (black). Error bars represent ±SD (n = 4). Bars with different letters are significantly different.

(C) PR1 mRNA levels are reduced to almost wild-type levels in camta3 mutants expressing DSC2-DN. PR1 mRNA expression levels are shown. Error bars represent ±SD (n = 3). Letters indicate statistical significance.

(D) EDS1 mRNA levels are elevated in camta3 mutants, but they are similar to Col-0 levels in camta3 DSC2-DN. The mRNA levels for EDS1 are shown. Error bars represent mean ± SD (n = 3). Means not sharing the same letter are significantly different.

(E) Expression of CAMTA3 rescues DSC2-induced cell death in N. benthamiana. Inoculation with Agrobacterium expressing DSC2 results in the induction of HR. Co-inoculation with CAMTA3 inhibits the DSC2-induced cell death. Co-inoculation with CAMTA1 or CAMTA2 failed to inhibit HR induction. Areas of infiltration are marked by dashed lines.
regulator of either EDS1 expression or resistance to the pathogen tested.

Nonetheless, Du et al. (2009) provided other evidence that CAMTA3 negatively regulates EDS1 expression. First, CAMTA3 recognized an EDS1 promoter element that was responsible for suppression of a reporter gene driven by the EDS1 promoter. Second, chromatin immunoprecipitation in protoplasts with transiently overexpressed, YFP-tagged CAMTA3 showed enrichment of EDS1 promoter elements, confirming that CAMTA3 can bind EDS1 promoter elements (Du et al., 2009). Third, plants that overexpress CAMTA3 exhibit increased susceptibility to virulent Pst DC3000 (Jing et al., 2011). Nonetheless, these and other data (Du et al., 2009; Nie et al., 2012) do not provide direct evidence for inhibition of transcription by CAMTA3.

More recently, the rapid stress response element (RSRE), characterized in promoters that rapidly respond to stresses including flg22 (Walley et al., 2007), was identified as a core CAMTA3-binding element. In addition, CAMTA3 could transiently activate the expression of a RSRE:LUC reporter (Benn et al., 2014), and a camta3 mutant exhibited reduced RSRE:LUC activity (Bjornson et al., 2014). Similarly, a general stress response and RSRE induction is CAMTA3 dependent (Benn et al., 2016). These findings indicate that CAMTA3 is a positive regulator of early stress responses. While CAMTA3 may thus possess both positive and negative regulatory activities, our data indicate that autoimmunity in camta3 is NLR triggered.

Our results are consistent with a model in which DSC1 and DSC2 guard CAMTA3 and/or a complex or pathway in which CAMTA3 functions. Importantly, we show that CAMTA3 may exist in complexes with DSC1 in planta (Figures 4B–4D).
Moreover, both DSC1 and DSC2 can trigger the HR when expressed in N. benthamiana, but co-expression of CAMTA3 prevents this (Figures 4A and 6E). Thus, these two NLRs appear inactive in the presence of CAMTA3 but are activated in its absence. This is analogous to immunity triggered by RPS2 upon effector-mediated degradation of the host guardee RIN4 (Axtell and Staskawicz, 2003; Mackey et al., 2003).

Interestingly, camta3 autoimmune phenotypes were not suppressed in camta3 dsc1 or camta3 dsc2 double loss-of-function mutants. This may be explained if both DSC1 and DSC2 can be triggered in the absence of CAMTA3. In line with this, autoimmunity was completely suppressed in camta3 dsc1 dsc2 triple loss-of-function mutants. Thus, autoimmunity in camta3 can be triggered by both NLRs, and the function of both must be abrogated to prevent autoimmunity.

These findings and the co-immunoprecipitation of DSC1 with DSC2 in N. benthamiana suggest that they interact. Such interactions probably do not only involve direct heterodimerization under natural conditions, as such heterodimer formation would be disrupted in their single dsc1 or dsc2 loss-of-function mutants, leading to the suppression of camta3 mutant phenotypes. Alternatively, the DSC1 and DSC2 co-precipitation is consistent with indirect associations via complexes with CAMTA3 or an N. benthamiana ortholog. In a simple model, if activation of such complexes was dependent on either or both DSC1 and DSC2, then activation might be compromised by overexpression of the DN form of either NLR, but not by loss of function of either single NLR. Elucidation of such models requires further biochemical and structural work on plant NLR self-association interfaces (Zhang et al., 2017) in light of animal NLR oligomerization (Hu et al., 2017).

More than one NLR may contribute to autoimmunity in other mutants, including acd11 and mpk4. For example, laz5-D2 can fully suppresses acd11 autoimmunity, although acd11 laz5-1 doubly homozygous recessive mutants still display significant cell death and activated defense under certain growth conditions (Palma et al., 2010). Similarly, summ2 only partially suppresses mpk4 (Zhang et al., 2012). In addition, some NLRs function in pairs of a sensor and a trigger (Cesari et al., 2014; Sarris and Jones, 2015). However, since both DSC1 and DSC2 can independently trigger immunity in the absence of CAMTA3, it is unlikely they constitute a sensor/trigger pair. It appears more likely that different activities of microbial effectors targeting CAMTA3 or CAMTA3-containing complexes or pathways are differentially sensed by DSC1 and DSC2. According to the NLR phylogeny of Meyers et al. (2003), DSC1 and DSC2 are not especially closely related. This may not be surprising, however, as two NLRs that monitor RIN4 function, RPS2 and RPM1, are also not especially closely related.

We conclude that our screen to link NLR-DN alleles to potential guardees is a more robust and timely method than suppression screens of double loss-of-function mutants. Furthermore, our dominant-negative method can identify NLRs with redundant functions or working in pairs. If exploited, our collection of NLR-DN constructs (Table S1) should clarify the relationships between guardees and numerous negative regulators of immunity and cell death in plants.

STAR METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information includes five figures and two tables and can be found with this article online at http://dx.doi.org/10.1016/j.chom.2017.03.005.

AUTHOR CONTRIBUTIONS


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REFERENCES


### Key Resources Table

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CONTACT FOR REAGENT AND RESOURCE SHARING

Further information and requests for resources and reagents should be directed to and will be fulfilled by the Lead Contact, Morten Petersen (shutko@bio.ku.dk).

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Arabidopsis thaliana

Arabidopsis plants were grown in 9 × 9 cm pots in growth chambers at 22°C and ~70% relative humidity and with an 8 hr photoperiod. The intensity of the light was set at ~140 μE m⁻² s⁻¹. The following Arabidopsis lines were used in this study: wild-type Colombia (Col-0), camta3-1 (referred to as camta3), SALK_001152 (Galon et al., 2008); dsc1, Sail_49_C05; dsc2, SALK_009668; rpm1-3 (Grant et al., 1995); pat1-1, summ2-8 (Zhang et al., 2012); pat1/summ2 (Roux et al., 2015); ndr1-1 (Century et al., 1995) and eds1-2 (Parker et al., 1996; Aarts et al., 1998). All lines have been authenticated by genotyping; the primers used are listed in Table S2. All P loop mutated NLR lines created in this study is listed in Table S1.

Nicotiana benthamiana

Plants were grown in greenhouses under controlled conditions (24°C and 40%–65% relative humidity), and a long-day photoperiod (16 hr light and 8 hr dark). Illumination were set to ~130-150 μE m⁻² sec⁻¹.

Escherichia coli

E.coli (XL blue) were grown on LB plates with appropriate antibiotic at 37°C and kept at 4°C for up to two weeks. For liquid cultures a bacterial scrape were inoculated in 5 mL LB supplemented with appropriate antibiotics and grown at 37°C under shaking.
Agrobacterium tumefaciens
Strains of Agrobacterium (GV3101 and Agl-1) were grown on YEP plates with appropriate antibiotic at 28°C and kept at 4°C for up to two weeks. For liquid cultures a bacterial scrape were inoculated in 5 mL YEP supplemented with appropriate antibiotics and grown at 28°C under shaking. After 24 hr, YEP was added to a total volume of 11 ml.

Pseudomonas syringae pv. tomato DC3000
Pst. DC3000 strains were grown on NYg plants containing 100 μg/ml rifampicin, 12.5 mikrogram/ml kanamycin, and 50 mikrogram/ml cyclohexamide at 28°C for two days. For liquid cultures 5 mL NYC supplemented with kanamycin and rifampicin were inoculated with a slab of bacteria. Pst. DC3000 containing the avirulence genes avrRpm1 (Grant et al., 1995), avrRps4 (Hinsch and Staskawicz, 1996), avrRpt2 (Bent et al., 1994) in the broad host range vector pvSP61, or DC3000 containing empty pvSP6, were used in this study.

METHOD DETAILS

Cloning
WT CAMTA3, DSC1 and DSC2 was amplified from genomic DNA (from Col-0 plants) without STOP codon and cloned into a modified USER compatible pENTR vector using uracil-excision based cloning (USER, New England Biolabs). Cloning primers were tagged with 5'ggcttaaU3' for the forward primer and 5'ggcttaaU3' for the reverse primer. Constructs were transferred to Gateway-compatible constitutive expression vectors by LR recombination reaction (Invitrogen). The plasmids were verified by sequencing and then electroporated into Agrobacterium tumefaciens GV3101.

For subcellular localization, FRET, cell death and immunoprecipitation, CAMTA3 was transferred to pGWB645 (35S pro, N-terminal CFP) and pGWB514 (35S pro, C-terminal HA); DSC1 was transferred to pGWB542 (35S pro, N-terminal YFP) and pGWB515 (35S pro, N-terminal HA) and DSC2 were transferred to pGWB541 (35S pro, C-terminal YFP) and pGWB542.

GFP was PCR amplified from plasmid template and cloned into pENTR/D-TOPO (Invitrogen). The construct was subsequently transferred to the Gateway-compatible constitutive expression vector pGWB517 (35S pro, C-terminal MYC) by LR recombination reaction (Invitrogen). The plasmids were verified by sequencing and then electroporated into Agrobacterium tumefaciens Agl-1.

CAMTA1 and CAMTA2 in pENTR/D-TOPO were obtained from the ABRC Stock center. CAMTA1 and CAMTA2 were transferred to pGWB645 (35S pro, N-terminal CFP) by LR recombination reaction (Invitrogen). Plasmids were verified by sequencing and then electroporated into Agrobacterium tumefaciens GV3101.

Generation of transgenic Arabidopsis lines
To generate the double mutants, camta3-1 homozygous plants were crossed with homozygous dsc1 or dsc2. Homozygous double mutant plants were identified in the F2 progeny by PCR. For the camta3/dsc1/dsc2 triple mutant, homozygous camta3/dsc1 double mutants were crossed with homozygous camta3/dsc2. Homozygous triple mutants were identified in the F2 progeny by PCR. Homozygosity and correct insertion T-DNA sites were verified by PCR using standard conditions. Genotyping primers for T-DNA lines are provided in Table S2.

Generation of camta1 camta3 DSC1-DN lines was done by genetic crossing of homozygote lines of the camta1 camta3 double mutants and DSC1-DN. Homozygous triple mutants were identified by PCR. Homozygosity and correct insertion T-DNA sites were verified by PCR using standard conditions. Genomic constructs used to complement camta3 dsc1 dsc2 triple mutants was inserted in pGWB601. Plants were transformed by floral dip (Clough and Bent, 1998).

NLR P loop collection
P loop mutated NLRs were created from genomic DNA by USER mutagenesis (Nour-Eldin et al., 2006) and cloned into a modified USER compatible pCAMBIA-3300, using uracil-excision based cloning (USER, New England Biolabs). Cloning primers were tagged with 5’ggcttaaU3’ for the forward primer and 5’ggcttaaU3’ for the reverse primer. Mutagenesis primers were made containing the P loop mutation GXXXXGKT(T/S) to GXXXXAAT(T/S) of the P loop motif and appropriate uracil’s incorporated to give seamless overlap of two fragments (Geu-Flores et al., 2007) generated with PfuX7 (Norholm, 2010).

The final constructs were verified by sequencing, electroporated into Agrobacterium tumefaciens strain GV3101 and used to transform camta3 or wild-type plants by the floral dip method (Clough and Bent, 1998). Transgenic plants were selected on soil with BASTA (10 mg/L).

Ion leakage
Four-week-old plants were syringe inoculated with Pst. DC3000 (avrRpm1) at OD600 = 0.2. Four leaf discs were punched out. Samples were taken from one side of the leaf between the central vein and leaf margin. Leaf discs were washed in distilled H2O to eliminate signal derived from wounded cells. Four discs from each line were then placed in tubes containing fresh distilled H2O, and measurements of solution conductivity were taken at the indicated time points using a conductivity meter.

Resistance assay
For bacterial growth assays, leaves of 5-week-old soil grown plants were inoculated by syringe infiltration (OD600 = 0.001) with Pst DC3000 either containing avirulence genes or the empty vector. Bacterial growth (Colony forming units per cm2) was determined
3 days post inoculation, day 0 counts were analyzed in infiltrated leaves to ensure that no statistical difference was present at inoculation and that day 3 showed positive growth. The experiments were repeated in at least three individual biological replicates, each with three technical replicates.

**Trypan blue staining**
Leaves of 6 week-old plants were boiled in Trypan blue 2-3 min and destained in chloral hydrate. Leaves were placed on slides in 50% glycerol for visualization of dead cells.

**Quantitative Real-Time PCR**
RNA was extracted from plant leaves using the NucleoSpin RNA Plant kit (Machery-Nagel). First-strand cDNA synthesis was carried out using RevertAid First Strand cDNA Synthesis Kit according to the manufacturer’s instructions (Thermo Scientific). The constitutively expressed UBQ10 gene was used as an internal control. qRT-PCR analysis was performed on a Bio-RAD CFX96 system with the dye SYBR Green (Thermo Scientific). All experiments were repeated at least three times each in technical triplicates. Primer sequences are listed in Table S2.

**Cell death**
For transient expression *N. benthamiana* was syringe infiltrated with *Agrobacterium* at OD<sub>600</sub> = 0.5 expressing indicated constructs. GV3101 carrying 35S p19 was co-infiltrated at OD<sub>600</sub> = 0.2. For cell death assays leaves were analyzed ~3 dpi.

**Subcellular localization and FRET**
*N. benthamiana* was infiltrated with *Agrobacterium* at OD<sub>600</sub> = 0.5 expressing indicated constructs. For subcellular localization and FRET, leaf disks were analyzed 2 or 3 dpi. Subcellular localization was done using a LSM700 Zeiss confocal microscope. All samples were imaged with a 63X water objective. The confocal images were edited with Zen2012 (Zeiss) software. FRET-AB was done using a Leica SP5-X inverted confocal microscope. All experiments were done with a 63X water objective. FRET analysis was performed using Leica FRET-AB wizard software.

**Protein extraction and Co-immunoprecipitation**
*N. benthamiana* was infiltrated with *Agrobacterium* at OD<sub>600</sub> = 0.5 expressing indicated constructs. GV3101 carrying 35S p19 was co-infiltrated at OD<sub>600</sub> = 0.2. Protein were extracted 24 hpi in 50mM Tris-HCl pH 7.5; 150mM NaCl; 10% (v/v) glycerol; 10mM DTT; 10mM EDTA; 0.5% (v/v) PVP; protease inhibitor cocktail (Roche); 0.1% (v/v) Triton X-100 added at 2ml/g tissue powder. Following 20 min centrifugation at 4°C and 13000 rpm sample supernatants were adjusted to ~3mg/ml protein and incubated 2 hr at 4°C with GFPTrap-A beads (Chromotek) or anti-HA antibody (Santa cruz) and EZview protein A agarose beads (Sigma). Beads were washed [20mM Tris pH 7.5; 150mM NaCl; 1mM EDTA] before adding 2x SDS and heating at 80°C.

**SDS-PAGE and immunoblotting**
Protein samples were separated on 8% SDS-PAGE, electroblotted to PVDF membrane (GE Healthcare), then blocked (1 hr in 5% (w/v) BSA or 5% (w/v) milk in TBS-Tween (0.1%)) and incubated 2 hr to overnight with primary antibodies: anti-GFP 1:5000 (AMS Biotechnology), anti-HA 1:1000 (Santa Cruz), anti-HA 1:1000 (Cell Signaling). Membranes were incubated in secondary antibodies, anti-rabbit or anti-mouse AP or HRP conjugate (Promega; 1:5000) for 1 hr. Chemiluminescent substrate (homemade or ECL Plus, Pierce) was applied before exposure to film (AGFA CP-BU) or camera detection. For AP-conjugated antibodies, membranes were incubated in NBT/BCIP (Roche) until bands were visible.

**QUANTIFICATION AND STATISTICAL ANALYSIS**
Statistical details of experiments are reported in the figures and figure legends. In short, n = 3 for all samples if nothing else is stated and ± standard deviation of the mean is indicated by error bars. Means not sharing the same letter are significantly different. Statistical significance between groups was determined by ANOVA One-Way comparison followed by Tukey’s HSD (honest significant difference) test, p < 0.05, was used unless otherwise stated. At least three individual replicas were always included. All statistics were done using the software OriginPro (OriginLab).