PAD4 Functions Upstream from Salicylic Acid to Control Defense Responses in Arabidopsis

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The Arabidopsis PAD4 gene was previously shown to be required for synthesis of camalexin in response to infection by the virulent bacterial pathogen Pseudomonas syringae pv maculicola ES4326 but not in response to challenge by the non-host fungal pathogen Cochliobolus carbonum. In this study, we show that pad4 mutants exhibit defects in defense responses, including camalexin synthesis and pathogenesis-related PR-1 gene expression, when infected by P. s. maculicola ES4326. No such defects were observed in response to infection by an isogenic avirulent strain carrying the avirulence gene avrRpt2. In P. s. maculicola ES4326-infected pad4 plants, synthesis of salicylic acid (SA) was found to be reduced and delayed when compared with SA synthesis in wild-type plants. Moreover, treatment of pad4 plants with SA partially reversed the camalexin deficiency and PR-1 gene expression phenotypes of P. s. maculicola ES4326-infected pad4 plants. These findings support the hypothesis that PAD4 acts upstream from SA accumulation in regulating defense response expression in plants infected with P. s. maculicola ES4326. A working model of the role of PAD4 in governing expression of defense responses is presented.

INTRODUCTION

Plants respond to pathogen attack by activating expression of a battery of defense responses. In some plant-pathogen interactions, host defense responses are triggered by specific recognition of the products of particular pathogen genes (called avirulence [avr] genes) by plant hosts carrying a corresponding resistance gene. Such gene-for-gene responses generally occur within 24 hr after infection and result in inhibition of pathogen growth and failure of the pathogen to cause disease. If the pathogen does not carry an avr gene recognized by the plant, defense responses are activated more slowly, the pathogen multiplies, and disease ensues. In this case, the pathogen is said to be virulent. Plants can acquire resistance to normally virulent pathogens through a phenomenon called systemic acquired resistance (SAR). Infection of part of a plant can result in expression of some defense-related genes in uninfected parts of the plant, with concomitant resistance to subsequent attack by virulent pathogens. Genetic analyses of plant responses to pathogen attack are being used to reveal the components of the signal transduction pathways controlling defense gene expression in response to avirulent and virulent pathogens as well as during SAR.

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bacterial salicylate hydroxylase gene (nahG) that converts SA to catechol (Gaffney et al., 1993). When infected with pathogens that induce SAR in wild-type plants, nahG plants fail to develop SAR and do not exhibit systemic expression of PR-1, PR-5, or BGL2 (Gaffney et al., 1993; Delaney et al., 1994). SA is required in the systemic tissue for expression of defense genes and SAR (Vernooij et al., 1994), but there is some debate as to whether it is also the signal molecule that is translocated from the infected leaves to the rest of the plant (Vernooij et al., 1994; Beffa et al., 1995; Shulaev et al., 1995; Mölders et al., 1996).

An Arabidopsis gene that has been variously named NPR1 (for non-expressor of PR genes; Cao et al., 1994), NIM1 (for non-inducible immunity; Delaney et al., 1995), and SAI1 (for salicylic acid-insensitive; Shah et al., 1997) is required for SA-mediated disease resistance. When infected with a pathogen that induces SAR in wild-type plants, npr1/nim1/sai1 mutants accumulate high levels of SA but do not activate expression of PR-1, PR-5, or BGL2 and do not develop SAR (Cao et al., 1994; Delaney et al., 1995; Shah et al., 1997). NPR1/NIM1/SAI1 was recently cloned and shown to encode a protein containing ankyrin repeats (Cao et al., 1997; Ryals et al., 1997). The precise role of this protein in mediating responses to SA is not known, but it was recently demonstrated that it functions in the nucleus in response to SA treatment (M. Kinkema and X. Dong, personal communication).

The phenotypes of nahG and npr1/nim1/sai1 plants indicate that SA-dependent responses are required for local defense against virulent and avirulent pathogens as well as for SAR. In response to local infections, nahG plants display reduced PR-1 expression and enhanced growth of virulent bacterial pathogens, avirulent bacterial pathogens, and avirulent Peronospora parasitica isolates (Delaney et al., 1994; Lawton et al., 1995; Glazebrook et al., 1996). Although camalexin synthesis is not inducible by SA, nahG plants synthesize greatly reduced amounts of camalexin in response to P. s. maculicola ES4326 infection, suggesting that SA is necessary, but not sufficient, for full activation of camalexin synthesis (Zhao and Last, 1996). Mutations in npr1/nim1/sai1 cause enhanced susceptibility to avirulent and virulent P. syringae strains and avirulent Peronospora isolates (Cao et al., 1994; Delaney et al., 1995; Glazebrook et al., 1996; Shah et al., 1997). The expression of PR-1 in npr1/nim1/sai1 plants in response to local infections or SA treatment is reduced relative to that in wild-type plants (Glazebrook et al., 1996; Shah et al., 1997). However, npr1/nim1/sai1 mutations have no effect on camalexin synthesis, suggesting that although camalexin synthesis requires SA, this requirement is mediated by an NPR1/NIM1/SAI1-independent pathway (Glazebrook et al., 1996; Zhao and Last, 1996).

In previous work, we isolated an Arabidopsis mutant, pad4, displaying reduced camalexin synthesis in response to P. s. maculicola ES4326 infection, enhanced susceptibility to P. s. maculicola ES4326, and susceptibility to Peronospora isolates that are avirulent on wild-type plants (Glazebrook et al., 1996, 1997b). Significantly, pad4 was unaffected in camalexin synthesis in response to challenge with the non-host fungal pathogen Cochliobolus carbonum, strongly suggesting that pad4 is a mutation affecting a regulatory factor rather than a camalexin biosynthetic enzyme (Glazebrook et al., 1997b).

In this report, we further characterize pad4 plants. We show that pad4 affects expression of some defense-related genes, including PR-1, in response to infection by P. s. maculicola ES4326, but does not affect responses to P. s. maculicola ES4326 carrying avrRpt2. Responses to SA treatment were unaffected by pad4. P. s. maculicola ES4326-infected pad4 plants displayed reduced synthesis and accumulation of SA and its glucoside (SAG), and the PR-1 expression and camalexin synthesis defects of pad4 plants were reversible by SA treatment. Taken together, the phenotypes of pad4 plants argue that PAD4 is required upstream from SA in the signal transduction pathway leading from P. s. maculicola ES4326 infection to activation of defense responses.

RESULTS

Camalexin Induction in Response to Some Elicitors Is Unaffected by pad4

Our previous demonstration that pad4 plants show a defect in camalexin synthesis in response to infection by the virulent bacterial pathogen P. s. maculicola ES4326, but not in response to challenge by the non-host fungal pathogen C. carbonum (Glazebrook et al., 1997b), led us to examine the effect of pad4 on camalexin synthesis in response to various elicitors. Wild-type and pad4 plants were infected with P. s. maculicola ES4326 or an isogenic strain carrying the avirulence gene avrRpt2. Camalexin levels in the infected leaves were determined at various intervals after infection. Figure 1A shows that when plants were infected with P. s. maculicola ES4326, camalexin levels in wild-type plants were much higher than those in pad4 plants. In contrast, when plants were infected with P. s. maculicola ES4326 carrying avrRpt2, camalexin levels in wild-type and pad4 plants were not significantly different. Similar results were obtained using a different virulent P. syringae strain, P. s. tomato DC3000, and P. s. tomato DC3000 carrying avrRpt2 (data not shown). This suggests that the signal transduction pathway leading to camalexin synthesis in response to P. s. maculicola ES4326 or P. s. tomato DC3000 infection requires PAD4, whereas camalexin synthesis in response to strains carrying avrRpt2 is mediated by a PAD4-independent pathway. Two other treatments known to trigger camalexin synthesis are infection with Xanthomonas campestris pv campestris BP109 and spraying with silver nitrate. Figures 1B and 1C show that pad4 did not affect camalexin synthesis in response to either of these treatments, suggesting that responses to these stimuli are also independent of PAD4.
The finding that PAD4 is required for activation of camalexin synthesis in response to infection by P. s. maculicola ES4326 raised the possibility that PAD4 might encode a regulator of defense responses. To test whether pad4 affects activation of other defense responses in addition to camalexin synthesis, mRNA levels of several defense-related genes were examined by RNA gel blot hybridization. Figure 2A shows that the mRNA levels of PR-1 were greatly reduced in infected pad4 leaves relative to the levels in wild-type plants. Expression of PR-5, BGL2, and ASA1 were affected less strongly, if at all, by the pad4 mutation. ASA1 encodes anthranilate synthase (Niyogi and Fink, 1992), which is required for camalexin synthesis because anthranilate is a precursor to camalexin (Tsuji et al., 1993). Zhao and Last (1996) have observed a tight correlation between camalexin levels and ASA1 expression; however, this correlation is not maintained in pad4 plants. Clearly, pad4 has effects on defense gene expression, but these effects are not consistent among all genes induced by P. s. maculicola ES4326 infection.

Infection with P. s. maculicola ES4326 carrying avrRpt2 also leads to increases in expression of defense genes, including PR-1 (Greenberg et al., 1994). Figure 2B shows that PR-1 mRNA levels in plants infected with P. s. maculicola

**Figure 1.** Camalexin Levels in Wild-Type and pad4 Plants after Various Treatments.

Each data point represents the mean and standard deviation of six replicate samples.

(A) Infection with P. s. maculicola ES4326 or P. s. maculicola ES4326 carrying avrRpt2. wt-Psm, wild-type plants infected with P. s. maculicola ES4326; pad4-Psm, pad4 plants infected with P. s. maculicola ES4326; wt-avr, wild-type plants infected with P. s. maculicola ES4326 carrying avrRpt2; pad4-avr, pad4 plants infected with P. s. maculicola ES4326 carrying avrRpt2.

(B) Infection with X. c. campestris (Xcc) BP109.

(C) Spraying with 5 mM silver nitrate.

**Figure 2.** Defense Gene Expression in Leaves Infected with P. s. maculicola ES4326 or P. s. maculicola ES4326 Carrying avrRpt2.

Leaves were excised at 0, 12, 24, 36, or 48 hr after infection. Mg indicates leaves mock inoculated with 10 mM MgSO\(_4\) sampled at 36 hr. rRNA indicates hybridization with an 18S rRNA probe used to evaluate equal loading.

(A) Infection with P. s. maculicola ES4326.

(B) Infection with P. s. maculicola ES4326 carrying avrRpt2.
ES4326 carrying avrRpt2 were unaffected by pad4. Taken together with the results in Figure 1A, this suggests that host defense responses to P. s. maculicola ES4326 carrying avrRpt2 are largely PAD4 independent.

Responses to SA Are Unaffected in pad4 Plants

SA is required for induction of PR-1 gene expression in infected leaves (Gaffney et al., 1993). SA treatment is also sufficient for PR-1 gene expression and SAR (White, 1979; Malamy et al., 1990). To determine whether pad4 affects responses to SA, pad4 plants were treated with SA and tested for PR-1 gene expression and pathogen resistance. Figure 3A shows that SA treatment induced similar levels of PR-1 expression in wild-type and pad4 plants, with PR-1 mRNA present at high levels 1 day after treatment and declining thereafter. Similarly, Figure 3B shows that SA treatment induced resistance to P. s. maculicola ES4326 in wild-type and pad4 plants. Based on these experiments, it appears that the signal transduction pathway between SA and PR-1 expression is intact in pad4 plants.

SA Accumulation in Response to P. s. maculicola ES4326 Infection Is Compromised in pad4 Plants

SA is required both for PR-1 gene expression and for camalexin synthesis. In the case of PR-1, SA is both necessary and sufficient for increased PR-1 expression in response to pathogen attack (Ryals et al., 1996). In the case of camalexin accumulation, SA is not sufficient, because SA treatment does not lead to significant camalexin accumulation. Nevertheless, SA is required, because nahG-transformed plants fail to accumulate camalexin in response to P. s. maculicola ES4326 infection (Zhao and Last, 1996). We tested the accumulation of camalexin in wild-type and nahG plants infected with either P. s. maculicola (Psm) ES4326 or P. s. maculicola ES4326 carrying avrRpt2 at a dose of 10^5 cfu/cm^2. Camalexin in the infected leaves was determined at the times that camalexin levels are high in wild-type plants: 24 hr after infection for P. s. maculicola ES4326 carrying avrRpt2 and 32 hr after infection for P. s. maculicola ES4326. Each bar represents the mean and standard deviation of eight replicate samples.

Figure 3. Exogenous SA Induces PR-1 Expression and Enhanced Resistance to P. s. maculicola ES4326 in Wild-Type and pad4 Plants.

Plants were sprayed with 5 mM SA in 0.02% [v/v] Silwet L-77 or with 0.02% Silwet alone until uniformly wet.

(A) PR-1 expression in response to SA. Samples were taken daily after spraying. The c indicates control; plants were sprayed with 0.02% Silwet alone and sampled at 3 days after spraying.

(B) Effect of spraying plants with SA on P. s. maculicola ES4326 growth. One day after treatment, plants were infected with P. s. maculicola ES4326 at a dose of 10^5 cfu/cm^2. Bacterial titer was determined 3 days after infection. Each bar represents the mean and standard deviation of eight replicates. Similar results were obtained in three other independent experiments. -SA, plants not treated with SA before infection; +SA, plants treated with SA before infection; wt, wild type.

Figure 4. Camalexin Accumulation in Wild-Type and nahG Plants Infected with Pathogens.

Wild-type (wt) Ler and Ler nahG transgenic plants were infected with either P. s. maculicola (Psm) ES4326 or P. s. maculicola ES4326 carrying avrRpt2 at a dose of 10^5 cfu/cm^2. Camalexin in the infected leaves was determined at the times that camalexin levels are high in wild-type plants: 24 hr after infection for P. s. maculicola ES4326 carrying avrRpt2 and 32 hr after infection for P. s. maculicola ES4326. Each bar represents the mean and standard deviation of eight replicate samples.

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One possible explanation for the phenotypes of pad4 plants is that they accumulate reduced amounts of SA in re-
sponse to P. s. maculicola ES4326 infection, resulting in reduced camalexin synthesis and reduced PR-1 expression. To test this idea, wild-type and pad4 plants were infected with P. s. maculicola ES4326 or P. s. maculicola ES4326 carrying avrRpt2, and both SA and its glucoside (SAG) were monitored over the course of the infection. Figure 5A shows that the SA levels in pad4 plants infected with P. s. maculicola ES4326 were lower than the levels in infected wild-type plants at all time points tested. In wild-type plants, SA levels were highest at 12 hr after infection, whereas in pad4 plants, SA levels were highest at 24 hr after infection. Figure 5C shows that after infection with P. s. maculicola ES4326, SAG levels were greatly reduced in pad4 plants. In contrast, when plants were infected with P. s. maculicola ES4326 carrying avrRpt2, there was very little difference between SA levels in pad4 and wild-type plants, as shown in Figure 5B. Figure 5D shows that after infection with P. s. maculicola ES4326 carrying avrRpt2, the SAG levels in pad4 plants were significantly lower than those in wild-type plants, but these differences were not as large as those observed in P. s. maculicola ES4326-infected plants (Figure 5C). Based on these results, it seems likely that the camalexin and PR-1 defects of pad4 mutants result from reduced SA accumulation in response to P. s. maculicola ES4326 infection.

Figure 5. SA and SAG Levels in Infected Wild-Type and pad4 Plants.

Wild-type (wt) and pad4 plants were infected with P. s. maculicola ES4326 (Psm), P. s. maculicola ES4326 carrying avrRpt2 (Psm avr), or mock infected with 10 mM MgSO4 (mock). Each column represents the mean of three replicate samples. Error bars representing the standard deviation are shown where they are large enough to be visible. SA and SAG were assayed on the same samples. The experiments with P. s. maculicola ES4326 and with P. s. maculicola ES4326 carrying avrRpt2 were conducted at different times; therefore, results should not be compared directly.

(A) SA levels in plants infected with P. s. maculicola ES4326.
(B) SA levels in plants infected with P. s. maculicola ES4326 carrying avrRpt2.
(C) SAG levels in plants infected with P. s. maculicola ES4326.
(D) SAG levels in plants infected with P. s. maculicola ES4326 carrying avrRpt2.
Exogenous SA Restores Camalexin Accumulation and PR-1 Expression in P. s. maculicola ES4326-Infected pad4 Plants

If the reduction in SA accumulation in response to P. s. maculicola ES4326 infection observed in pad4 plants is the cause of the camalexin accumulation and PR-1 gene expression defects, then it should be possible to restore camalexin synthesis and PR-1 gene expression to P. s. maculicola ES4326-infected pad4 plants by supplying them with SA. Figure 6A shows that pad4 plants treated with SA before infection displayed much higher camalexin levels than did pad4 plants that were not pretreated with SA. In the experiment shown in Figure 6A, SA treatment of wild-type plants had little effect on camalexin levels. In some experiments, we observed significant reductions in camalexin levels in wild-type plants treated with SA, whereas SA always caused a large increase in camalexin levels in pad4 plants.

The possibility that SA treatment might also rescue the PR-1 expression defect of pad4 plants was tested. Wild-type and pad4 plants were sprayed with either 5 mM SA or water. After 1 day, plants were infected with P. s. maculicola ES4326, and PR-1 mRNA levels were assessed 2 days after infection. Figure 6B shows that 1 day after SA treatment, PR-1 mRNA levels were elevated in both wild-type and pad4 plants (lanes 2 and 6) and declined to barely detectable levels by day 2 (lanes 10 and 12). In plants that were treated with SA before infection, the PR-1 mRNA level in pad4 plants was comparable to that in wild-type plants (Figure 6B, lanes 4 and 8). The PR-1 expression in SA-treated, P. s. maculicola ES4326-infected pad4 plants cannot be solely due to the SA treatment, because the PR-1 mRNA level in pad4 plants treated with SA only had declined by 2 days after treatment. Rather, the SA treatment must have restored the ability of the pad4 plants to respond to P. s. maculicola ES4326, demonstrating that the PR-1 gene expression defect caused by pad4 is also reversed by SA treatment. The observations that SA treatment can reverse the camalexin accumulation and PR-1 gene expression defects of P. s. maculicola ES4326-infected pad4 plants provide strong support for the idea that reduced SA accumulation in pad4 plants is the cause of the camalexin and PR-1 defects.

**Genetic Map Position of PAD4**

The pad4 mutant (ecotype Columbia [Col] background) was crossed with an ecotype Landsberg erecta (Ler) plant to map the pad4 mutation in the F2 progeny. However, segregation of the camalexin-deficient phenotype of pad4 in the F2 progeny was found to be 1 Pad−:9 Pad+ (21 Pad− plants and 190 Pad+ plants), rather than the 1:3 ratio observed in backcrosses to Col (Glazebrook et al., 1996). Apparently, there is a gene in Ler that masks the Pad− phenotype of pad4 homozygotes. Consequently, the Ler mapping strategy was abandoned. The pad4 mutant was then crossed with wild-type ecotype Keswick (Ksk). The camalexin-deficient phenotype segregated 1 Pad−:3 Pad+ in this cross; therefore, these plants were used for cleaved amplified polymorphic sequence (CAPS) mapping (Konieczny and Ausubel, 1993). PAD4 was found to lie on chromosome 3, between the markers GL1 and BGL2. (Of 64 chromosomes tested,
DISCUSSION

We have previously described five complementation groups of pad mutants, defined as mutants displaying defects in camalexin synthesis in response to P. s. maculicola ES4326 infection (Glazebrook and Ausubel, 1994; Glazebrook et al., 1997b). Mutations in PAD1, PAD2, or PAD4 cause enhanced susceptibility to P. s. maculicola ES4326, whereas mutations in PAD3 or PAD5 have no effect on P. s. maculicola ES4326 growth (Glazebrook and Ausubel, 1994; Glazebrook et al., 1997b). One model (the regulatory model) explaining this result postulates that camalexin does not play a crucial role in limiting P. s. maculicola ES4326 growth but that PAD1, PAD2, and PAD4 are pleiotropic defense response regulators affecting expression of other defense responses, in addition to camalexin accumulation, that are important for limiting P. s. maculicola ES4326 growth (Glazebrook and Ausubel, 1994). An alternative model (the biochemical model) postulates that camalexin does play a crucial role in limiting P. s. maculicola ES4326 growth but that the pad3 and pad5 mutations block the camalexin biosynthetic pathway at a point such that antimicrobial camalexin precursors accumulate, compensating for the loss of camalexin itself (Glazebrook and Ausubel, 1994).

The results reported in this study demonstrating that PAD4 has pleiotropic effects on resistance responses are most consistent with the regulatory model for explaining the phenotypes of pad mutants. Mutations that affect regulation of defense responses are useful in dissecting the signal transduction pathways controlling expression of defense responses. The studies reported here strongly suggest that the pad4 mutation affects SA accumulation, thereby causing pleiotropic effects on expression of defense responses.

Figure 7 shows our working model of the role of PAD4 in defense response signaling. When plants are infected with P. s. maculicola ES4326, PAD4 is needed for SA concentrations to reach the level required for camalexin synthesis and expression of PR-1. In contrast, when plants are infected with P. s. maculicola ES4326 carrying avrRpt2, SA accumulates in a PAD4-independent manner. The accumulation of SA causes PR-1 expression in an NPR1/NIM1/SAI1-dependent manner. SA accumulation is necessary, but not sufficient, to activate camalexin synthesis. NPR1/NIM1/SAI1 is not required for camalexin synthesis. If the pad4 allele used in this work does not cause complete loss of function, then a single-pathway model could explain our results. In such a model, responses to P. s. maculicola ES4326 carrying avrRpt2 might be triggered by a strong signal that requires PAD4 function for its transmission but is adequately transmitted by a partially functional PAD4. In response to P. s. maculicola ES4326, this signal might be much weaker and inadequately transmitted by a partially functional PAD4.

In leaves infected with P. s. maculicola ES4326 carrying avrRpt2, PAD4 does not play a major role in activation of defense responses. However, it is likely that PAD4 is required for activation of responses during some other gene-for-gene resistance responses. In previous work, we showed that pad4 mutants fail to demonstrate resistance to several different avirulent isolates of the oomycete pathogen Peronospora. Although wild-type plants challenged with these parasites allowed little or no sporulation, pad4 plants allowed profuse sporulation (Glazebrook et al., 1997b).

Mutations in EDS1 (for enhanced disease susceptibility) also cause increased susceptibility to virulent pathogens (P. s. tomato DC3000 and compatible Peronospora isolate Emwa1) and to some but not all avirulent pathogens (many avirulent Peronospora isolates but not P. s. tomato DC3000 carrying avrB) (Parker et al., 1996). Recent results suggest that EDS1 is required for gene-for-gene resistance responses mediated by the TIR-NBS-LRR (for Toll/Interleukin-1/resistance-nucleotide binding site-leucine rich repeat) class of resistance genes (J. Parker, personal communication). The spectrum of pathogens affected by the pad4 and eds1 mutations differs in that the eds1-1 mutant is susceptible to the non-host Peronospora isolate P-006, whereas pad4 is not (Parker et al., 1996; Glazebrook et al., 1997a). Comparison of the Arabidopsis–pathogen interactions affected by pad4 and eds1 is complicated by the fact that pad4 is in the Col background, whereas the eds1-1 allele is in the Wassilewskija (Ws) background, and there are many differences in genes affecting disease resistance between the two ecotypes. In the future, analysis of pad4 and eds1 alleles that recently were isolated in the Ler background will allow comparison of pad4 and eds1 phenotypes in the absence of potentially interfering differences between ecotypes, thereby helping to resolve the issue of whether EDS1 and
PAD4 act in the same or different pathways (J. Parker, personal communication).

The phenotypes of pad4 and eds1 mutants support the idea that different gene-for-gene resistance responses lead to resistance via different signaling pathways. Presumably, these pathways converge at some point, but the observation that gene expression patterns in response to bacteria carrying the avirulence gene avrRpt2 are quite different from the patterns in response to bacteria carrying the avirulence gene avrRpml suggests that the differences between pathways may be extensive (Reuber and Ausubel, 1996; Ritter and Dangl, 1996). Furthermore, both pad4 and eds1 mutants affect growth of compatible pathogens in addition to growth of certain incompatible pathogens, suggesting that elements of the signal transduction pathway(s) activated by recognition of certain avirulent pathogens are also involved in signal transduction in response to infection by certain virulent pathogens.

The genes PR-1, PR-5, and BGL2 are coordinately induced in response to treatment with SA. When plants were infected with P. s. maculicola ES4326, the phenotypes of pad4 plants revealed differential regulation of defense responses. Synthesis of camalexin and expression of PR-1 were reduced in pad4 plants. Expression of PR-5, BGL2, and ASA1 were less strongly affected. The eds5 mutation also causes reduced PR-1 expression in response to P. s. maculicola ES4326 infection but has no effect on the expression of PR-5 and BGL2 or on camalexin synthesis (Rogers and Ausubel, 1997). The npr1/nim1/sai1 mutations cause similar effects in that mRNA levels of PR-1, but not those of PR-5 or BGL2, are reduced in response to pathogen infection. This does not seem to be due to “leakiness” of the allexes, because expression of PR-1, PR-5, and BGL2 in response to SA treatment was completely abolished in the npr1/nim1/sai1 mutants (Cao et al., 1994; Delaney et al., 1995; Glazebrook et al., 1996; Shah et al., 1997).

These results are difficult to reconcile with the idea that expression of PR-1, PR-5, and BGL2 in infected leaves is due solely to coordinate regulation through the SA pathway. One possible explanation is that an SA-independent pathway acts in conjunction with the SA-dependent pathway to control expression of PR-1, PR-5, and BGL2, and the relative contribution of each pathway varies among the different genes (this potential pathway is not shown in Figure 7). An alternative explanation is that expression of each gene could be variably affected by different mutations because of quantitative differences in their induction. Such differences could result partly from the fact that in infected leaves, both the fold induction and the absolute expression level of PR-1 are much higher than those of PR-5 or BGL2.

Camalexin synthesis in response to X. c. campestris BP109 infection or silver nitrate treatment was not affected by pad4. These stimuli induce much less camalexin synthesis than does infection by P. s. maculicola ES4326. Possibly, such low levels of camalexin synthesis do not require PAD4 function. The quantities of camalexin synthesized by pad4 plants in response to P. s. maculicola ES4326 infection are greater than are the amounts in wild-type plants infected with X. c. campestris BP109 or treated with silver nitrate.

The observation that SA treatment can reverse the defense response expression defects of pad4 plants raises interesting questions about the relationship between SA levels and PR-1 gene expression. Treatment of pad4 plants with SA 1 day before P. s. maculicola ES4326 infection restored PR-1 gene expression 2 days after infection (3 days after SA treatment). In contrast, by 2 days after SA treatment, PR-1 expression in uninfected leaves was very low. Does this imply that SA levels at this time are also very low? If so, how does SA treatment restore PR-1 expression in pad4 plants? If SA levels are still high 3 days after treatment, then why are PR-1 mRNA levels low? Low levels of SA potentiate responses to pathogen attack (Shirasu et al., 1997), and evidence supports the idea that there is a feedback loop in the SAR signal transduction pathway (Ryals et al., 1996), further complicating analysis of the role of SA in signal transduction.

In conclusion, we have shown that PAD4 is a regulator of defense responses and acts upstream from SA to affect expression of PR-1 and camalexin synthesis. PAD4 function does not seem to be required for these defense responses when plants are infected with P. s. maculicola ES4326 carrying avrRpt2, suggesting that there is a PAD4-independent mechanism that supplies SA in response to this avirulent strain. Further analysis of the responses of pad4 plants to pathogen attack is likely to reveal more interesting features of the regulatory mechanisms controlling expression of defense responses in plants.

METHODS

Plants and Growth Conditions

Wild-type plants (Arabidopsis thaliana ecotype Columbia [Col]) and pad4 plants from a line that had been backcrossed four times to the wild-type parent (Col) (Glazebrook et al., 1996) were used in this study. Arabidopsis ecotype Keswick (Ksk) was a gift from E. Holub (Horticulture Research International, Warwick, UK). Landsberg erecta (Ler) plants carrying the nahG transgene were a gift from X. Dong (Duke University, Durham, NC) (Bowling et al., 1994). Plants were grown in pots in Metro-Mix 200 soil (Scotts-Sierra Horticultural Products Company, Marysville, OH) in a growth chamber (22 ± 2°C, 85% relative humidity, 100 μE m⁻² sec⁻¹ fluorescent illumination) on a 12-hr-light and 12-hr-dark cycle. Fully expanded leaves of 4-week-old plants were used for all experiments.

Inoculations with Bacteria and Treatment with Chemicals

Pseudomonas syringae pv maculicola ES4326 (Dong et al., 1991), P. s. pv tomato DC3000 (Cuppels, 1986), and Xanthomonas campestris pv campestris BP109 (Weiss et al., 1994) have been described previously. The avirulence gene avrRpt2 was carried on plasmid pLH12, as described previously (Dong et al., 1991; Whalen et al., 1991).
syringae strains were grown in King’s B medium supplemented with appropriate antibiotics (Glazebrook and Ausubel, 1994), and X. c. campestris BP109 was grown in Luria-Bertani medium supplemented with 50 μg/mL rifampicin. Bacteria were infiltrated into Arabidopsis plants, as described by Glazebrook and Ausubel (1994). Unless stated otherwise, for camalexin assays, the bacterial dose for P. syringae strains was 3 × 10^4 colony-forming units (cfu)/cm^2 leaf area (equivalent to OD_600 = 0.006); for X. c. campestris BP109, it was 5 × 10^4 cfu/cm^2 (OD_600 = 0.1). For experiments involving extraction of total RNA from infected leaves, P. s. maculicola ES4326 and P. s. maculicola ES4326 carrying avrRpt2 were introduced at a dose of 10^4 cfu/cm^2 leaf area (equivalent to OD_600 = 0.002). For determination of P. s. maculicola ES4326 growth, plants were infected with P. s. maculicola ES4326 at a dose of 10^6 cfu/cm^2 leaf area (equivalent to OD_600 = 0.0002). After 3 days, leaves were excised and bacterial growth was assayed, as described by Glazebrook et al. (1996). Data are reported as means and standard deviations of the log (cfu/cm^2) of six replicates. For chemical treatment, plants were sprayed with 5 mM SA or 5 mM silver nitrate with 0.02% Silwet L-77 (Lehle Seeds, Round Rock, TX) to reduce surface tension. Control plants were sprayed with water containing 0.02% Silwet L-77.

**Camalexin Quantitation**

For P. syringae–infected leaves, fresh weight changes markedly over the course of infection because of water loss from the infected tissue. Therefore, for P. syringae–infected leaves, samples consisted of four leaf discs cut with a number 3 cork borer (1.1 cm^2 total), and camalexin concentrations were normalized to leaf area. For leaves infected with X. c. campestris BP109 or treated with silver nitrate, samples consisted of ~100 mg of tissue, and camalexin concentrations were normalized to fresh weight. Camalexin assays were performed as described by Glazebrook et al. (1996). For each data point, the results are reported as the mean and standard deviation from six replicates.

**RNA Gel Blot Analysis**

Tissue samples consisting of three to five leaves were collected and frozen in liquid nitrogen and stored at −80°C. Total RNA was extracted, and 5 μg of RNA per sample was separated on formaldehyde-agarose gels (Ausubel et al., 1995; Reuber and Ausubel, 1996). After blotting onto a Hybond-N+ membrane (Amersham Corp., Arlington Heights, IL), hybridizations were performed using various digoxigenin-labeled probes described below, followed by washes in 0.5 × SSC (1 × SSC is 0.15 M NaCl and 0.015 M sodium citrate) at 65°C and chemiluminescent detection with CSPD, according to instructions provided by the supplier (Boehringer Mannheim). For hybridization with more than one probe, blots were stripped and reprobed. Single-stranded DNA probes were prepared by amplification of appropriate sequences from cDNA clones (PR-1 and PR-5; Uken et al., 1992) and from plasmid pATBG12 (BGL2; Dong et al., 1991), as described by Glazebrook et al. (1996), except that digoxigenin-11-dUTP was used as the label, according to the instructions of the supplier (Boehringer Mannheim). For the ASA1 probe, a single-stranded probe was made from plasmid pKN41 (Niyoji and Fink, 1992) by using sense primer 5'–GCTACCGTTTGGTGTC-3′ and antisense primer 5'–AGCAATGTCCATGTCACC-3′. For the 18S rRNA probe, a single-stranded probe was made from the clone J HD2-15A (stock no. CD3-197; Arabidopsis Biological Resource Center, Ohio State University, Columbus, OH) by using sense primer 5'–CTGGTTGATCCCTGCGACATG-3′ and antisense primer 5'–CAGGTTCACTACGGAAAAC-3′. Blots were stripped and reprobed with the 18S rRNA probe to assess equal loading of RNA samples.

**Determination of Endogenous Levels of SA and SAG**

Mature leaves of 4-week-old wild-type and pad4 plants were infected with P. s. maculicola ES4326 at a dose of 10^6 cfu/cm^2 (equivalent to OD_600 = 0.002) or mock infected with 10 mM MgSO_4. At intervals after infection, samples were collected (1 g of tissue per sample, from approximately seven plants) and frozen in liquid nitrogen. SA and SAG were determined as described by Bowling et al. (1994). Raw data were multiplied by 2 to reflect 50% recovery of SA and SAG in this assay.

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