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A MPK3/6-WRKY33-ALD1-Pipecolic Acid Regulatory Loop Contributes to Systemic Acquired Resistance[OPEN]

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Plants induce systemic acquired resistance (SAR) upon localized exposure to pathogens. Pipecolic acid (Pip) production via AGD2-LIKE DEFENSE RESPONSE PROTEIN1 (ALD1) is key for SAR establishment. Here, we report a positive feedback loop important for SAR induction in *Arabidopsis thaliana*. We showed that local activation of the MAP kinases MPK3 and MPK6 is sufficient to trigger Pip production and mount SAR. Consistent with this, mutations in *MPK3* or *MPK6* led to compromised Pip accumulation upon inoculation with the bacterial pathogen *Pseudomonas syringae* pv *tomato* DC3000 (*Pto*) AvrRpt2, which triggers strong sustained MAPK activation. By contrast, *P. syringae* pv *maculicola* and *Pto*, which induce transient MAPK activation, trigger Pip biosynthesis and SAR independently of MPK3/6. *ALD1* expression, Pip accumulation, and SAR were compromised in mutants defective in the MPK3/6-regulated transcription factor WRKY33. Chromatin immunoprecipitation showed that WRKY33 binds to the *ALD1* promoter. We found that Pip triggers activation of MPK3 and MPK6 and that MAPK activation after *Pto* AvrRpt2 inoculation is compromised in *wrky33* and *ald1* mutants. Collectively, our results reveal a positive regulatory loop consisting of MPK3/MPK6, WRKY33, ALD1, and Pip in SAR induction and suggest the existence of distinct SAR activation pathways that converge at the level of Pip biosynthesis.

INTRODUCTION

Plants have evolved two types of innate immune system to deal with attacks by microbial pathogens: cell surface receptor-mediated immunity (pattern-triggered immunity [PTI]) and intracellular receptor-mediated immunity (effector-triggered immunity [ETI]) (Jones and Dangl, 2006; Tsuda and Katagiri, 2010). PTI is induced by the recognition of microbe-associated molecular patterns (MAMPs) by pattern recognition receptors on the plasma membrane, which are receptor-like kinases (RLKs) or receptor-like proteins (RLPs) (Jones and Dangl, 2006; Boutrot and Zipfel, 2017; Yu et al., 2017). For instance, the bacterial MAMP flg22, a part of bacterial flagellin, is recognized by FLAGELLIN-SENSITIVE2 (FLS2) and the coreceptors BRI1-ASSOCIATED RECEPTOR KINASE1 (BAK1) and BAK1-LIKE1 (BKK1) in *Arabidopsis thaliana* (Gómez-Gómez and Boller, 2000; Zipfel et al., 2004; Chinchilla et al., 2007; Roux et al., 2011). ETI is triggered by recognition of virulence factors such as bacterial type III effectors (T3Es) with which pathogens subvert plant immunity in susceptible plants by mostly nucleotide binding/leucine-rich repeat (NLR) receptors (Jones and Dangl, 2006; Cui et al., 2015; Tran et al., 2017; Zhang et al., 2017). For instance, AvrRpt2 and AvrRpm1 are T3Es of the bacterial pathogen *Pseudomonas syringae* whose virulence actions are recognized by the NLR receptors RESISTANCE TO P. SYRINGAE2 and RESISTANCE TO P. SYRINGAE PV MACULICOLA1, respectively, in Arabidopsis (Mackey et al., 2002; Axtell and Staskawicz, 2003).

PTI and ETI share signaling components such as the phytohormone salicylic acid (SA) and mitogen-activated protein kinases (MAPKs) (Tsuda and Katagiri, 2010). SA regulates a major portion of plant immunity against biotrophic and hemibiotrophic pathogens such as *P. syringae* via the central regulator/receptor of SA signaling NONEXPRESSER OF PR GENES1 (NPR1) (Delaney et al., 1994; Cao et al., 1997; Wu et al., 2012; Pajerowska-Mukhtar et al., 2013; Ding et al., 2018). Arabidopsis MAPKs, MPK3 and MPK6, positively contribute to immunity against a wide range of pathogens via phosphorylation of substrates in a partially redundant manner (Beckers et al., 2009; Meng and Zhang, 2013; Xu et al., 2016; Ding et al., 2018). For instance, the WRKY family transcription factor WRKY33, a direct phosphorylation target of MPK3 and MPK6, is necessary for MPK3 and MPK6-mediated production of the phytoalexin camalexin and the phytohormone ethylene (Mao et al., 2011; Li et al., 2012).

Plants systemically induce broad spectrum resistance called systemic acquired resistance (SAR) upon localized exposure to pathogens (Fu and Dong, 2013). Although the identity of the mobile signal that relays local immune activation for SAR activation in systemic tissues is still under debate, several molecules have

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Background: Plants have the ability to increase disease resistance in distant, systemic leaves after a local pathogen infection. This phenomenon is called systemic acquired resistance (SAR), which is a long-lasting and broad-spectrum resistance. Furthermore, SAR is a conserved trait in various plant species and is important for agricultural practice. Some mobile metabolites need to move from infected leaves to distant leaves to establish SAR. The lysine-derived amino acid pipecolic acid (Pip) and its derivative *N*-hydroxy-pipecolic acid (NHP) are regulatory metabolites necessary for SAR and have been proposed to function in SAR long-distance signaling. The enzymes encoded by *ALD1* and *FMO1* mediate Pip and NHP production, respectively. How expression of these key SAR genes is regulated remains poorly understood.

Question: We wanted to understand the molecular mechanism by which expression of *ALD1* and *FMO1* is regulated.

Findings: In the model plant *Arabidopsis thaliana*, we found that (1) local activation of mitogen-activated protein kinases (MAPKs) triggers SAR; (2) sustained MAPK activation induces *ALD1* and *FMO1* expression as well as Pip and NHP production; (3) the transcription factor WRKY33, whose activity is regulated by MAPKs, directly controls *ALD1* expression; (4) MAPK-mediated SAR is disrupted by a mutation in *WRKY33*, *ALD1*, or *FMO1*; (5) Pip induces MAPK activation; and (6) sustained MAPK activation during pathogen infection is compromised in *wrky33*, *ald1*, and *fmo1* mutant plants. These results reveal that a positive regulatory loop, consisting of MAPKs, WRKY33, ALD1, FMO1, and Pip/NHP, is a critical regulatory mechanism of SAR induction. Furthermore, we showed that Pip-induced MAPK activation requires *BAK1* and *BKK1*, which encode coreceptors of multiple plasma membrane-localized receptors for pathogen-derived molecules.

Next steps: Our results suggest that Pip or a Pip-derived metabolite is sensed by a plasma membrane-localized receptor, a missing component in the SAR regulatory loop uncovered in this study. Identification of the actual metabolite and receptor would help us further dissect the mechanism of SAR and pave the way for development of new plant protection strategies.

been implicated in the establishment of SAR, such as methyl salicylate (Park et al., 2007), dehydroabietinal (Chaturvedi et al., 2012), glycerol-3-phosphate (Chanda et al., 2011), azelaic acid (Jung et al., 2009), and pipecolic acid (Pip) (Návarová et al., 2012). Pip is a Lys catabolite that is present ubiquitously in the plant kingdom and accumulates to high levels in *P. syringae*-inoculated leaves and in distant, uninfected leaves at the onset of SAR (Návarová et al., 2012; Zeier, 2013). Pip is synthesized by AGD2-LIKE DEFENSE RESPONSE PROTEIN1 (ALD1) and SAR-DEFICIENT4 (SARD4) (Návarová et al., 2012; Ding et al., 2016; Hartmann et al., 2017). The biosynthesis of Pip is fully dependent on ALD1, which functions as an α-L-Lys amino-transferase and generates the biosynthetic intermediate 2,3-dehydropipecolic acid (2,3-DP). 2,3-DP is subsequently reduced to Pip by SARD4 and another reductase activity (Návarová et al., 2012; Ding et al., 2016; Hartmann et al., 2017). Pip is further converted by Flavin-dependent monooxygenase1 (FMO1) to *N*-hydroxypipecolic acid (NHP), which is a critical component for SAR activation (Chen et al., 2018; Hartmann et al., 2018). The accumulation of Pip and NHP in pathogen-inoculated plants is required for SAR, and exogenous application of Pip or NHP is sufficient to systemically trigger immunity (Návarová et al., 2012; Vogel-Adghough et al., 2013; Chen et al., 2018; Hartmann et al., 2018). The expression of *ALD1* and *SARD4* is positively regulated by the transcription factors SARD1 and CALMODULIN BINDING PROTEIN 60g (CBP60g) (Sun et al., 2015), which also regulate expression of *SALICYLIC ACID INDUCTION DEFICIENT2* (*SID2*), encoding an SA biosynthesis enzyme that is required for SA production upon pathogen infection in Arabidopsis (Wildermuth et al., 2001; Zhang et al., 2010; Wang et al., 2011). It was recently found that expression of *SARD1* and *CBP60g* is regulated by the transcription factors TGA1, TGA4, and WRKY70 (Sun et al., 2018; Zhou et al., 2018).

Although SA is not the mobile signal for SAR, it contributes to SAR (Vernooij et al., 1994; Lawton et al., 1995; Park et al., 2007). SA is required for SAR in systemic leaves but not local infected leaves of tobacco (*Nicotiana tabacum*) plants (Vernooij et al., 1994). Furthermore, SA contributes to SAR signal amplification together with ALD1 and FMO1 in Arabidopsis systemic leaves, exemplifying the important role of SA in systemic tissues for SAR (Bernsdorff et al., 2016).

Previous research showed that MPK3 and MPK6 can regulate immune responses redundantly with SA signaling when they are activated in a sustained manner but not in a transient manner (Tsuda et al., 2013). Artificial sustained activation of MPK3 and MPK6 triggered by dexamethasone (DEX)-induced expression of $MKK4^{DD}$, a constitutively active form of MAPK kinase 4 that can phosphorylate the downstream MPK3 and MPK6 (Ren et al., 2002; Tsuda et al., 2013), was sufficient to induce expression of SA-responsive genes without *SID2* (Nawrath and Métraux, 1999; Wildermuth et al., 2001; Tsuda et al., 2013). These results suggest that MPK3 and MPK6 contribute to SAR. Indeed, it has been shown that *MPK3* is required for SAR triggered by local infection with *Pto* AvrRpt2 (Beckers et al., 2009). However, the molecular mechanism by which the MAPK signaling regulate the establishment of SAR is yet unknown.

Here, we show that a positive regulatory loop for local Pip accumulation contributes to SAR in Arabidopsis. Sustained MAPK activation induces *ALD1* expression via WRKY33 to increase local Pip accumulation. Pip application triggers activation of MPK3 and MPK6. MAPK activation during *Pto* AvrRpt2 infection is compromised in *wrky33*, *ald1*, and *fmo1* mutant plants. These results suggest that the regulatory loop consisting of MPK3/MPK6, WRKY33, ALD1, and Pip in local leaves plays a critical role in the establishment of SAR when the MAPKs are locally activated in a sustained manner.

RESULTS

Local MAPK Activation Triggers SAR

SA application triggers SAR (Lawton et al., 1995), and MPK3 and MPK6 regulate immune responses redundantly with SA, when they are activated in a sustained manner (Tsuda et al., 2013). Therefore, we hypothesized that sustained MPK3/MPK6 activation in local leaves triggers SAR in systemic leaves of Arabidopsis. Transgenic plants expressing MKK4^{DD} (MKK4^{DD}) under the control of a DEX-inducible promoter (Ren et al., 2002; Tsuda et al., 2013) were employed to investigate the effect of localized MAPK activation. DEX treatment induced the expression of defense marker genes *PATHOGENESIS-RELATED1* (*PR1*) and *FLG22-INDUCED RECEPTOR-LIKE KINASE1* (*FRK1*) in MKK4^{DD} plants as well as in MKK4^{DD} *sid2* (Figure 1A). Interestingly, expression of *ALD1* was also induced by activation of MPK3 and MPK6 in both MKK4^{DD} and MKK4^{DD} *sid2* plants (Figure 1A), pointing to a role of MPK3/MPK6 in SAR establishment without SA. Indeed, we observed that SAR is triggered in MKK4^{DD} and, to a lesser extent, MKK4^{DD} *sid2* plants after DEX treatment in local leaves (Figure 1B), whereas no SAR was observed after DEX treatment in Col-0, *sid2*, and transgenic plants harboring DEX-inducible GUS (GVG:GUS) (Figure 1B). We did not detect expression of the *MKK4^{DD}* or *GUS* transgene in systemic leaves of MKK4^{DD} or GVG:GUS plants, respectively, after local DEX application, suggesting that DEX itself did not translocate from local leaves to systemic leaves (Supplemental Figures 1A and 1B). Thus, local MAPK activation appeared to trigger SAR. Consistent with this, expression of *PR1*, *FRK1*, *ALD1*, and SAR was induced in both Col-0 and *sid2* plants upon infection with *Pto* AvrRpt2 (Figures 1C and 1D), which triggers strong sustained MAPK activation (Tsuda et al., 2013).

MAPK-Mediated SAR Requires *ALD1*

Next, we tested whether known SAR components are required for the MAPK activation-triggered SAR. MKK4^{DD} plants were crossed with *fmo1*, *ald1*, and *npr1* mutants, in which SAR was shown to be robustly compromised in various conditions (Cao et al., 1997; Mishina and Zeier, 2006; Bernsdorff et al., 2016; Hartmann et al., 2018). SAR assay after local DEX application showed that *FMO1*, *ALD1*, and *NPR1*, but not *SID2*, are required for the MAPK-mediated SAR (Figure 2A). Immunoblotting of MKK4^{DD}-flag, MPK3, and MPK6 showed that the MKK4^{DD} inducible system is intact and MPK3 and MPK6 protein accumulation remain unaltered in these genetic backgrounds (Figure 2B). Notably, MAPK activation was compromised in *ald1* and *fmo1* backgrounds (Figure 2B), suggesting that MAPK activation triggered by MKK4^{DD} requires the Pip pathway. Consistent with this, we found that *FMO1*, *ALD1*, and *NPR1* are required for SAR triggered by local *Pto* AvrRpt2 infection (Supplemental Figure 2A). MAPK-mediated *ALD1* (Figure 1A) and *FMO1* induction (Figure 4A) prompted us to test whether MAPK activation triggers increased Pip and NHP accumulation in local leaves. Indeed, Pip and NHP accumulation was increased in local leaves of MKK4^{DD} plants after DEX application (Figure 2C). These results suggest that MAPK activation induces *ALD1* and *FMO1* expression to increase local Pip and NHP accumulation, thereby contributing to SAR. Considering that Pip is metabolized to NHP by FMO1 and that Pip-induced responses require *FMO1* (Chen et al., 2018; Hartmann et al., 2018), this indicates that NHP is the key signaling molecule in MAPK-mediated SAR. Consistent with previous reports (Ren et al., 2008), accumulation of the phytoalexin camalexin also increased (Supplemental Figure 1C).

MPK3 and MPK6 Positively Regulate Pip Accumulation upon Infection with *Pto* AvrRpt2

We investigated the genetic requirement of *MPK3* or *MPK6* for the establishment of SAR. We first employed two systems to trigger SAR, local infection with *Pto* or *Pto* AvrRpt2, which activates MPK3 and MPK6 in a transient or sustained manner, respectively (Tsuda et al., 2013). Upon local infection with *Pto*, SAR was detected in Col-0, *mpk3*, and *mpk6* but not *sid2*, *mpk3 sid2*, and *mpk6 sid2* (Supplemental Figure 3A), suggesting that SA is required for *Pto*-triggered SAR. In contrast, upon local infection with *Pto* AvrRpt2, SAR was observed in Col-0, *mpk3*, *mpk6*, and *sid2* but not in *mpk3 sid2* and *mpk6 sid2* (Figure 3A). *Pto* AvrRpt2-triggered induction of *ALD1* and *FMO1* in local leaves was compromised in *mpk3*, *mpk6*, *mpk3 sid2*, and *mpk6 sid2*, but not in *sid2* (Figure 3B), pointing to the positive roles of MPK3 and MPK6 for local *ALD1* and *FMO1* expression. As previously reported (Tsuda et al., 2013), *PR1* expression was redundantly regulated by the MAPKs and SA (Figure 3B). Local Pip accumulation was decreased in *mpk3* and *mpk6* compared with Col-0 and in *mpk3 sid2* and *mpk6 sid2* compared with *sid2* (Figure 3C), indicating positive roles of *MPK3* and *MPK6* in Pip accumulation. Pip accumulation was elevated in *sid2* compared with Col-0 and in *mpk3 sid2* and *mpk6 sid2* compared with *mpk3* and *mpk6*, suggesting that SA negatively regulates Pip accumulation (Figure 3C). Curiously, *mpk3 sid2* and *mpk6 sid2* showed Col-0-like Pip accumulation yet compromised SAR (Figures 3A and 3C). Thus, the amount of locally accumulating Pip alone does not explain the observed SAR phenotypes.

MAPK-Mediated Pip Accumulation and SAR Are Compromised in *wrky33*

The transcription factor WRKY33 regulates defense responses against a wide range of pathogens (Zheng et al., 2006; Liu et al., 2015; Liao et al., 2016) and is activated by MPK3 and MPK6 via phosphorylation (Mao et al., 2011). Therefore, we hypothesized that WRKY33 regulates MAPK-mediated *ALD1* expression and Pip accumulation. Consistent with our hypothesis, levels of local *ALD1* expression as well as *PR1* and *FMO1* and Pip accumulation after MAPK activation were reduced in *wrky33* (Figures 4A and 4B), while MKK4^{DD} protein was induced after DEX treatment similarly to the wild-type background (Figure 2B). MAPK-mediated SAR was also partially but significantly reduced in MKK4^{DD} *wrky33* compared with MKK4^{DD} plants (Figure 4C), suggesting that *WRKY33* mediates MAPK-regulated SAR via *ALD1* induction. Consistent with this, the levels of *ALD1* expression as well as *PR1* and *FMO1*, Pip accumulation, and SAR were significantly reduced in *wrky33* upon local *Pto* AvrRpt2 infection (Figures 4D and 4E). Similar to Figure 3, *wrky33 sid2*

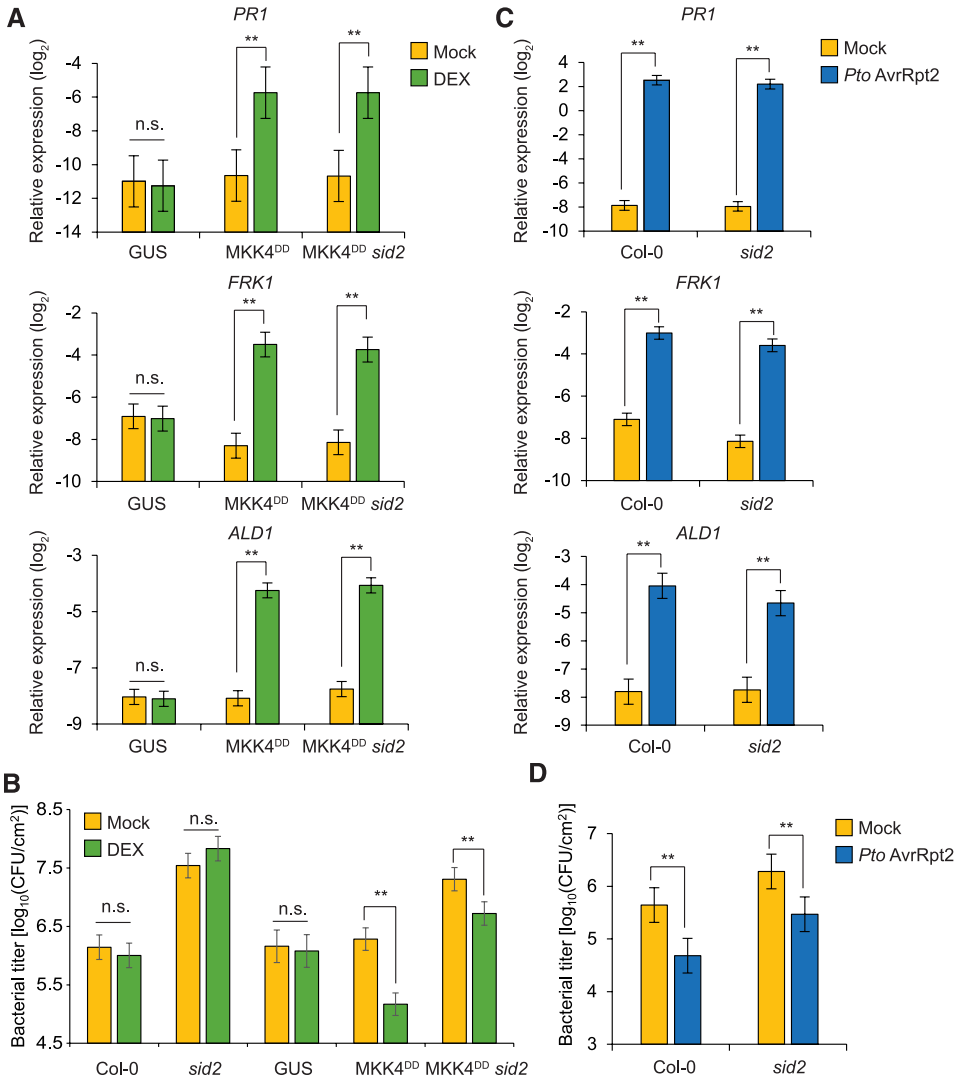

Figure 1. MAPK-Mediated SAR Is Largely Independent of SA.

(A) and **(C)** Expression levels of *PR1*, *FRK1*, and *ALD1* relative to *ACTIN2* in 4-week-old leaves determined by RT-qPCR. Leaves of DEX-inducible GUS, MKK4^{DD}, and MKK4^{DD} *sid2* plants were harvested 24 h after infiltration with 1 μM DEX or mock **(A)** and of Col-0 and *sid2* 24 h after infiltration with *Pto* AvrRpt2 (OD_{600} = 0.001) or mock **(C)**.

(B) and **(D)** Bacterial titers in systemic leaves. Primary leaves of Col-0, *sid2*, GUS, MKK4^{DD}, and MKK4^{DD} *sid2* were infiltrated with 1 μM DEX or mock **(B)** and of Col-0 and *sid2* with *Pto* AvrRpt2 (OD_{600} = 0.001) or mock **(D)**. After 1 d, systemic leaves were infiltrated with *Pto* (OD_{600} = 0.001), and bacterial titers in the systemic leaves were measured at 2 d after systemic infection.

Bars represent means and standard errors calculated from three independent experiments each with three biological replicates using a mixed linear model. **P < 0.01; two-tailed Student's *t* tests. n.s., not significant.

showed Col-0-like Pip accumulation but compromised SAR and Pip accumulation was elevated in *sid2* compared with Col-0 and in *wrky33 sid2* compared with *wrky33* (Figures 4E and 4F). Moreover, the *Pto*-induced SAR fully depended on functional *WRKY33* as well (Supplemental Figure 3B).

SAR Triggered by Multiple Stimuli Converges at WRKY33, ALD1, and FMO1

To better understand the roles of the MAPK-WRKY33 and SA pathways in SAR induced by different stimuli, we also investigated local Pip accumulation and SAR triggered by local infection with the bacterial strain *P. syringae* pv *maculicola* ES4326 (*Pma*). *Pma* inoculation induces robust SAR in Arabidopsis and has been used extensively to investigate the underlying molecular mechanisms (Mishina and Zeier, 2006; Liu et al., 2011; Bernsdorff et al., 2016; Hartmann et al., 2018). Similar to *Pto* but in contrast to *Pto* avrRpt2 or *Pma* expressing avrRpm1, *Pma* did not trigger sustained MAPK activation in inoculated leaves (Supplemental Figure 4A). Consistent with previous findings (Bernsdorff et al., 2016), a weak but significant SAR response was observed in *sid2* after *Pma*

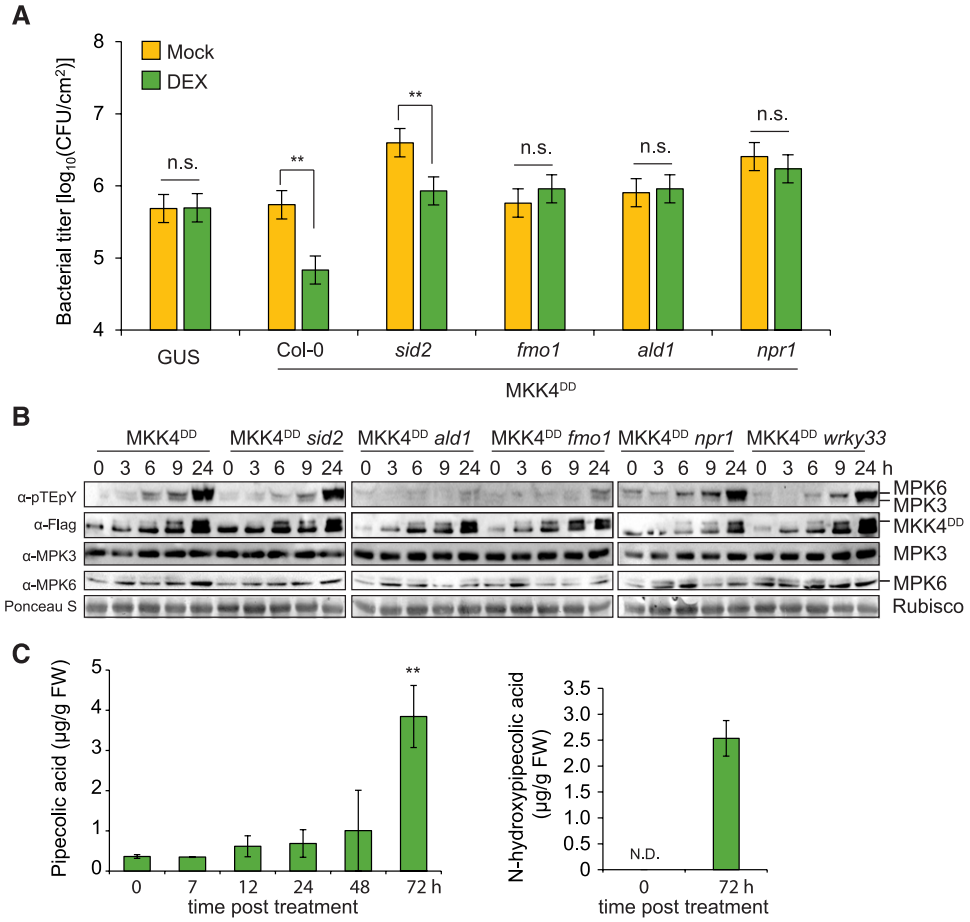

Figure 2. MAPK-Mediated SAR Requires *ALD1*.

(A) Bacterial titers in systemic leaves of GUS, MKK4^{DD}, MKK4^{DD} *sid2*, MKK4^{DD} *fmo1*, MKK4^{DD} *ald1*, and MKK4^{DD} *npr1*. Primary leaves were infiltrated with 1 μM DEX or mock. After 1 d, systemic leaves were infiltrated with *Pto* (OD_{600} = 0.001), and bacterial titers in the systemic leaves were measured at 2 d after systemic infection. Bars represent means and standard errors calculated from three independent experiments each with three biological replicates using a mixed linear model. Asterisks indicate significant difference from mock ($P < 0.01$; two-tailed Student's *t* tests). n.s., not significant
(B) Phosphorylation of MPK3 and MPK6, and protein level accumulation of MKK4^{DD}, MPK3, and MPK6 in local leaves of MKK4^{DD}, MKK4^{DD} *sid2*, MKK4^{DD} *fmo1*, MKK4^{DD} *ald1*, MKK4^{DD} *npr1*, and MKK4^{DD} *wrky33* plants at the indicated time points after infiltration with 1 μM DEX.
(C) Pipecolic acid and *N*-hydroxypipecolic acid levels in local leaves of MKK4^{DD} plants infiltrated with 1 μM DEX or mock at the indicated time points. N.D. indicates under the detection limit. Bars represent means and standard errors calculated from three independent experiments. Asterisks indicate significant difference from 0 h after infiltration ($P < 0.01$; two-tailed Student's *t* tests).

inoculation, as well as in *mpk3 sid2* (Figure 5A). Thus, similar to SAR triggered by local *Pto* infection, the *Pma*-triggered SAR establishment was predominantly dependent on SA (Figure 5A). In addition, *Pma* inoculation triggered SAR in both *mpk3* and *mpk6* to nearly same levels with Col-0 wild type (Figure 5A). This was accompanied with wild-type-like accumulation of Pip in the locally inoculated and systemic leaves of both *mpk3* and *mpk6* mutants (Figure 5C). However, the *Pma*-induced biosynthesis of NHP and camalexin was specifically reduced in *mpk3* (Figure 5C; Supplemental Figure 4B). Moreover, SAR triggered by *Pma* was attenuated in *wrky33* plants (Figure 5B), and local Pip and NHP, as well as systemic Pip accumulation was reduced in *wrky33* upon local *Pma* infection (Figure 5C).

Thus, the absence of just *MPK3* or *MPK6* appears to have only minor effects on Pip accumulation and SAR when local MAPK activation is not sustained, as is the case for *Pma*- and *Pto* inoculation. Nevertheless, *WRKY33* plays common roles in SAR triggered by multiple pathogen stimuli irrespective of the MAPK activation kinetics in local leaves (Figures 4F and 5B; Supplemental Figure 4B), suggesting that WRKY33 activity may also be regulated by other factors than the MAPKs. The growth assays with the different bacterial strains also indicate a WRKY33-independent signaling branch to SAR that is activated after *Pma* inoculation and induces a partial SAR. Consistent with previous reports (Návarová et al., 2012; Hartmann et al., 2018), these different signaling pathways leading to SAR induction converge at *ALD1* (Figure 2A; Supplemental Figure 2)

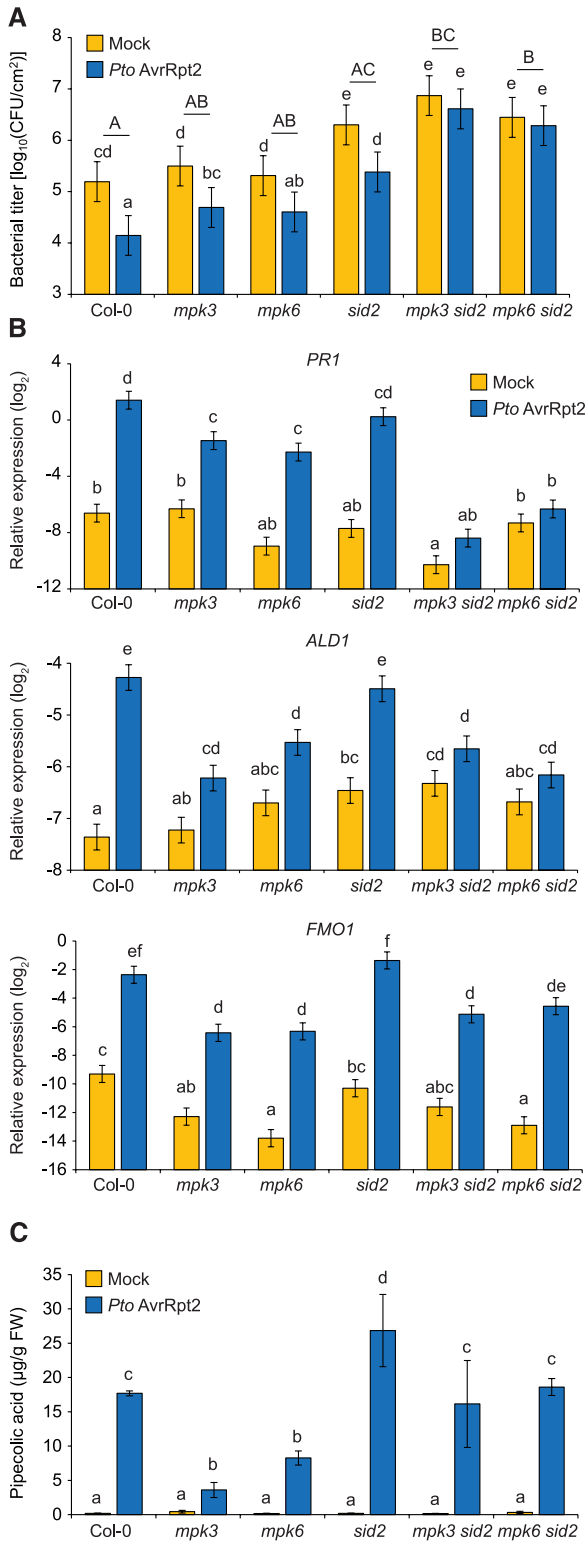

Figure 3. MPK3 and MPK6 Positively Regulate Pip Accumulation during *Pto* AvrRpt2 Infection.

(A) Bacterial titers in systemic leaves of Col-0, *mpk3*, *mpk6*, *sid2*, *mpk3 sid2*, and *mpk6 sid2*. Primary leaves were infiltrated with *Pto* AvrRpt2 (OD_{600} = 0.001) or mock. After 1 d, systemic leaves were infiltrated with *Pto* (OD_{600} = 0.001), and bacterial titers were measured at 2 d after systemic infection. Bars represent means and standard errors calculated from six independent experiments each with four biological replicates using a mixed linear model.

(B) Expression of *PR1*, *ALD1*, and *FMO1* in Col-0, *mpk3*, *mpk6*, *sid2*, *mpk3 sid2*, and *mpk6 sid2* at 24 h after infiltration with *Pto* AvrRpt2 (OD_{600} = 0.001) or mock determined by RT-qPCR. Bars represent means and standard errors of the $\log_2$ expression levels relative to *ACTIN2* calculated from three independent experiments each with three biological replicates using a mixed linear model.

(C) Local Pip accumulation in leaves of Col-0, *mpk3*, *mpk6*, *sid2*, *mpk3 sid2*, and *mpk6 sid2* at 24 h after infiltration with *Pto* AvrRpt2 (OD_{600} = 0.001) or mock. Bars represent means and standard errors of four independent biological replicates. Statistical differences were calculated using a mixed linear model followed by two-tailed Student's *t* tests. Different letters above the bars denote statistically significant differences (adjusted $P < 0.05$). Uppercase letters indicate comparisons between genotypes for SAR effects.

WRKY33 Binds to the *ALD1* Promoter

Compromised *ALD1* expression and Pip accumulation triggered by MAPK activation in *wrky33* (Figures 4A and 4B) suggests WRKY33 directly regulates *ALD1* expression. Indeed, three W-boxes, the binding motif of WRKYs, were found in the *ALD1* promoter (Figure 6A). Therefore, we investigated WRKY33 binding to these W-boxes by chromatin immunoprecipitation followed by quantitative PCR (ChIP-qPCR) in *Pwrky33:WRKY33-HA* plants (Liu et al., 2015). Accumulation of WRKY33 was detected from 6 h postinfiltration with *Pto* AvrRpt2 (Figure 6B). We detected strong enrichment of *Pwrky33:WRKY33-HA* for W-box 2/3 compared with Col-0 control but not for W-box 1 (Figure 6C). This result is consistent with the large-scale ChIP sequencing study showing that WRKY33 binds to W-box 2/3 but not W-box 1 in the *ALD1* promoter (Birkenbihl et al., 2017). Thus, WRKY33 appears to regulate *ALD1* expression via direct binding to the W-box 2/3 in the *ALD1* promoter.

Pip Triggers MAPK Activation and *ALD1* Is Required for Sustained MAPK Activation upon *Pto* AvrRpt2 Infection

Since it is known that defense activation often results in growth retardation (Huot et al., 2014), we investigated whether Pip affects root growth. We found that Pip triggers root growth retardation although its effect was weaker than that of flg22, a MAMP and known inducer of root growth retardation (Chinchilla et al., 2007) (Figure 7A). Root growth retardation triggered by Pip as well as flg22 was abolished in *bak1 bkk1*, which is deficient in the coreceptors of some membrane-localized MAMP receptors (Figure 7A). Moreover, Pip-triggered root growth retardation was not observed with the isomeric and nonactive form of Pip (D-Pip) but the active form of Pip (L-Pip) (Návarová et al., 2012) (Figure 7A). We then explored the possibility that Pip triggers MAPK activation. Strikingly, L-Pip but not D-Pip triggered transient activation of MPK3 and MPK6 dependently on *BAK1 BKK1* (Figure 7B; Supplemental Figure 5). These results may suggest that Pip is sensed by plant membrane-localized receptor(s) to trigger MAPK activation.

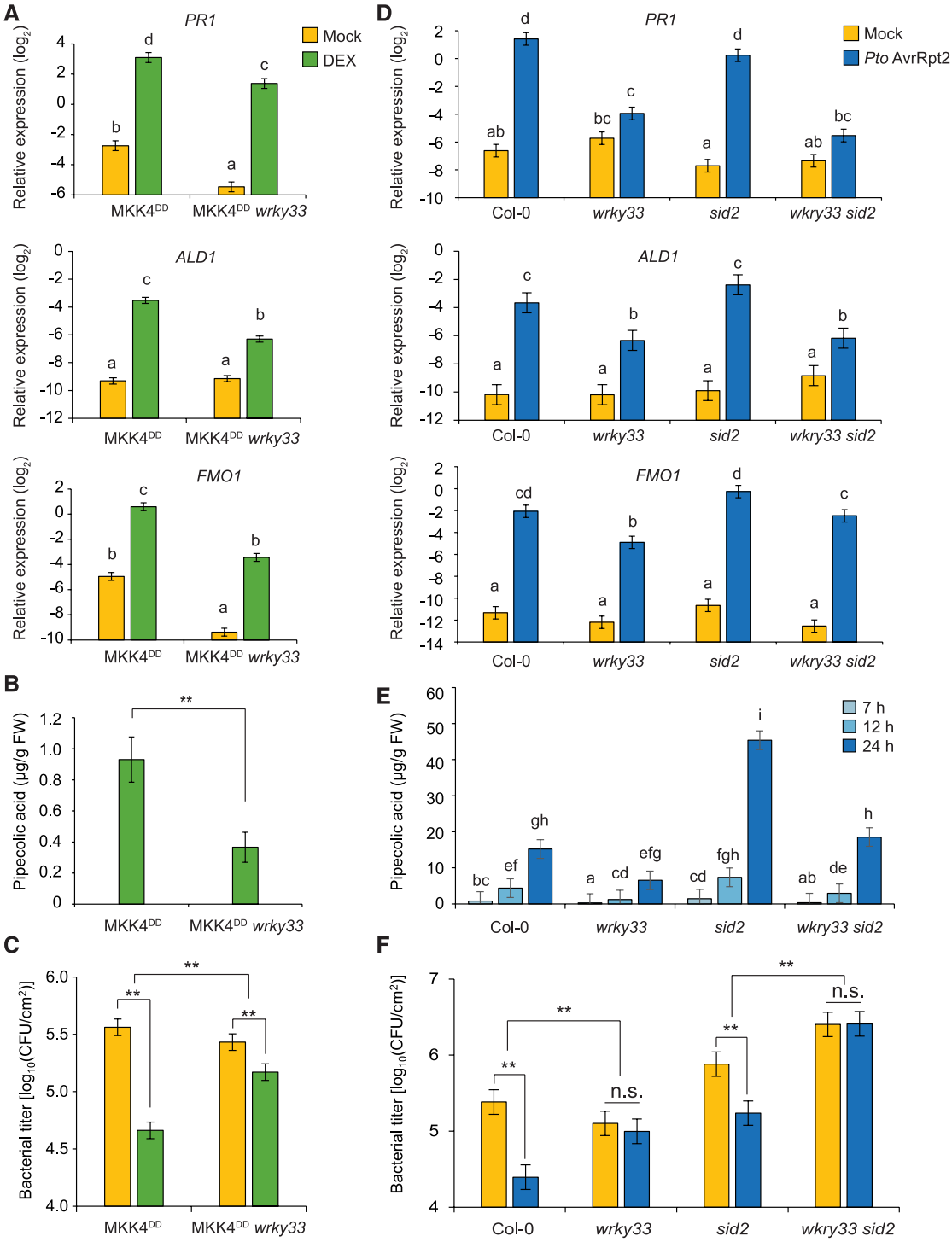

Figure 4. MAPK-Mediated Pip Accumulation and SAR Are Compromised in *wrky33*.

(A) and **(D)** *PR1*, *ALD1*, and *FMO1* expression in leaves of MKK4^{DD} and MKK4^{DD} *wrky33* at 24 h after infiltration with 1 µM DEX or mock determined by RT-qPCR **(A)** and of Col-0, *wrky33*, *sid2*, and *wrky33 sid2* at 24 h after infiltration with *Pto* AvrRpt2 (OD_{600} = 0.001) or mock **(D)**. Bars represent means and standard errors calculated from two independent experiments each with three biological replicates using a mixed linear model.

(B) and **(E)** Pip accumulation in leaves of MKK4^{DD} and MKK4^{DD} *wrky33* at 24 h after infiltration with 1 µM DEX **(B)** and of Col-0, *wrky33*, *sid2*, and *wrky33 sid2* at 7, 12, and 24 h after infiltration with *Pto* AvrRpt2 (OD_{600} = 0.001) or mock **(E)**. Bars represent means and standard errors calculated from five **(B)** or three **(E)** independent biological replicates. Statistical differences were calculated using a mixed linear model followed by two-tailed Student's *t* tests.

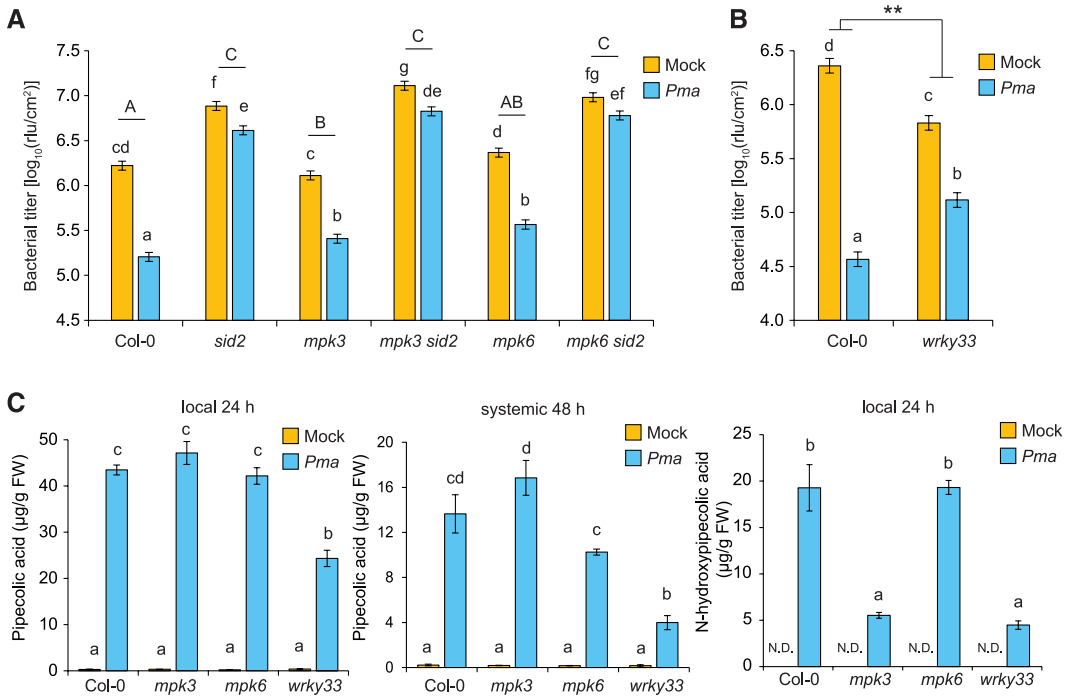

Figure 5. SA and *WRKY33* Contribute to SAR Triggered by *Pma* Infection.

(A) and **(B)** Bacterial titers in systemic leaves of Col-0, *mpk3*, *mpk6*, *sid2*, *mpk3 sid2*, and *mpk6 sid2* **(A)** and of Col-0 and *wrky33* **(B)**. Primary leaves were infiltrated with *Pma* (OD_{600} = 0.005) or mock. After 2 d, systemic leaves were infiltrated with *Pma lux* (OD_{600} = 0.001), and the bioluminescence of *Pma* lux was determined at 60 h after systemic infection. Bars represent means and standard errors calculated from at least four independent experiments each with three biological replicates using a mixed linear model.

(C) Pip accumulation in local leaves at 24 h and systemic leaves at 48 h, and *N*-hydroxypipecolic acid accumulation in local leaves of Col-0, *mpk3*, *mpk6*, and *wrky33* at 24 h after infiltration with *Pma* (OD_{600} = 0.001) or mock (10 mM $MgCl_2$). Bars represent means and standard errors of three biological replicates. N.D. indicates under the detection limit. Statistical differences were calculated using a mixed linear model followed by two-tailed Student's *t* tests.

Different letters above the bars denote statistically significant differences (adjusted P < 0.05). Uppercase letters indicate comparisons between genotypes for SAR effects. **P < 0.01; two-tailed Student's *t* tests.

Since the MAPK-WRKY33-ALD1 pathway positively regulated Pip accumulation under sustained MAPK activation conditions (Figures 2B and 4B), these results also suggest the existence of a regulatory loop for defense amplification. If this holds true, MAPK activation should be compromised in mutant plants deficient in this regulatory loop. Indeed, we observed that sustained local MAPK activation triggered by *Pto* AvrRpt2 infection was compromised in *wrky33*, *ald1*, and *fmo1* (Figures 7C and 7D), supporting the regulatory loop consisting of MPK3/MPK6, WRKY33, ALD1, FMO1, and Pip/NHP for SAR establishment under induction conditions involving local sustained MAPK activation. This amplification loop might be circumvented if Pip levels were elevated in the plant to high levels by exogenous treatment. To test this hypothesis, we supplemented plants with a dose of 10 µmol Pip, a treatment known to result in Pip augmentation in leaves to SAR-like levels and in the induction of systemic immunity (Návarová et al., 2012; Vogel-Adghough et al., 2013; Bernsdorff et al., 2016), and performed *Pma* growth assay in Col-0, *mpk3*, *mpk6*, and *wrky33* plants. We observed significant Pip-induced resistance against *Pma* in Col-0, as well as *mpk3*, *mpk6*, and *wrky33* (Figure 7E), indicating that the MPK3/MPK6- and WRKY33-based regulatory loop can be bypassed by high amounts of Pip. However, consistent with our observation that Pip-induced root growth inhibition and MAPK activation

Figure 4. (continued).

(C) and **(F)** Bacterial titers in systemic leaves of $MKK4^{DD}$ and $MKK4^{DD}$ *wrky33* **(C)** and of Col-0, *wrky33*, *sid2*, and *wrky33 sid2* **(F)**. Primary leaves were infiltrated with 1 µM DEX or mock **(C)** and with *Pto* AvrRpt2 (OD_{600} = 0.001) or mock **(F)**. After 1 d, systemic leaves were infiltrated with *Pto* (OD_{600} = 0.001), and bacterial titers in the systemic leaves were measured at 2 d after systemic infection. Bars represent means and standard errors calculated from at least four independent experiments each with three biological replicates using a mixed linear model.

Different letters above the bars denote statistically significant differences (adjusted P < 0.05). **P < 0.01; two-tailed Student's *t* tests. n.s., not significant.

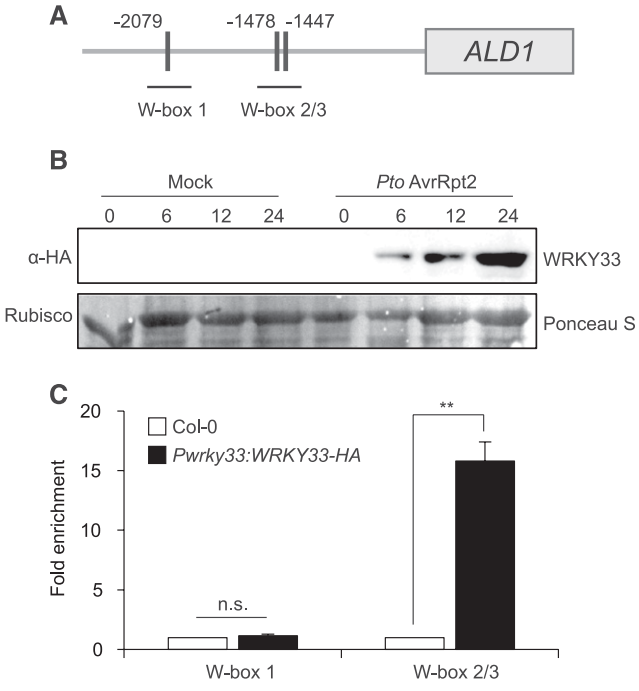

Figure 6. WRKY33 Binds to *ALD1* Promoter.

(A) Schematic diagram of *ALD1* promoter. The vertical black bars represent W-boxes. The horizontal lines show the regions amplified by different qPCR primers.

(B) Protein accumulation of WRKY33 in WRYK33-HA *wrky33* plants after infiltration with *Pto* AvrRpt2 (OD_{600} = 0.001) or mock at the indicated time points visualized by immunoblotting using anti-HA antibody. Ponceau S-stained Rubisco is shown as a loading control.

(C) ChIP-qPCR was performed using Col-0 and WRYK33-HA *wrky33* at 1 d after infiltration with *Pto* AvrRpt2 (OD_{600} = 0.001). Bars represent means and standard errors of the fold enrichment relative to Col-0 (set to 1), calculated from three independent biological replicates. **P value < 0.01, two-tailed Student's *t* tests. n.s., not significant.

were compromised in *bak1 bkk1* mutant plants (Figures 7A and 7B), Pip-induced immunity against *Pma* required *BAK1 BKK1* (Figure 7E).

DISCUSSION

In this study, we identified a regulatory loop for Pip accumulation upon local pathogen exposure which contributes to SAR in Arabidopsis (Figure 7F). Our results and previous publications demonstrate that (1) local MAPK activation triggers SAR; (2) sustained MAPK activation induces *ALD1* and *FMO1* expression as well as Pip and NHP accumulation; (3) direct activation of WRKY33 by MPK3 and MPK6 was previously shown (Mao et al., 2011); (4) WRKY33 directly regulates *ALD1* expression; (5) MAPK-mediated SAR is compromised in *wrky33*, *ald1*, and *fmo1* mutant plants; (6) Pip triggers MAPK activation; and (7) sustained MAPK activation triggered by *Pto* AvrRpt2 is compromised in *wrky33*, *ald1*, and *fmo1* mutants. Thus, the positive regulatory loop consisting of MPK3/MPK6, WRKY33, ALD1, FMO1, and Pip/NHP contributes to the establishment of SAR triggered by local sustained MAPK activation.

The SAR processes can be divided into three steps: local immune activation, information relay from local to systemic tissues by mobile signal(s), and defense activation and priming in systemic tissues (Jung et al., 2009; Shah and Zeier, 2013). In this study, we focused on local immune activation important for SAR establishment. We showed that artificial local activation of MPK3 and MPK6 by the $MKK4^{DD}$ system is sufficient to trigger SAR (Figure 1). Genetic requirement of *MPK3* and *MPK6* for SAR was also detected when SAR is activated by local *Pto* AvrRpt2 infection, which triggers sustained MAPK activation (Figure 3). In contrast, SAR predominantly depends on SA when it is activated by local infection with *Pto* and *Pma*, both of which do not trigger sustained MAPK activation (Figure 5A; Supplemental Figures 3A and 4A; Tsuda et al., 2013). Thus, the regulatory loop for SAR identified in this study may kick in and play critical roles in SAR when local MAPK activation is sustained.

ALD1 is commonly required for SAR triggered by local infection with *Pma* and *Pto* AvrRpt2 and by local MAPK activation as well as for systemic immunity induced by β-aminobutyric acid and azelaic acid (Figure 2A; Supplemental Figure 2) (Zimmerli et al., 2000; Jung et al., 2009; Návarová et al., 2012). ALD1- and FMO1-mediated Pip and NHP production, respectively, are highly induced during immunity (Návarová et al., 2012; Hartmann et al., 2018). Thus, the regulation of pathogen-induced *ALD1* and *FMO1* expression is crucial for SAR. We showed that WRKY33 positively regulates *ALD1* via its direct binding to the *ALD1* promoter to increase Pip accumulation (Figure 6). Induction of *ALD1* expression and Pip accumulation was not totally compromised in *wrky33* (Figures 4A and 4B), suggesting that other transcription factors also contribute to *ALD1* expression. Indeed, the transcription factors SARD1 and CBP60g directly regulate expression of *ALD1* as well as *SARD4* (Sun et al., 2015). *SARD4* encodes the dehydropipecolate reductase enzyme that reduces ALD1-produced 2,3-DP to Pip (Ding et al., 2016; Hartmann et al., 2017). More recently, it was shown that transcription factors TGA1 and TGA4 directly regulate the expression of *SARD1* and *CBP60g* and that Pip accumulation upon *Pma* infection is significantly reduced but not abolished in *tga1 tga4* and *sard1 cbp60g* mutants (Sun et al., 2018). Furthermore, SAR was abolished in *wrky33* when it is activated by local *Pto* infection irrespective to modes of MAPK activation (Figure 4; Supplemental Figure 3B), whereas SAR activated by local *Pma* infection was attenuated but not fully abolished in *wrky33* (Figure 5B). These results suggest that both TAG1/TAG4-SARD1/CBP60g and WRKY33 regulate Pip accumulation and SAR triggered by local *Pma* infection, while WRKY33 is the major regulator of SAR triggered by local *Pto* infection. Our study thus indicates the existence of distinct branches of SAR signaling that are differentially activated by different pathogen types. These signaling branches converge at *ALD1* and Pip production (Figure 7F). SAR induction also depends on *FMO1* for both MAPK activating *Pto* AvrRpt2 and non-activating *Pma* (Supplemental Figure 2) (Návarová et al., 2012), supporting the finding that Pip to NHP conversion by FMO1 is a critical step for SAR activation (Hartmann et al., 2018).

SA is required for SAR in systemic leaves but not local infected leaves of tobacco plants (Vernooij et al., 1994). Furthermore, SA

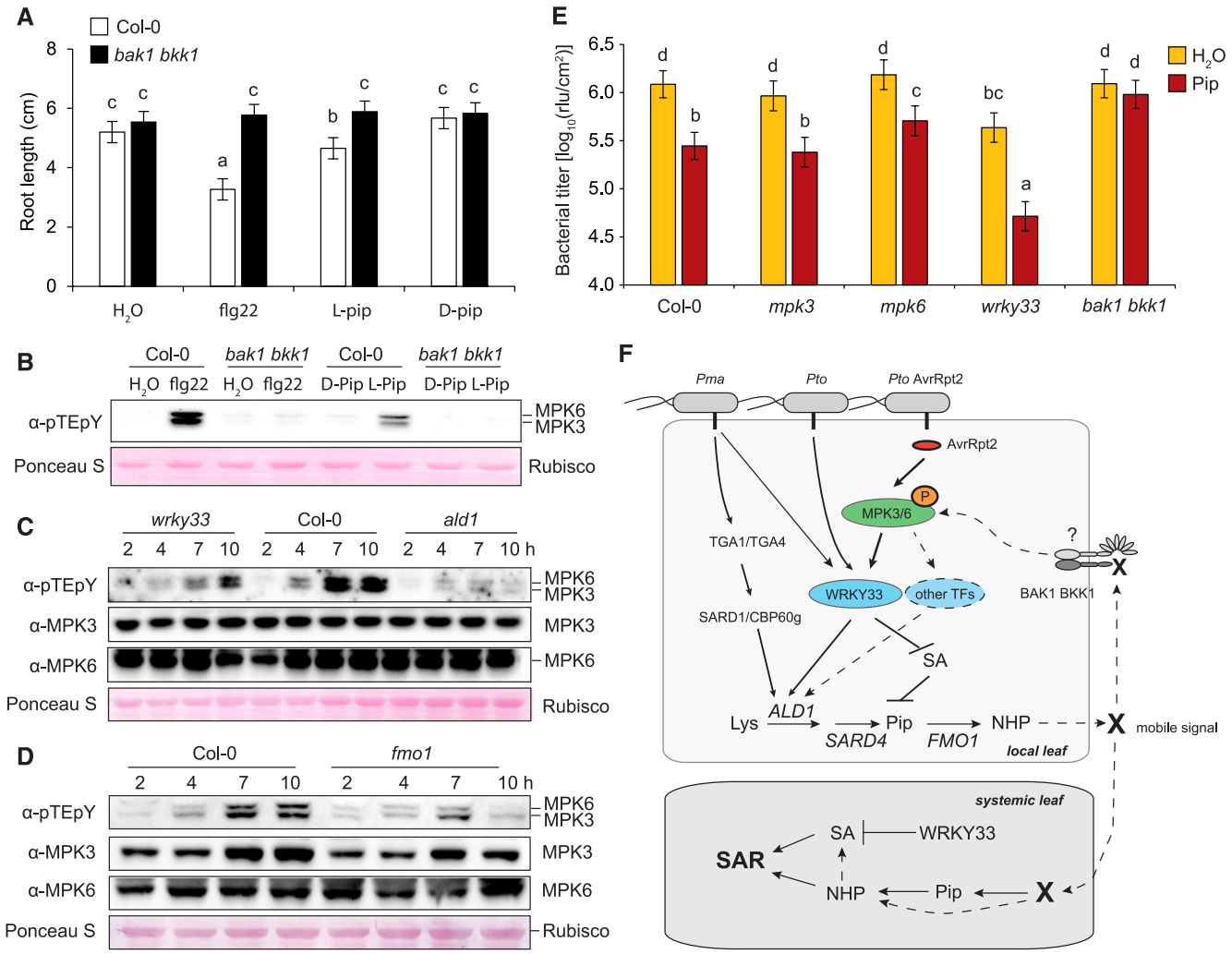

Figure 7. Pip Triggers MAPK Activation.

(A) Col-0 and *bak1 bkk1* plants were grown on 1/2 MS medium containing 1 μM flg22, 1 μM L-Pip, 1 μM D-Pip, or mock, and primary root length was measured at 10 d old. Bars represent means and standard errors calculated from four independent biological replicates using a mixed linear model.
(B) MAPK activation in 10-d-old seedlings of Col-0 and *bak1 bkk1*. Seedlings were collected at 15 min after the treatment with 1 μM flg22, 1 μM L-Pip, 1 μM D-Pip, or mock.
(C) and **(D)** MAPK activation in leaves of 4-week-old Col-0, *wrky33*, *ald1*, and *fmo1* after infiltration with *Pto* AvrRpt2 (OD_{600} = 0.001), and samples were collected at the indicated time points.
(B) to **(D)** Proteins were detected by immunoblotting using the indicated antibodies. Ponceau S-stained RuBisCo is shown as a loading control. Similar results were observed in three independent experiments.
(E) Bacterial titers in leaves of Col-0, *mpk3*, *mpk6*, *wrky33*, and *bak1 bkk1*. Five-week-old plants were supplied with 10 mL of 1 mM Pip (dosage of 10 μmol) or water via the root system. Three leaves per plant were infiltrated with *Pma lux* (OD_{600} = 0.001) at 1 d after treatment, and relative luminescence light units (rlu) per cm^2 (log_{10}) were measured at 60 h after systemic infection. Bars represent means and standard errors of at least three independent biological replicates using a mixed linear model.
(A) and **(E)** Different letters above the bars denote statistically significant differences (adjusted $P < 0.01$).
(F) Model for the immune amplification loop consisting of MPK3/6, WRKY33, ALD1, and pipecolic acid.

contributes to SAR signal amplification together with ALD1 and FMO1 in Arabidopsis systemic leaves (Bernsdorff et al., 2016). These results suggest that SA is an important component for SAR in systemic tissues but not local infected tissues. Previous results indicate that the SA-deficient *sid2* mutant strongly overproduces NHP upon *Pma* infection, suggesting that SA negatively modulates levels of NHP (Hartmann et al., 2018). Similarly, we found here that SA acts as a negative regulator of *Pto AvrRpt2*-triggered local Pip accumulation (Figures 3C and 4E). This elevated Pip accumulation appears to be sufficient for *Pto* AvrRpt2-triggered SAR in the absence of SID2-produced SA (Figures 3A and 3C). However, *mpk3 sid2* and *mpk6 sid2*,

which accumulate wild-type levels of Pip in local leaves, did not trigger SAR after *Pto* AvrRpt2 infection (Figures 3A and 3C). One explanation for these observations is that elevated Pip/NHP levels but not wild-type levels of Pip in local leaves are sufficient for SAR signal amplification in systemic leaves without SA. Thus, the strength of SAR appears to be determined by activities of local Pip/NHP pathway and systemic SA pathway. Interestingly, WRKY33 negatively regulates SA accumulation and signaling (Birkenbihl et al., 2012; Liu et al., 2015). Consistent with this, we found that compared with wild-type plants, *wrky33* plants are more resistant against *Pma*, which is sensitive to SA-mediated immunity (Figure 5B). Thus, WRKY33 is a negative regulator of local defense via SA suppression and a positive regulator of SAR via Pip accumulation, exemplifying that regulations of local immunity and SAR are tightly linked.

Pip-triggered MAPK activation, root growth inhibition, and Pip-induced SAR required *BAK1* and *BKK1* (Figures 7A, 7B, and 7E). BAK1 and BKK1 belong to the SOMATIC EMBRYOGENESIS RECEPTOR KINASEs that function as coreceptors for the recognition of multiple MAMPs as well as plant-derived damage-associated molecular patterns (DAMPs) on the plasma membrane (Chinchilla et al., 2007; Heese et al., 2007; Shan et al., 2008; Krol et al., 2010). The coreceptors BAK1 and BKK1 function with receptors belonging to RLKs or RLPs. Therefore, it is tempting to speculate that Pip or perhaps a Pip-derived product is sensed by RLKs or RLPs together with BAK1/BKK1, thereby triggering MAPK activation as described for flg22 recognition by FLS2 (Asai et al., 2002; Beckers et al., 2009). Recently, an NHP-hexose conjugate that accumulates dependently on *ALD1* and *FMO1* in *Pma*-inoculated leaves was detected in Arabidopsis (Hartmann and Zeier, 2018). Forward/reverse genetic screens and genome-wide association analysis using diverse Arabidopsis accessions might help to identify receptor(s) for Pip, NHP, or further NHP derivative(s) such as NHP-hexose, which may function as mobile metabolites involved in SAR long-distance signaling (Chen et al., 2018; Hartmann and Zeier, 2018). In Arabidopsis, the DAMP receptors PEPR1 and PEPR2 recognize endogenous PROPEP-derived Pep epitopes that activate immunity and function together with BAK1/BKK1 (Boller and Felix, 2009; Yamaguchi et al., 2010; Yamada et al., 2016). Interestingly, mutant plants deficient in *PEPR1* and *PEPR2* showed compromised SAR phenotypes triggered by local infection with *Pto* AvrRpm1 that triggers strong sustained MAPK activation (Ross et al., 2014). Likewise, application of Pep epitopes activates immune responses such as MAPK activation (Yamada et al., 2016). Thus, the SAR inducer Pip and the DAMPs Pep epitopes are both endogenously produced in plants and activate immunity and SAR, which renders the difference of DAMPs and SAR-related molecules ambiguous. Further research will be required to fully establish the difference and similarity between DAMPs and SAR inducers.

Pip triggers transient activation of MPK3 and MPK6 (Figure 7B; Supplemental Figure 5), yet *ALD1* and *FMO1* contribute to sustained MAPK activation after *Pto* AvrRpt2 infection (Figure 7C). One explanation for this is that sustained MAPK activation is achieved by multiple signal inputs including Pip/NHP and others. Alternative but not exclusive explanation is that Pip/NHP triggers transient activation of the MAPKs in different cells at different time points, resulting in sustained MAPK activation in local infected leaves. Measuring the temporal dynamics of the MAPK activities at the single cell resolution would help solve this issue.

The observation that MAPK activation triggered by MKK4^{DD} requires *ALD1* and *FMO1* (Figure 2B) was rather surprising to us because MKK4^{DD} would be able to directly phosphorylate MPK3 and MPK6 without other components. However, this suggests that MKK4^{DD} requires additional components whose activity depends on Pip/NHP to achieve sustained activation of MPK3 and MPK6 in plants. We speculate that Pip/NHP may condition the proper formation of MKK4DD-MPK3/MPK6 complex through, for instance, affecting the subcellular localization of MKK4^{DD}, MPK3, and MPK6. Alternatively, MKK4^{DD} triggers initial phosphorylation of MPK3 and MPK6, which then triggers sustained activation of MPK3 and MPK6 dependently on Pip/NHP. Recent work showed that MPK6 phosphorylates the upstream MAPK kinase kinase MAPKKK5 to enhance activation of MPK3 and MPK6 (Bi et al., 2018). Thus, Pip/NHP signaling may ensure, for instance, expression of *MAPKKK5*, and this positive feedback mechanism may be required for MKK4^{DD}-triggered sustained activation of MPK3 and MPK6. Nevertheless, this speculation needs to be experimentally tested.

METHODS

Plant Materials and Growth Conditions

Arabidopsis thaliana plants were grown in a chamber at 22°C with a 10-h-light (white fluorescence lamps) period and 60% relative humidity. The Arabidopsis accession Col-0 was used as the wild type. Arabidopsis mutants and transgenic lines, *sid2-2* (Wildermuth et al., 2001), *mpk3-1* (Wang et al., 2007), *mpk6-2* (Liu and Zhang, 2004), *mpk3-1 sid2-2*, *mpk6-2 sid2-2* (Tsuda et al., 2013), *ald1-T2* (Mishina and Zeier, 2006), *fmo1-1* (Návarová et al., 2012), *npr1-1* (Cao et al., 1997), *wrky33-2* (Zheng et al., 2006), *Pwrky33:WRKY33-HA* (Liu et al., 2015), MKK4^{DD}, MKK4^{DD} *sid2* (Ren et al., 2002), MKK4^{DD} *npr1* (Tsuda et al., 2013), and *rpm1-3 rps2 101C* (Belkhadir et al., 2004) were previously described. The MKK4^{DD} *fmo1*, MKK4^{DD} *ald1*, and MKK4^{DD} *wrky33* mutants were generated by crossing MKK4^{DD} with *fmo1*, *ald1*, and *wrky33*. The *wrky33 sid2* double mutant was generated by crossing *wrky33-2* with *sid2-2*. The primers and methods used for mutant genotyping are listed in Supplemental Table 1.

Bacterial Cultivation and Inoculation

Pseudomonas syringae pv *tomato* DC3000 harboring empty vector (*Pto*) or AvrRpt2 (*Pto* AvrRpt2) was cultivated as described (Tsuda et al., 2013). Bacterial cells were washed with water, diluted to the appropriate density, and infiltrated into Arabidopsis leaves using a needleless syringe. Similarly, *P. syringae* pv *maculicola* ES4326 (now classified as *Pseudomonas cannabina* pv *alisalensis* ES4326), carrying either no transgene (*Pma*), *avrRpm1* (*Pma* AvrRpm1), or the *luxCDABE* operon of *Photorhabdus luminescens* (*Pma lux*) were grown in King's B medium containing 50 μg/mL rifampicin. For *Pma AvrRpm1* 15 μg/mL tetracycline and for *Pma lux* 50 μg/mL kanamycin were additionally added to the medium. Bacteria from overnight cultures were washed three times with 10 mM $MgCl_2$ before adjusting to the appropriate density.

Bacterial Growth Assay

To induce SAR with *Pto* or *Pto* AvrRpt2, bacterial suspension was infiltrated into three local leaves of 4-week-old Arabidopsis plants. Sterilized

water was infiltrated as mock control. Systemic leaves were inoculated with *Pto* 24 h after local infiltration. The bacterial titer in systemic leaves was determined 2 d after systemic infiltration. For *Pma*-induced SAR, three local leaves of 4- to 5-week-old Arabidopsis plants were infiltrated with either mock (10 mM $MgCl_2$) or *Pma*. Two days after treatment, three systemic leaves were infiltrated with *Pma lux*. Bacterial growth in systemic leaves was assessed 2 d after systemic infiltration via luminescence as described by Hartmann et al. (2017). To assess Pip-induced resistance to *Pma*, plants were watered with 10 mL of 1 mM Pip or water 1 d prior to infiltration of three rosette leaves with *Pma lux* as described (Návarová et al., 2012). Log_{10}-transformed colony-forming units (cfu) per cm^2 leaf surface area or relative luminescence light units (rlu) per cm^2 were calculated and the following model was fit to the data, $CFU_{gyr} = GY_{gy}+R_r+e_{gyr}$, where GY, genotype:treatment interaction, and random factors; R, biological replicate; e, residual. The mean estimates of the fixed effects were used as the modeled bacterial titers and compared by two-tailed *t* test.

RNA Isolation and Quantitative RT-PCR Analysis

Total RNA was isolated from plant samples using TRIzol reagent (Thermo Fisher Scientific) following the manufacturer's instructions. Five micrograms of total RNA was reverse transcribed using SuperScript II first-strand synthesis system (Thermo Fisher Scientific) with an oligo(dT) primer. Real-time DNA amplification was monitored using Bio-Rad iQ5 optical system software (Bio-Rad). The expression level of genes of interest was normalized to that of the endogenous reference gene *ACTIN2*. Primers used are listed in Supplemental Table 1. The following models were fit to the relative Ct value data compared with *ACTIN2*: $Ct_{gyr} = GY_{gy}+R_r+e_{gyr}$, where GY, genotype:treatment interaction, and random factors; R, biological replicate; e, residual; $Ct_{ytr} = YT_{yt}+R_r+e_{ytr}$, where YT, treatment:time interaction; $Ct_{gytr} = GYT_{gyt}+R_r+e_{gytr}$, where GYT, genotype:treatment:time interaction. The mean estimates of the fixed effects were used as the modeled relative Ct values, visualized as the relative log_2 expression values, and compared by two-tailed *t* test.

Metabolite Quantification

Determination of pipecolic acid levels in leaves was performed using a protocol detailed by Návarová et al. (2012) using gas chromatography/mass spectrometry (GC/MS)-based analysis following propyl chloroformate derivatization. Camalexin was determined by a method based on vapor-phase extraction and GC/MS analysis of metabolites as described previously (Attaran et al., 2009; Návarová et al., 2012). Determination of *N*-hydroxypipecolic acid levels in leaves was performed using a protocol detailed by Hartmann et al. (2018) using GC/MS-analysis of leaf extracts after trimethylsilylation of analytes with *N*-methyl-*N*-trimethylsilyltrifluoroacetamide.

Growth Suppression and MAP Kinase Assay

Arabidopsis seeds were germinated on 1/2 MS plates (0.5× MS salt, 1% [w/v] sucrose, and 0.8% agar), and the 3-d-old seedlings with similar size were transferred on 1/2 MS plate with or without 1 μM L-pipecolic acid (Sigma-Aldrich), D-pipecolic acid (Sigma-Aldrich), or 1 μM flg22. Primary root length was measured 7 d after the transfer. MAP kinase assays were performed as described previously (Lee and Ellis, 2007). Briefly, 10-d-old seedlings were transferred to 12-well plates (three seedlings per well) containing 2 mL of liquid MS medium with water (mock), 1 μM L-pipecolic acid, 1 μM D-pipecolic acid, and 1 μM flg22. Seedlings were frozen in liquid nitrogen at the indicated time points. The frozen seedlings were ground in liquid nitrogen and homogenized in MPK extraction buffer (100 mM HEPES, pH 7.5, 5 mM EDTA, 5 mM EGTA, 2 mM DTT, protease inhibitor cocktail [Roche Applied Science], and phosphatase inhibitor cocktail [Roche Applied Science]). The supernatant was collected after centrifugation at 12,000 rpm for 30 min at 4°C. The protein concentration was determined using a Bradford assay (Bio-Rad) with BSA as a standard. Five micrograms of protein was separated in a 12% SDS-PAGE. Immunoblot analysis was performed using anti-phospho-p44/42 MAPK (α-pTEpY, 1:5000; Cell Signaling Technology) as the primary antibody and peroxidase-conjugated goat anti-rabbit IgG (1:20,000; Sigma-Aldrich) as the secondary antibody.

ChIP-qPCR

Four-week-old Col-0 and *Pwrky33:WRKY33-HA* plants were infiltrated with *Pto* AvrRpt2 (OD = 0.001) or mock and the samples were collected at 24 h postinfiltration. ChIP assay was performed as described previously (Yamaguchi et al., 2014) using rabbit polyclonal anti-HA antibody. *ALD1* specific primers described in Supplemental Table 1 were used for qPCR analysis as described above.

Statistical Analyses

Statistical analysis was performed using the mixed linear model function (lmer) implemented in the package lme4 in the R environment. When appropriate, raw data were log transformed to meet the assumptions of the mixed linear model. For the *t* tests, the standard errors were calculated using the variance and covariance values obtained from the model fitting. The Benjamini-Hochberg method was applied to correct for multiple hypothesis testing when all pairwise comparisons of the mean estimates were made.

Accession Numbers

The accession numbers for the genes discussed in this article are as follows: At2g14610 (*PR1*), AT2G19190 (*FRK1*), AT1G74710 (*SID2*), AT1G19250 (*FMO1*), AT2G13810 (*ALD1*), AT2G38470 (*WRKY33*), AT1G64280 (*NPR1*), AT1G51660 (*MKK4*), AT3G45650 (*MPK3*), AT2G43790 (*MPK6*), and AT3G18780 (*ACTIN2*).

Supplemental Data

Supplemental Figure 1. Local DEX application does not activate systemic activation of GVG system.

Supplemental Figure 2. *Pto* AvrRpt2-triggered SAR requires *ALD1*.

Supplemental Figure 3. SA and *WRKY33* contribute to SAR triggered by *Pto* infection.

Supplemental Figure 4. MAPK activation and camalexin accumulation by *Pma* infection.

Supplemental Figure 5. Pipecolic acid triggers transient MAPK activation.

Supplemental Table 1. Primers used in this study.

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AUTHOR CONTRIBUTIONS

Y.W., J.Z., and K.T. conceived and designed the experiments. Y.W., S.S., J.W., P.Y., and A.-C.D. performed experiments. Y.W., J.Z., and K.T.

analyzed the data. Y.W., S.S., J.Z., and K.T. wrote the article. All authors commented on the manuscript.

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