Pipecolic Acid, an Endogenous Mediator of Defense Amplification and Priming, Is a Critical Regulator of Inducible Plant Immunity

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Metabolic signals orchestrate plant defenses against microbial pathogen invasion. Here, we report the identification of the non-protein amino acid pipecolic acid (Pip), a common Lys catabolite in plants and animals, as a critical regulator of inducible plant immunity. Following pathogen recognition, Pip accumulates in inoculated Arabidopsis thaliana leaves, in leaves distal from the site of inoculation, and, most specifically, in petiole exudates from inoculated leaves. Defects of mutants in AGD2-LIKE DEFENSE RESPONSE PROTEIN1 (ALD1) in systemic acquired resistance (SAR) and in basal, specific, and β-aminobutyric acid–induced resistance to bacterial infection are associated with a lack of Pip production. Exogenous Pip complements these resistance defects and increases pathogen resistance of wild-type plants. We conclude that Pip accumulation is critical for SAR and local resistance to bacterial pathogens. Our data indicate that biologically induced SAR conditions plants to more effectively synthesize the phytoalexin camalexin, Pip, and salicylic acid and primes plants for early defense gene expression. Biological priming is absent in the pipecolate-deficient ald1 mutants. Exogenous pipecolate induces SAR-related defense priming and partly restores priming responses in ald1. We conclude that Pip orchestrates defense amplification, positive regulation of salicylic acid biosynthesis, and priming to guarantee effective local resistance induction and the establishment of SAR.

INTRODUCTION

The plant immune system is multilayered and includes constitutive and inducible defenses to counteract colonization by microbial pathogens (Thorvaldsen and Pieterse, 2003). In inoculated plant tissue, defense responses are initiated by recognition of microbial structures common to many pathogen types (pathogen-associated molecular patterns [PAMPs]) or effector molecules specific to particular pathogen isolates (Jones and Dangl, 2006). PAMP-triggered immunity (PTI) ensures basal plant resistance to pathogens but is not effective enough to entirely contain infection by a compatible pathogen. Although the signaling pathways leading to effector-triggered immunity (ETI) partially overlap with those of PTI, ETI is usually associated with a hypersensitive response (HR) and provides a more effective resistance than PTI (Jones and Dangl, 2006). Localized inoculation of leaves with compatible or incompatible pathogens also leads to broad-spectrum resistance of the whole plant shoot to subsequent pathogen attack, a phenomenon designated systemic acquired resistance (SAR; Durrant and Dong, 2004; Mishina and Zeier, 2007). Both effector- and PAMP-triggered events have been proposed to contribute to SAR initiation at the site of pathogen inoculation (Cameron et al., 1999; Mishina and Zeier, 2007).

In response to pathogens, plants synthesize a variety of defense-related small metabolites, including the defense hormones salicylic acid (SA) and jasmonic acid (JA), which activate distinct plant defense pathways. JA acts in concert with ethylene to induce resistance against several necrotrophic pathogens, whereas SA-mediated defense responses are effective against hemibiotrophs and biotrophs (Glazebrook, 2005). SA and JA signaling can negatively influence each other (Koornneef and Pieterse, 2008). SA biosynthesis via ISOCORISMATE SYNTHASE1 (ICS1), its positive regulation by PHYTOALEXIN-DEFICIENT4 (PAD4), and SA downstream signaling via NONEXPRESSOR OF PATHOGENESIS-RELATED GENES1 (NPR1) is critical for PTI, ETI, and SAR (Jirage et al., 1999; Nawrath and Métraux, 1999; Wildermuth et al., 2001; Durrant and Dong, 2004). Other phytohormones, such as auxin, abscisic acid, and gibberellic acid, can also influence defense signaling and resistance (Mauch-Mani and Mauch, 2005; Grant and Jones, 2009). In Arabidopsis thaliana, the indolic phytoalexin camalexin and several other Trp-derived compounds accumulate in inoculated leaves and can protect against fungal infection (Bednarek et al., 2009; Schlaeppi et al., 2010). Moreover, the unsaturated sterol stigmastanol is synthesized at pathogen inoculation sites, integrates into plant cell membranes, and favors susceptibility to bacterial pathogens (Griebel and Zeier, 2010).

The regulatory plant metabolite most closely associated with plant resistance against biotrophic and hemibiotrophic pathogen invasion is SA. In the course of SAR, SA accumulates in inoculated leaves and in systemic leaves distal from the initial inoculation site (Malamy et al., 1995). Although SA has been proposed to be a mobile SAR signal able to travel via the vasculature (Shulaev et al., 1995; Mölders et al., 1996), grafting studies rather suggest that SA is not transported from inoculated to distal leaves but...
that its systemic accumulation is critical for SAR (Vernooij et al., 1994). Systemic SA accumulation proceeds via upregulation of ICS1 and de novo SA biosynthesis (Attaran et al., 2009); this is likely triggered by perception of mobile long-distance signals in the cells of distal leaves (Shah, 2009). Expression of two other SAR regulatory genes, AGD2-LIKE DEFENSE RESPONSE PROTEIN1 (ALD1) and FLAVIN-DEPENDENT MONOOXYGENASE1 (FMO1), is locally and systemically enhanced in SAR-induced plants. Both genes are not only indispensable for systemic SA accumulation and SAR, but are also critical for full PTI and ETI responses at inoculation sites (Song et al., 2004a; Bartsch et al., 2006; Mishina and Zeier, 2006; Koch et al., 2006). Pathogen-induced expression of ALD1, FMO1, and ICS1 in inoculated tissue proceeds in-dependently of SA (Métrax, 2002; Song et al., 2004a; Bartsch et al., 2006; Mishina and Zeier, 2006). This suggests that ALD1 and FMO1 are involved in SA-independent signaling upstream of SA biosynthesis, processes that are required for systemic SA accumulation and SAR. The SAR-induced state provides enhanced pathogen protection via increased defense-related gene expression and is associated with defense priming, enabling the plant to more effectively induce defense responses (Durrant and Dong, 2004; Beckers et al., 2009).

Recent findings indicate significant interconnections between different branches of amino acid metabolism and plant resistance to microbial pathogens or herbivorous insects (van Damme et al., 2009; Liu et al., 2010; Adio et al., 2011; Cecchini et al., 2011; Stuttmann et al., 2011; von Saint-Paul et al., 2011). In this study, we investigate changes in free amino acids that occur during the establishment of SAR in Arabidopsis. We show that several free amino acids, including branched-chain amino acids, aromatic amino acids, and Lys enrich in leaves inoculated with SAR-inducing Pseudomonas syringae bacteria. Most strikingly, the Lys catabolites α-amino adipic acid (Aad) and piperolic acid (Pip), which are only faintly detectable in leaves of noninoculated plants, accumulate to high levels at pathogen inoculation sites. We show that pathogen-induced biosynthesis of Aaαd is dependent on Lys ketoglutarate reductase/saccharopine dehydrogenase (LKR/SDH; Galili et al., 2001) but that its production is dispensable for resistance induction. Pip biosynthesis proceeds via a separate pathway involving the ALD1 aminotransferase. Our metabolite and genetic analyses suggest a substantial role for Pip in systemic plant immunity because, unlike other amino acids and metabolites, it strongly accumulates in leaves distal from initial inoculation and in petiole exudates collected from pathogen-inoculated leaves. The critical role for Pip in inducible immunity is corroborated by the findings that defects of ald1 mutant plants in SAR, PTI, and ETI are associated with a lack of Pip production and that exogenous Pip can complement these resistance defects. Our results also offer mechanistic insights into β-amino butyric acid (BABA)-induced plant resistance to bacterial pathogen infection that proceeds via Pip accumulation. We show that Pip orchestrates inducible immunity and SAR via defense amplification and priming and demonstrate a role for the Lys catabolite as a novel metabolic defense regulator. Since Pip has neurotransmitter activity in the brain, our study reveals interesting similarities between signaling aspects in plants and animals and might furthermore have applied significance in modern plant protection.

RESULTS

Changes in Free Amino Acid Levels during SAR

We performed comparative analyses of free amino acids extracted from locally treated and nontreated, distal (systemic) leaves of mock-control plants and of plants inoculated with the hemibiotrophic, SAR-inducing bacterial pathogen Pseudomonas syringae pv maculicola ESB436 (Psm). Amino acids were analyzed following propyl chloroformate derivatization via gas chromatography–mass spectrometry (GC-MS) (Kugler et al., 2006). The virulent Psm strain triggers a robust SAR response in Arabidopsis from day 2 after leaf inoculation that is mechanistically indistinguishable from the SAR induced by avirulent P. syringae (Mishina and Zeier, 2006, 2007; Attaran et al., 2009; Zhang et al., 2010; Liu et al., 2011). Psm-induced SAR is accompanied by massive changes in the contents of free amino acids in pathogen-inoculated leaves (Figure 1, left column). A strong increase, by a factor of 5–20-fold, was observed for Lys, the aliphatic amino acids Val, Leu, Ile, and β-Ala, and the aromatic amino acids Phe, Tyr, Trp, and His (Figure 1, highlighted in orange). Moderate but still significant pathogen-triggered increments were detected for GABA, Cys, Asn, Ala, Gly, Ser, and Orn. Notably, two substances that were only faintly present in mock-treated leaves increased by ~70-fold in pathogen-inoculated leaves: Aaαd and an unknown compound (Figure 1). An conclusion by analogy taking into account the mass spectra of the Lys, Orn, and Pro derivatives strongly suggested the identity of the unknown compound to be Pip (piperidine-2-carboxylic acid, homoproline), the methylene homolog of Pro (see Supplemental Figure 1 online). This assumption was confirmed by examination of the authentic Pip derivative, which gave rise to mass spectra and GC retention times identical with the extract peak (see Supplemental Figures 1 and 2 online). A single amino acid, Asp, showed significant and reproducible decreases after Psm inoculation (Figure 1).

Pip and Aad are both catabolites of Lys, an Asp-derived amino acid (Galili et al., 2001; see Supplemental Figure 3 online). The accumulation of Pip, Aad, and Lys and the concomitant decreases of Asp levels after P. syringae attack (Figure 1) indicated that Lys biosynthesis and catabolism are pathogen-triggered events. Pip was produced faster in leaves inoculated with the incompatible HR-inducing PsmavrP1 strain than in leaves infected with the compatible Psm strain but accumulated to high levels during later stages of the compatible interaction (Figure 2A). Aad biosynthesis was also triggered upon inoculation with both compatible and incompatible bacteria but trailed behind Pip accumulation (Figure 2B).

Defense Regulation of Local Pip and Aad Accumulation and Induction of Lys Catabolism by Bacterial PAMPs

At inoculation sites, induction of Pip biosynthesis was independent of SA production, since the ics1-defective sid2/ics1 mutant accumulated Pip to similar levels than the wild type (Figures 2C and 2D). NPR1-mediated signaling seems to positively influence Pip biosynthesis particularly in earlier stages of the Arabidopsis–Psm interaction because of reduced Pip accumulation in the npr1 mutant at day 1 but not day 2 after inoculation (Figures 2C and 2D). Moreover, Psm-induced Pip production was strongly
reduced but not totally blocked, in the pad4 mutant, indicating a positive regulation of Pip biosynthesis by the lipase-like defense regulator PAD4 (Figures 2C and 2D). By contrast, local accumulation of Pip was independent of the SAR regulator FMO1 (Figure 2C). We even observed overaccumulation of Pip in fmo1 mutants at day 2 after Psm inoculation (Figure 2D). However, the regulation of induced Aad and Pip biosynthesis seems to differ because Psm-induced Aad accumulation was partially dependent on ICS1-, NPR1-, PAD4-, and FMO1-mediated defense signaling at 2 d after inoculation (DAI; Figure 2E). Moreover, the basal levels of Pip and particularly of Aad were elevated in the constitutively resistant cpr5 mutant (Figures 2D and 2E). Pip biosynthesis in response to Psm and Psm avrRpm1 inoculation follows similar mechanistic routes, as shown by the observations that Pip accumulation after leaf infiltration with the avirulent bacterial strain was ALD1 dependent and partially PAD4 dependent but was independent of the SA pathway and FMO1 (see Supplemental Figure 4A online).

Perception of PAMPs can trigger local and systemic defense responses and activate distinct metabolic pathways in Arabidopsis (Mishina and Zeier, 2007; Griebel and Zeier, 2010). We thus investigated whether exogenous application of two well-characterized bacterial PAMPs, flagellin, the proteinaceous building unit of the bacterial flagellum, and lipopolysaccharide (LPS), a major component of the outer membrane of Gram-negative bacteria, would be sufficient to activate the biosynthesis of Pip and Aad. Infiltration of 200 nM fg22, a peptide corresponding to the elicitor active epitope of flagellin (Gómez-Gómez et al., 1999), into Columbia-0 (Col-0) leaves indeed

<table>
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<th>µg g⁻¹ FW</th>
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<th>µg g⁻¹ FW</th>
<th>distal leaves (2 DAI)</th>
<th>µg ml⁻¹ leaf⁻¹</th>
<th>petiole exudates (6-48 h)</th>
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Figure 1. Changes in the Levels of Free Amino Acids in Arabidopsis Col-0 Plants upon Leaf Inoculation with SAR-Inducing Psm.

Left column: Inoculated, lower (1°) leaves at 2 DAI. Central column: Nontreated, upper (distal, systemic, 2°) leaves at 2 DAI. Right column: Petiole exudates from inoculated leaves collected between 6 to 48 h after inoculation. Mean values for leaf samples are given in µg g⁻¹ fresh weight (FW) ± sd and for leaf exudate samples in ng mL⁻¹ exudate solution leaf⁻¹ ± sd from at least four replicate samples. Mock treatments were performed by infiltration of leaves with a 10 mM MgCl₂ solution. Asterisks denote statistically significant differences between Psm (P) and MgCl₂ (M) samples (two-tailed t test; ***P < 0.001, **P < 0.01, and *P < 0.05).
provoked a considerable accumulation of both Pip and Aad at 48 h after treatment (Figures 2F and 2G). Lower but still significant increases of the Lys catabolites also occurred when leaves were treated with a gel-purified bacterial LPS preparation (Figures 2F and 2G). Thus, onetime treatments of leaves with flagellin or LPS are sufficient to activate Lys catabolism in Arabidopsis leaves.

**Pip Accumulates Systemically in the Plant and Is Enriched in Petiole Exudates of Inoculated Leaves**

Amino acid changes in distal, noninoculated leaves of *P. syringae*-treated plants were less pronounced than at inoculation sites. The only amino acid with a strong, 10-fold systemic increase at 48 h after local *Psm* inoculation was Pip (Figure 1, central column). The systemic levels of Aad, Phe, Tyr, and Val also rose significantly, albeit to much lower amounts (approximately twofold), and the systemic leaf contents of the remaining amino acids did not differ significantly between mock and pathogen treatments. Significantly enhanced systemic levels of Pip but not of SA were already observed at 36 h after *Psm* inoculation (Figures 3A and 3B), suggesting that Pip accumulation precedes SA accumulation in systemic leaves at the onset of SAR. Moreover, the HR-inducing *Psm avrRpm1* strain triggered systemic Pip increases to a similar extent than the compatible *Psm* strain (see Supplemental Figure 4B online). Although the systemic accumulation of Pip was

![Figure 2. Pip and Aad Accumulation in *P. syringae*-Inoculated and PAMP-Treated Arabidopsis Leaves.](image-url)
markedly reduced in the SAR-defective *fmo1* and *ics1* mutants, localized bacterial treatment still provoked significant increases of Pip in distal leaves of these mutants (Figure 3C). By contrast, systemic levels of Pip were not enhanced in the *npr1* and *pad4* mutants (Figure 3C).

The apparently outstanding accumulation pattern of Pip during SAR establishment was corroborated in analyses of petiole exudates collected from inoculated leaves between 6 and 48 h after inoculation (Figure 1, right column). Upon pathogen treatment, levels of Pip increased by sevenfold, whereas other amino acid levels remained at control values and showed less pronounced increases (Phe, Gly, and Ala) or were reduced (Lys, Aad, lle, and Thr). Compared with the substantial pathogen-induced increase of Pip in exudates, the levels of other defense-related metabolites, such as SA, SA glucoside, methyl salicylate, azelaic acid (AZA), JA, or camalexin in exudates did not change or only modestly increased after pathogen inoculation (see Supplemental Figure 5 online). Along with Pip, several of these metabolites and amino acids did strongly accumulate in inoculated leaves (Figure 1; Malamy et al., 1990; Mishina and Zeier, 2007; Attaran et al., 2009; Jung et al., 2009). The release of Pip out of the petioles of inoculated leaves seems therefore favored over the release of many other accumulating metabolites, at least under the experimental conditions used for exudate collection. Enrichment of Pip in petiole exudates of pathogen-inoculated leaves was also detected in *fmo1* and *ics1* and thus was independent of FMO1- and SA-mediated signaling (Figure 3D).

Pathogen-Induced Activation of Lys Catabolism and *ALD1*-Dependent Biosynthesis of Pip

In plants and animals, Aad biosynthesis occurs via the saccharopine pathway, which is considered a major metabolic route for Lys catabolism (Galli et al., 2001). A bifunctional polypeptide with both LKR and SDH activities catalyzes the first two steps of the saccharopine pathway and converts Lys via saccharopine into $\alpha$-aminoacidic semialdehyde (see Supplemental Figure 3 online). The aldehyde can be enzymatically oxidized to Aad or spontaneously cyclized to $\Delta^1$-piperideine-6-carboxylic acid, which might be reduced to Pip. However, isoelation labeling studies suggest that Pip is formed from Lys via $\epsilon$-amino-$\alpha$-ketocaproic acid and $\Delta^1$-piperideine-2-carboxylic acid (Gupta and Spenser, 1969). This would require an amino transferase reaction converting Lys into $\epsilon$-amino-$\alpha$-ketocaproic acid (see Supplemental Figure 3 online).

We reasoned that *ALD1*, an aminotransferase with Lys converting activity (Song et al., 2004b), might be involved in Pip biosynthesis. *ALD1* is critical for the activation of local and systemic defenses in *Arabidopsis* (Song et al., 2004a), and *ALD1* transcript levels strongly increased in *Psm*-inoculated Col-0 plants in both infected and in distal leaves (Figures 4A and 4B). Consistent with our hypothesis, the *ald1-1T2 (ald1)* knockout mutant (Song et al., 2004a) not only failed to express *ALD1* in inoculated and distal leaves (see Supplemental Figures 6A and 6C online), but was also fully blocked in *Psm*-induced Pip biosynthesis at inoculation sites (Figure 4C). *Psm*-triggered elevation of Pip levels in systemic leaves (Figure 3C), and enrichment of Pip in petiole exudates (Figure 3D). Our data thus demonstrate that *ALD1* is required for pathogen-induced Pip biosynthesis. By contrast, *ALD1* is not essential for Aad production, since *ald1* leaves accumulated wild-type levels of Aad upon treatment with *Psm* (Figure 4D).

The strong accumulation of Aad at sites of bacterial infection occurs with a significant enhancement of local LKR/SDH transcript levels (Figures 2B and 4A). We isolated two independent, homozygous T-DNA insertion lines with markedly reduced expression of LKR/SDH (*lkr-1*, Salk_068769; *lkr-2*, Salk_127160; see Supplemental Figure 6B online). *Psm*-induced Aad production in leaves was strongly attenuated in both *lkr-1* and *lkr-2* (Figure 4D), indicating that LKR/SDH and the saccharopine pathway are involved in pathogen-induced Aad production. By contrast, *Psm*-inoculated leaves of *lkr-1* and *lkr-2* plants accumulated Pip to levels similar to those of the wild type (Figure 4C). Together, these data suggest two distinct biochemical pathways for pathogen-induced Pip and Aad biosynthesis, namely, the *ALD1*-dependent piperocolate pathway and the LKR/SDH-mediated saccharopine pathway (see Supplemental Figure 3 online). Blockage of either pathway in *ald1* or *lkr-1*/*2* leads to a hyperaccumulation of the common precursor Lys after pathogen infection (Figure 4E).

L-Pip Is a Metabolic Regulator of Several Forms of Induced Resistance in Plants

The Pip-deficient *ald1* mutant exhibits strongly attenuated basal and specific resistance and is also fully blocked in SAR (Song et al., 2004a; Figure 5A), suggesting that endogenous accumulation of Pip is critical for these different forms of inducible resistance. By contrast, Aad biosynthesis seems not essential for SAR or local resistance to *P. syringae*, since *lkr-1* and *lkr-2* exhibit wild-type-like resistance phenotypes following *Psm* infection (Figure 5A).

We tested whether exogenous application of Pip could complement the attenuated local resistance in *ald1* and its defect in SAR. When racemic D,L-Pip was applied via the root system, a significant uptake into the shoot was observed in both Col-0 and *ald1* plants. Watering of plants with 10 µmol of D,L-Pip 1 d prior to pathogen inoculation led to increases of Pip levels in leaves comparable in magnitude to the pathogen-induced elevations (see Supplemental Figure 7A online). Exogenous Pip also markedly increased resistance of Col-0 wild-type leaves to compatible *Psm* (Figures 5B and 6A to 6C) and incompatible *Psm avrRpm1* (Figure 5D). Quantitatively, this Pip-induced resistance in wild-type plants varied in independent experiments between a threefold and 25-fold reduction in pathogen growth and proved highly significant in each experiment (Figures 5B, 5D, 6B, and 6C; see Supplemental Figures 8A, 8B, and 8E online). Exogenous Pip reproducibly increased resistance when applied via the root but not when infiltrated into the apoplastic space of leaves, presumably due to a lack of efficient uptake of the amino acid via the plasma membrane into the cell interior (see Supplemental Figure 8A online). Remarkably, root application of Pip also chemically complemented *ald1* defects in local resistance, strongly boosting basal and specific resistance of the piperolate-deficient mutant to wild-type-like levels (Figures 5B to 5D). Along with the strong reduction of apoplastic bacterial growth, a remarkable reduction of disease symptomology was apparent in Pip-treated Col-0 and *ald1* plants (Figure 5C). Application of 1 µmol Pip per plant was sufficient to significantly enhance resistance to *Psm* in Col-0 or *ald1*, with 10 µmol further augmenting.
the effect, but 100 nmol showing no effect (see Supplemental Figure 8B online). The L- but not the D-enantiomer chemically complemented the ald1 resistance defect, suggesting that L-Pip is the active metabolite in Arabidopsis (see Supplemental Figure 8C online). This is consistent with the exclusive detection of the naturally occurring L-enantiomer in plants (Morrison, 1953; Zacharius et al., 1954; Fujioka et al., 1987). Importantly, in the presence of Pip, Psm or Psm avrRpm1 inoculation of ald1 plants in lower leaves also rendered upper leaves more resistant to subsequent infection, demonstrating that exogenous Pip is able to restore SAR in ald1 (Figure 6A; see Supplemental Figure 8D online).

The amino acid BABA is not produced in plants but effectively enhances plant disease resistance via a SAR-like mechanism when exogenously supplied through the soil (Zimmerli et al., 2000). Similar to exogenous Pip treatment, feeding with 10 µmol BABA via the root system resulted in an uptake of the amino acid and translocation into the shoot (see Supplemental Figure 7D online). BABA feeding also led to a moderate augmentation of Lys and Aad levels and, more importantly, to a strong increase of Pip levels in leaves. This augmentation was quantitatively comparable to the systemic accumulation of Pip during SAR (see Supplemental Figure 7D online; Figures 3B and 3C). BABA application increased the resistance of Col-0 plants toward Psm to an extent comparable to exogenous Pip treatment, and simultaneous application of both BABA and Pip had no synergistic effect. In the ald1 mutant, however, BABA-induced resistance was fully blocked, indicating that induced biosynthesis of Pip following BABA application causes the enhanced resistance to P. syringae (Figure 6B). Similar to SAR (Mishina and Zeier, 2006), BABA-induced resistance was also fully blocked in fmo1, but exogenous Pip was neither able to restore SAR nor BABA-induced resistance in this mutant (Figures 6A and 6B). This is consistent with a possible function of FMO1 downstream of Pip in resistance induction. Exogenous Pip was also not able to abolish the severe defects in basal resistance of pad4 and npr1, although a small Pip-mediated resistance effect in these mutants was detected (Figure 6C). In comparison, Pip more pronouncedly induced resistance in the SA-deficient ics1 mutant, rendering this mutant approximately as resistant as the non-treated but less resistant than the Pip-treated wild type (Figure 6C). These findings indicate that Pip is capable of inducing resistance in the absence of SA but that SA is required for full Pip-induced resistance. Similar to FMO1, PAD4 and NPR1 seem to have a role downstream of Pip in resistance induction.

We furthermore observed that exogenous Pip application via the root not only resulted in increased Pip levels in Col-0 or ald1 leaves (see Supplemental Figure 7A online) but also to a moderate but significant increase in Aad levels (see Supplemental Figure 7B online). This indicates that plants can convert some of the exogenous Pip to Aad. Exogenous Aad application, by contrast, did not heighten the levels of Pip in plants (see Supplemental Figure 7C online). Aad application also resulted in a moderate resistance increase in plants, but this effect was quantitatively not comparable to the strong Pip-induced resistance effect (see Supplemental Figure 8E online).
Biologically Induced SAR Confers Priming of Defense Metabolite Accumulation and Defense Gene Expression in an ALD1-Dependent Manner

Our results indicate that L-Pip is a critical mediator of several forms of inducible plant immunity, including SAR, basal, specific, and BABA-induced resistance. BABA application is known to promote plants to a primed state in which they are able to more quickly and vigorously mobilize defense responses after pathogen attack (Zimmerli et al., 2000). Although defense priming induced by resistance-activating chemicals, such as BABA or S-methyl-1,2,3-benzo thiadiazole-7-carbothioate (BTH) is a well-studied phenomenon, evidence for priming in plants in which SAR has been biologically induced is rare (Beckers et al., 2009; Jung et al., 2009). To examine defense priming during biological SAR, we conducted a double inoculation experiment. Arabidopsis plants were first treated in lower (1°) leaves with Psm to induce SAR. Two days later, a challenge infection with Psm in upper (2°) leaves was performed that was scored for early defense response activation at 10 h after inoculation. Mock and Psm inoculations in 1° and 2° leaves were combined to yield four different cases: a control situation (1° mock/2° mock), a systemic pathogen trigger (1° Psm/2° mock), a local pathogen trigger (1° mock/2° Psm), and a combination of both the systemic and the local stimulus (1° Psm/2° Psm).

When free SA levels were monitored as a defense output, we observed that Psm-triggered SA accumulation at 10 h after inoculation was similar in control plants and in SAR preinduced plants, suggesting that SA production is not subject to priming during biological SAR (Figure 7A). However, since SA can be converted to different derivatives upon infection, we reasoned that the determination of total SA would be a more relevant parameter to assess SA production over time. For total SA, we observed that the increases detected for the combined pathogen treatments approximately represented the sum of the systemic and the local SA enhancements (Figure 7B), indicating an additive contribution of the local and systemic pathogen trigger for SA accumulation during SAR. By contrast, ald1 mutants lacked the systemic response and exhibited an attenuated local response with respect to SA production, resulting in a comparatively low and similar accumulation of (total) SA after the mock/Psm and Psm/Psm treatments (Figures 7A and 7B). In the Col-0 wild type, Pip levels increased in 2° leaves due to the systemic pathogen trigger, resulting from 1° leaf infection, but not yet due to the local Psm trigger at 10 h after inoculation. However, a substantial increase of Pip biosynthesis was observed 10 h after the challenge infection in SAR-induced plants, indicating a strong potentiation of Pip biosynthesis during SAR (Figure 7C). By contrast, the Arabidopsis phytoalexin camalexin accumulated only as a consequence of the local but not the systemic pathogen trigger in Col-0, and local camalexin production was again strongly potentiated when SAR had been biologically activated (Figure 7D). This priming effect was completely absent in the Pip-deficient ald1 mutant (Figure 7D).

Next, we monitored defense gene expression as an output and detected reproducible priming responses for the transcript...
accumulation of ALD1, FMO1, and the SA-inducible PR-1 gene following biological SAR induction in Col-0. This demonstrates that plants exhibiting biological SAR are promoted into an alarmed state that enables fortified defense gene expression. The ald1 mutant essentially lacked this priming capacity (Figures 7E to 7G). Together, the SAR-induced state provides moderate, additive priming for SA accumulation and strong, multiplicative priming for both Pip and camalexin production as well as expression of the defense-related genes ALD1, FMO1, and PR-1. These priming responses are absent in ald1, indicating the importance of endogenous Pip generation for defense priming during SAR (Figures 7A to 7G).

Exogenous Pip Promotes Plants to a Primed, SAR-Like State

We next tested whether plant defense responses would be potentiated by exogenous Pip in early stages of the Arabidopsis–Psm interaction. Accumulation of total SA in leaves at 10 h after Psm infection was significantly higher in Col-0 than in ald1, and exogenous Pip boosted induction of SA biosynthesis in both genotypes to 2.5-fold to threefold higher levels than those detected in Psm-infected leaves of unfed Col-0 plants (Figure 8A). Pip feeding also restored the capacity of ald1 plants to systemically enhance SA levels upon localized pathogen inoculation, indicating the importance of Pip for systemic SA accumulation during SAR (Figure 8B). Moreover, exogenously applied Pip influenced SA levels of untreated leaves only slightly but markedly elevated local and systemic SA levels in plants pressure infiltrated with 10 mM MgCl₂, a treatment that routinely serves as a mock control for P. syringae inoculation (Figures 8A and 8B). These findings suggest that Pip alone is not sufficient to efficiently stimulate SA biosynthesis but that it positively regulates local and systemic SA production in the presence of pathogen-derived, SAR-related, or mechanical stimuli.

At 10 h after inoculation, accumulation of the phytoalexin camalexin was just detectable in Psm-infected Col-0 leaves, but camalexin biosynthesis was strongly potentiated in plants exogenously

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**Figure 5.** Exogenous Pip Enhances Disease Resistance of Wild-Type Arabidopsis and Overrides ald1 Defects in PTI and ETI. (A) SAR assay in Col-0, ald1, and lkr plants. Lower (1°) leaves were infiltrated with either 10 mM MgCl₂ or Psm (OD 0.001), and 2 d later, three upper leaves (2°) were challenge infected with Psm (OD 0.001). Bacterial growth in upper leaves was assessed 3 d after 2° leaf inoculation. (B) and (D) Bacterial numbers of compatible Psm (applied in titers of OD 0.001) (B) and incompatible Psm avrRpm1 (applied in titers of OD 0.002) (D) in Arabidopsis Col-0 and ald1 leaves at 3 DAI. Plant pots were supplied with 10 mL of water or 10 mL of 1 mM (≡ 10 µmol) Pip 1 d prior to inoculation. (C) Disease symptoms of Psm-infected Col-0 and ald1 plants in the absence and presence of exogenous Pip. Arrowheads denote inoculated leaves. Bars represent the mean ± so of at least seven replicate samples. Asterisks denote statistically significant differences between indicated samples (***P < 0.001 and **P < 0.01; ns, not significant; two-tailed t test).
fed with Pip (Figure 8C). Thus, similar to the priming response characteristic for biological SAR, exogenous Pip positively regulates SA biosynthesis and strongly potentiates camalexin production. Pip feeding also led to an early, Psm-triggered camalexin accumulation in ald1 that exceeded the respective wild-type value in the absence of exogenous Pip but was lower than the wild-type levels in the presence of exogenous Pip (Figure 8C). This suggests that defense priming mediated by exogenous Pip biosynthesis present in the wild type. In addition, Pip application to Col-0 plants significantly increased ALD1 transcript levels and strongly primed plants for pathogen-triggered expression of FMO1 and PR-1 expression (Figures 8E and 8F). Together, these findings indicate that Pip accumulation is sufficient to promote plants into a state that enables SAR-like priming. Furthermore, the observation that Pip-deficient ald1 is defective in SAR priming suggests that endogenously accumulating Pip mediates priming during SAR (Figure 7). The facts that the biosynthesis of the regulatory metabolite itself is boosted during SAR (Figure 7C) and that Pip promotes enhanced induction of ALD1 expression (Figure 8D) indicate the existence of a positive defense amplification loop within SAR in which Pip acts as a central player. This amplification mechanism also seems to include FMO1, since the SAR-defective fmo1 mutant is unable to establish Pip-induced resistance (Figure 6), and expression of FMO1 is primed during SAR and upon Pip treatment (Figures 7F and 8E).

As described above, Pip positively regulates SA biosynthesis. A converse positive feedback of SA on Pip production seems to exist in systemic rather than in inoculated tissue because functional ICS1 is required for normal pathogen-induced Pip accumulation in distal but not in inoculated leaves (Figures 2C, 2D, and

**Figure 6.** Exogenous Pip Overrides ald1 Defects in SAR and BABA-Induced Resistance.

(A) SAR assay in Col-0, ald1, and fmo1. Water or 10 µmol Pip was applied through the soil (s) of each plant pot, and 1 d later a 1° leaf infiltration with either 10 mM MgCl₂ or Psm (OD 0.005) in three lower leaves was performed. Another 2 d later, three upper leaves (2°) were challenge infected with Psm (OD 0.001). Bacterial growth in upper leaves was assessed 3 d after 2° leaf inoculation. ns, not significant.

(B) BABA-induced resistance assay in Col-0, ald1, and fmo1. Water, BABA (10 µmol), Pip (10 µmol), or a combination of both BABA and Pip (10 µmol each) were applied through the soil, and resistance toward Psm was assessed. Bars represent mean values (± so) of colony-forming units (cfu) per cm² from at least seven replicate samples, each consisting of three leaf disks. Asterisks denote statistically significant differences between indicated samples. No significant differences in initial bacterial numbers (1 h after inoculation) were detected.

(C) Pip-induced resistance in wild-type Col-0 and different mutant lines to Psm infection. Colony-forming units of Psm (applied in titers of OD 0.001) at 3 DAI. Plant pots were supplied with 10 mL of water or 10 mL of 1 mM (=10 µmol) Pip 1 d prior to inoculation.
Biological SAR Confers Defense Priming on the Metabolite and Gene Expression Levels in an ALD1-Dependent Manner.

Double inoculation experiment to assess defense priming during SAR in Col-0 and ald1. Plants were treated in lower (1°) leaves with MgCl₂ or Psm (OD 0.005), and 2 d later, upper (2°) leaves were infiltrated with MgCl₂ or Psm. Upper leaves were then scored for defense metabolite accumulation or defense gene expression at 10 h after inoculation. This yielded four distinguishable cases corresponding to a control situation (1° MgCl₂/2° MgCl₂), a systemic pathogen stimulus (1° Psm/2° MgCl₂), a local pathogen stimulus (1° MgCl₂/2° Psm), and a combination of both the systemic and the local stimuli (1° Psm/2° Psm). FW, fresh weight.

(A) to (D) SAR priming of defense metabolite accumulation. Free SA (A), total SA (sum of free SA and conjugated SA) (B), Pip (C), and camalexin (D) accumulation at 10 h after 2° treatment. Bars represent the mean ± SD of at least four replicate samples. Different letters above the bars denote statistically significant differences between pairwise compared samples (P < 0.05, two-tailed t test).

(E) to (G) SAR priming of defense gene expression. Relative ALD1 (E), FMO1 (F), and PR-1 (G) expression at 10 h after 2° treatment. Transcript levels were assessed by quantitative real-time PCR analysis, are given as means ± SD of three replicate samples, and are expressed relative to the respective mock control value. Statistical differences in transcript abundance upon 2° Psm infection of SAR-noninduced versus SAR-induced plants were assessed. Closed (open) circles indicate whether statistically significant differences in Col-0 (ald1) between the 1° MgCl₂/2° Psm and the 1° Psm/2° Psm treatments exist (two-tailed t test).
transcript levels also rose slightly, to accumulation (see Supplemental Figure 9A online). The response was small compared with pathogen-induced Pip plants. Indeed, 24 h after in inoculation of 0.5 mM SA, we detected a significant increase of Pip in Col-0 leaves. However, this response was small compared with the strong, more than 3000-fold SA-induced increase of PR-1 transcript levels in the same experiment (see Supplemental Figure 9B online).

**DISCUSSION**

The widespread occurrence of the non-protein amino acid l-Pip in plants, animals, fungi, and microorganisms and its biosynthetic origin from Lys in plants and animals was realized in the 1950s (Morrison, 1953; Zachariou et al., 1954; Broquist, 1991). The pipocecal pathway represents the major Lys catabolic route in rat brain (Chang, 1976), and Pip has been recognized as a weak inhibitory neurotransmitter and GABA agonist (Charles, 1986). In plants, enhanced Pip levels have been measured following growth-affecting treatments, such as application of the plant growth regulator maleic hydrazide and osmotic stress (Yatsu and Boynton, 1959; Moulin et al., 2006). The physiological function of Pip in plants has remained elusive, although it was described as a flower-inducing substance in the aquatic plant Lemna gibba and as an indicator of abnormal protein metabolism in diseased plants (Pálfy and Dézsi, 1968; Fujjoka et al., 1987).

Here, we demonstrate that Pip is a critical metabolic mediator of several forms of inducible resistance in Arabidopsis. These include PTI, ETI, and BABA-induced resistance directed against hemibiotrophic bacterial pathogens, and, in particular, SAR. The reported neurotransmitter function of Pip in the brain (Charles, 1988) and our findings indicate that Pip can have regulatory roles in both animals and plants. Evidence for a critical function of Pip in inducible plant immunity is provided by the findings that ald1 mutant plants, which fail to establish SAR (Figures 5A and 6A; Song et al., 2004a), BABA-induced resistance to P. syringae (Figure 6B), and exhibit enhanced disease susceptibility against incompatible and compatible P. syringae strains (Figures 5B to 5D; Song et al., 2004a), are completely defective in induced Pip biosynthesis (Figures 3C, 3D, and 4C). Moreover, exogenous Pip is able to complement the resistance defects of ald1 plants and increases PTI and ETI of wild-type plants toward P. syringae infection (Figures 5B to 5D). Thus, our study uncovers a plant resistance pathway that is activated in an SA-independent manner in inoculated leaf tissue. The occurrence of Pip is widespread in the plant kingdom, and pathogen-induced Pip accumulation has been reported to take place in leaves of rice (Oryza sativa), soybean (Glycine max), potato (Solanum tuberosum), and tobacco (Nicotiana tabacum) (Yatsu and Boynton, 1959; Pálfy and Dézsi, 1968; Moulin et al., 2006). It is therefore likely that Pip also orchestrates immune responses in plant species other than Arabidopsis.

Along with another Lys catabolite, α-aminoacidic acid, its biosynthetic precursor Lys, and several aromatic and branched-chain amino acids, Pip strongly accumulates in pathogen-inoculated leaves (Figures 1, 2A, and 9). In addition, Pip production is triggered by exogenous treatment of leaves with PAMPs (Figure 2F). The biosynthesis of Pip is positively influenced by the defense regulator PAD4 (Figures 2C and 2D) and proceeds via the ALD1 aminotransferase (Figure 4C). Expression of ALD1 is upregulated at sites of pathogen attack and in distal, non-inoculated leaves (Figures 4A and 4B; Song et al., 2004a). The partial dependency of Pip biosynthesis on PAD4 is consistent with an attenuated expression of ALD1 in pad4 mutants after P. syringae infection (Song et al., 2004a). A second pathogen-inducible Lys catabolic pathway produces Aad via LKR/SDH and the saccharopine pathway. Our data indicate that pathogen-induced Lys catabolism leading to Aad has no major relevance for induced resistance to hemibiotrophic bacteria and the establishment of SAR (Figure 5A), although exogenous Aad resulted in modestly enhanced P. syringae resistance. Via Aad and acetyl-CoA, the saccharopine pathway provides a possibility for plants to convert Lys to Glu, which can serve as a precursor for several stress-related metabolites (Arruda et al., 2000; Galli et al., 2001).

Our mutant analyses suggest that in pathogen-infected Arabidopsis plants, Pip and Aad are essentially produced independently of each other via separate ALD1- and LKR/SDH-dependent pathways, respectively (Figures 4C and 4D; see Supplemental Figure 3 online). However, Pip can be converted in vitro to the Aad precursor Δ1-piperideine-6-carboxylic acid by recombinant Arabidopsis sarcosine oxidase (Goyer et al., 2004). Decreased amounts of basal Aad in Pip-deficient ald1 mutants and modestly increased Aad levels in plants upon Pip feeding indicate that in planta, a pathway enabling direct Pip to Aad conversion might exist. Both Aaad feeding and lkr mutant analyses suggest that a reverse Aaad-to-Pip transition does not take place in Arabidopsis (Figures 4B and 4C; see Supplemental Figures 3, 7A and 7B online).

ALD1 functions as an aminotransferase with high in vitro activity for Lys (Song et al., 2004b). Possible products of Lys transamination are ε-amino-α-ketocaproic acid or α-amino adipic semialdehyde, depending on the abstraction of the α- or ε-amino group from Lys, respectively. Feeding of bean (Phaseolus vulgaris) with isotope-labeled Lys suggests that conversion of Lys to Pip in plants proceeds via ε-amino-α-ketocaproic acid and/or the cyclized form Δ1-piperideine-2-carboxylic acid (Gupta and Spenser, 1969; see Supplemental Figure 3 online). Whether the Lys aminotransferase ALD1 produces these intermediates and whether a subsequent reductase exists to generate Pip from these intermediates remains to be determined. It is noteworthy in this context that bacteria use a cyclodeaminase to convert Lys to Pip in a reductive one-step reaction with a concomitant loss of ammonia (Gatto et al., 2006).

In this study, we also addressed mechanistic aspects that underlie Pip-mediated pathogen resistance. The Pip induction-deficient ald1 mutant shows attenuated SA accumulation, callose production, and defense gene expression at sites of bacterial inoculation (Figures 7A, 7B, 7D, 7F, and 7G; Song et al., 2004a), suggesting that endogenously generated Pip contributes to full PTI and ETI by amplification of defense responses (Figure 9). This is corroborated by the fact that exogenous Pip boosts SA
Figure 8. Exogenous Pip Confers SAR-Related Defense Priming on the Metabolite and Gene Expression Level and Restores Systemic SA Accumulation in ald1.

Water or 10 µmol Pip were applied to plants through the soil. Leaves were infiltrated 1 d later with Psm or MgCl₂. FW, fresh weight.

(A) and (C) to (F) Local defense responses were scored 10 h after infiltration. At the same time, a set of samples consisting of untreated leaves was assessed.

(B) Total SA accumulation in upper (2°) leaves upon Psm or MgCl₂ infiltration of lower (1°) leaves was assessed at 2 DAI for Col-0 and ald1.

(A) and (C) Accumulation of total SA (A) and camalexin (C) in Col-0 and ald1 plants. Bars represent the mean ± SD of at least four replicate samples. Different letters above the bars denote statistically significant differences between pairwise compared samples (P < 0.05, two-tailed t test).

(D) to (F) Relative expression of ALD1 (D), FMO1 (E), and PR-1 (F). Transcript levels were assessed by quantitative real-time PCR analysis, are given as means ± SD of three replicate samples, and are expressed relative to the respective mock control value. Asterisks denote statistically significant differences between indicated samples (***P < 0.001; two-tailed t test).
biosynthesis and early camalexin production in the wild type and leads to an overcompensation of ald1 defects in these defense responses (Figures 8A and 8C). The action of Pip in amplification of defense responses explains why exogenous Pip is able to enhance resistance in the wild type and restore full PTI and ETI in ald1 (Figures 5B to 5D and 6C).

Defense amplification is important for effective PTI and ETI, local forms of induced resistance that are activated upon direct pathogen contact via recognition of preexisting PAMPs and pathogen effectors, respectively (Jones and Dangl, 2006). By contrast, induction of systemic immunity is indirect, relying on the recognition of mobile, endogenous signals in leaves distal from pathogen contact that are generated in inoculated leaves (Shah, 2009). The overall direct defense eliciting capacity of numerous PAMPs and/or pathogen effectors at infection sites is presumably higher than the elicitor strength of SAR signals in leaves distal from inoculation, and signal amplification should thus be of particular importance for SAR. This is exemplified by the fact that genetic defects in defense regulators such as NON-RACE SPECIFIC DISEASE RESISTANCE1, ALD1, or FMO1 do not generally entail a complete suppression of local defense responses but do imply a total loss of the SAR response (Shapiro and Zhang, 2001; Song et al., 2004a; Bartsch et al., 2006; Mishina and Zeier, 2006; Figure 7).

We previously proposed the existence of an FMO1-dependent signal amplification loop operating in noninoculated, distal leaves that is critical for SAR establishment (Mishina and Zeier, 2006). Similar to ald1 (Figures 7A and 7B; Song et al., 2004a), fmo1 plants do allow significant rises of SA in inoculated leaves, whereas SA accumulation is fully absent in systemic leaves. Since SA is not transported from locally infected to systemic leaves (Vernooij et al., 1994; Attaran et al., 2009), the systemic accumulation of SA necessary for SAR induction must occur by de novo biosynthesis of SA in distal tissue, and this proceeds via isochorismate synthase (Wildermuth et al., 2001). Our findings that exogenous Pip does restore the capacity of ald1 to systemically enhance SA levels and establish SAR demonstrate that Pip is a critical SAR player that is required for systemic SA accumulation. A role of Pip upstream of SA in SAR (Figure 9) is consistent with our findings that Pip accumulation precedes SA accumulation at the systemic level (Figures 3A and 3B). The observation that FMO1 is required for SAR and Pip-mediated resistance induction (Figure 6) suggests that FMO1 acts downstream of Pip to realize SAR (Figure 9). Flavin-dependent monoxygenases from plants, animals, or fungi oxidize either nitrogen- or sulfur-containing substrates (Schlaich, 2007). It is thus tempting to speculate that FMO1 could convert Pip or a Pip derivative into an oxidized form and thereby transduce the Pip signal. This hypothesis would also

Figure 9. Proposed Model for the Role of Pip during Activation of Local Resistance, SAR, and Defense Priming.

1°, pathogen-inoculated leaf; 2°, distal leaf. Pathogen-induced changes in free amino acids, activation of Lys catabolism, including Pip formation, the roles for Pip in defense amplification and priming, and the proposed feedback amplification cycle in 2° leaves enabling SAR establishment that involves ALD1, Pip, FMO1, ICS1, and SA are illustrated. Dotted lines represent still hypothetical events. A possible role for Pip in long-distance signaling from 1° to 2° leaves remains to be clarified.
explain our observation that fmo1 overaccumulates Pip in inoculated tissue at later stages of Psm infection (Figures 2D and 3D). Future experiments are necessary to clarify the exact biochemical role of FMO1 in Pip-mediated resistance induction.

To extend our previous working model for SAR, we propose that early Pip accumulation in systemic leaves drives further Pip production via upregulation of ALD1 and subsequent FMO1-mediated activation of SA biosynthesis. Since systemic Pip accumulation is markedly attenuated in both the fmo1 and the ics1 mutant (Figure 3C), we assume a feedback amplification mechanism that requires SA to activate ALD1-mediated increases in Pip. This can, via the action of FMO1, lead to higher SA levels that will further fuel feedback amplification. Further repetition of this amplification cycle would then ultimately lead to SAR establishment (Figure 9). Modest Pip increases upon SA feeding also support this feedback scenario (see Supplemental Figure 9 online).

A more stringent requirement of the proposed amplification loop for the activation of systemic compared with local resistance responses would explain why Pip accumulation, which does occur independently of SA and FMO1 at inoculation sites (Figures 2C, 2D, and 3D), essentially becomes SA- and FMO1-dependent at the systemic defense level (Figure 3C).

Two other regulatory proteins involved in the Pip-mediated amplification cycle are PAD4 and NPR1 (Figure 8). PAD4 positively regulates pathogen-induced Pip production (Figures 2C and 2D; see Supplemental Figure 4A online), presumably because it potentiates ALD1 transcription (Song et al., 2004a). Transcriptional control of downstream components, such as FMO1 (Bartsch et al., 2006), could be causative for our finding that PAD4 is also required to transduce the Pip signal (Figure 6C). The requirement of NPR1 to mediate Pip-induced resistance (Figure 6C) might partly rely on its function as a downstream mediator of SA signaling (Durrant and Dong, 2004). However, because of the significant Pip-induced resistance effect in SA-deficient ics1 (Figure 6C), an additional, SA-independent function of NPR1 in Pip signal transduction is probable.

As discussed above, our working model implies small initial systemic rises of Pip at the onset of SAR (Figure 9). Two scenarios are imaginable to realize this. A first possibility is that systemic Pip levels after the perception of SAR long-distance signals, increase exclusively by de novo synthesis via systemic upregulation of ALD1. Alternatively, the initial small rises of Pip in distal leaves might be a consequence of long-distance transport of Pip from inoculated leaves, which accumulate high levels of Pip (Figure 2). Movement of Pip out of inoculated leaves is conceivable because of its strong and selective enrichment in collected petiole exudates (Figure 1; see Supplemental Figure 4 online). Furthermore, small systemic rises of Pip in fmo1 mutant plants that completely lack systemic upregulation of ALD1 might indicate long-distance transport of Pip (see Supplemental Figure 5C online). However, the possible mobile character of Pip and its putative function in long-distance transport are hypothetical at this stage. Grafting experiments and tracer studies using isotope-labeled Pip may be helpful to clarify this issue in the future.

In recent years, SAR long-distance signaling has become a matter of intense debate. It appears that several cross-interacting signals activate SAR and that some signals vary in their contribution to resistance induction under different environmental conditions (Liu et al., 2011; Dempsey and Klessig, 2012). Proposed candidates for mobile SAR long-distance signals include the putative lipid transfer protein DIR1 (Maldonado et al., 2002), glycerol-3-phosphate (Chanda et al., 2011), the abietane diterpenoid dehydroabietinal (Chaturvedi et al., 2012), the C9-dicarboxylic acid AZA (Jung et al., 2009), and, depending on experimental conditions, methyl salicylate (Park et al., 2007; Attaran et al., 2009; Liu et al., 2011). Light availability and activated phytochrome signaling are essential factors for SAR establishment (Zeier et al., 2004; Griebel and Zeier, 2008), and the length of a light period before pathogen infection can influence the significance of individual long-distance signals (Liu et al., 2011). Recent experiments from Liu et al. (2011) suggest that FMO1 represents a central SAR node required for systemic resistance induction irrespective of the light environment applied. It was also shown that FMO1 is required for dehydroabietinal- and AZA-induced resistance (Jung et al., 2009; Chaturvedi et al., 2012). Moreover, AZA enhances resistance in an ALD1-dependent manner (Jung et al., 2009). These findings indicate that the proposed Pip/FMO1-dependent amplification loop (Figure 9) is necessary to mediate SAR signal transduction of at least a subset of mobile SAR signals. An important future task will be to systematically clarify the interrelationship between Pip and other metabolic SAR activators.

SAR can be activated by localized inoculation with avirulent and virulent bacterial pathogens. Both kinds of pathogens elicit highly similar systemic response patterns that include SA accumulation, Pip accumulation, and enhanced expression of a variety of classical SAR marker genes, such as PR-1, PR-2, and PR-5 (Mishina and Zeier, 2006; see Supplemental Figure 4B online). Furthermore, various resistance assays with SAR-defective and SAR-competent Arabidopsis mutants demonstrate that establishment of the SAR response following avirulent and virulent pathogen inoculation proceeds via a closely related mechanistic network (Mishina and Zeier, 2006, 2007; Zhang et al., 2010; Liu et al., 2011). This network involves SA biosynthesis and downstream signaling (Mishina and Zeier, 2007; Zhang et al., 2010) and an intact Pip pathway that includes functional ALD1 and FMO1 (Mishina and Zeier, 2006; Figure 5A; see Supplemental Figure 8D online). This does not rule out that discrete differences in the contributions of particular signals might exist for SAR elicited by different pathogen types or by the same pathogen type under different experimental conditions, as discussed below for the oxylipin derivatives JA and AZA, which have both been implicated with SAR long-distance signaling (Truman et al., 2007; Jung et al., 2009).

It is well documented that the degree of formation of the oxylipin derivatives JA and AZA after bacterial inoculation is positively correlated with the inoculum density and the concomitant extent of tissue necrosis formation (Mishina and Zeier, 2007; Zoller et al., 2012). Leaf necrosis also occurs much earlier and is more pronounced in response to HR-inducing avirulent bacterial infection than in response to virulent bacteria. This can explain observed differences in exudate composition in our experiments and those of other groups (Truman et al., 2007; Jung et al., 2009). Truman et al. (2007) have reported accumulation of JA in petiole exudates collected from leaves treated with high doses (OD600 0.2) of avirulent Pst harboring avrRpm1, and Jung et al. (2009)
have detected elevated AZA levels in exudates following Psm avrRpt2 inoculation (OD600 0.01). By contrast, JA or AZA levels in exudates collected from leaves inoculated with lower densities (OD600 = 0.005) of virulent Psm are not elevated (see Supplemental Figure 5 online). AZA application has been reported to confer local and systemic plant resistance (Jung et al., 2009), but, according to our analyses, its accumulation in exudates is not a requirement for SAR. Thus, AZA might add an additional resistance contribution to the overall SAR effect without being essential to establish the response per se. Genetic and physiological evidence suggests that the previously proposed role of JA as a mobile SAR signal (Truman et al., 2007) is strongly debatable (reviewed in Shah, 2009).

Our study reveals that biologically induced SAR promotes plants into an alarmed state that accelerates the reaction to subsequent pathogen attack on several levels. The phenomenon of defense priming has been most extensively studied in context with chemical priming (i.e., plant defense activation with unnatural compounds, such as BTH or BABA). Compelling evidence that defense priming also occurs during biological SAR is still rare (Beckers et al., 2009; Jung et al., 2009; Conrath, 2011). We show that, on the metabolite level, SAR priming is characterized by a strongly potentiated induction of both camalexin and Pip biosynthesis after pathogen inoculation (Figures 7C and 7D), which can be explained by a synergistic interplay between signaling events triggered by the 1° inducing and the 2° challenge infection. SAR priming has been previously reported also for SA accumulation (Jung et al., 2009). Our results confirm that SAR allows a more pronounced accumulation of SA in the early Psm–Arabidopsis interaction. However, the difference in SA levels between challenged SAR-induced and control plants essentially results from a nonsynergistic additive contribution of the systemic SA increase resulting from the 1° inoculation on top of the rise resulting from the challenge infection in 2° leaves (Figure 6B). We also show that biological SAR enables plants to more pronouncedly increase expression levels of the two essential SAR regulatory genes ALD1 and FMO1, and, as previously reported by Jung et al. (2009), of the SA-inducible PR-1 gene (Figures 7E to 7G). Importantly, the Pip-deficient ald1 plants are defective in these SAR-associated priming responses (Figure 7), providing genetic evidence for a critical action of Pip in SAR priming. Moreover, the facts that exogenous Pip promotes plants into a primed state highly similar to SAR and partially restores defense priming in ald1 corroborates the role of Pip as an endogenous mediator of defense priming. As discussed in the context of SAR establishment (see above), feedback mechanisms within the proposed Pip resistance pathway also underlie defense priming: Pip not only triggers enhanced induction of ALD1 to enforce its own biosynthesis (Figures 7C, 7E, and 8C), but it also amplifies expression of the downstream mediator FMO1 (Figures 7F and 8D).

The individual responses that are conditioned upon SAR establishment might add different contributions to the enhanced resistance effect toward subsequent infection. For a P. syringae challenge, priming of the SA- and Pip-associated pathways most likely provide significant protection because these pathways positively regulate resistance toward this bacterial pathogen. By contrast, camalexin priming might not contribute to SAR directed against P. syringae, since camalexin-deficient pad3 mutants display normal basal resistance to this pathogen (Glazebrook and Ausubel, 1994). However, SAR confers broad-spectrum resistance against different pathogen types, and the potentiated production of the antimicrobial phytoalexin might protect against other microbes, such as fungal or oomycete pathogens (Thomma et al., 1999; Schlaeppi et al., 2010).

Defense priming is considered as the central mechanistic aspect of BABA-induced resistance against P. syringae or Hyp ocleronomspora arabilodopsis infection (Zimmerli et al., 2000; Ton et al., 2005). We found that BABA application entails Pip accumulation and induces resistance to P. syringae in an ALD1-dependent manner, indicating that Pip also orchestrates BABA-induced resistance against bacterial pathogen infection (Figure 6B; see Supplemental Figure 7B online). Interestingly, the plant activator BTH triggers ALD1 expression in Arabidopsis (Song et al., 2004a), suggesting a contribution of Pip defense signaling also to BTH-triggered resistance. BTH is an example of a synthetic plant activator that is commercially applied (Du et al., 2012). In this context, our finding that the endogenous plant natural product Pip activates priming and resistance when exogenously applied to plants might gain applied relevance in modern plant protection.

METHODS

Plant Material and Growth Conditions

Arabidopsis thaliana plants were grown in individual pots containing a mixture of soil (Klasmann-Deilmann, Substrat BP3), vermiculite, and sand (8:1:1) inside a controlled environmental chamber with a 9-h day (9 AM to 6 PM) photon flux density 100 μmol m⁻² s⁻¹)/15-h night cycle and a relative humidity of 70%. Growth temperatures during the day and night period were 21 and 18°C, respectively. Experiments were performed with 5- to 6-week-old, naïve, and unstressed plants exhibiting a uniform appearance.

The ald1 (ald1 T2; Song et al., 2004a), irkr1, and irkr2 mutants correspond to the SALK T-DNA insertion lines SALK_007673, SALK_068769, and SALK_127160, respectively, which are all in the Col-0 background. To identify homozygous T-DNA insertion lines by PCR, the method described by Alonso et al. (2003) was applied, using gene-specific primers (see Supplemental Table 1 online).

Other lines used in this study are fmo1 (Mishina and Zeier, 2006), npr1-2 (npr1, NASC ID N3801), pad4-1 (pad4; Jirage et al., 1999), cpr5 (Bowling et al., 1997), and sid2-1 (ics1; Nawah and Métraux, 1999). Wild-type plants in the Col-0 background were used as control plants.

Cultivation of Bacteria

Pseudomonas syringae pv maculicola strain ES426 (Psm) and Psm carrying the avrRpm1 avirulence gene (Psm avrRpm1) were grown in King’s B medium containing the appropriate antibiotics at 28°C (Zeier et al., 2004). Overnight log phase cultures were washed three times with 10 mM MgCl₂ and diluted to different final optical densities (OD) at 600 nm for leaf inoculations.

Assessment of SAR, Defense Priming during SAR, and Local Plant Resistance

To induce SAR, plants were infiltrated between 10 and 12 AM into three lower (1°) leaves with a suspension of Psm (±avrRpm1) at OD 0.005. Infiltration with 10 mM MgCl₂ served as a control treatment. Upper (2°) leaves were routinely harvested 2 d after the primary treatment for the determination of systemic responses (except for the time-course analyses depicted in Figures 3A and 3B).
For SAR growth assays, 2° leaves were inoculated with \textit{Psm} (OD 0.001) 2 d after the 1° treatment. Growth of \textit{Psm} in 2° leaves was scored another 3 d later by homogenizing discs originating from infiltrated areas of three different leaves in 1 mL 10 mM MgCl\textsubscript{2}, plating appropriate dilutions on King’s B medium, and counting colony numbers after incubating the plates at 28°C for 2 d.

For the assessment of defense priming during SAR, 2° leaves were infiltrated with either 10 mM MgCl\textsubscript{2} or \textit{Psm} (OD = 0.005) 2 d after the 1° treatment. The 2° leaves were collected 10 h after they had been treated.

For the determination of local defense responses, bacterial suspensions of OD 0.005 (determination of gene expression and metabolite levels), OD 0.001 (\textit{Psm} growth assays), or OD 0.002 (\textit{Psm avrApm1} growth assays) were infiltrated into three full-grown leaves per plant. Bacterial growth was assessed 3 d after infiltration as described above.

\textbf{flg22, LPS, and SA Treatments}

The \textit{flg22} peptide and purified LPS from \textit{Escherichia coli} were diluted in 10 mM MgCl\textsubscript{2} to final concentrations of 200 nM (\textit{flg22}) and 100 µg mL\textsuperscript{-1} (LPS) and infiltrated into leaves. The \textit{flg22} peptide was synthesized by Mimotopes. The chromatographically purified LPS preparation was acquired from Sigma-Aldrich (L3024). Control infiltrations were performed with 10 mM MgCl\textsubscript{2}. SA was infiltrated into leaves in a concentration of 0.5 mM.

\textbf{Exogenous Application of Pip, BABA, and Aad}

One day prior to bacterial inoculation or 1° treatments in the case of SAR experiments, 10 mL of a 1 mM (10 µmol) \textit{L}-Pip solution (S47167; Sigma-Aldrich), 10 mL of 0.5 mM (5 µmol) \textit{L}-Pip (P1404; TCI Europe) solution, 10 mL of 0.5 mM (5 µmol) \textit{d}-Pip (P1830; TCI Europe) solution, 10 mL of 1 mM (10 µmol) BABA (A44207; Sigma-Aldrich) solution, or 10 mL of 1 mM (10 µmol) Aad (AT275; Sigma-Aldrich) solution was pipetted onto the soil substrate of individually cultivated plants. Control plants were supplemented in the same manner with 10 mL of water.

\textbf{Determination of Defense Metabolites}

Determination of the levels of free SA, conjugated SA, camalexin, methyl amino acids (Kugler et al., 2006; see Supplemental Figure 1 online). Fifty milligrams of homogenized leaf material was extracted with 200 µL of buffer (25% acetonitrile in 0.01 M HCl). The sample was shaken thoroughly for 15 min at room temperature and centrifuged at 14,000 rpm for 4 min. An aliquot (100 µL) of the supernatant was extracted following the protocol of the EZ:faast user’s manual. The sample was finally dissolved in 70 µL of dichloromethane and subjected to GC-MS analysis. Three microliters of the sample mixture was separated on a silica capillary column (ZB-AAA 10 m × 0.25 mm; Zebron, Phenomenex). The injector temperature was set to 250°C, and a constant flow of helium (1.2 mL/min) and the following temperature program were used: 70°C/3 min with 8°C/min to 240°C, with 20°C/min to 320°C/2 min. For quantitative determination of individual amino acids, peaks originating from selected ion chromatograms were integrated: Gly (mass-to-charge ratio [m/z] 116), Ala (m/z 130), Val (m/z 158), \textit{j}-Ala (m/z 116), Leu (m/z 172), Ile (m/z 172), GABA (m/z 130), Ser (m/z 146), Thr (m/z 101), Pro (m/z 136), Pip (m/z 170), Aad (m/z 244), Asp (m/z 216), Glu (m/z 84), Asn (m/z 69), Glu (m/z 84), Cys (m/z 248), Orn (m/z 156), Lys (m/z 170), His (m/z 282), Phe (m/z 148), Tyr (m/z 107), and Trp (m/z 130). The area of a substance peak was related to the peak area of norvaline (m/z 158), which served as an internal standard. Experimentally determined correction factors for each amino acid were considered. Arg and Met could not be analyzed with the applied method.

\textbf{Quantitative Real-Time PCR Analysis}

Total RNA was isolated from frozen leaves usingpeqGOLD RNAPure reagent (PeqLab) following the manufacturer’s instructions. One micrograms of RNA was treated with DNase I (Fermentas) for 30 min at 37°C to remove genomic DNA, and the DNase was inactivated by incubation at 70°C for 10 min in the presence of 2.5 mM EDTA. mRNA was converted to cDNA with the oligo(dT) primers and reverse transcriptase (OmniScript RT kit, Qiagen) according to the manufacturer’s instructions. cDNA (2.5 µL) was amplified in 10 µL of reaction volume with 5 µL of SenzMix SYBR Green (Bioline) and 0.75 µM gene-specific primers (see Supplemental Table 1 online). The gene encoding a polypropyrimidine tract binding (PTB) protein 1 (At3g01150) which is nonresponsive to \textit{P. syringae} inoculation was used as a reference gene (Czechowski et al., 2005). The quantitative PCR reaction was performed in triplicate in a Rotor-Gene Q apparatus (Qiagen) using the cycling program: 95°C for 7 min, followed by 45 cycles at 95°C for 10 s, 60°C for 30 s, and finally 72°C for 3 min. The data were analyzed using the Rotor-Gene Q 2.0.2 software, setting the threshold of the normalized fluorescence to 0.1, which corresponded to the exponential phase of the fluorescence signal. The resulting cycle threshold (C\textsubscript{T}) and E values were used to calculate the relative mRNA abundance according to the ΔΔC\textsubscript{T} method. The values were normalized to those of the reference gene and expressed relative to the MgCl\textsubscript{2}-treated wild-type control sample.

\textbf{Petoile Exudate Collection and Analyses}

Petoile exudates were collected essentially as described (Maldonado et al., 2002; Chaturvedi et al., 2012). Plant leaves were either infiltrated with a suspension of \textit{Psm} (OD 0.005) or 10 mM MgCl\textsubscript{2} as a control treatment. Six hours after infiltration, leaves were cut at the base of their petioles and the cut surface sterilized by successive dipping in 50% ethanol and 0.005% bleach for 10 s. After rinsing with sterile 1 mM EDTA, pH 8.0, the petioles were submerged in fresh EDTA solution for exudate collection. Twelve-well tissue culture plates were used for this purpose, whereas each well was filled with 2.5 mL of collection solution and equipped with 10 harvested leaves. Exudates were continuously collected in the period from 6 to 48 h after inoculation. For the determination of amino acid (defense metabolite) contents, 100 µL (1 mL) of collected exudates was analyzed as described above.

\textbf{Reproducibility of Experiments and Statistical Analyses}

The presented data generally resulted from a single biological experiment. Unless otherwise stated, the results were similar in three biologically independent experiments. Statistical analyses were performed using Student’s t test.
Accession Numbers
Sequence data from this article for the major genes discussed in this article can be found in the Arabidopsis Genome Initiative or GenBank/EMBL databases under the following accession numbers: ALD1 (At2g13810), LKR (At4g33150), FMO1 (At1g19250), ICS1 (At1g74710), PR-1 (At2g14610), PAD4 (At3g52430), NPR1 (At1g64280), and PTB (At3g01150).

Supplemental Data
The following materials are available in the online version of this article.
Supplemental Figure 1. Mass Spectral Identification of the Initially Unknown Substance Detected in Extracts of P. syringae–Inoculated Plants as Pipelic Acid.
Supplemental Figure 2. The Plant-Derived Substance Identified as Pip and Authentic Pip Have Identical GC Retention Times.
Supplemental Figure 3. Proposed Scheme for Pathogen-Inducible Pip and Aad Biosynthesis in Plants via Lys Catabolism.
Supplemental Figure 4. Psm avrRpm1–Induced Pip Accumulation in Inoculated and Distal Leaves.
Supplemental Figure 5. Metabolite Levels in Petiole Exudates of Leaves Collected between 6 and 48 h Post Psm or MgCl2 Treatment.
Supplemental Figure 6. Pathogen-Induced ALD1 and LKR Expression in Wild-Type Col-0 and Different Mutant Plants.
Supplemental Figure 7. Metabolite Levels in Leaves Following Pip, Aad, and β-Amine Butyric Acid Application via the Root in Col-0 and ald1 Plants.
Supplemental Figure 8. Concentration Dependency of Resistance Induction by Exogenous Pipelic Acid, Resistance-Enhancing Activity of L- but Not D-Pip, and Chemical Complementation of ald1 Defects in Psm avrRpm1–Induced SAR by Exogenous Pip.
Supplemental Figure 9. Effect of Exogenous SA on Leaf Pip Levels, ALD1 Transcript Levels, and PR-1 Transcript Levels.
Supplemental Table 1. Primers Used in This Study.

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AUTHOR CONTRIBUTIONS
H.N., F.B., A.-C.D., and J.Z. performed the experiments. H.N. and J.Z. contributed to article preparation. J.Z. designed the research and wrote the article.

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