Phenazines are not essential for Pseudomonas chlororaphis PA23 biocontrol of Sclerotinia sclerotiorum, but do play a role in biofilm formation

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Abstract

Pseudomonas chlororaphis strain PA23 is a biocontrol agent capable of suppressing disease caused by the fungal pathogen Sclerotinia sclerotiorum. This bacterium produces the diffusible antibiotics phenazine-1-carboxylic acid, 2-hydroxyphenazine and pyrrolnitrin (PRN). Because the individual contribution of these antibiotics to PA23 biocontrol has not been defined, mutants deficient in the production of phenazine (PHZ), PRN or both antibiotics were created. Analysis of the PHZ mutant revealed enhanced antifungal activity in vitro and wild-type levels of disease suppression. Conversely, the PRN- and the PRN/PHZ-deficient strains exhibited decreased antifungal activity in vitro and markedly reduced the ability to control Sclerotinia infection of canola in the greenhouse. These findings suggest that PRN is the primary antibiotic mediating biocontrol of this pathogen. Analysis of prnA–lacZ and phzA–lacZ transcriptional fusions revealed that PRN and PHZ are not subject to autoregulation; moreover, they do not cross-regulate each other. However, HPLC showed a twofold increase in PRN levels in the PHZ background. Finally, PHZ, but not PRN production, is involved in biofilm development in P. chlororaphis PA23.

Introduction

Compared with chemical pesticides, biological control represents a safer, more environment-friendly approach to managing plant pathogens. Fluorescent pseudomonads are present in high numbers in natural soils and various strains have been found to produce metabolites deleterious to fungal pathogens. Inhibitory compounds include antibiotics, for example 2,4-diacetylphloroglucinol (2,4-DAPG), phenazines (PHZ), pyrrolnitrin (PRN), pyoluteorin (PLT), cyclic lipopeptides and hydrogen cyanide (HCN), together with hydrolytic enzymes such as proteases, cellulase, β-glucanase and chitinase (Dowling & O’Gara, 1994; Thomashow & Weller, 1995; Haas & Défago, 2005). This potent arsenal of antimicrobial metabolites enables pseudomonads to inhibit a myriad of plant pathogens.

Pseudomonas chlororaphis strain PA23 is a biocontrol agent initially isolated from soybean root tips. In both greenhouse and field studies, this bacterium is able to protect canola from the devastating effects of stem rot caused by the fungus Sclerotinia sclerotiorum (Lib.) de Bary (Savchuk & Fernando, 2004; Zhang, 2004; Fernando et al., 2007). Sclerotinia sclerotiorum is a ubiquitous, soilborne fungus that infects > 400 plant hosts, causing significant loss of economically important crops (Purdy, 1979). In commercially grown canola cultivars, there is no known resistance against S. sclerotiorum, making management of this pathogen essential. A well-defined zone of inhibition surrounding PA23 on antifungal plates suggests that antibiotic production is the primary mechanism of pathogen inhibition (Savchuk & Fernando, 2004; Poritsanos et al., 2006). Strain PA23 produces the diffusible antibiotic phenazine-1-carboxylic acid (PCA), 2-hydroxyphenazine (2-OH-PHZ) and PRN (Zhang et al., 2006); however, the individual contribution of these antibiotics to PA23 biocontrol is yet to be defined.
Many biocontrol agents display excellent disease control in the greenhouse, but show inconsistent performance in the field, due in part to the variable expression of disease-suppressive factors (Cook, 1993; Walsh et al., 2001; Haas & Keel, 2003). Environmental conditions can have a dramatic impact on antibiotic production and conditions that favor expression of one antibiotic may not be optimal for others. For instance, maximal PHZ production by *P. chlororaphis* strain PCL1391 was found to occur when glucose, l-pyroglutamic acid or glycerol was used as the carbon source (van Rij et al., 2004), whereas fructose and mannitol favored PRN production by *Pseudomonas fluorescens* strain CHA0 (Duffy & Défago, 1999). Other factors that influence the production of PHZ and PRN include pH, temperature, oxygen availability and mineral amendment (Slininger & Jackson, 1992; Slininger & Shea-Wilbur, 1995; Duffy & Défago, 1999; Hwang et al., 2002; van Rij et al., 2004). Identifying metabolites that are essential for PA23 biocontrol is an important first step in the development of a successful biocontrol agent. Once this has been established, factors affecting the production of key compounds can be determined.

The aim of the present study was to assess the contribution of PHZ and PRN to PA23 inhibition of the fungal pathogen *S. sclerotiorum*. We also examined whether these antibiotics are subject to autoregulatory or coregulatory control. Finally, the impact of PHZ and PRN on biofilm formation was examined.

### Materials and methods

#### Bacterial strains and growth conditions

The bacterial strains and plasmids used in this study are listed in Table 1. *Escherichia coli* strains were cultured at 37°C on Lennox Luria–Bertani (LB) agar (Difco Laboratories, Detroit, MI). *Pseudomonas chlororaphis* PA23 and its derivatives were routinely cultured at 28°C on LB agar plates and broth, Minimal M9 casamino acid media +0.2% glucose (M9CA; Difco Laboratories), Terrific broth

<table>
<thead>
<tr>
<th>Strain/plasmid/primer</th>
<th>Relevant genotype or phenotype</th>
<th>Source or reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strain</strong></td>
<td></td>
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<tr>
<td><em>P. chlororaphis</em></td>
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<tr>
<td>PA23</td>
<td>PRN&lt;sup&gt;+&lt;/sup&gt; PHZ&lt;sup&gt;+&lt;/sup&gt; Rif&lt;sup&gt;R&lt;/sup&gt; wild type (soybean plant isolate)</td>
<td>Savchuk &amp; Fernando (2004)</td>
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<tr>
<td>PA23-63</td>
<td>PHZ&lt;sup&gt;+&lt;/sup&gt; Rif&lt;sup&gt;R&lt;/sup&gt; phzE::Tn5-OT182 genomic fusion</td>
<td>This study</td>
</tr>
<tr>
<td>PA23-8</td>
<td>PRN&lt;sup&gt;+&lt;/sup&gt; Rif&lt;sup&gt;R&lt;/sup&gt; prn&lt;sup&gt;B&lt;/sup&gt;C deletion mutant</td>
<td>This study</td>
</tr>
<tr>
<td>PA23-63-1</td>
<td>PHZ&lt;sup&gt;+&lt;/sup&gt; PRN&lt;sup&gt;+&lt;/sup&gt; Rif&lt;sup&gt;R&lt;/sup&gt; phzE::Tn5-OT182 genomic fusion; prn&lt;sup&gt;B&lt;/sup&gt;C deletion mutant</td>
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<td>E. coli</td>
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<td>DH5α</td>
<td>supE44 ΔlacU169 (q80 lacZAM15) hsdR17 recA1 endA1 gyrA96 thi-1 relA1</td>
<td>Gibco</td>
</tr>
<tr>
<td>SM10</td>
<td>Mobilizing strain; R43 tra genes integrated in chromosome; Km&lt;sup&gt;R&lt;/sup&gt; Tc&lt;sup&gt;R&lt;/sup&gt;</td>
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<tr>
<td>C. violaceum CVO26</td>
<td>Autoinducer synthase (cvi) mutant from <em>C. violaceum</em> ATCC 31532, autoinducer biosensor</td>
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<td><strong>Plasmids</strong></td>
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</tr>
<tr>
<td>pOTI82</td>
<td>pSUP102(GM):::Tn5-OT182 Cm&lt;sup&gt;R&lt;/sup&gt; Km&lt;sup&gt;R&lt;/sup&gt; Amp&lt;sup&gt;R&lt;/sup&gt; Tc&lt;sup&gt;R&lt;/sup&gt;</td>
<td>Merrim &amp; Lamont (1993)</td>
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<tr>
<td>pOTI82-63 (EcoRI)</td>
<td>pOT182 containing phzE::Tn5-OT182 genomic fusion</td>
<td>This study</td>
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<tr>
<td>pCR&lt;sup&gt;R&lt;/sup&gt;2.1-TOPO</td>
<td>Cloning vector for PCR products</td>
<td>Invitrogen</td>
</tr>
<tr>
<td>pTOPO-prn</td>
<td>pCR&lt;sup&gt;R&lt;/sup&gt;2.1-TOPO containing prn&lt;sup&gt;B&lt;/sup&gt;ACD genes</td>
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<td>pEX18Ap</td>
<td>Suicide vector</td>
<td>Hoang et al. (1998)</td>
</tr>
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<td>pUCGm</td>
<td>Source of Gm&lt;sup&gt;R&lt;/sup&gt; cassette</td>
<td>Schweizer (1993)</td>
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<td>pEX18Ap-prn</td>
<td>5.7-kb prn cluster containing a Gm&lt;sup&gt;R&lt;/sup&gt; cassette insertion within prn&lt;sup&gt;B&lt;/sup&gt;B and prn&lt;sup&gt;C&lt;/sup&gt;C</td>
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<td>This study</td>
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<td>pLP170</td>
<td>Promoterless lacZ transcriptional fusion vector</td>
<td>Preston et al. (1997)</td>
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<td>pME3219</td>
<td>pME6010 containing an hcn&lt;sup&gt;A&lt;/sup&gt;-lacZ translational fusion</td>
<td>Laville et al. (1998)</td>
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<td><strong>Primers</strong></td>
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<td>prnF</td>
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<td>This study</td>
</tr>
<tr>
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<td>This study</td>
</tr>
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<tr>
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<td>This study</td>
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<td>Tn5-ON82</td>
<td>5′-ctctgctgcgtgaaacg-3′</td>
<td>Poritsanos et al. (2006)</td>
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<tr>
<td>Tn5-OT182 right</td>
<td>5′-agtctggagggatc-3′</td>
<td>Poritsanos et al. (2006)</td>
</tr>
</tbody>
</table>
(Sambrook et al., 1989) or peptone tryptic soy broth (PTSB; Ohman et al., 1980). For PRN and PHZ analysis, cells were grown in 523 (Kato & Heskett, 1970) and PPM media (Levitch & Stadtman, 1964), respectively. As required, media were supplemented with the following antibiotics: tetracycline (Tc; 15 μg mL⁻¹), gentamicin (Gm; 15 μg mL⁻¹) and ampicillin (100 μg mL⁻¹) for E. coli, and rifampicin (25 μg mL⁻¹), tetracycline (15 or 100 μg mL⁻¹), gentamicin (25 μg mL⁻¹) and pipericillin (13 or 100 μg mL⁻¹) for P. chlororaphis. All antibiotics were obtained from Research Products International Corp. (Mt. Prospect, IL).

**Nucleic acid manipulation**

Cloning, purification, electrophoresis and other manipulations of nucleic acid fragments and constructs were performed using standard techniques (Sambrook et al., 1989). PCR was performed under standard conditions as suggested by Invitrogen Life Technologies data sheets supplied with their Taq polymerase.

**Tn5-OT182 transposon mutagenesis**

Bacterial conjugations were performed to introduce Tn5-OT182 into P. chlororaphis PA23 by biparental mating following the method of Lewenza et al. (1999). For each mating, 5–10 TcR colonies were screened by PCR to ensure that transconjugants contained a Tn5 insertion using TNP5-Forward and TNP5-Reverse primers (Table 1). To determine the site of Tn5-OT182 insertion, rescue cloning was performed following previously described methods (Lewenza et al., 1999).

**Generation of PA23 PRN-deficient strains**

The PRN biosynthetic gene cluster was PCR amplified from PA23 genomic DNA using primers prnF and prnR (Table 1). The 5.6-kb PCR product was cloned into pCR2.1-TOPO, yielding pEX18Ap-prn (Table 1). Plasmid pEX18Ap-prn was released from pTOPO-prn with XbaI and BamH1 and isolated from pUCGm. The interrupted prn operon was subsequently released from pTOPO-prn with XbaI and BamH1 and cloned into the same sites of suicide vector pEX18Ap, yielding pEX18Ap-prn (Table 1). Plasmid pEX18Ap-prn was mobilized into PA23 and PA23-63 by triparental mating. Putative PRN-deficient mutants PA23-8 and PA23-63-1 were screened by PCR analysis to verify that a double-crossover event had occurred.

**Sequence analysis**

The sequence of the prnABCD operon on plasmid pTOPO-prn was determined using a combination of universal primers and primer walking. The PA23 prnABCD sequence was submitted to GenBank (accession number EU188755). Sequence analysis of the Tn5 XhoI rescue clones was performed using oligonucleotide primer Tn5-ON82 (Table 1), which anneals to the 5’ end of Tn5-OT182. Sequencing was performed at the University of Calgary Core DNA Services facility, and sequences were analyzed with BLASTN and BLASTX databases.

**Antifungal assays**

Radial diffusion assays to assess fungal inhibition in vitro were performed according to previously described methods (Poritsanos et al., 2006). Six replicates were analyzed for each strain and assays were repeated four times.

**PHZ and PRN gene expression**

To monitor PHZ gene expression, a phzA–lacZ transcriptional fusion was created using PCR primers phzAR-F and phzAR-R (Table 1). The phzA promoter region was PCR amplified and cloned into pCR2.1-TOPO. A 1.1-kb HindIII and EcoRV fragment was removed and cloned into HindIII–SmaI-digested pLP170, yielding pPHZA-lacZ. To generate a prn (PRN) transcriptional fusion, PCR primers prnA-F and prnA-R (Table 1) were used to amplify a 1.5-kb fragment corresponding to the prnA promoter region of PA23. The PCR product was first cloned into pCR2.1-TOPO, and then excised using HindIII and XbaI and ligated into the same sites of pLP170, yielding pPHZAlacZ. The phzA-lacZ and prnA-lacZ transcriptional fusions were mobilized into PA23, PA23-63 (phzE), PA23-8 (prnBC) and PA23-63-1 (phzEprnBC). Cultures harboring these plasmids were grown in PTSB and β-galactosidase assays were performed at various points throughout growth (Miller, 1972). Samples were analyzed in triplicate and the experiment was repeated three times.

**Quantification of PRN**

The amount of PRN produced by PA23, PA23-8, PA23-63 and PA23-63-1 was quantified by HPLC. Each strain was grown in 10 mL of 523 media on a rotary shaker for 4 days. The 10 mL volume was extracted with 50 mL ethyl acetate according to the method of Hwang et al. (2002). Samples were dissolved in 500 μL of methanol and 500-μL aliquots of each sample were injected into a Gemini C18 column (100 × 4.6 mm; 5-μm particle diameter) (Phenomenex Inc, Torrance, CA) and analyzed in an isocratic solution of 45% acetonitrile/35% water/20% methanol. The eluent flow rate was 1.0 mL min⁻¹. Peaks were detected by UV absorption at 225 nm using a Dionex AD20 Detector (Dionex, Sunnyvale, CA). The concentration of PRN in each sample was based on standard curves prepared from purified PRN (Sigma,
St. Louis, MO). HPLC-grade solvents were obtained from Fisher Scientific. Cultures were analyzed in triplicate and the PRN analysis was repeated twice.

Quantification of PHZ

Overnight cultures of *P. chlororaphis* strain PA23, PA23-63, PA23-8 and PA23-63-1 grown in PPM were subjected to PHZ extraction following the method of Chancey et al. (1999). Extractions were quantified with UV-visible spectroscopy according to Maddula et al. (2008); the absorption maxima for PCA and 2-OH-PHZ were measured at 367 and 490 nm, respectively. The relative amounts of PCA and 2-OH-PHZ were calculated by dividing the absorption maxima by their standard extinction coefficients (PCA: 3019; 2-OH-PHZ: 7943; Olson & Richards, 1967). The PHZ quantification was repeated three times.

HCN analysis

Production of HCN was determined qualitatively using Cyantesmo paper (Machery-Nagel GmbH & Co., Düren, Germany). To monitor expression of the genes encoding HCN, plasmid pME3219 containing an hcnA–lacZ translational fusion was transformed into PA23, PA23-63, PA23-8 and PA23-63-1. Cultures were grown in PTSB until they reached the stationary phase (OD<sub>600 nm</sub>= 2.5–3.0), at which point hcnA expression was assessed using β-galactosidase assays (Miller, 1972). Samples were analyzed in triplicate and experiments were repeated three times.

Exoproduct analyses

Protease activity, lipase activity and the production of homoserine lactone autoinducer molecules were assessed according to previously described methods (Poritsanos et al., 2006). Data represent the average of six replicates and assays were repeated three times.

Motility analysis

Flagellar (swimming) and swarming motility were monitored according to Poritsanos et al. (2006). For motility assays, five replicates were analyzed and the experiment was repeated three times.

Growth analysis

Growth rate analysis of PA23, PA23-63 (*phzE*), PA23-8 (*prrBC*) and PA23-63-1 (*phzE;prnBC*) was performed in rich (LB, PTSB, TB) and minimal (M9CA + 0.2% glucose) media using a Bioscreen<sup>®</sup> C automated turbidimeter. Overnight cultures were adjusted to an OD<sub>600 nm</sub> of 0.1 by diluting with the same media and 100 μL of culture was inoculated into each well of a Bioscreen<sup>®</sup> C microtiter plate. Control wells contained an equal volume of sterile media. Growth of the cultures at 28 °C was monitored every 15 min over a 45-h period. Samples were analyzed in triplicate and the growth rate analysis was repeated three times.

Biofilm development

A static, 96-well plate assay was used to assess the ability of PA23, PA23-63, PA23-8 and PA23-63-1 to form biofilms (O’Toole & Kolter, 1998). Briefly, overnight cultures grown in M9 minimal casamino acid media + 0.2% glucose were adjusted to an OD of 1.0 and then diluted 1 in 100 in fresh media. One hundred-microliter aliquots of the diluted culture were inoculated into 96-well plates (Becton-Dickenson, Oakville, ON) and allowed to form biofilms. After 24 and 48 h, the adherent cell population was quantified by crystal violet (CV) staining and measuring the OD<sub>490 nm</sub>. Results are averages of eight replicates (± SD) and representative of five independent experiments. For direct enumeration of the adherent cell population, cultures were prepared as described above, except that 1.5-ml aliquots were added to each well of a six-well plate (Becton-Dickenson). Biofilms were allowed to form for 24 and 48 h, after which wells were washed four times with phosphate-buffered saline (PBS) to remove planktonic cells. A 1-ml aliquot of PBS was added to each well and the surface-attached cells were removed by a combination of scraping and sonication. Cell suspensions were diluted and viable plate counting was performed. Results are averages of four replicates (± SD) and representative of three independent experiments.

Biocontrol under greenhouse conditions

Strains PA23, PA23-63, PA23-8 and PA23-63-1 were assessed for their efficiency in suppressing stem rot of canola [*Brassica napus* (cv. Westar)] under greenhouse conditions. *Brassica napus* (cv. Westar) plants were grown in pots (21 cm × 20 cm) at 24/16 °C with a 16-h photoperiod. The plants were sprayed at 30% flowering with bacterial strains (2.0 × 10<sup>8</sup> CFU mL<sup>−1</sup>) suspended in 100 mM phosphate buffer, pH 7.0, with 0.02% Tween 20 and kept in a humidity chamber (24/16 °C, 16-h photoperiod). Twenty-four hours after bacterial inoculation, canola petals were sprayed with ascospores of *S. sclerotiorum* (8 × 10<sup>4</sup> spores mL<sup>−1</sup>) suspended in 100 mM phosphate buffer, pH 7.0, containing 0.02% Tween 20. The pathogen control plants were inoculated with ascospores, while the healthy control plants were sprayed with phosphate buffer. All plants were incubated in a humidity chamber. Fourteen days after inoculation of *Sclerotinia* ascospores, symptom development on stem and leaves was observed and recorded using a 0–7 scale (0, no lesions on the stem; 1, leaf lesion with no stem symptom; 2, 1–20-mm stem lesion; 3, 21–40-mm stem lesion; 4, 41–60-mm stem lesion; 5, 61–80-mm stem lesion; 6,
Results

Isolation of a P. chlororaphis PHZ-deficient mutant

To identify genes involved in PA23 biocontrol, Tn mutagenesis was performed. Out of approximately 5000 mutants, one mutant was identified (PA23-63) that was white in color, indicative of no PHZ production. Surprisingly, this strain exhibited increased antifungal activity compared with the wild type (Table 2). Sequence analysis of DNA flanking the Tn insertion in this mutant showed 92% identity to the phzE gene of P. chlororaphis PCL1391 (GenBank accession #AF195615). PhzE is an enzyme involved in PHZ biosynthesis (Chin-A-Woeng et al., 2003). Sequencing of the PHZ operons from a number of Pseudomonas spp. has revealed a conserved seven-gene operon comprised of phzABCDEFG (Mavrodi et al., 2006). As such, the Tn insertion in phzE is expected to also affect the expression of phzF and phzG.

Isolation of the prn gene cluster and generation of PRN-deficient mutants

Because no PRN biosynthetic mutants were identified in our Tn screen, they were generated using allelic exchange. To accomplish this, the PA23 prn biosynthetic operon was isolated through PCR amplification. Sequence analysis revealed that the prn cluster is comprised of four genes, prnABCD, exhibiting 93% identity at the nucleotide level to the prn operon of P. fluorescens Pf-5 (GenBank accession #NC001429). The same prnABCD genetic arrangement has been reported for other bacteria including P. fluorescens, Pseudomonas pyrocinia and Burkholderia cepacia (Hammer et al., 1997). PRN-deficient derivatives of PA23 and PA23-63, called PA23-8 (PHZ−, PRN+) and PA23-63-1 (PHZ+, PRN−), respectively, were created as described in Materials and methods.

Production of antifungal metabolites in the wild-type and mutant strains

Strain PA23 produces the compounds PCA and 2-OH-PHZ, resulting in an orange phenotype (Zhang et al., 2006). The loss of orange color, together with the presence of a phzE-Tn insertion in PA23-63, suggested that this strain was not producing PHZ. Spectral analysis confirmed that PHZ compounds were not present in culture extracts of this mutant (Table 3). The increased antifungal activity led us to hypothesize that some other antifungal metabolite(s) was upregulated in PA23-63. Through HPLC analysis, we found that PRN production is increased over twofold in the PHZ− background (Table 3). However, the reverse was not true; wild-type levels of PHZ were produced by the PRN-deficient mutant PA23-8 (Table 3). As expected, no PRN was detected in the culture supernatants of the prnBC mutants PA23-8 and PA23-63-1 (Table 3).

### Table 2. Phenotypic characterization of Pseudomonas chlororaphis PA23 and mutants PA23-8 (PRN−), PA23-63 (PHZ−) and PA23-63-1 (PHZ− PRN−)

<table>
<thead>
<tr>
<th>Strain</th>
<th>Extracellular metabolite activity</th>
<th>Antifungal*</th>
<th>Protease*</th>
<th>Autoinducer*</th>
<th>HCN*</th>
<th>Lipase</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA23</td>
<td></td>
<td>5.8 (1.3)</td>
<td>19.3 (1.3)</td>
<td>12.4 (0.5)</td>
<td>+</td>
<td>+</td>
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<tr>
<td>PA23-8 (PRN−)</td>
<td></td>
<td>3.8 (0.7)</td>
<td>20.3 (1.5)</td>
<td>12.2 (0.3)</td>
<td>+</td>
<td>+</td>
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<tr>
<td>PA23-63 (PHZ−)</td>
<td></td>
<td>9.9 (0.5)</td>
<td>20.1 (1.4)</td>
<td>13.3 (1.3)</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>PA23-63-1 (PHZ− PRN−)</td>
<td></td>
<td>0 (0)</td>
<td>20.1 (1.1)</td>
<td>12.2 (1.0)</td>
<td>+</td>
<td>+</td>
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</tbody>
</table>

*Mean (SD) of the zones of activity (mm) obtained from six replicates.
^1* Determined using Cyantesmo paper.
^2* Significantly different from the wild type (P < 0.01).
^3* Significantly different from the wild type (P < 0.001).
^4* Not significantly different from the wild type.

**Statistical analysis**

An unpaired Student’s t-test was used for statistical analysis of antifungal, protease and autoinducer activity, PRN and PHZ levels, CV staining and viability counts.

**Table 3. PRN and PHZ production by Pseudomonas chlororaphis PA23 and mutants PA23-8 (PRN−), PA23-63 (PHZ−) and PA23-63-1 (PHZ− PRN−)**

<table>
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<tr>
<th>Strain</th>
<th>Antibiotic (µg mL−1)</th>
<th>PRN*</th>
<th>PCA*</th>
<th>2-OH-PCA*</th>
<th>Total PHZ*</th>
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<tr>
<td>PA23</td>
<td>1.37 (0.31)</td>
<td>28.5 (0.3)</td>
<td>4.9 (0.2)</td>
<td>33.7 (0.6)</td>
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<tr>
<td>PA23-8 (PRN−)</td>
<td>ND</td>
<td>29.2 (0.4)</td>
<td>4.7 (0.7)</td>
<td>33.4 (1.0)</td>
<td></td>
</tr>
<tr>
<td>PA23-63-1 (PHZ− PRN−)</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td></td>
</tr>
</tbody>
</table>

*Mean (SD) from three replicates.
^1* Significantly different from the wild type (P < 0.01).
^2* Not significantly different from the wild type.
ND, not detectable.
In addition to PHZ and PRN, PA23 produces a number of compounds believed to contribute to biocontrol, including HCN, protease, lipase and autoinducer molecules (Poritsanos et al., 2006). Accordingly, PA23, PA23-63 (phzE), PA23-8 (prnBC) and PA23-63-1 (phzE:prnBC) were analyzed for the production of these molecules. Using Cyantesmo paper, all three strains demonstrated the production of the volatile antibiotic HCN (Table 2). Analysis of an hcnA–lacZ translational fusion revealed no significant differences in expression between PA23-63 (10 200 ± 230 Miller units), PA23-63-1 (10 481 ± 318 Miller units), PA23-8 (10 889 ± 311 Miller units) and the PA23 wild-type strain (10 545 ± 655 Miller units). Similarly, no differences were detected in protease activity, lipase activity and autoinducer production among the strains (Table 2).

**Expression of phzA and prnA in the wild type and antibiotic-deficient mutants**

The increased production of PRN in PA23-63 led us to speculate that PHZ might be acting as a repressor of the _prn_ operon. Therefore, we generated a _prnA–lacZ_ transcriptional fusion (pPRNA–lacZ) to monitor expression of the PRN biosynthetic genes. We were particularly interested in two parameters: (1) the onset of _prnA_ gene expression and (2) the level of transcriptional activity. As illustrated in Fig. 1a, no difference in either the initiation of _prnA_ transcription or the level of expression was observed between PA23 and PA23-63. Similarly, _prnA_ expression in PA23-8 and PA23-63-1 was identical to that of the wild type (Fig. 1a). These findings indicate that PHZ does not have a repressive effect on _prn_ transcription. Moreover, the _prn_ operon is not subject to autoregulation. When we monitored _phz_ gene activity, the expression kinetics of the _phzA–lacZ_ fusion were nearly identical in all four strains (Fig. 1b). Therefore, we conclude that (1) PRN has no impact on _phz_ gene expression and (2) PHZ neither stimulates nor represses the PA23 _phz_ operon.

**Effect of PHZ and PRN production on growth rate and motility**

One of the determining factors for the success of a biocontrol agent in managing plant disease is how quickly it can achieve a sufficient population size to begin the production of pathogen-inhibiting compounds. To explore whether antibiotic production represents a significant metabolic burden for the bacteria, growth rate analysis was undertaken. No differences were detected in the growth rate between PA23, PA23-63, PA23-8 and PA23-63-1 in either rich or minimal media (data not shown). Motility is a trait that can also impact biocontrol (Lugtenberg et al., 2001); accordingly, the influence of PHZ and/or PRN deficiency on bacterial translocation was assessed. We previously reported that strain PA23 is capable of swimming and swarming motility (Poritsanos et al., 2006). Over the course of 72 h, PA23-63 (_phzE_), PA23-8 (_prnBC_) and PA23-63-1 (_phzE:prnBC_) were able to swim and swarm at the same rate as the wild type (data not shown), indicating that the production of these two antibiotics does not affect motility _in vitro._

**The effect of PHZ and PRN production on PA23 biofilm formation**

We used a highly reproducible 96-well plate assay to assess the ability of PA23, PA23-63, PA23-8 and PA23-63-1 to form biofilms. As illustrated in Fig. 2a, a statistically significant decrease in biofilm production was observed for the PHZ strains, compared with the wild-type and mutant PA23-8. Conversely, PRN was shown to have no impact on biofilm formation (Fig. 2a). Because CV stains biofilm matrix components as well as bacterial cells, we performed direct enumeration of the adherent cell population. The results of these analyses revealed the same outcome: PHZ, but not PRN, production leads to increased attached biomass (Fig. 2b).

**The contribution of PHZ and PRN to PA23 biocontrol of _S. sclerotiorum_ in the greenhouse**

The wild-type PA23, PA23-63 (_phzE_), PA23-8 (_prnBC_) and PA23-63-1 (_phzE:prnBC_) were evaluated for their ability to protect canola from stem rot disease caused by _S.
sclerotiorum. Two parameters were evaluated: (1) incidence of leaf infection and (2) stem rot disease severity. The PHZ-deficient strain PA23-63 was equivalent to the wild type in its ability to control fungal infection of stems and leaves and reduce disease severity (Fig. 3). For strain PA23-8, which produces the diffusible antibiotic PHZ, but no PRN, some biocontrol was observed, but it was significantly decreased from that of the wild type (Fig. 3). Compared with the disease control, no difference in the incidence of leaf infection (Fig. 3a) and only a modest decline in disease severity were observed for the PRN−/PHZ− double mutant PA23-63-1 (Fig 3b). Collectively, these findings indicate that PRN is the primary antibiotic underlying PA23 biocontrol of S. sclerotiorum infection in canola. Although PHZ can inhibit the fungus to some degree, it plays a more minor role in disease suppression.

Discussion

Sclerotinia sclerotiorum is the causative agent of Sclerotinia stem rot, one of the most important diseases of canola in Western Canada (Martens et al., 1994). Much of the research on S. sclerotiorum biocontrol is focused on hyperparasitism by fungal antagonists that degrade sclerotia in the soil (McLaren et al., 1996; Gerlagh et al., 1999). This approach is limited, however, by the fact that reducing the sclerotial soil load does not eliminate the risk of crop infection. Therefore, our group has focused on biocontrol of S. sclerotiorum through application of the antagonist directly at the site of pathogen entry, the canola petal. In greenhouse and field trials, P. chlororaphis strain PA23 has demonstrated excellent biocontrol of S. sclerotiorum (Savchuk & Fernando, 2004; Zhang, 2004; Fernando et al., 2007). This bacterium produces metabolites that are believed to inhibit mycelial growth (Poritsanos et al., 2006) and it also stimulates the production of plant defense enzymes (Fernando et al., 2007); therefore, fungal antagonism is multifactorial.

Pseudomonads that function as biocontrol agents frequently produce more than one antibiotic (Haas & Keel, 2007). Pseudomonas chlororaphis PA23 produces the PHZ derivatives PCA and 2-OH-PHZ, together with PRN (Zhang et al., 2006). PHZ production plays an essential role in the
disease-suppressive ability of many biocontrol agents. For example, phzB and phzH mutants of P. chlororaphis strain 1391, deficient in phenazine-1-carboxamide (PCN), were unable to control Fusarium oxysporum f. sp. radicis-lycopersici tomato foot and root rot (Chin-A-Woeng et al., 1998). Pseudomonas fluorescens 2–79 mutants no longer producing PCA exhibited dramatically decreased suppression of takeall disease of wheat (Thomashow & Weller, 1988). Similarly, a PHZ-deficient mutant of Pseudomonas aeruginosa, PNA1, exhibited reduced ability to suppress Fusarium wilt of chickpea or Pythium damping off of bean compared with the wild type (Anjaiah et al., 1998). In light of these findings, we were surprised to discover an increased zone of inhibition surrounding the PHZ-deficient mutant PA23-63 (Table 2).

The antifungal activity observed in vitro was supported by our greenhouse analysis, where PA23-63 was able to suppress stem rot of canola as well as the wild type (Fig. 3). We postulated that a second metabolite, most likely PRN, was upregulated in the phz− background, accounting for the increased antifungal activity in vitro. Balanced metabolite production has been observed for P. fluorescens CHA0, which produces the antibiotics 2,4-DAPG and PLT (Schnider-Keel et al., 2000; Baehler et al., 2005). Regulation of these two antibiotics occurs at the transcriptional level; 2,4-DAPG and PLT activate their own biosynthesis while at the same time repressing synthesis of the other (Schnider-Keel et al., 2000; Baehler et al., 2005). Strain CHA0 also produces PRN, but expression of this antibiotic had no impact on the 2,4-DAPG:PLT balance (Baehler et al., 2005). When we analyzed culture supernatants of the PHZ-deficient mutant PA23-63, we observed a twofold increase in PRN production (Table 3). This finding led us to explore whether PHZ is acting as a transcriptional repressor of the prn biosynthetic operon. Analysis of a prnA-lacZ TS fusion revealed no difference in the expression kinetics between the phzE mutant and the wild type (Fig. 1a). Therefore, a mechanism other than TS repression must account for the increased PRN production. As depicted in Fig. 4, both PHZ and PRN are produced via the shikimic acid pathway. PhzE is responsible for converting chorismic acid into 2-amino-2-deoxy-isochorismic acid (Pierson & Thomashow, 1992; Mavrodi et al., 1998; McDonald et al., 2001). In the PHZ locus, phzC lies upstream of phzE. The phzC gene encodes a deoxy-arabino-heptulosonate-7-phosphate (DAHP) synthase, which shunts C3 and C4 organic phosphates into the shikimic acid pathway (Wilson et al., 1998). Bacterial DAHP synthases are regulated at the transcriptional level and through feedback inhibition (Herrmann, 1983); therefore, PhzC is an important control point for regulating carbon flow into the shikimic acid pathway. The phzE mutation in PA23-63 prevents end-product formation and consequently feedback inhibition. As a result, PhzC continuously pumps carbon into the shikimic acid pathway, which leads to elevated PRN production by PA23-63.

Through our expression analysis, we discovered that PRN is not subject to autoregulation as there was no change in prn transcription in the PRN-deficient mutants (Fig. 1a). Examination of the PA23 prn upstream region revealed the presence of genes encoding a putative efflux pump; however, no regulatory genes were detected (data not shown). These findings are consistent with others who have reported an absence of pathway-specific regulators for the prn operons of P. fluorescens strains BL915 and CHA0 (Hammer et al., 1997; Kirner et al., 1998; van Pée & Ligon, 2000; Baehler et al., 2005). In terms of the phz operon, a deficiency in PRN and/or PHZ production had no impact on transcription, suggesting that these genes are neither autoregulated nor controlled by PRN. In P. chlororaphis strains 30–84 and PCL1391, PHZ gene expression is under QS control (Pierson et al., 1994; Chin-A-Woeng et al., 2001). We expect the same will hold true for PA23 because this bacterium produces AI
signal molecules (Table 2), and two genes with high homology to the \( \text{phzI} \) and \( \text{phzR} \) QS genes are located immediately upstream of the PA23 PHZ operon (data not shown).

It was previously demonstrated that strain PA23 is capable of forming a biofilm and cells within this adherent community are significantly more resistant to antibiotics (Poritsanos et al., 2006). When growing as a biofilm, the increased antimicrobial resistance as well as protection from environmental stresses, such as desiccation and UV radiation, likely facilitates PA23 survival in the environment. In the current study, the role of PHZ and PRN in PA23 biofilm formation was investigated. A static, microtiter biofilm assay was used to mimic the phyllosphere/rhizosphere, which can be best characterized as a no-flow or a low-flow environment, depending on the prevailing conditions. We discovered that PHZ production enhances biofilm formation in PA23 (Fig. 2). A role for PHZ in biofilm development has been reported previously by Maddula et al. (2008). Not only did PHZ production enhance \( P. \ Chlororaphis \) (\( aureofaciens \)) 30–84 biofilm production by amounts similar to those reported here, but altering the \( \text{PCA:2-OH-PCA} \) ratio affected the initial attachment, dispersal and the mature biofilm structure (Maddula et al., 2008). Our discovery that PRN does not affect biofilm development (Fig. 2) suggests that this trait is not linked to antibiotic production in general; rather it may be unique to PHZ. Recently, it has been proposed that antibiotics play multiple, concentration-dependent roles (see Davies et al., 2006; Fajardo & Martinez, 2008 for reviews). At lower concentrations, antibiotics act as signaling molecules capable of modulating gene expression, whereas at higher concentrations, they function as inhibitors. Consistent with this, Dietrich et al. (2006) demonstrated that the PHZ derivative pyocyanin can induce expression of a set of \( P. \ aeruginosa \) genes called the ‘PYO stimulon’, indicating that pyocyanin can function both as an antibiotic and a QS signal. In a number of bacterial species, a connection has been established between QS and biofilms (Irie & Parsek, 2008). It is possible that PHZ is functioning as a signaling molecule, and in this manner, affects \( P. \ Chlororaphis \) biofilm development.

In summary, our findings indicate that PRN is the primary antibiotic responsible for PA23 biocontrol of \( S. \ sclerotiorum \). Our next step is to elucidate the factors influencing PRN production, with the end goal of maximizing disease suppression in the field. Although PHZ production is not essential for \( Sclerotinia \) biocontrol, it leads to enhanced biofilm formation by PA23. Others have shown that PHZ-producing biocontrol strains are better able to colonize roots and persist in the wheat rhizosphere compared with PHZ” mutants (Mazzola et al., 1992). Whether PHZ contributes to PA23 persistence in the environment is yet to be established.

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