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Quorum-Sensing Signals and Quorum-Sensing Genes in *Burkholderia vietnamiensis*

Barbara-Ann Conway† and E. P. Greenberg*

Department of Microbiology, University of Iowa, Iowa City, Iowa 52242

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Acyl-homoserine lactone (acyl-HSL) quorum sensing is common to many *Proteobacteria* including a clinical isolate of *Burkholderia cepacia*. The *B. cepacia* isolate produces low levels of octanoyl-HSL. We have examined an environmental isolate of *Burkholderia vietnamiensis*. This isolate produced several acyl-HSLs. The most abundant species was decanoyl-HSL. Decanoyl-HSL in *B. vietnamiensis* cultures reached concentrations in excess of 20 μ M. We isolated a *B. vietnamiensis* DNA fragment containing a gene for the synthesis of decanoyl-HSL (*bviI*) and an open reading frame that codes for a putative signal receptor (*bviR*). A *B. vietnamiensis* *bviI* mutant did not produce detectable levels of decanoyl-HSL.

Many *Proteobacteria* produce *N*-acyl homoserine lactone (acyl-HSL) quorum-sensing signals. Examples include *Pseudomonas aeruginosa*, which uses *N*-butyryl-HSL (C_4 -HSL) and *N*-3-oxododecanoyl-HSL ($3OC_{12}$ -HSL) as signals to control the expression of dozens of genes, many of which encode virulence factors (24, 28, 47). *Ralstonia solanacearum*, a plant pathogen, uses *N*-octanoyl-HSL (C_8 -HSL) in quorum sensing, *Agrobacterium tumefaciens* uses *N*-3-oxooctanoyl-HSL ($3OC_8$ -HSL) to control conjugal transfer, and *Erwinia carotovora* uses *N*-3-oxohexanoyl-HSL ($3OC_6$ -HSL) to control antibiotic production and other factors (2, 4, 9, 25, 37). Generally, acyl-HSL quorum sensing involves a member of the LuxI family of signal generators and a member of the LuxR family of signal receptor transcription factors (for a recent review, see reference 3).

The genus *Burkholderia* has been a subject of recent attention. Species classifications in this genus remain in flux. Some members of the genus have emerged as serious opportunistic pathogens. For example, some strains of *Burkholderia cepacia* and perhaps other *Burkholderia* species can colonize the lungs of people with cystic fibrosis. In part because *B. cepacia* is resistant to antibiotic therapy, it can be a major health problem in colonized cystic fibrosis patients (10). The fact that *Burkholderia* spp. have multiple chromosomes and very plastic genomes (13) has also brought a research focus to the genus. Furthermore, some members of the genus are capable of degrading environmental pollutants and have been the subject of studies aimed at developing tools for bioremediation (29, 30, 31). For example, the subject of this study, *Burkholderia vietnamiensis* G4, was isolated from a holding pond at an industrial

waste treatment facility, and it can degrade trichloroethylene and toluene (18).

A previous report shows that a clinical isolate of *B. cepacia* makes low levels of C_8 -HSL in laboratory cultures and that quorum sensing is involved in the regulation of virulence factors including lipases, protease, and siderophores (14). Another strain of *B. cepacia* produces multiple acyl-HSLs, but these signals have not been identified, nor have their concentrations been determined (17). A recent study shows that *B. vietnamiensis* has at least two acyl-HSL generator and receptor gene pairs (16). Here we show that *B. vietnamiensis* G4 produces several acyl-HSLs and we define the genetic element responsible for the production of the most abundant of these acyl-HSLs. This study provides the groundwork for identification of quorum sensing-controlled genes in *B. vietnamiensis* and investigations of the role of quorum sensing in the degradation of environmental pollutants like trichloroethylene.

The bacterial strains and plasmids used in this study are described in Table 1. For acyl-HSL bioassays and for partial purification of *B. vietnamiensis*-produced acyl-HSLs, cultures were grown to an optical density at 600 nm of 1.6 to 2.0 (the late-logarithmic phase of growth) in Difco tryptic soy broth (pH 7.0) at 30°C with shaking (250 rpm). For ^{14}C labeling of acyl-HSLs, cultures were grown as above in basal salts medium (pH 7.0) with 20 mM lactate as a carbon source (8). For conjugation, *B. vietnamiensis* was grown in Luria-Bertani broth (L broth) (6). Antibiotics were included as appropriate. For *Escherichia coli*, the antibiotic concentrations were as follows: ampicillin, 100 μ g/ml; chloramphenicol, 35 μ g/ml; gentamicin, 10 μ g/ml; kanamycin, 35 μ g/ml; tetracycline, 10 μ g/ml. The antibiotic concentrations for *B. vietnamiensis* G4 were as follows: chloramphenicol, 25 to 35 μ g/ml; gentamicin, 10 μ g/ml; kanamycin, 35 μ g/ml. Plating was carried out on media solidified with 1.5 % agar. *E. coli* was grown in L broth or on Luria-Bertani agar using standard procedures (6).

To detect acyl-HSLs and to determine their relative abundance, we used a radiotracer procedure as described elsewhere

* Corresponding author. Mailing address: Department of Microbiology, University of Iowa, Iowa City, IA 52242. Phone: (319) 335-7775. Fax: (319) 335-7949. E-mail: epgreen@blue.weeg.uiowa.edu.

† Present address: Division of Infectious and Immunological Diseases, Department of Pediatrics, and the Canadian Bacterial Diseases Network, University of British Columbia, Vancouver, British Columbia, Canada V5Z 4H4.

TABLE 1. Bacterial strains and plasmids used in this study

Strain or plasmid	Relevant genotype or characteristics	Source or reference
<i>B. (cepacia) vietnamiensis</i>		
G4	Typed as <i>B. vietnamiensis</i> by J. LiPuma (personal communication)	15
FMT-05	<i>fabF</i> mutant derived from G4	This study
IMT-61	<i>bviI</i> mutant derived from G4	This study
RMT-14	<i>bviR</i> mutant derived from G4	This study
<i>E. coli</i>		
DH5 α	<i>supE44</i> Δ <i>lacU169</i> (ϕ 80 <i>lacZ</i> Δ M15) <i>hsdR17</i> <i>recA1</i> <i>endA1</i> <i>gyrA96</i> <i>thi-1</i> <i>relA1</i>	27
MG4	Δ (<i>argF-lac</i>) <i>U169</i> <i>zah-735::Tn 10</i> <i>recA56</i> <i>srl::Tn 10</i>	26
S17-1 (λ <i>pir</i>)	<i>recA</i> <i>thi</i> <i>pro</i> <i>hsdR</i>	32
VJS533	<i>rec</i> Δ <i>A56</i> <i>ara</i> Δ (<i>lac-proAB</i>)X111 <i>rpsL</i> (ϕ 80 <i>lacZ</i> Δ M15)	35
XL-1 Blue	<i>recA1</i> <i>endA1</i> <i>gyrA96</i> <i>thi-1</i> <i>hsdR17</i> <i>supE44</i> <i>relA1</i> <i>lac</i> [F' <i>proAB</i> <i>lacI</i> ^q Δ M15 Tn 10 (Tet ^r)]	Stratagene
<i>R. solanacearum</i>		
AW1-AI8	<i>solI8::SP</i>	2
Plasmids		
p395B	<i>sol</i> reporter; <i>aidA::lacZ</i> , Tc ^r	2
pBBR1MCS-2	Mobilizable broad-host-range cloning vector, Km ^r	11
pBBR1MCS-5	Mobilizable broad-host-range cloning vector, Gm ^r	11
pBCL5-2	8.5-kb <i>Hind</i> III fragment containing the <i>bviI</i> , <i>bviR</i> , and <i>fabF</i> -like gene from <i>B. vietnamiensis</i> G4 in pUC19	This study
pBCSFM	A 952-bp <i>Rsr</i> II fragment of the <i>fabF</i> -like gene from pBCL-2 was replaced with the pBBR1MCS-5 Gm ^r marker; the resulting DNA was digested with <i>Pst</i> I, treated with the Klenow fragment, and cloned into the <i>EcoRV</i> site in pSUP102	This study
pBCSIM	<i>bviI</i> , <i>fabF</i> -like gene <i>Pst</i> I fragment from pBCL5-2 treated with Klenow fragment and blunt-end cloned into <i>EcoRV</i> -digested pSUP102; a 570-bp <i>BsiW</i> <i>bviI</i> fragment replaced with a Gm ^r fragment PCR amplified from pBBR1MCS-5	This study
pBCSRM	4.4-kb <i>bviR</i> <i>bviI</i> <i>EcoRV</i> fragment from pBCL5-2 cloned into the <i>EcoRV</i> site of pSUP102, 1-kb Gm ^r marker from pBBR1MCS-5 cloned into unique <i>Sfi</i> I site	This study
pECP61.5	<i>rhl</i> reporter; <i>rhlR</i> <i>rhlA::lacZ</i> Ap ^r	24
pHV200I ⁻	<i>lux</i> reporter; <i>luxR</i> <i>luxI'</i> <i>CDABE</i> Ap ^r	22
pHV300I ⁻	<i>lux</i> reporter; <i>luxR</i> <i>luxI'</i> <i>CDABE</i> Cm ^r	7
pKDT17	<i>las</i> reporter; <i>lasB::lacZ</i> <i>plac-lasR</i> Ap ^r	21
pSUP102	<i>E. coli</i> -specific mobilizable vector Cm ^r Tc ^r	32

(33). Unless otherwise specified, *B. vietnamiensis* was grown in 5 ml of basal salts plus lactate medium. When the culture reached late logarithmic phase, 5.0 μ Ci of L-[1-¹⁴C]methionine was added. After a 10-min incubation, the culture was extracted twice with equal volumes of acidified ethyl acetate and the extract was evaporated to dryness. The radiolabeled acyl-HSLs were dissolved in 20% methanol and fractionated by C₁₈ reverse-phase high-performance liquid chromatography (HPLC). The amount of radiolabel in each fraction was determined by standard scintillation counting procedures. The retention times of the radioactive peaks corresponded to the retention times of synthetic acyl-HSL standards (Quorum Sciences Inc, Coralville, Iowa).

To confirm the results of the radiotracer analysis and to gain quantitative data about each of the acyl-HSLs produced by *B. vietnamiensis*, we measured the levels of acyl-HSLs in HPLC-fractionated culture fluid extracts by using bioassays. Four different bioassays were employed, each being selective for different acyl-HSLs. The *E. coli*(pHV200I⁻) assay shows greatest sensitivity to 3OC₆-HSL (22). The *E. coli* MG4(pKDT17) assay shows greatest sensitivity to 3OC₁₂-HSL (21, 22). The *E. coli*(pECP61.5) assay shows greatest sensitivity to C₄-HSL (20). The *Ralstonia solanacearum* AW1-AI8(p395B) assay shows greatest sensitivity to C₈-HSL (2). The material analyzed by

the bioassays was obtained as follows: cells were removed from the fluid of a 3-liter culture by centrifugation, and the culture fluid was extracted twice with equal volumes of acidified ethyl acetate. The extract was concentrated by rotary evaporation at 40 to 45°C and fractionated by C₁₈ HPLC. Samples from each fraction eluted in HPLC were analyzed by the bioassays. Standard curves with synthetic acyl-HSLs were generated, and the amounts of acyl-HSLs in HPLC fractions were determined by comparison to the standard curves.

To confirm assignments based on HPLC retention times, fractions constituting peaks were pooled, concentrated by rotary evaporation, and subjected to further separation by HPLC in water containing methanol at a percentage of 15% lower than that in which they were eluted in the gradient. Active fractions were concentrated and analyzed by gas chromatography-mass spectrometry as described previously (23).

DNA manipulations were done by standard procedures (1, 27). For cloning the *B. vietnamiensis* quorum-sensing genes, an unsized library of *Hind*III chromosomal DNA fragments was constructed in pUC19 (38). The library was used to transform *E. coli* DH5 α (pHV300I⁻). Ampicillin-resistant, luminescent colonies were selected for further study. DNA sequencing was performed at the University of Iowa DNA Facility.

For insertional mutagenesis, genes were cloned in pSUP102

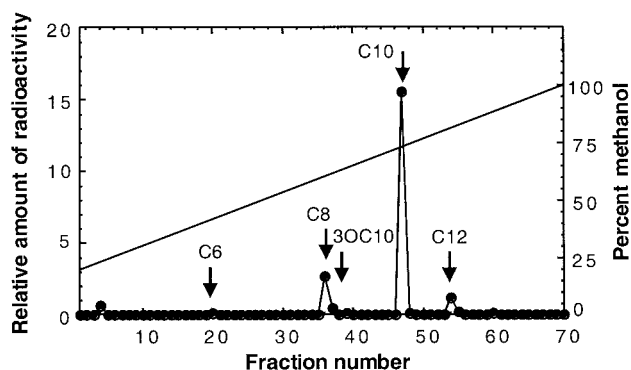


FIG. 1. HPLC analysis of acyl-HSLs produced by *B. vietnamiensis* G4. Acyl-HSLs were labeled with ^{14}C , extracted from culture fluid, and fractionated by HPLC. Radioactivity was measured to identify peaks containing ^{14}C -labeled acyl-HSLs. As indicated by the arrows, synthetic acyl-HSL standards were eluted as follows: C_6 -HSL, fraction 20; C_8 -HSL, fraction 36; C_{10} -HSL, fraction 47; 3OC_{10} -HSL, fraction 39; C_{12} -HSL, fraction 54. The methanol concentration of the gradient is shown by the solid line.

and a gentamicin cassette from pBBR1MCS-5 was inserted in the cloned gene (Table 1). The pSUP102 derivatives were transferred from *E. coli* S17-1 (λpir) into *B. vietnamiensis* by conjugation using the following procedure: donors (mid-log phase) and recipients (stationary phase) were grown in L broth with appropriate antibiotics. Cells were mixed at a donor-to-recipient ratio of 4:1, washed in phosphate-buffered saline (pH 7.4), and suspended in a small volume of phosphate-buffered saline. Mating mixtures were spotted on Luria-Bertani (LB) agar and grown at 30°C overnight. Transconjugants were obtained by selection on Simmons citrate agar (SCA) (6) containing gentamicin. Screening transconjugants for chloramphenicol sensitivity allowed us to obtain insertion mutants. The constructs were confirmed by PCR and Southern blotting.

Chrome azurol S assays were used to measure siderophore activity (28). Egg yolk agar assays were used to estimate bacterial production of lecithinase (6). Difco brain heart infusion agar assays were used to measure extracellular protease activity (34).

To gain information on whether *B. vietnamiensis* produced acyl-HSLs and, if so, in what sort of relative abundance, we incubated cultures with carboxy-labeled [^{14}C]methionine. The cell-free culture fluid was extracted with ethyl acetate and fractionated by HPLC. As described previously, the amount of radiolabel in fractions that comigrate with known acyl-HSLs corresponds to the relative abundance of that acyl-HSL (33). There were three main peaks of radioactivity (Fig. 1). The largest peak corresponded to C_{10} -HSL, the next largest peak corresponded to C_8 -HSL, and the third peak comigrated with C_{12} -HSL.

To confirm that the radioactive peaks in the experiments described above represented acyl-HSLs and to gain information about the concentrations of acyl-HSLs in culture fluid, we performed quantitative bioassays on HPLC fractions of an ethyl acetate extract of 3 liters of fluid from an early-stationary-phase culture. We identified C_6 -, C_8 -, C_{10} -, and C_{12} -HSLs, and we also identified 3OC_{10} -HSL. The concentrations of these molecules in the culture fluid were $0.12\ \mu\text{M}$ C_6 -HSL, $2.2\ \mu\text{M}$

C_8 -HSL, $22.4\ \mu\text{M}$ C_{10} -HSL, $0.003\ \mu\text{M}$ 3OC_{10} -HSL, and $0.65\ \mu\text{M}$ C_{12} -HSL. As expected, gas chromatography-mass spectrometry of the three most abundant peaks showed spectra identical to the spectra of synthetic C_{10} -, C_8 -, and C_{12} -HSLs (data not shown).

We screened a library of *B. vietnamiensis* genes in *E. coli* containing a reporter plasmid, pHV300I $^-$. This plasmid contains the acyl-HSL-responsive *Vibrio fischeri lux* gene cluster and does not contain a functional acyl-HSL synthase gene. We obtained a luminous strain of *E. coli* that contained a plasmid (pBCL5-2) with an 8.5-kb insert of *B. vietnamiensis* DNA. In *E. coli*, pBCL5-2 directed the synthesis of C_6 -, C_8 -, C_{10} -, and C_{12} -HSL. As in *B. vietnamiensis*, C_{10} -HSL was the most abundant of the acyl-HSLs. The *B. vietnamiensis* DNA in pBCL5-2 was sequenced, and an analysis revealed a gene that coded for a LuxI homolog and a divergently transcribed gene coding for a LuxR homolog with a rather large 1.2-kb intergenic region.

The gene coding for the LuxI homolog was 660 bp, and it was identical to the recently described *bviI* (16). The gene coding for the LuxR homolog was 714 bp and was identical to *bviR* (16). There was a gene coding for a putative transport protein downstream of *bviR* and a gene showing greatest similarity to *fabF*-like genes from *P. aeruginosa* and *A. tumefaciens* (BLAST scores of 10^{-145}) downstream of *bviI*. The intergenic region contained an assortment of small open reading frames, the longest of which was 384 bp. None of these open reading frames showed significant similarity to known gene products. It is possible that the intergenic region codes for a small regulatory RNA or protein.

We analyzed acyl-HSL production in the *B. vietnamiensis* *bviR*, *bviI*, and *fabF*-like gene mutants. As monitored by the radiotracer assay, the *bviI* mutant did not make detectable levels of any acyl-HSL except C_8 -HSL, which was present in trace amounts [$<10\ \text{nM}$, compared to $2,200\ \text{nM}$ C_8 -HSL in the parent as measured by the *E. coli*(pHV200I $^-$) bioassay]. This, together with the analysis of acyl-HSL production by *bviI*-containing *E. coli* (see above), indicates that *bviI* codes for an acyl-HSL synthase that is responsible for the production of all of the abundant acyl-HSLs. The presence of traces of octanoyl-HSL in cultures of the *bviI* mutant suggests that there is another poorly expressed or poorly active acyl-HSL synthase, one that directs the synthesis of C_8 -HSL, the same signal as that produced by CepI in *B. cepacia*. This is consistent with a recent report by Lutter et al. (16). The parent *B. vietnamiensis* produces much more C_8 -HSL than the mutant. One explanation is that BviI is responsible for the majority of the C_8 -HSL produced in the parent and the hypothetical second acyl-HSL synthase contributes very little to the total C_8 -HSL level.

The acyl-HSL production pattern of the *bviR* mutant was essentially identical to that of the *bviI* mutant. We interpret this to indicate that, like many other acyl-HSL synthesis and response systems, *bviI* is positively autoregulated by the acyl-HSL signal it produces and the cognate R protein (5). Because of its proximity to *bviR-bviI*, we wondered if the *fabF*-like gene was involved in generation of acyl-ACPs for *bviI* specifically. To investigate this, we generated a null mutation in the *fabF*-like gene. The strain with the mutation in the *fabF*-like gene grew somewhat slower than the parent. That it could grow at all indicates that there are other fatty acid synthesis genes in *B. vietnamiensis* that can fulfill the role played by this gene. Al-

though the absolute levels were somewhat reduced (two- to threefold lower), the mutant produced acyl-HSLs in the same relative abundance as the parent did. Therefore, we conclude that this *fabF*-like gene is not involved in the specificity of quorum-sensing signal generation.

BviR and BviI did not appear to regulate factors controlled by quorum sensing in *B. cepacia*. Previous reports showed that quorum sensing in *B. cepacia* controlled siderophore, protease, and lipase production (14, 17). Therefore, we examined the influence of the BviR-BviI system on these factors in *B. vietnamiensis*. Neither the parent, *B. vietnamiensis* G4, nor the *bviR* or *bviI* mutants produced detectable levels of protease or lipase. All three strains produced siderophores, as measured by the chrome azurol S assay, and the levels of the siderophores produced were indistinguishable. Presumably, the genes regulated by quorum sensing in *B. vietnamiensis* are different from those regulated by quorum sensing in *B. cepacia*. In fact, *B. vietnamiensis* produces an antibiotic, which appears to be under quorum-sensing control (K. Lee, personal communication).

In summary we have shown that *B. vietnamiensis* produces detectable levels of several acyl-HSLs, the most abundant of which is C₁₀-HSL. This is present in 10-fold excess over the second most abundant acyl-HSL, C₈-HSL. Other bacteria make acyl-HSLs with acyl side chains ranging from 4 to 14 carbons. To our knowledge, this is the first report of a bacterium that makes predominantly C₁₀-HSL. Other investigators have used gas-chromatography-mass spectrometry and have obtained similar results with respect to acyl-HSL production by *B. vietnamiensis* G4 (Lee, personal communication). The *B. cepacia* acyl-HSL is C₈-HSL, and cultures of the one studied strain of *B. cepacia* make <0.01% of the total acyl-HSLs made by *B. vietnamiensis* G4 (14). Most acyl-HSL-producing bacteria make micromolar quantities of acyl-HSLs, as does *B. vietnamiensis* G₄. The *bviI* gene directs *E. coli* to produce *B. vietnamiensis* acyl-HSLs, and a *B. vietnamiensis* *bviI* mutation results in the loss of C₁₀-HSL production. The *bviI* mutant produced trace amounts of C₈-HSLs. This is consistent with the finding of a *bviI* homolog in *B. vietnamiensis* (16).

Work by other investigators suggests that extracellular lipase, protease, and siderophore production may be controlled by quorum sensing in some *B. cepacia* clinical isolates (14, 17). We found that *B. vietnamiensis* G4 did not produce extracellular proteases or lipases that were comparable to the *B. cepacia* enzymes and that siderophore production did not seem to be controlled by quorum sensing. Our results are consistent with those obtained by K. Lee and colleagues (personal communication). Further studies are required to elucidate the targets of quorum-sensing control in *B. vietnamiensis* G4. There is a suggestion that antibiotic synthesis in *B. vietnamiensis* G4 may be controlled by quorum sensing (Lee, personal communication). The availability of a *bviI* mutant strain and the knowledge that C₁₀-HSL is the main acyl-HSL should allow the development of screens of quorum-sensing-controlled genes in *B. vietnamiensis* G4.

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REFERENCES

1. Ausubel, F. M., R. Brent, R. E. Kingston, D. D. Moore, J. G. Seidman, J. A. Smith, and K. Struhl (ed.). 1989. Current protocols in molecular biology, vol. 1. John Wiley & Sons, Inc., New York, N.Y.
2. Flavler, A. B., L. M. Ganova-Raeva, M. A. Schell, and T. P. Denny. 1997. Hierarchical autoinduction in *Ralstonia solanacearum*: control of acyl-homoserine lactone production by a novel autoregulatory system responsive to 3-hydropalmitic acid methyl ester. *J. Bacteriol.* **179**:7089–7097.
3. Fuqua, C., and E. P. Greenberg. 1998. Self-perception in bacteria: quorum sensing with acylated homoserine lactones. *Curr. Opin. Microbiol.* **1**:183–189.
4. Fuqua, W. C., and S. C. Winans. 1994. A LuxR-LuxI type regulatory system activates *Agrobacterium* Ti plasmid conjugal transfer in the presence of a plant tumor metabolite. *J. Bacteriol.* **176**:2796–2806.
5. Fuqua, W. C., S. C. Winans, and E. P. Greenberg. 1994. Quorum sensing in bacteria: the LuxR-LuxI family of cell density-responsive transcriptional regulators. *J. Bacteriol.* **176**:269–275.
6. Gerhardt, P., R. G. E. Murray, W. A. Wood, and N. R. Krieg (ed.). 1994. Methods for general and molecular bacteriology. American Society for Microbiology, Washington, D.C.
7. Gray, K. M., and E. P. Greenberg. 1992. Physical and functional maps of the luminescence gene cluster in an autoinducer-deficient *Vibrio fischeri* strain isolated from a squid light organ. *J. Bacteriol.* **174**:4384–4390.
8. Harelund, W., R. L. Crawford, P. J. Chapman, and S. Dagley. 1975. Metabolic function and properties of 4-hydroxyphenylacetic acid 1-hydroxylase from *Pseudomonas acidovorans*. *J. Bacteriol.* **121**:272–285.
9. Hwang, I. Y., P. L. Li, L. H. Zhang, K. R. Piper, D. M. Cook, M. E. Tate, and S. K. Farrand. 1994. TraI, a LuxI homologue, is responsible for production of conjugation factor, the Ti plasmid *N*-acylhomoserine lactone autoinducer. *Proc. Natl. Acad. Sci. USA* **91**:4639–4643.
10. Isles, A., I. Macluskay, M. Corey, R. Gold, C. Prober, P. Fleming, and H. Levison. 1984. *Pseudomonas cepacia* infection in cystic fibrosis; an emerging problem. *J. Pediatr.* **104**:206–210.
11. Kovach, M. E., P. H. Elzer, D. S. Hill, G. T. Robertson, M. A. Farris, R. M. Roop, Jr., and K. M. Peterson. 1995. Four new derivatives of the broad-host-range cloning vector pBBR1MCS, carrying different antibiotic-resistance cassettes. *Gene* **166**:175–176.
12. Latifi, A., M. K. Winson, M. Foglino, B. W. Bycroft, G. S. Stewart, A. Lazdunski, and P. Williams. 1995. Multiple homologues of LuxR and LuxI control expression of virulence determinants and secondary metabolites through quorum sensing in *Pseudomonas aeruginosa* PAO1. *Mol. Microbiol.* **17**:333–343.
13. Lessie, T. G., W. Hendrickson, B. D. Manning, and R. Devereux. 1996. Genomic complexity and plasticity of *Burkholderia cepacia*. *FEMS Microbiol. Lett.* **144**:117–128.
14. Lewenza, S., B. Conway, E. P. Greenberg, and P. A. Sokol. 1999. Quorum sensing in *Burkholderia cepacia*: identification of the LuxRI homologs CepRI. *J. Bacteriol.* **181**:748–756.
15. Lipuma, J. J., S. E. Dasen, D. W. Nielson, S. E. Stern, and T. L. Stull. 1990. Person-to-person transmission of *Pseudomonas cepacia* between patients with cystic fibrosis. *Lancet* **336**:527–532.
16. Lutter, E., S. Lewenza, J. J. Dennis, M. B. Visser, and P. A. Sokol. 2001. Distribution of quorum-sensing genes in the *Burkholderia cepacia* complex. *Infect. Immun.* **69**:4661–4666.
17. McKenney, D., K. E. Brown, and D. G. Allison. 1995. Influence of *Pseudomonas aeruginosa* exoproducts on virulence factor production in *Burkholderia cepacia*: evidence of interspecies communication. *J. Bacteriol.* **177**:6989–6992.
18. Nelson, M. J. K., S. O. Montgomery, E. J. O'Neill, and P. H. Pritchard. 1986. Aerobic metabolism of trichloroethylene by a bacterial isolate. *Appl. Environ. Microbiol.* **52**:383–384.
19. Ochsner, U. A., A. K. Koch, A. Fiechter, and J. Reiser. 1994. Isolation and characterization of a regulatory gene affecting rhamnolipid biosurfactant synthesis in *Pseudomonas aeruginosa*. *J. Bacteriol.* **176**:2044–2054.
20. Parsek, M. R., A. L. Schaefer, and E. P. Greenberg. 1997. Analysis of random and site-directed mutations in *rhlI*, a *Pseudomonas aeruginosa* gene encoding an acylhomoserine lactone synthase. *Mol. Microbiol.* **26**:301–310.
21. Passador, L., J. M. Cook, M. J. Gambello, L. Rust, and B. H. Iglewski. 1993. Expression of *Pseudomonas aeruginosa* virulence genes requires cell-to-cell communication. *Science* **260**:1127–1130.
22. Pearson, J. P., K. M. Gray, L. Passador, K. D. Tucker, A. Eberhard, B. H. Iglewski, and E. P. Greenberg. 1994. Structure of the autoinducer required for the expression of *Pseudomonas aeruginosa* virulence genes. *Proc. Natl. Acad. Sci. USA* **91**:197–201.
23. Pearson, J. P., L. Passador, B. H. Iglewski, and E. P. Greenberg. 1995. A second *N*-acylhomoserine lactone signal produced by *Pseudomonas aeruginosa*. *Proc. Natl. Acad. Sci. USA* **92**:1490–1494.
24. Pesci, E. C., J. P. Pearson, P. C. Seed, and B. H. Iglewski. 1997. Regulation

- of *las* and *rhl* quorum sensing in *Pseudomonas aeruginosa*. *J. Bacteriol.* **179**:3127–3132.
25. Pirhonen, M., D. Flego, R. Heikinheimo, and E. T. Palva. 1993. A small diffusible signal molecule is responsible for the global control of virulence and exoenzyme production in the plant pathogen *Erwinia carotovora*. *EMBO J.* **12**:2467–2476.
 26. Ralling, G., S. Bodrug, and T. Linn. 1985. Growth rate-dependent regulation of RNA polymerase synthesis in *Escherichia coli*. *Mol. Gen. Genet.* **201**:379–386.
 27. Sambrook, J., E. F. Fritsch, and T. Maniatis. 1989. *Molecular cloning: a laboratory manual*, 2nd ed. Cold Spring Harbor Laboratory Press, Cold Spring Harbor, N.Y.
 28. Schwyn, B., and J. B. Neilands. 1987. Universal chemical assay for the detection and determination of siderophores. *Anal. Biochem.* **160**:47–56.
 29. Shields, M. S., S. O. Montgomery, P. J. Chapman, S. M. Cuskey, and P. H. Pritchard. 1989. Novel pathway of toluene catabolism in the trichloroethylene-degrading bacterium G4. *Appl. Environ. Microbiol.* **55**:1624–1629.
 30. Shields, M. S., and M. J. Reagin. 1992. Selection of a *Pseudomonas cepacia* strain constitutive for the degradation of trichloroethylene. *Appl. Environ. Microbiol.* **58**:3977–3983.
 31. Shields, M. S., M. J. Reagin, R. R. Gerger, R. Campbell, and C. Somerville. 1995. TOM, a new aromatic degradative plasmid from *Burkholderia (Pseudomonas) cepacia* G4. *Appl. Environ. Microbiol.* **61**:1352–1356.
 32. Simon, R., M. O'Connell, M. Labes, and A. Pühler. 1986. Plasmid vectors for the genetic analysis and manipulation of Rhizobia and other Gram-negative bacteria. *Methods Enzymol.* **118**:640–659.
 33. Singh, P. K., A. L. Schaefer, M. R. Parsek, T. O. Moninger, M. J. Welsh, and E. P. Greenberg. 2000. Quorum sensing signals indicate that cystic fibrosis lungs are infected with bacterial biofilms. *Nature* **407**:762–764.
 34. Sokol, P. A., D. E. Ohman and B. H. Iglewski. 1979. A more sensitive plate assay for detection of protease production by *Pseudomonas aeruginosa*. *J. Clin. Microbiol.* **9**:538–540.
 35. Stewart, V., and J. V. Parales, Jr. 1988. Identification and expression of genes *narL* and *narX* of the *nar* (nitrate reductase) locus in *Escherichia coli* K-12. *J. Bacteriol.* **170**:1589–1597.
 36. Whiteley, M., K. M. Lee, and E. P. Greenberg. 1999. Identification of genes controlled by quorum sensing in *Pseudomonas aeruginosa*. *Proc. Natl. Acad. Sci. USA* **96**:13904–13909.
 37. Williams, P., N. J. Bainton, S. Swift, S. R. Chhabra, M. K. Winson, G. S. A. B. Stewart, G. P. C. Salmond, and B. W. Bycroft. 1992. Small molecule-mediated density-dependent control of expression in prokaryotes: bioluminescence and the biosynthesis of carbapenem antibiotics. *FEMS Microbiol. Lett.* **100**:161–168.
 38. Yannisch-Perron, C., J. Vieira, and J. Messing. 1985. Improved M13 phage cloning vectors and host strains: nucleotide sequences of the M13mp18 and pUC19 vectors. *Gene* **33**:103–119.