PrcR, a PucR-type transcriptional activator, is essential for proline utilization and mediates proline-responsive expression of the proline utilization operon putBCP in Bacillus subtilis

Shih-Chien Huang, Ta-Hui Lin and Gwo-Chyuan Shaw

The soil bacterium Bacillus subtilis can utilize exogenous proline as a sole nitrogen or carbon source. The proline-inducible putBCP (formerly ycgMNO) operon encodes proteins responsible for proline uptake and two-step oxidation of proline to glutamate. We now report that a gene (formerly ycgP, now designated prcR) located downstream of the putBCP operon is essential for B. subtilis cells to utilize proline as a sole nitrogen or carbon source. Disruption of the prcR gene also abolished proline induction of putB transcription. prcR expression is not subject to autoregulation and proline induction. The PrcR protein shows no significant amino acid sequence similarity to the known transcriptional activators for proline utilization genes of other bacteria, but it does show partial amino acid sequence similarity to the transcriptional regulator PucR for the pyruvate degradation genes of B. subtilis. PrcR orthologues of unknown function are present in some other Bacillus species. Primer-extension analysis suggests that both putB and prcR are transcribed by a σ76-dependent promoter. Deletion and mutation analysis revealed that an inverted repeat (5′-TGTTGG-N5-CCACAA-3′) centred at position −76 relative to the transcriptional initiation site of putB is essential for putB expression. Electrophoretic mobility shift assays showed that the purified His-tagged PrcR was capable of binding specifically to this inverted repeat. Altogether, these results suggest that PrcR is a PucR-type transcriptional activator that mediates expression of the B. subtilis putBCP operon in response to proline availability.

However, the regulatory mechanism for proline induction of putBCP expression in B. subtilis remains unknown.

In Escherichia coli, Salmonella typhimurium and some other bacteria, the putA gene encodes a bifunctional proline utilization protein with both the proline dehydrogenase and Δ¹-pyrroline-5-carboxylate dehydrogenase activities for the two-step oxidation of proline to glutamate (Menzel & Roth, 1981; Lee et al., 2003; Tanner, 2008). In some of these bacteria, the PutA protein can also act as a transcriptional repressor for controlling expression of the putA and putP genes. PutA switches between its roles as a transcriptional repressor and as a catabolic enzyme in response to proline availability (Ostrovsky de Spicer & Maloy, 1993; Muro-Pastor et al., 1997; Soto et al., 2000; Gu et al., 2004; Commichau & Stülke, 2008). In Agrobacterium tumefaciens, Rhodobacter capsulatus and Vibrio vulnificus, expression of the putA gene is activated by the Lrp/AsnC-type transcriptional activator PutR in response to exogenous proline (Keuntje et al., 1995; Cho & Winans, 1996; Lee & Choi, 2006). In Pseudomonas aeruginosa PAO1, the putAP operon is positively regulated by the ArcC/XylS-type transcriptional activator PruR (Nakada et al., 2002). In this study, we have

Abbreviations: EMSA, electrophoretic mobility shift assay; RT-qPCR, real-time quantitative PCR.

A supplementary table, showing the oligonucleotide primers used in this study, is available with the online version of this paper.

INTRODUCTION

The soil bacterium Bacillus subtilis can use exogenous proline as a sole nitrogen or carbon source. The gene products of the putBCP (formerly ycgMNO) operon are responsible for proline uptake and two-step oxidation of proline to glutamate (Bremer, 2002). The putB, putC and putP genes encode proline dehydrogenase, Δ¹-pyrroline-5-carboxylate dehydrogenase, and a proline uptake protein, respectively. Disruption of the putBCP operon abolishes the ability of B. subtilis cells to use exogenous proline as a sole nitrogen or carbon source (Bremer, 2002). Proline can also serve as a source of glutamate for B. subtilis mutants deficient in glutamate synthase, since proline can be metabolized to glutamate by PutB and PutC (Atkinson et al., 1990). Exogenous proline can induce the expression of the putBCP operon and proline dehydrogenase activity in B. subtilis (Atkinson et al., 1990; Bremer, 2002).
found that the prcR gene is essential for B. subtilis cells to utilize proline as a sole nitrogen or carbon source. PrcR shows no significant amino acid sequence similarity to the above-mentioned transcriptional regulators of proline utilization genes from various bacteria. We present evidence that the above-mentioned transcriptional regulators of proline utilization genes from various bacteria show no significant amino acid sequence similarity to the prcR gene.

**METHODS**

**Bacterial strains and growth conditions.** The bacterial strains and plasmids used in this study are listed in Table 1. The oligonucleotide primers are listed in Supplementary Table S1. E. coli and B. subtilis cells were grown in Luria–Bertani (LB) medium (Sambrook & Russell, 2001) or in modified M9 minimal medium, which consisted of 0.05% NaCl, 0.05% MgSO4, 0.1% NH4Cl, 0.0001% FeSO4, 0.0002% MnSO4, 0.002% CaCl2, 0.3% KH2PO4, 1.7% Na2HPO4, 12H2O, 1% glucose, unless specified otherwise. Tryptophan was supplemented at a final concentration of 50 μg ml⁻¹. Antibiotics were used at the following concentrations (μg ml⁻¹): ampicillin, 100; chloramphenicol, 5; erythromycin, 1.

**Plasmid construction.** To construct plasmid pGS2047, a DNA fragment carrying an internal region close to the N terminus of the prcR gene was amplified by PCR and cloned between HinI and BamHI sites was amplified by PCR and cloned into pDL. To construct plasmid pGS2135, which carries a 4 bp mutation in the right arm of the inverted repeat (with sequence alteration from CCAC to GGTG), a two-step PCR method (Ishizaki et al., 1988) was used for site-directed mutagenesis. The PCR-amplified DNA fragment was restricted with EcoRI plus BamHI and then cloned into pDL. To construct plasmid pGS2111, which can overproduce His-tagged PrcR, a DNA fragment carrying the coding sequence of prcR and flanked by BamHI and HindIII sites was amplified by PCR and cloned between BamHI and HindIII sites of pQE80 (Qiagen). The correctness of sequences of PCR-amplified DNA fragments was verified by DNA sequencing.

**Disruption of the chromosomal prcR gene.** Disruption of the chromosomal prcR gene by integration of plasmid pRN5101-derived pGS2047 through a Campbell-like single-crossover recombination was performed as described previously (Fedhila et al., 2002). The integration plasmid was introduced into B. subtilis cells by the protoplast method (Chang & Cohen, 1979). The correctness of integrants was verified by PCR.

**Construction of strains with a bgaB fusion integrated at the amyE locus.** Competent cells of B. subtilis were prepared and transformed with pGS2111, which contains a DNA fragment carrying a mutation in the inverted repeat of the regulatory region of prcR and flanked by BamHI and HindIII sites of pQE80. The correctness of the amplified DNA fragments was verified by DNA sequencing.

**Table 1. Strains and plasmids used in this study**

<table>
<thead>
<tr>
<th>Strain or plasmid</th>
<th>Genotype or description</th>
<th>Source or reference</th>
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<tbody>
<tr>
<td><strong>E. coli strain</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JM109</td>
<td>recA1 supE44 endA1 hsdR17 gyrA96 relA1 thi Δ(lac-proAB) F' [traD36 proAB + lacIq lacZAM15]</td>
<td>Takara</td>
</tr>
<tr>
<td><strong>B. subtilis strains</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>168</td>
<td>trpC2</td>
<td>Laboratory stock</td>
</tr>
<tr>
<td>BM1657</td>
<td>trpC2 amyE::pGS2090 [CmR]</td>
<td>This work</td>
</tr>
<tr>
<td>BM1660</td>
<td>trpC2 amyE::pGS2090 prcR::pGS2047 [CmR EmR]</td>
<td>This work</td>
</tr>
<tr>
<td>BM1663</td>
<td>trpC2 prcR::pGS2047 [EmR]</td>
<td>This work</td>
</tr>
<tr>
<td>BM1667</td>
<td>trpC2 amyE::pGS2097 [CmR]</td>
<td>This work</td>
</tr>
<tr>
<td>BM1668</td>
<td>trpC2 amyE::pGS2098 [CmR]</td>
<td>This work</td>
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<tr>
<td>BM1704</td>
<td>trpC2 amyE::pGS2135 [CmR]</td>
<td>This work</td>
</tr>
<tr>
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<td>trpC2 amyE::pGS2140 [CmR]</td>
<td>This work</td>
</tr>
<tr>
<td>BM1736</td>
<td>trpC2 amyE::pGS2140 prcR::pGS2047 [CmR EmR]</td>
<td>This work</td>
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<td><strong>Plasmids</strong></td>
<td></td>
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<tr>
<td>pQE80</td>
<td>Expression vector for producing His-tagged proteins, ApR</td>
<td>Qiagen</td>
</tr>
<tr>
<td>pGS2047</td>
<td>pRN5101 carrying an internal region close to the N terminus of prcR; prcR disruption plasmid</td>
<td>This work</td>
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<td>pGS2090</td>
<td>pDL carrying the regulatory region of putB</td>
<td>This work</td>
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<tr>
<td>pGS2097</td>
<td>pDL containing the inverted repeat in the regulatory region of putB</td>
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<tr>
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<td>pDL containing half of the inverted repeat in the regulatory region of putB</td>
<td>This work</td>
</tr>
<tr>
<td>pGS2111</td>
<td>pQE80 expressing the prcR gene</td>
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</tr>
<tr>
<td>pGS2135</td>
<td>pDL carrying a mutation in the inverted repeat of the regulatory region of putB</td>
<td>This work</td>
</tr>
<tr>
<td>pGS2140</td>
<td>pDL carrying the regulatory region of prcR</td>
<td>This work</td>
</tr>
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</table>
transformed by pDL-derived integrative plasmids, as described elsewhere (Contente & Dubnau, 1979). Transformants were selected by growth on chloramphenicol-containing LB agar plates. Correct integrants were screened by a method described elsewhere (O’Kane et al., 1986).

RNA isolation, cDNA synthesis and primer-extension analysis.
Total RNA was isolated according to a procedure described elsewhere (Zuber & Losick, 1983). Isolated RNA was treated with RQ1 RNase-free DNase (Promega) at 37 °C for 30 min. The reaction solution was then incubated with RQ1 stop buffer at 65 °C for 10 min to inactivate DNase. AMV reverse transcriptase (Promega) and random hexamer were used to synthesize cDNA for RT-PCR and real-time quantitative PCR (RT-qPCR) according to the instructions of the manufacturer. Determination of the transcriptional initiation sites of putB and prcR by primer-extension was carried out as described elsewhere (Inoue & Cech, 1985), using primers A251 and A364, respectively.

RT-PCR and RT-qPCR. RT-PCR and RT-qPCR were performed with the above-mentioned synthesized cDNA as the template and a putB-specific PCR primer pair (A365 and A368) plus a 16S rRNA-specific PCR primer pair (A366 and A367). RT-qPCR was carried out with the StepOnePlus Real-Time PCR System (Applied Biosystems) using the SYBR Green PCR Master Mix kit (Applied Biosystems) according to the instructions of the manufacturer. The 16S rRNA level was used as an internal control to normalize the putB mRNA level. A non-template negative control in which cDNA was replaced with water was also included in each PCR run.

Overproduction and purification of the His-tagged PrcR protein. E. coli JM109 cells bearing plasmid pGS2111 were grown in LB medium. After the OD600 had reached 0.5, IPTG was added at a final concentration of 0.3 mM and incubation was continued for 2 h. After harvesting cells by centrifugation and disrupting resuspended cells by sonication on ice, the disrupted cells were subjected to centrifugation at 15 000 g for 10 min. The resulting supernatant was used for the purification of His-tagged PrcR protein by affinity chromatography on a nickel-nitrilotriacetic acid (Ni-NTA) agarose column according to the instructions of the manufacturer (Qiagen).

Electrophoretic mobility shift assays (EMSAs). EMSAs used to determine the binding of PrcR to DNA were carried out as described elsewhere (Fried & Crothers, 1981). Binding solutions were run on 5% native polyacrylamide gels. Bands were visualized by using a Molecular Dynamics PhosphorImager. The phosphorimage was analysed with ImageQuant software.

RESULTS AND DISCUSSION

Genetic organization and sequence analysis of the flanking genes of the putBCP operon
The ycgL gene, located adjacent to and upstream from the putBCP operon of B. subtilis (Fig. 1a), encodes a potential protein of 260 aa predicted to be a putative member of the nucleotide diphosphate kinase superfamily. The spacing between ycgL and putB is 190 bp. The ycgP gene, located downstream of the putBCP operon and separated from putB by a 152 bp intergenic region (Fig. 1a), is now designated prcR (for proline catabolism regulator), because prcR is absolutely required for putB expression as shown below. A potential promoter-independent transcription terminator (−20.1 kcal mol⁻¹; −84.1 kJ mol⁻¹) is present within the putP–prcR intergenic region. Further downstream of prcR is the convergently orientated ycgQ gene (Fig. 1a), which encodes a putative protein of 285 aa of unknown function. These features suggest that the prcR gene constitutes a monocistronic operon. PrcR (411 aa) shows no significant amino acid sequence similarity with the known proline catabolism-related transcriptional activator PruR (250 aa) of P. aeruginosa PAO1 or PutR activators (154–164 aa) of various bacteria, whereas it shows partial amino acid sequence similarity with the transcriptional regulator PucR (531 aa) of B. subtilis purine degradation genes (Schultz et al., 2001; Beier et al., 2002) (22.2% identity and 43.8% similarity between amino acids 112–409 of PrcR and amino acids 227–528 of PucR). A potential helix–turn–helix DNA-binding motif (Dodd & Egan, 1990) is present at the C terminus of PucR (amino acids 361–382). A similar helix–turn–helix DNA-binding motif is present at the corresponding positions of PucR (amino acids 480–501).

Role of prcR in utilization of proline as a sole nitrogen or carbon source for growth
The putBCP operon is known to be responsible for proline utilization in B. subtilis (Bremer, 2002). To examine whether its downstream gene prcR plays a role in utilization of proline as a sole nitrogen or carbon source for cell growth, a prcR disruption mutant (BM1663) was constructed as described in Methods. It was found that the wild-type B. subtilis cells and the prcR mutant grew equally well (doubling time about 60 min) in modified M9 minimal medium containing 0.4% glucose and 20 mM NH₄Cl as the sole carbon and nitrogen sources, respectively. However, when 20 mM proline was used to substitute for 20 mM NH₄Cl as the sole nitrogen source, the prcR mutant could not grow within 24 h, whereas the wild-type grew with a doubling time of about 95 min. When 0.4% proline was used to substitute for 0.4% glucose as the sole carbon source, the wild-type grew with a doubling time of about 120 min, whereas the growth of the prcR mutant was undetectable under the same growth condition. These observations indicate that the prcR gene is essential for B. subtilis cells to utilize proline as a sole nitrogen or carbon source.

prcR is necessary for expression of the putBCP operon
To determine whether the requirement of prcR for proline utilization is due to the fact that prcR is required for expression of the putBCP operon, a transcriptional fusion of the regulatory region of putB to bgaB was constructed (pGS2090) and integrated at the amyE locus of the wild-type cells and the prcR mutant to generate strains BM1657 and BM1660, respectively. Cells were grown in LB medium for various periods of time. It was found that expression of the putB promoter region–bgaB fusion was abolished in the prcR mutant when compared with that in the wild-type (Fig. 2a). We also analysed the effect of disruption of prcR on putB expression by RT-PCR in a qualitative manner and by RT-qPCR. RNA was isolated from wild-type B. subtilis
cells and the \( prcR \) mutant grown in LB medium for 5 h. As shown in Fig. 2(b, c), disruption of \( prcR \) abolished \( putB \) expression at the RNA level. Taken together, these results indicate that \( prcR \) is necessary for expression of the \( putBCP \) operon.

**Proline induction of \( putB \) expression is \( PrcR \)-dependent**

It is known that proline can induce the expression of the \( putBCP \) operon and proline dehydrogenase activity in \( B. subtilis \) (Atkinson et al., 1990; Bremer, 2002). We next attempted to investigate whether proline induction of \( putB \) expression is mediated through \( PrcR \). The above-mentioned strains BM1657 and BM1660 were grown in modified M9 minimal medium containing 0.4% glucose to OD\(_{600}\) 0.3, and then treated or not treated with 1 mM proline. It was found that proline could induce expression of the transcriptional fusion of the \( putB \) promoter region to \( bgaB \) in the wild-type cells (BM1657) (Fig. 3a), but not in the \( prcR \) mutant (BM1660) (Fig. 3b). These results indicate that proline induction of \( putB \) expression is \( PrcR \)-dependent.

**Identification of the transcriptional initiation sites of \( putB \) and \( prcR \)**

We next performed primer-extension analysis to determine the transcriptional initiation sites of \( putB \) and \( prcR \). A synthetic oligonucleotide complementary to the 5' end of \( putB \) or \( prcR \) was used as the probe. RNA was isolated from \( B. subtilis \) cells grown in LB medium to OD\(_{600}\) 0.5. As shown in Fig. 4(a), one major extension product was detected for \( putB \). The 5' end of the transcript is located 40 bp upstream from the translational start site of \( putB \). This transcriptional initiation site is at an appropriate distance from a \( \sigma^A \)-dependent promoter with a spacing of 18 bp between the -35 box (TTGTTA) and the -10 box (TATAAT) (Fig. 1b). One major extension product was also detected for \( prcR \) (Fig. 4b). The 5' end of the \( prcR \) transcript is deduced to be located 24 bp upstream from the translational start site of \( prcR \). This transcriptional initiation site is at an appropriate distance from a \( \sigma^A \)-dependent promoter with a spacing of 17 bp between the -35 box (TATACA) and the -10 box (TATGAT) (Fig. 1c).
Effect of deletion or mutation of the inverted repeat in the regulatory region of putB on putB expression in vivo

Inspection of the sequence of the regulatory region of putB revealed a 17 bp inverted repeat (TTGTGG-N5-CCACAA) that is centred at position −76 relative to the transcriptional initiation site of putB (Fig. 1b). To examine whether this inverted repeat plays a regulatory role in putB expression, we constructed three plasmid pDL-based derivatives as shown in Fig. 5(a), and integrated them individually at the amyE locus of the wild-type cells. Fig. 5(b) shows that either deletion of the left arm or mutation in the right arm of the inverted repeat abolished the expression of the putB promoter region–bgaB fusion. These results indicate that the inverted repeat centred at position −76 is important for putB expression. It is interesting to note that the transcriptional activator PurR of Lactococcus lactis binds to a PurBox that is also centred at position −76 relative to the transcriptional initiation site of purC and purD (Kilstrup et al., 1998). This PurBox has been found to be required for high-level promoter activity.

Interaction of PrcR with the inverted repeat in the regulatory region of putB in vitro

To explore whether PrcR could bind to the regulatory region of putB in vitro, we constructed plasmid pGS21111,
which was able to overproduce His-tagged PrcR in *E. coli*, and then purified His-tagged PrcR by affinity chromatography on an Ni-NTA agarose column. A $^{32}$P-labelled DNA fragment containing the *putB* promoter region was used as the probe. A $^{32}$P-labelled DNA fragment containing the *proH* promoter region (Belitsky et al., 2001) was used as the control probe. An EMSA showed that purified His-tagged PrcR could retard the DNA fragment containing the *putB* promoter region, but could not retard the control probe at the assay concentrations (Fig. 6a). We also used the unlabelled DNA fragment containing the *putB* promoter region as the specific competitor DNA and the unlabelled DNA fragment containing the *proH* promoter region as the non-specific competitor DNA. The $^{32}$P-labelled DNA fragment containing the *putB* promoter region was used as the probe in an EMSA. It was found that the specific competitor DNA could reduce the formation of PrcR–DNA complex, whereas the non-specific competitor DNA at the same range of concentrations could not (Fig. 6b). Taken together, these results indicate that PrcR can bind to the regulatory region of *putB* in a specific manner.

To further investigate whether PrcR is able to interact specifically with the inverted repeat in the regulatory region of *putB*, a double-stranded oligonucleotide containing the inverted repeat [oligo(*putB*), wild-type] and a double-stranded oligonucleotide containing a mutation in the inverted repeat [oligo(*putB*), mutant] (Fig. 6c) were used as the probes in an EMSA. It was found that PrcR could form a complex with the wild-type oligo(*putB*) but could not form a complex with the mutant oligo(*putB*) under similar assay conditions (Fig. 6c). These results indicate that PrcR can bind to the inverted repeat in a specific manner.
To investigate whether prcR expression is not autoregulated and is not subject to proline induction

To investigate whether prcR expression is autoregulated, a transcriptional fusion of the regulatory region of prcR to bgaB (pGS2140) was constructed and integrated at the amyl locus of the wild-type cells and the prcR mutant. Cells were grown in LB medium for various periods of time. It was found that there was no difference in the expression level of the prcR promoter region–bgaB fusion between the wild-type cells and the prcR mutant (data not shown). We also tested whether prcR expression is subject to proline induction. Cells were grown in modified M9 minimal medium as described above. No proline induction of prcR expression was observed (data not shown).

Concluding remarks

In conclusion, proline utilization in B. subtilis is PrcR-dependent. PrcR mediates proline-responsive expression of the proline utilization operon putBCP through interaction with the inverted repeat in the regulatory region of putB. During the submission of this manuscript, we were aware that B. R. Belitsky had also independently reported the characterization of YcgP, which he designated PutR (Belitsky, 2011).

**ACKNOWLEDGEMENTS**

This research was supported by the National Science Council with grant NSC 97-2311-B-010-003-MY3 and a grant, Aim for the Top University Plan, from the Ministry of Education of the Republic of China.

**REFERENCES**


Edited by: P. Zuber