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Heterologous production and secretion of Clostridium perfringens β-toxoid in closely related Gram-positive hosts

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Abstract

The spore forming bacterium Clostridium perfringens is a widely occurring pathogen. Vaccines against C. perfringens type B and C are currently manufactured using β-toxin secreted by virulent C. perfringens strains. Large-scale production of vaccines from virulent strains requires stringent safety conditions and costly detoxification and control steps. Therefore, it would be beneficial to produce this toxin in a safe production host and in an immunogenic, but non-toxic form (toxoid). For high-level expression of β-toxoid, we cloned the highly active ribosomal rpsF promoter of Bacillus subtilis in a broad host range multicopy plasmid. In B. subtilis, we obtained high intracellular production, up to 200 μg ml⁻¹ culture. However, the β-toxoid was poorly secreted. The employed rpsF expression system allowed using the same expression plasmids in other heterologous hosts such as Lactococcus lactis and Streptococcus pneumoniae. In these organisms secretion of β-toxoid was ten times higher compared to the best producing B. subtilis strain. These results show the usefulness of the rpsF based broad host range expression system. © 2006 Elsevier B.V. All rights reserved.

Keywords: Clostridium perfringens β-toxin; Bacillus subtilis; Lactococcus lactis; Heterologous protein expression; Protein secretion; rpsF promoter; Vaccine production

1. Introduction

Clostridium perfringens is the main cause of clostridial enteric disease in domesticated animals. C. perfringens types B and C secrete β-toxin that causes necrotic enteritis in cattle, sheep, pigs and goats (Sonner, 1996; Springer and Selbitz, 1999). Vaccines against C. perfringens type B and C are currently manufactured using β-toxin produced by the virulent C. perfringens strain itself. The toxin is secreted into the
medium, and the culture medium is harvested and used for subsequent vaccine development. However, the production of vaccines from a virulent strain requires time consuming detoxification and control steps and stringent safety conditions. Therefore, it would be beneficial to produce this toxin in a safe production host, preferably as a non-toxic variant of the protein, which still retains full immunogenicity. For high-level expression and production it will be necessary to use a strong promoter, preferably non-artificially induced by costly inducers. Potential useful promoter candidates are promoters of highly expressed housekeeping genes.

The gene coding for S6 ribosomal protein (rpsF) is such a gene. Recently, we have described the regulation of rpsF in Bacillus subtilis. In this bacterium rpsF forms an operon with ssb and rpsR, encoding single stranded DNA binding protein and ribosomal protein S18, respectively. In B. subtilis the rpsF promoter is highly active during logarithmic growth (Lindner et al., 2004). Since the rpsF promoter controls genes essential for growth, which are strongly expressed in fast growing cells, it is likely that this promoter has a growth dependent control mechanism. We hypothesized that this particular feature can be utilized when producing heterologous proteins that are toxic when produced at high levels. In theory: when a cell produces a protein that causes cell growth to slow down, a cell growth dependent promoter will slow down the transcription of the protein cloned behind it, resulting in an equilibrium with optimal growth rate and protein production. Another advantage of the use of a promoter like rpsF is that, due to the conserved function of these genes, the promoter might be active in different bacterial species. This would enable a quick assessment of production hosts with a single expression construct.

B. subtilis is a promising heterologous host for β-toxoid production. It has an established record for protein production and secretion and general safety. B. subtilis does not contain endotoxins, has been granted a GRAS status by the FDA, and can secrete proteins up to 20 g L⁻¹ yields (Harwood, 1992; Schallmey et al., 2004). Furthermore, like C. perfringens, B. subtilis is a Gram-positive organism, which increases the chance of success for production of β-toxin. In this study we have tested the applicability of the rpsF promoter as a high expression promoter for β-toxin production in B. subtilis. For this purpose we used a variant of the β-toxin, β-toxoid, that contains three point mutations rendering it no longer toxic, but still immunogenic (Segers et al., 1999). In addition, we have examined the effect of secretion on total production of β-toxoid. Finally, we have tested whether the rpsF promoter of B. subtilis can advantageously be used for β-toxoid production in other Gram-positive heterologous hosts, such as Lactococcus lactis and Streptococcus pneumoniae.

2. Materials and methods

2.1. Bacterial strains, medium and growth conditions

Table 1 lists the bacterial strains and plasmids used in this study. B. subtilis strains were grown at 37°C under vigorous agitation in TY (1% tryptone, 0.5% yeast extract, 1.0% NaCl) or minimal medium (Spizizen, 1958). L. lactis strains were grown at 30°C in M17 broth with 0.5% glucose (GM17) (Terzaghi and Sandine, 1975). S. pneumonia was grown at 37°C in GM17 broth. For the selection of transformants, appropriate antibiotics were added to the growth media at the following concentrations: for B. subtilis erythromycin 2 μg ml⁻¹, chloramphenicol 5 μg ml⁻¹, spectinomycin 100 μg ml⁻¹, hygromycin 125 μg ml⁻¹; for L. lactis chloramphenicol 5 μg ml⁻¹ and erythromycin 5 μg ml⁻¹; for S. pneumoniae erythromycin 0.25 μg ml⁻¹. A 1% starch was added to solid media to visualise amylase activity when appropriate.

2.2. Strain constructions and transformation

The cloning and transformation procedures were performed according to established techniques (Bron and Venema, 1972; Sambrook et al., 1989) and supplier’s manuals. Restriction enzymes, DNA polymerases, deoxynucleotides, T4 DNA ligase, plasmid isolation kits and PCR-product purification kits were obtained from Roche Diagnostics (Mannheim, Germany), and used as specified by the supplier. For all PCR-reactions PWO polymerase was used unless specified differently. Nucleotide sequences of primers used for PCR are listed in Table 2.

The rpsF and yukE promoter fragments were amplified by PCR from B. subtilis 168 chromosomal DNA using primers rpsF-3 and rpsF-5, and pyukE4-fw and
Table 1
Strains and plasmids used in this study

<table>
<thead>
<tr>
<th>Strains</th>
<th>Genotype</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. subtilis</td>
<td>trpC2</td>
<td>Anagnostopoulos and Spizizen (1961)</td>
</tr>
<tr>
<td>B. subtilis</td>
<td>nprE aprE epr bpr mpr::ble bsr Δxpr</td>
<td>Wu et al. (2002)</td>
</tr>
<tr>
<td>B. subtilis</td>
<td>168 amyE::PhtrA-bgaB</td>
<td>Noone et al. (2000)</td>
</tr>
<tr>
<td>L. lactis</td>
<td>Plasmid-free strain</td>
<td>Gasson (1983)</td>
</tr>
<tr>
<td>S. pneumonia</td>
<td>D39 Serotype 2, virulent strain, NCTC 7466</td>
<td>Avery et al. (1944)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Plasmids</th>
<th>Characteristics and description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>pDH32M</td>
<td>CmR, AmyE-integration vector</td>
<td>Kraus et al. (1994)</td>
</tr>
<tr>
<td>pRBT</td>
<td>pTRKH2::PrpsF-β-toxoid-gntT</td>
<td>This study</td>
</tr>
<tr>
<td>pRST</td>
<td>pTRKH2::PrpsF-β-toxoid without SS-gntT</td>
<td>This study</td>
</tr>
<tr>
<td>pRAT</td>
<td>pTRKH2::PrpsF-amyQ-gntT</td>
<td>This study</td>
</tr>
<tr>
<td>pRN1</td>
<td>pTRKH2::NdeI-NdeI</td>
<td>This study</td>
</tr>
<tr>
<td>pYBT</td>
<td>pTRKH2::PyukE-β-toxoid-gntT</td>
<td>This study</td>
</tr>
<tr>
<td>pYST</td>
<td>pTRKH2::PyukE-β-toxoid without SS-gntT</td>
<td>This study</td>
</tr>
<tr>
<td>pYA60BT</td>
<td>pTRKH2::PyukE-amyQ signal sequence-mature β-toxoid-gntT</td>
<td>This study</td>
</tr>
<tr>
<td>plV60</td>
<td>pDH32M::PrpsF-β-toxoid-gntT</td>
<td>This study</td>
</tr>
<tr>
<td>pNZ8048</td>
<td>reflective vector containing nisin inducible promoter Pnis</td>
<td>de Ruyter et al. (1996)</td>
</tr>
<tr>
<td>pNZbtox</td>
<td>pNZ8048::β-toxoid</td>
<td>This study</td>
</tr>
<tr>
<td>pKTH10</td>
<td>Replicative plasmid containing AmyQ</td>
<td>Darmon et al. (2002)</td>
</tr>
<tr>
<td>pBtox1</td>
<td>his6-β-toxoid-his6</td>
<td>Intervet Int., Boxmeer, NL</td>
</tr>
</tbody>
</table>

PythonE4-rv, respectively. B. subtilis yukE is a gene of unknown function that probably has not correctly been annotated in the B. subtilis R16.1 annotation as available on SubtiList (Moszer et al., 1995), since the most likely promoter and ribosome binding site sequences overlap with the annotated open reading frame. Furthermore, in all annotated homologs found, the annotated first 8 amino acids are absent. We therefore assumed that not the first ATG codon but the second ATG codon, starting at basepair 25, is the actual start codon, and we have cloned the promoter accordingly.

The β-toxoid gene was amplified by PCR using primers Btox-RN1-fw and 2Btoxoid2 and pBtox1 plasmid as a template. The β-toxoid gene without signal sequence (β-toxoid-SS) was amplified from the same template using primers Btoxoid-ss+ATG and 2Btoxoid2. amyQ was amplified using primers AmyQ2-fw and AmyQ-rv and pTKH10 plasmid as a template. The gnt-terminator sequence was amplified using Exten- sor polymerase (ABgene, Epsom, United Kingdom), B. subtilis 168 chromosomal DNA, and primers Gntterm-3 and Gntterm-2.

After amplification, the promoter fragments were digested by NdeI. The β-toxoid, β-toxoid-SS, and amyQ PCR fragments were digested by NdeI and BamHI. The gnt-terminator (gntT) was digested BamHI. All digested fragments were purified using the High pure PCR-purification kit, and ligated in a three point ligation using T4 DNA ligase. The complete expression cassettes were subsequently amplified by PCR directly from the ligation mixture. When this PCR did not yield a single fragment, the fragment of the right size was isolation from gel using a High Pure PCR Product Purification Kit.

Purified expression cassettes were digested with PstI and HpaI, and ligated into a SmaI/PstI digested pTRKH2 high copy vector.

The single copy integration plasmid pIV60 was constructed by ligation of the PrpsF-β-toxoid-gntT cassette in pDH32m. To construct a fusion of the mature β-toxoid gene to the AmyQ signal sequence, the AmyQ signal sequence was amplified using primers AmyQfw-2 and AmyQss-rv. The DNA fragment encoding mature β-toxoid was amplified using primers Btox-mature-fw and 2Btoxoid-2. Both fragments were...
Table 2
Primers used in this study

| Primer name     | Description                                                                 | Sequence (5′–3′)
|-----------------|-----------------------------------------------------------------------------|----------------
| rpsF-3          | Forward primer to amplify the rpsF promoter region                           | GGAATTCCTGCAGGTGACTTTTGACGGGGCCTTC
| rpsF-5          | Reverse primer to amplify the rpsF promoter region with RBS and ATG         | CGTACTTTTCTCATATGTTCAGCACC
| Gnt-term-3      | Forward primer for gnt-terminator                                           | GCGGATCTAGTAAACTAATTAACCTGTATTAAAAACACG
| Gnt-term-2      | Reverse primer for gnt-terminator                                           | GCTCTAGAATTTACCTTCTGTTGTTGGGATAG
| Btoxoid-RN1-fw  | Forward primer for β-toxoid with RBS and ATG                               | GGCTCTAGACATATGAAGAAAAATTTATTTTCTAGTTATAG
| Btoxoid-ss+ATG  | Forward primer for β-toxoid without signal sequence                         | GGCTCTAGACATATGAATGATATAGGTTAACAACCTACTATAAA
| 2B-toxoid2      | Reverse primer for β-toxoid                                                 | CGCGGATCCTAAATAGCTGTTACTTTTGAG
| Btoxoid-RN2-fw  | Forward primer for β-toxoid cloning in pNZ8048                              | CGTTGCCATGGAGAAAAATTTATTTCATTAGTTATAG
| Btoxoid-RN2-rv  | Reverse primer for β-toxoid cloning in pNZ8048                              | CGCTCTAGATTTAAATAGCTGTTACTTTTGAG
| Btox-mature-fw  | Forward primer for mature β-toxoid, enabling fusion to signal sequences     | CGGTCTCAATGATATAGGTTAACAACCTACTATAAA
| pyukE4-fw       | Forward primer for pyukE promoter region with RBS and ATG                  | GCAACTGCAAGCGGAGCAAGACTAAATAG
| pyukE4-rv       | Reverse primer for pyukE promoter region                                    | TAATCCTGCCATATGTCCTACC
| amyQfw-2        | Forward primer to amplify amyQ                                              | CAATACGCATATGTTACAAAACGAAGAAGC
| AmyQrv          | Reverse primer to amplify amyQ                                             | GCGGATCTCAGTTGGAGGGTTT
| AmyQ_ss-rv      | Reverse primer for AmyQ-signal sequence, enabling fusion with mature       | CGGTCTCACATGGCTGATGTTTTGTAATCG
| RNlacZ-fw       | Universal primer on puc18 derived MCS                                       | GTGAGCGGATAACATTTCACACAGG
| RNlacZ-rv       | Universal primer on puc18 derived MCS                                       | GGTGGTCCCCAGTCAGCGACTTGTA

\* Underlined nucleotides indicate introduced hexameric restriction sites.

digested with Eco3I and ligated, resulting in a gene encoding an exact fusion of the AmyQ signal sequence to the mature β-toxoid at the signal peptidase cleavage site. The fused DNA was amplified by PCR from the ligation mixture and digested by NdeI and BamHI, and ligated in the likewise digested pYBT plasmid, resulting in pYAasBT.

pNZbtox was constructed by ligation of a NcoI and PstI digested β-toxoid PCR product, resulting from a PCR on pBtox-1 using primers Btox-RN2-fw and Btox-RN2-rv, into the likewise digested vector pNZ8048. An overview of all constructed plasmids is given in Table 1.

All ligation mixtures were transferred to electrocompetent L. lactis MG1363 or L. lactis NZ9000 using a Gene pulser (Biorad laboratories, Hercules, California), as described earlier (Leenhouts et al., 1989).

Colonies were selected on solid media for the appropriate antibiotic resistance and were subsequently screened by colony PCR. From positive clones plasmids were isolated, which were inspected by EcoRI-digestion and DNA-sequencing.

B. subtilis 168, WB700 or WB800 were transformed with the constructed replicative plasmids isolated from L. lactis, and selected on solid medium for erythromycin resistance. B. subtilis strain BIV60 was obtained by a double crossover of plasmid pIV60 into the chromosomal amyE gene of B. subtilis WB700. S. pneumonia D39 was transformed by growing the strain at 37°C in GM17 to an OD600 of 0.1; competence-stimulating protein CSP-1 (Pozzi et al., 1996) was used at 100 ng ml−1 for inducing competence. Transformed cells were selected on solid medium for erythromycin resistance.

2.3. Protein isolation, gel electrophoresis and Western blotting

Strains were grown as described and growth was followed by taking OD600 measurements every hour.
From an OD$_{600}$ of 0.7 onwards, every hour, 2.0 ml samples were taken from the cultures. The cells were immediately separated from the supernatant by centrifugation for 1 min at 14,000 rpm, and cells and supernatant were separately frozen in liquid nitrogen. When the sample collection was finished all samples were thawed on ice. Cell fractions of \textit{B. subtilis} and \textit{S. pneumonia} were prepared for SDS-PAGE as described previously (Veening et al., 2004). For \textit{L. lactis} this protocol was adjusted and the cells were protoplasted at 50°C instead of the described 37°C. Supernatant fractions were concentrated 10 times upon trichloroacetic acid (TCA) precipitation, and samples for SDS-PAGE were prepared as described previously (Laemmli, 1970).

Proteins were separated by SDS-PAGE, and either stained with Coomassie Brilliant Blue directly, or transferred to a polyvinylidene-difluoride (PVDF) membrane (Molecular Probes Inc., Eugene, Oregon). β-Toxoid protein was visualised using a monoclonal anti-β-toxoid antibody (Intervet Int., Boxmeer, NL), and a secondary horse radish peroxidase-conjugated goat anti-mouse antibody (Amersham Biosciences, Buckinghamshire, UK). β-Toxoid concentrations were estimated using dilution series loaded on a Coomassie brilliant blue stained polyacrylamide gel with a Bovine Serine Albumin standard as reference.

2.4. β-Galactosidase activity assay

To assay β-galactosidase activities, overnight cultures were diluted in fresh medium, and samples were taken at hourly intervals for optical density readings at 600 nm (OD$_{600}$) and β-galactosidase activity determinations. The β-galactosidase assay, and the calculation of β-galactosidase units (Miller units), were performed as described (Miller, 1982), with the adaptations for the heat resistant bgaB variant as described by Darmon et al. (2002).

2.5. Addition of β-toxoid to growing cultures of \textit{B. subtilis}

\textit{B. subtilis} 168 was grown as described with a starting OD$_{600}$ of 0.01. OD$_{600}$ was measured every hour, and after 2 h of growth β-toxoid was added at final concentrations of 2.0 and 5.0 μg ml$^{-1}$. Growth was followed by OD$_{600}$ measurements until cells were 4 h into stationary growth phase. β-Toxoid was obtained from a \textit{L. lactis} culture harbouring the pRBT plasmid. Whole supernatant of this \textit{L. lactis} culture was concentrated using TCA precipitation. As a control, concentrated supernatant of a \textit{L. lactis} strain containing an empty vector was used.

2.6. Automated growth assays and nisin-induction of β-toxoid production in \textit{L. lactis} NZ9000

For automated growth assays a Genious microplate reader (Tecan Instruments, Maennedorf, Switzerland) was used, using 96 well flat bottom microplates containing 200 μl of GM17 medium with antibiotics, inoculated with O/N grown \textit{L. lactis} strains diluted to an OD$_{595}$ of 0.1. The strains were grown at 30°C and the OD was measured every 20 min after orbital shaking for 15 s to prevent sedimentation. After 2 h of growth, nisin from a culture supernatant of strain NZ9700 (de Ruyter et al., 1996) was added to half of the samples at a 1:1000 dilution, and growth was monitored for another 10 h while measuring optical density. From a separate microplate, the cultures from five wells were pooled 2 h after nisin-induction. These samples were separated in cell and supernatant fraction, and analyzed for β-toxoid production and secretion.

2.7. Biological activity of \textit{L. lactis} produced β-toxoid

Female mice weighing 18–22 g were immunized IP on day 0 and day 14 with 250 μl antigen in Diluvac Forte as outlined in Table 3. The mice were bled on day 28.

The obtained sera were used in a competitive ELISA which was performed as follows. Monoclonal antibody against native β-toxin F126 was coated in 96 wells plate overnight. The plate was blocked for 2 h with 1% PBS-T-BSA. In a separate plate the mice sera were

<table>
<thead>
<tr>
<th>Vaccine</th>
<th>Approximately β-toxoid concentration (μg/ml)</th>
<th>Mean titer ± S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.8</td>
<td>32 ± 15</td>
</tr>
<tr>
<td>2</td>
<td>5.4</td>
<td>14 ± 19</td>
</tr>
<tr>
<td>3</td>
<td>2.7</td>
<td>11 ± 13</td>
</tr>
<tr>
<td>4</td>
<td>1.3</td>
<td>15 ± 14</td>
</tr>
<tr>
<td>5</td>
<td>0.7</td>
<td>&lt;4</td>
</tr>
</tbody>
</table>

For the preparation of the vaccine, see Table 3.
titrated three-fold, native β-toxin was added as a fix concentration to all wells. The antibodies were allowed to react with the β-toxin for 30 min at 37 °C and then transferred to the Mab coated plate. The plates were incubated at room temperature for 1 h. Horse radish peroxidase conjugate rabbit polyclonal antibodies were added and incubated for 1 h. After washing the plates were colorimetrically developed with OPD. Titers were calculated as half of the maximum OD490 of the negative control relative to the internal serum control, which was defined as titer 50 i.u. ml⁻¹.

3. Results

3.1. β-Toxoid production in B. subtilis

Previously, we have investigated the expression pattern of the strong ribosomal promoter rpsF in B. subtilis (Lindner et al., 2004). To test suitability and efficacy of this promoter for heterologous expression of β-toxoid, we constructed the high copy theta replicating expression plasmid pRST, containing the B. subtilis rpsF-promoter and C. perfringens β-toxoid gene without its endogenous signal sequence. This construct was introduced in B. subtilis 168 and resulted in high intracellular β-toxoid expression, up to 200 µg ml⁻¹ culture, corresponding to 25% of total intracellular protein (Fig. 1A).

To test a secretion construct of β-toxoid, a plasmid was constructed containing the B. subtilis rpsF-promoter and the β-toxoid gene with its original clostridial signal sequence (pRBT). Unfortunately, this plasmid could not be stably maintained in B. subtilis. Several attempts to construct this clone failed or resulted in strains that grew poorly and lost the plasmid after overnight growth. A single copy integration into the ectopic amyE locus did yield a stable strain. However, hardly any β-toxoid could be detected in the medium (data not shown). To test whether this could be due to the expression vector used, we tested the production and secretion of AmyQ, the alpha-amylase of B. amyloliquefaciens, which is widely used for testing secretion efficiencies in B. subtilis (Vitikainen et al., 2001; Hyyrylainen et al., 2001; Westers et al., 2004). The introduction of the vector with the rpsF promoter in front of amyQ (pRAT) resulted in high-level secretion of alpha-amylase. This shows that the rpsF expression system itself is capable of yielding high secretory levels.

To further investigate the bottlenecks in β-toxoid secretion we investigated the possibility that accumulation of secreted β-toxoid in the medium is toxic to B. subtilis. We therefore tested growth of B. subtilis in medium with externally added β-toxoid. No effect on growth was observed even when extracellular concentrations were five times higher than the maximal concentration observed in a β-toxoid producing strain; thus, low production is not a consequence of external toxicity (data not shown).

B. subtilis is well known for its capability of producing degradative enzymes, especially during stationary growth. It is therefore possible that β-toxoid is degraded when in it is secreted into the medium. To test this, the expression cassette was integrated in the amyE locus of a B. subtilis strain WB700 in which seven of the major extracellular proteases are deleted (Wu et al., 2002). In this strain, secreted β-toxoid was detected in the medium at concentrations of 0.1–0.5 µg ml⁻¹ culture. Expression was highest.
during logarithmic growth and still present in stationary growth (Fig. 1B).

Unfortunately, the use of a single copy integration of the expression cassette in the amvE locus results in the production of only low levels of β-toxoid. By using a different strong promoter it might be possible to obtain a stable multicopy construct carrying the β-toxoid gene. The B. subtilis yukE promoter is strong, however its expression timing differs from that of the rpsF promoter. YukE expression is highest during the transition from logarithmic to stationary growth phase when the cells are grown in rich medium ([MICADO, http://locus.jouy.inra.fr/cgi-bin/gemnic/madbase_home.pl, Biaudet et al., 1997]). Indeed, it proved to be possible to introduce the PyukE containing vector into B. subtilis 168 and WB700 without severe effects on cell growth. As shown in Fig. 2, in B. subtilis WB700 the expression of β-toxoid started at the end of logarithmic growth and showed highest secretion around transition point. WB800 is the same as B. subtilis strain as WB700 except that the major cell-wall proteases wprA is deleted as well. Introduction of plasmid pYBT in this strain resulted in considerably more β-toxoid in the medium (0.5–1.0 μg ml⁻¹), showing the involvement of WprA in secreted β-toxoid breakdown. Notably, during all time points measured about twice as much β-toxoid was present intracellularly compared to the secreted fractions, indicating that secretion is a bottleneck in the production of β-toxoid in B. subtilis (Fig. 2). This was not caused by the signal sequence since swapping with amyQ gave no improvement. To test whether the signal peptide of β-toxoid protein is the bottleneck we swapped it with the signal peptide of AmyQ, which can be secreted in B. subtilis to high amounts (Vitikainen et al., 2001). However, this did not yield more secreted β-toxoid, indicating that the signal peptide itself is not the limiting factor (data not shown).

3.2. β-Toxoid secretion causes secretion stress in B. subtilis

To investigate whether the inefficient β-toxoid secretion may lead to a stress response in B. subtilis, we made use of strain DN2 (Noone et al., 2000) containing the promoter of htrA fused to a thermostable β-galactosidase gene integrated in the amvE locus (amyE::P_{htrA}-bgaB). The B. subtilis HtrA protease is involved in the folding of secreted proteins and the degradation of malfolded proteins after secretion (Pallen and Wren, 1997). Its expression is upregulated in response to overexpression of secreted proteins, the so-called secretion stress response. This response is activated by the two component sensor system CssRS (Darmon et al., 2002). As shown in Fig. 3, the production of β-toxoid results in a strong induction of htrA expression. This effect is not observed when cssS is deleted or when β-toxoid was expressed without signal sequence (data not shown). Together these data clearly indicate that β-toxoid secretion results in secretion stress in B. subtilis.

3.3. The rpsF expression system in other Gram-positive bacteria

The rpsF-ssb-rpsR operon is conserved among many Gram-positive bacteria. An alignment of the upstream regions of the rpsF-ssb-rpsR operons of B. subtilis, L. lactis and S. pneumoniae was made using Genedoc (http://www.psc.edu/biomed/genedoc). As shown in Fig. 4, the promoter regions are highly similar. The pRBT plasmid (P_{rpsF}-β-toxoid) was introduced in L. lactis MG1363 and S. pneumoniae D39, and resulted in 5–10 μg ml⁻¹ of secreted β-toxoid (Fig. 5). In L. lactis β-toxoid up to 30% of the total secreted proteins in the medium consisted of β-toxoid. This considerable production shows that the rpsF promoter of B. subtilis is active in L. lactis and S. pneumonia, and that
the β-toxoid signal sequence functions as an efficient export signal in both organisms.

To study the strength of the rpsF expression system in L. lactis, we compared it to results obtained with the nisin inducible expression system (NICE). The NICE system is generally regarded as one of the best production systems in L. lactis where the maximally produced amount of protein is limited only by the organisms production bottlenecks for the specific protein (de Ruyter et al., 1996). As shown in Fig. 5, the rpsF expression system yields similar levels of secreted β-toxoid as induction with the nisin inducible promoter, demonstrating the rpsF expression system provides a very efficient broad host range production platform.

3.4. Immunity and biological activity of β-toxoid

To determine biological activity and immunogenic properties the β-toxoid was not purified. Instead total medium fraction of the cultures was used, which has a clear cost-advantage over purification, and has no adverse effects on the animals health (Norton et al., 1994). Material produced in L. lactis MG1363 was tested for both biological activity and immunogenic properties. Toxicity of the β-toxoid was tested in mice. The β-toxoid, specifically constructed to have a reduced toxicity, is indeed non-toxic at levels at which the wild-type toxin is lethal. When 2.5 μg/mouse (average weight 20 g) was administered 5/5 mouse survived. The β-toxoid was toxic when administered at 10 μg/mouse (0/2 survived). These results show a toxicity reduction of three orders of magnitude compared to the WT β-toxin, which has a LD50 of 0.4 μg/kg in mouse (i.v.) (Gill, 1982).

To test immunogenic properties of β-toxoid vaccines were prepared as described in the materials and methods section with β-toxoid concentrations as outlined in Table 3. The mice were immunized according to a standard protocol and 14 days after second immunization, the animals were bled. Anti β-toxin antibodies
Fig. 5. β-Toxoid expression in L. lactis and S. pneumoniae. Upper panels: β-toxoid expression in L. lactis. (A) CBB stained PAA gel of culture supernatant of strain containing nisin inducible β-toxoid production plasmid, 2 h after addition of nisin (+) or buffer (−). (B) CBB stained PAA gel of culture supernatant of MG1363 containing the pRBT plasmid. β-Toxoid is indicated by the arrows. (C) Western blot of culture supernatant of strain containing nisin inducible β-toxoid, 2 h after addition of nisin (+) or buffer (−). (D) Western blot of culture supernatant of MG1363 containing the pRBT plasmid. β-Toxoid visualized using monoclonal anti-β-toxoid antibody. Lower panels: β-toxoid expression in S. pneumoniae. (E) CBB stained PAA gel of culture supernatant and cell fractions, and (F) Western blot of culture supernatant and cell fractions, β-toxoid visualized using monoclonal anti-β-toxoid antibody. β-Toxoid is indicated by the arrows. (−) Strain containing an empty vector control. (+) Strain containing the pRBT expression plasmid.

were determined as titers relative to WHO International Standard in a competitive ELISA which shows results comparable to European Pharmacopeia (Ph.Eur.) (or 9 CFR test). Both Ph.Eur. and 9 CFR require that a vaccine induces 10 neutralizing international units in average in 10 rabbits, tested as neutralization in mice. All vaccine induced titers in mice with the exception of the vaccine preparation with lowest concentration of the antigen (Table 3).

4. Discussion and conclusion

To obtain high yields of any heterologous protein, the use of a strong promoter is a prerequisite. In this research we show that the promoter of the B. subtilis ribosomal rpsF gene is a strong promoter that is capable of high expression of C. perfringens β-toxoid intracellularly. However, high production of β-toxoid in the growth medium turned out to be impossible. In fact, the presence of the complete β-toxoid gene (including secretion signals) under expression of the rpsF promoter on a high copy vector was lethal. Our evidence suggests that high expression of β-toxoid leads to a considerable stress, which, when pushed to the limits by a strong promoter as rpsF, is apparently toxic to the cells. These results also imply that the rpsF expression system does not autoregulate itself as we have postulated in Section 1. We anticipated to find that a cell growth dependent promoter would slow down the transcription of the protein cloned behind it when the produced protein causes stress that slows down the growth, resulting in an equilibrium with optimal growth rate and protein production. However, the stress on cell growth did not result in a sufficient decrease in β-toxoid expression to prevent plasmid instability and cell death.

B. subtilis is able to secrete several proteins up to 20 g l⁻¹ (Schallmey et al., 2004), however it is now that secretion of heterologous proteins in B. subtilis is usually lower (Li et al., 2004). A frequently encountered problem with expression and secretion of heterologous proteins in B. subtilis is the rapid degradation of the secreted protein by extracellular proteases (Wu et al., 2002). It has also been reported that β-toxoid is sensitive to protease activity (Hunter et al., 1993). Therefore, it was not surprising to find that employing extracellular protease deficient B. subtilis strains increased the amounts of β-toxoid in the medium considerably.

4.1. Secretion signals

It was previously shown, that adapting the signal sequence can improve protein secretion (Schallmey et al., 2004). The C. perfringens β-toxoid native signal sequence is a consensus Sec-type signal sequence, and in theory compatible with the B. subtilis secretion system (Tjalsma et al., 2000). Swapping the β-toxoid signal sequence with the signal sequence of a well
secreted *Bacillus* protein (AmyQ) did not increase its presence in the growth medium. Apparently, the β-toxoid signal sequence itself is not responsible for the poor secretion. These findings are in agreement with previous studies on the production of wildtype β-toxin, which has different properties than the β-toxoid, but contains the same signal sequence (Steinthorsdottir et al., 1998, 2000). Most likely the poor secretion and/or low extracellular stability is caused by characteristics of the mature β-toxoid protein, for instance by premature folding in the absence of suitable chaperones or rapid degradation due to slow folding kinetics directly after secretion at the cell membrane cell-wall interface. The expression of the gene encoding the *B. subtilis* HtrA protease is upregulated in response to overexpression of β-toxoid which is indicative for secretion stress (Fig. 3). Induction of HtrA is related to problems that occur in late stages of protein secretion (Leloup et al., 1997), presumably as a consequence of slow folding at the membrane-cell-wall interface (Braun et al., 1999).

The response of the cells to secretion stress appears to be not sufficient to increase β-toxoid secretion, as the accumulation of non-secreted β-toxoid intracellularly indicates.

4.2. Broad host range expression system

pTRKH2 is a stably replicating vector in a broad range of Gram-positive micro-organisms (O’Sullivan and Klaenhammer, 1993), making it a suitable broad host range vector. In addition, the *rpsF* promoter is well conserved in all Gram-positive organisms. Together, these genetic elements form a potential versatile protein expression system, which we have illustrated here by the heterologous production of β-toxoid in both *L. lactis* and *S. pneumoniae*. The expression yield of β-toxoid in *L. lactis* using the *rpsF* promoter was as high as the yield using the NICE expression system, showing that also in *L. lactis* the *rpsF* promoter on a high copy vector results in maximum obtainable expression levels of secreted protein in these organisms. As apparent from the results obtained, the secretion of β-toxoid in *B. subtilis* encounters bottlenecks that are less severe in *L. lactis* or *S. pneumoniae*. A likely bottleneck is degradation of the protein by a *B. subtilis* specific proteases that are absent in the other organisms. We are currently investigating the exact nature of this and other bottlenecks. With this study we have shown that an opportunistic broad host range strategy can be advantageous to achieve optimal protein secretion yields, where it cannot, *a priori*, be predicted which host would be most suitable.

4.3. Applicability

As shown by the immunity and biological activity experiments the produced β-toxoid has substantial reduced toxicity and still induces high titers in vaccination experiments. These results indicate that the β-toxoid is a very suitable vaccine component against *C. perfringens* type B and C.

β-Toxoid in *L. lactis* was produced in culture flasks using standard medium. Induction of expression using the NICE system yielded sufficient amounts of β-toxoid for in small scale experiments. Until recently experience with large-scale application and fermentation of the NICE system was very limited. However, recent publications showed that the NICE system is well suited to produce target protein at industrial scale. Careful optimization of key parameters, like pH control, medium, and spore elements, leads to a significant increase in target protein yields (Mierau et al., 2005a,b), indication that also of β-toxoid commercially interesting yield are within reach.

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