Characterisation of SEQ0694 (PrsA/PrtM) of Streptococcus equi as a functional peptidyl-prolyl isomerase affecting multiple secreted protein substrates†

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Peptidyl-prolyl isomerase (PPIase) lipoproteins have been shown to influence the virulence of a number of Gram-positive bacterial human and animal pathogens, most likely through facilitating the folding of cell envelope and secreted virulence factors. Here, we used a proteomic approach to demonstrate that the Streptococcus equi PPIase SEQ0694 alters the production of multiple secreted proteins, including at least two putative virulence factors (FNE and IdeE2). We demonstrate also that, despite some unusual sequence features, recombinant SEQ0694 and its central parvulin domain are functional PPIases. These data add to our knowledge of the mechanisms by which lipoprotein PPIases contribute to the virulence of streptococcal pathogens.

Introduction

In order to interact with their environments, bacteria translocate significant numbers of proteins across their plasma membranes, either for eventual release (secretion) or for localisation within the cell envelope.1–3 In pathogens, this ‘secretome’ plays a vital role in host–pathogen interactions and consequently the mechanisms of protein translocation are of much interest as virulence-associated functions. Proteins exported by the Sec translocase emerge on the extracytoplasmic side of the plasma membrane as unfolded proteins and the subsequent correct folding of these proteins is therefore critical to their functioning. In ‘dimmer’ bacteria (those with outer membranes), a variety of periplasmic chaperones are required to allow protein folding in the periplasm and/or translocation across or into the outer membrane.1,4 In monoderm Gram-positive bacteria, secreted proteins fold at the membrane-wall interface with the assistance of a range of accessory components of the Sec translocase.5 These include proteins belonging to the peptidyl-prolyl Isomerase (PPIase) family, which assist protein folding by catalysing cis-trans isomerisation of the peptide bond preceding proline residues.6,7 In many Gram-positive bacteria, these PPIases are N-terminally lipid-anchored lipoproteins, presumably because the localisation of a PPIase peripheral to the plasma membrane surface places it in an optimal position to engage with substrate proteins emerging from the Sec translocon.3

Several lipoprotein PPIases have been shown to have significant roles in bacterial physiology, notably PrsA in Bacillus subtilis.9 Moreover, in some pathogens PPIases have been shown to affect virulence,7 including PrsA of Bacillus anthracis,10 Enterococcus faecalis EF0685 and EF1534,11 Listeria monocytogenes PrsA2,12,13 Streptococcus pneumoniae SrlA and PpmA14 and Streptococcus pyogenes PrsA.15 Some of these PPIase belong to the cyclophilin subfamily (e.g. S. pneumoniae SrlA; E. faecalis EF1534) but many belong to the parvulin subfamily,16 including the members of PrsA family that appear to be ubiquitous in Firmicute genomes.

Streptococcus equi is the causative agent of the widespread equine disease Strangles.17,18 We have previously shown that the PrsA homologue of S. equi (UniProt: C0M9L5, originally denoted PrtM) plays a significant role in S. equi virulence, both in an air interface tissue culture model, a mouse model and, most significantly, in the equine host.19 PrtM is here referred to as SEQ0694, based on its annotation in the S. equi genome.17

To further investigate the role of SEQ0694 we have here characterised the recombinant protein as a functional PPIase and used a proteomic approach to demonstrate that SEQ0694 likely influences the folding and activity of multiple secreted...
proteins of *S. equi*, including at least two putative virulence factors.

**Materials and methods**

**Bacterial strains and growth**

*S. equi* strain 4047 (wild type) and its isogenic mutant strain (ΔprtM\_138–213) with a deletion of codons 138 to 213 in *seq0694* (i.e. lacking the central domain of SEQ0694, ESI,† Fig. S1) are described in Hamilton *et al.*[^19]. *S. equi* strains were grown in Todd Hewitt media. *Escherichia coli* TOP10 and BL21 were grown in LB media.

**Production and purification of recombinant proteins**

Genomic DNA from *S. equi* 4047 was isolated using a DNeasy extraction kit (Qiagen). To produce recombinant N-terminally His-tagged full-length SEQ0694 using the primer pair 5’GATCGATCAGTCTACAAATGACAATAAGTG 3’ (forward primer, NdeI site underlined) and 5’GATGATCCCTCTGATTTTGTGATTTAGAAGATTGAC 3’ (reverse primer, XhoI site underlined) and KOD Hot Start polymerase (Merck Chemicals) according to the manufacturer’s instructions. The amplified ORF was cloned into pET28a (Merck Chemicals) using NdeI and XhoI site underlined and sequenced. The identity of rSEQ0694 was confirmed by peptide mass fingerprinting of trypsinized bands excised from Coomassie blue-stained SDS-polyacrylamide gels (see below).

In addition to rSEQ0694, the section of the *seq0694* ORF encoding the predicted parvulin domain of SEQ0694 (amino acids 148–242, ESI,† Fig. S1; rSEQ0694parv) was amplified using primer pair TGCCATAGCATGCTACCTAGTCATCACAGTCAACATATG (forward, Ndel site underlined) and TGCCATAGCTCGAATTACGCGTTACCTTACAC (reverse, XhoI site underlined), cloned, expressed and the protein parvulin domain purified as described above, except that 5 kDa, 6 mL cut-off centrifugetal concentrator units (Viva Science) were used.

The concentration of both purified proteins was determined using the Bradford Assay.

**Protease-coupled peptidylprolyl isomerase (PPIase) assay**

The standard protease-coupled PPIase assay was[^21] employed using three peptide substrates having a consensus sequence Suc-Ala-X-Pro-Phe-pNA (Suc, succinyl; X = alanine, lysine or phenylalanine; pNa, paranitroaniline). Assays were performed by mixing 10 μL of purified rSEQ0694 (60 mg mL\(^{-1}\)) or rSEQ0694-parv (40 mg mL\(^{-1}\)) (diluted in 20 mM HEPES, pH 7.4; 140 mM NaCl; 10% v/v glycerol), cyclosporin (positive control) or diluent alone (negative control) with 480 μL of buffer (20 mM HEPES, pH 7.4; 140 mM NaCl; 1 mM DTT) and allowing the mixture to equilibrate on ice for 5 min. 10 μL of ice-cold chymotrypsin (20 mg mL\(^{-1}\) in 0.001 M HCl; 0.002 M CaCl\(_2\)) was pipetted into a cuvette in a spectrophotometer (Spectronic Unicam Helios-α, Thermos Electronic Corporation), zeroed at 390 nm. The 490 μL ice-cold assay mixture was quickly added and mixed with the chymotrypsin, followed by 500 μL tetrapeptide substrate in ice-cold 20 mM HEPES, pH 7.4, 140 mM NaCl, 1 mM DTT, so as to give a final concentration of 37.5–75 μM peptide, and mixed quickly by pipetting. The final chymotrypsin concentration in the reaction mixture was 0.2 mg mL\(^{-1}\). The rate of the reaction (cis-trans isomerization) was measured by following colour formation (absorbance at 390 nm) resulting from pNA release from the trans form of the tetrapeptide substrate by chymotrypsin, for a maximum of 6 min. Spectrophotometric readings were recorded automatically via Vision 32 (Unicam Ltd) software.

Reported kinetic data are given as the mean value of triplicate measurements for each condition. To ascertain if these data reflected true Michaelis–Menten kinetics, a Lineweaver–Burk plot was constructed and used to determine value of *K_m* (calculated by reciprocally the X intercept in the Line-weaver-Burk plot). The specificity constant (*K_m* / *V_0*) was determined by dividing *K_cat* by *K_m*.

**Effect of chymotrypsin on rSEQ0694 and rSEQ0694parv recombinant proteins**

To determine if chymotrypsin had any significant effect on the recombinant proteins, 10 μL purified rSEQ0694 (60 mg mL\(^{-1}\)) or rSEQ0694parv (40 mg mL\(^{-1}\)) was incubated with chymotrypsin (10 μL, 20 μg mL\(^{-1}\)) in 880 μL assay buffer (20 mM HEPES, pH 7.4; 140 mM NaCl; 1 mM DTT) for 20 s, 2 min and 5 min at 0 °C. The reaction was stopped by the addition of 100 μL 10 mM PMSF and subsequent incubation for 5 min at 0 °C. Incubations containing rSEQ0694 or rSEQ0694parv incubated with PMSF-inactivated chymotrypsin, chymotrypsin with PMSF, chymotrypsin alone, recombinant proteins with PMSF and recombinant proteins alone served as controls. The reactions were analyzed by SDS-PAGE.

**Proteomic & bioinformatic methods**

To compare protein expression in *S. equi* 4047 and ΔprtM\_138–213 the strains were grown to mid-log phase in Todd Hewitt broth, harvested by centrifugation and total cell proteins prepared as described previously.[^22,23] After removal of cells, supernatant proteins were precipitated with 100% (v/v) trichloroacetic acid, washed three times with ice-cold acetone and processed as for total-cell proteins. Two-dimensional electrophoresis (2DE) and protein spot identification following trypsinolysis and mass spectrometry were performed as described previously.[^22,23] Only proteins identified with ≥ 2 peptide matches and Mascot total scores ≥ 50 were included.

Protein sequence alignments were performed using Clustal Omega[^24](http://www.ebi.ac.uk/Tools/msa/clustalo/).
Physiological tests
Survival of *S. equi* strains in saline solutions was tested by resuspending early stationary phase cells in 0, 0.9%, 14.7% or 29.4% NaCl w/v essentially as described by Reffuveille *et al.*\textsuperscript{25} Cell suspensions were sampled after 24 and 48 h by serial dilution to $10^{-3}$ in the same medium and then plated on Todd Hewitt agar plates for enumeration of surviving colony forming units. Antibiotic sensitivity testing was performed by the standard disc diffusion method using discs containing ampicillin (10 $\mu$g per disc), penicillin G (6 $\mu$g per disc), streptomycin (500 $\mu$g per disc), norflaxacin (5 $\mu$g per disc) and vancomycin (30 $\mu$g per disc). Zones of inhibition were measured after 48 h incubation.

Results and discussion
rSEQ0694 encodes a functional PPIase
Our earlier study of *S. equi* SEQ0694\textsuperscript{19} confirmed that this lipoprotein is needed for full virulence but did not directly address its function. Bioinformatic analyses indicated that SEQ0694 exhibits significant pairwise homologies to members of the PrsA/parvulin family of PPIases. In *Firmicutes*, these proteins typically contain a central parvulin domain, flanked by N- and C-terminal domains with likely additional chaperone functions or roles in substrate recruitment,\textsuperscript{13,26,27} although these flanking domains show limited sequence homology (ESI,† Fig. S1). Notably, the parvulin domains of streptococcal and lactococcal PrsA/PrtM family members have been noted to lack key conserved residues\textsuperscript{13,28} (see below) and both *L. lactis* PpmA and *S. pneumoniae* PpmA apparently lack PPIase activity,\textsuperscript{14,29} although it is notable that these proteins can complement some, but not all phenotypes, of a *L. monocytogenes* prsA2 mutant.\textsuperscript{30}

To confirm in vitro PPIase activity of SEQ0694, we produced full-length SEQ0694 as a recombinant protein, rSEQ0694 (ESI,† Fig. S2), for assay using a standard protease-coupled PPIase assay in which the rate of cis to trans isomerisation of a tetrapeptide substrate is measured through selective and colourigenic chymotrypsin hydrolysis of the trans isomer.\textsuperscript{12,21} In addition we produced the central parvulin domain of SEQ0694 as a recombinant protein, rSEQ0694parv. Both recombinant proteins were assayed against three tetrapeptide substrates varying in the amino acid preceding the critical proline residue. Whereas no activity could be detected using tetrapeptide substrates containing lysine–proline or alanine–proline bonds (data not shown), both rSEQ0694 and rSEQ0694parv were found to exhibit PPIase activity using Suc-Ala-Phe-Pro-Phe-pNA as substrate (Fig. 1). However, both recombinant proteins exhibited notably lower activities than the calf thymus cyclophilin used as a positive control.

Recombinant protein stability to chymotrypsin under the assay conditions was assessed. Significant cleavage of rSEQ0694parv by chymotrypsin was observed (ESI,† Fig. S3), whereas rSEQ0694 remained relatively stable for up to 5 min. This meant that although rSEQ0694parv showed an apparently faster rate of reaction compared with rSEQ0694 (Fig. 1), enzyme kinetics could only be determined for the latter (Fig. 2). A $K_{cat}$, $K_m$ of $5.84 \times 10^3$M s$^{-1}$ for rSEQ0694 was calculated from triplicate PPIase assays, suggesting that rSEQ0694 is a moderately active PPIase compared to other members of the parvulin family, with a similar activity to *E. coli* PpiC (Table 1). This activity was somewhat surprising as sequence alignments indicate that several amino acids considered functionally significant in parvulins\textsuperscript{31–35}
are not conserved in rSEQ0694 (Fig. 3). However, a candidate Asp (D187) which might fulfil the role of the critical conserved Asp/Cys could be identified in rSEQ0694 (Fig. 3). Although a role of this Asp/Cys as a catalytic nucleophile is not yet fully resolved, its conservation in rSEQ0694 is likely to be significant. Moreover, the conserved residues in bacterial PrsA proteins identified by Jakob et al. are well conserved in SEQ0694 (ESI† Fig. S1).

Proteomic analyses to identify putative SEQ0694 substrates

Having established that rSEQ0694 is a bona fide PPIase in vitro, we were interested to further explore the nature of its substrates. As SEQ0694 is a lipoprotein, we hypothesised that its substrates would be secreted proteins emerging from the Sec translocase, which need to fold rapidly en route to secretion. Misfolded proteins are typically turned over rapidly by extracytoplasmic proteases such as Htra family members. Proteomic approaches have therefore been used to identify extracytoplasmic proteins for which folding is dependent on a lipoprotein PPIase.

Thus we used proteomics to analyse differential protein expression in the proteomes of S. equi 4047 and an isogenic mutant, ΔprtM138–213, expressing a SEQ0694 N + C domains fusion protein lacking much of the central parvulin domain of SEQ0694 (Fig. 3). Note that as the seq0694 mutant strain was originally designated ΔprtM138–213 for consistency we have retained this designation.

Master 2D PAGE gels from 6 matched gel pairs (ESI† Fig. S4) were analysed for differential protein expression and significant spots identified by mass spectrometry (Tables 2 and 3). Of the detectable total cell proteins, 12 differentially expressed proteins in 10 spots were identified (Table 2). The changes were primarily in cytoplasmic enzymes (e.g. enolase) which, because the proteins fold in the cytoplasm, may reflect general responses to stress due to lack of fully functional SEQ0694 (see below). Four of these proteins were also detected in the cell-free supernatant proteins (Table 3). In the cell-free supernatant proteomes, 13 proteins in 17 spots were found to be differentially expressed. As expected, the majority of these are proteins predicted to be either secreted or cell envelope localised and because of this could be plausible substrates for SEQ0694 (Table 3). As multiple proteins were found to be absent from the cell-free supernatant proteome of the mutant strain ΔprtM138–213, we hypothesise that SEQ0694 is likely to influence folding and secretion of multiple substrates rather than a specific substrate. Interestingly, two previously reported virulence factors of S. equi were notably absent from the cell-free supernatant proteome of the ΔprtM138–213 mutant: the truncated fibronectin-binding protein FNE40–42 and IgG endopeptidase IdeE2.43 FNE is noted to folding and secretion of multiple substrates rather than a specific substrate. Cumulatively, these proteomic changes likely explain, at least in part, the attenuation of the ΔprtM138–213 mutant.19

Table 1 Comparison of the activities of parvulin family members

| Parvulin   | Substrate a | $K_{cat}/K_{m}/M$ s | Ref.   |
|------------|-------------|---------------------|--------|
| rSEQ0694   | Phe         | $5.8 \times 10^6$   | This study |
| rSEQ0694   | Lys         | Inactive            | This study |
| rSEQ0694   | Ala         | Inactive            | This study |
| B. subtilis PrsA | Lys     | $1.5 \times 10^3$   | 27 and 33 |
| B. subtilis PrsA | Ala     | $0.6 \times 10^6$   | 33      |
| B. subtilis PrsA | Glu      | $0.8 \times 10^6$   | 33      |
| S. aureus PrsA | Lys      | $0.5 \times 10^6$   | 33      |
| S. aureus PrsA | Ala      | $1.7 \times 10^6$   | 33      |
| S. aureus PrsA | Glu      | $3.3 \times 10^4$   | 33      |
| E. coli PpiC (Par10) | Leu | $1.3 \times 10^7$   | 46      |
| E. coli PpiC (Par10) | Ser | $3.7 \times 10^7$   | 47      |
| E. coli PpiD (Par68) | Ala | $1.1 \times 10^7$   | 48      |
| E. coli PpiD (Par68) | Glu | $3.4 \times 10^7$   | 48      |
| E. coli PpiD (Par68) | Leu | $2.3 \times 10^7$   | 48      |
| Human Pn4 (Par14) | Arg | $3.9 \times 10^7$   | 46      |
| L. lactis PpmA | Ala     | Inactive c           | 29      |
| S. pneumoniae PpmA | Ala, Phe, Gly, Val, Leu, Gln, Glu | Inactive | 14      |

a Data from protease-coupled assays where substrate is a colourigenic tetrapeptide Succ-Ala-X-Pro-Phe-pNA in which X is the amino acid indicated in the Table. b Estimation from Fig. 1 in Heikkinen et al.33. c Subsequently Weininger et al.49 have reported that PpiD is inactive as a PPIase using modified substrates in a protease-free assay. d Data from a protease-free assay using the tetrapeptide Succ-Ala-Ala-Pro-Phe-2,4-difluoromide as substrate.
However, as the DprtM138–213 mutant should still express a N + C domain fusion protein (lacking most of the parvulin domain), it may be that more dramatic proteome changes would be evident in an seq0694 null mutant, since a L. monocytogenes PrsA N + C construct partly complemented the proteome defect of a full prsA deletion and an N + C fusion construct of B. subtilis PrsA partially restored secretion of an AmyQ reporter protein (although it did not restore viability to PrsA-depleted cells). In B. subtilis, the N and C domain is notable in driving dimerization of PrsA and, although lacking primary sequence homology, has structural similarity to other ‘foldases’ such as trigger factor. Without structural characterisation of the N + C fusion encoded by the

Fig. 3  Sequence alignment of SEQ0694 with representative members of the parvulin family. Alignment produced with Clustal Omega. The signal peptide sequences of the Firmicutes proteins have been removed so that each sequence starts from the lipidated cysteine at the N-terminus of the mature protein. Key active site residues of the characterised parvulins are highlighted in yellow. For the longer bacterial sequences, the region aligning with the short E. coli PpiC sequence corresponds to the central parvulin domain. Realignment of the gapping in the central parvulin domain region in SEQ0694 could bring D187 into alignment with the critical D/C residue present in the characterised parvulins. The position of the region deleted in the S. equi mutant strain DprtM19 is shown in bold. Abbreviations and UniProt accession codes for the sequences are: Bsu_PRSA (Q81U45); B. subtilis PrsA (P24327); Eco_PpiC, E. coli PpiC/Par10 (P0A9L5); Hsa_Par14, Homo sapiens Pin4 (Q9Y237); LMO_PrsA2, L. monocytogenes PrsA2 (Q71XE6); Sau_PrsA, Staphylococcus aureus PrsA (A6QI23); and SEQ0694, S. equi PrsA (C0M9L5).
Table 2  Proteins identified in differentially expressed spots on 2DE of cell associated protein extracts of *S. equi* 4047 compared to its isogenic mutant producing an internally deleted SEQ0694

| Spot #  | Protein identified | Score | Matched peptides | % cover | Predicted function  | Signal peptide |
|---------|--------------------|-------|------------------|---------|---------------------|----------------|
| WT2201  | SEQ0698            | 1229  | 17               | 54      | Enolase (PF00113, PF03952) | No             |
| WT2201  | SEQ1657            | 117   | 3                | 8       | Cyclophilin PPlase (PF00160) | Lipoprotein    |
| WT2201  | SEQ2010            | 91    | 2                | 26      | 10 kDa chaperonin GroES (PF00166) | No             |
| WT3201  | SEQ1366            | 206   | 5                | 14      | Xaa-His dipeptidase (PF01546) | No             |
| WT3601  | SEQ0434            | 158   | 3                | 14      | Mannose-6-phosphate isomerase (PF01238) | No             |
| WT4001  | SEQ0408            | 318   | 6                | 68      | 3OS ribosomal protein S6 (PF01230) | No             |
| WT4204  | SEQ1025            | 188   | 3                | 25      | Asp23 domain protein (PF03780) | Pyrophosphatase |
| WT5302  | SEQ1354            | 184   | 3                | 23      | Purine nucleoside phosphorylase (PF01489) | No             |
| WT5504  | SEQ0046            | 293   | 6                | 30      | Alcohol dehydrogenase (PF00107, PF08240) | No             |
| WT6201  | SEQ1418            | 163   | 4                | 26      | Putative tTDP-4-keto-6-deoxyglucose-3,5-epimerase (PF00908) | No             |
| WT6501  | SEQ1011            | 408   | 6                | 22      | 6-Phosphofructokinase (PF00365) | No             |
| Prt1401 | SEQ1642            | 103   | 3                | 23      | Recombinase-binding factor (PF01765) | No             |

a  Spot marked in ESI, Fig. S4. WT spots are upregulated or only detected in the wild type strain 4047, Prt spots were only detected in the mutant prtM138–213 mutant proteome. b As annotated in Holden et al., Mascot score. c Number of non-redundant peptides identified for each protein. d Percent amino acid coverage of entire protein. e As determined from Uniprot annotation, BlastP and PFAM analysis.

Table 3  Proteins identified in differentially expressed spots on 2DE of supernatant extracts of *S. equi* 4047 compared to its isogenic mutant producing an internally deleted SEQ0694. WT spots are upregulated or only detected in the wild type strain 4047, Prt spots were only detected in the mutant prtM138–213 proteome

| Spot #  | Protein identified | Score | Matched peptides | % cover | Predicted function  | Signal peptide |
|---------|--------------------|-------|------------------|---------|---------------------|----------------|
| WT1002  | SEQ0210            | 174   | 4                | 57      | 10 kDa chaperonin GroES (PF00166) | No             |
| WT1401  | SEQ1821            | 334   | 4                | 38      | PepSy (PF03413) protease inhibitor domain lipoprotein | Pyrophosphatase |
| WT1402  | SEQ1177            | 198   | 5                | 22      | Domain of Unknown Function (PF06207/DFU1002) | Present        |
| WT2101  | SEQ1800            | 119   | 2                | 30      | Unknown function, no conserved domains. Restricted distribution within streptococci; spot position shifted compared to mutant Prt1103 | Present        |
| WT2202  | SEQ1025            | 146   | 3                | 20      | Asp23 domain protein (PF03780) | No             |
| WT2202  | FNE                | 72    | 2                | 6       | Truncated fibronectin binding protein (PF08341) | Present        |
| WT2401  | SEQ1177            | 526   | 8                | 36      | Domain of unknown function (PF06207/DFU1002) | Present        |
| WT3301  | SEQ1657            | 409   | 6                | 35      | Cyclophilin type PPlase (PF00160) | Lipoprotein    |
| WT3701  | SEQ0882            | 519   | 7                | 39      | DNA/RNA non-specific endonuclease | Present        |
| WT7301  | FNE                | 361   | 6                | 26      | Truncated fibronectin binding protein (PF08341) | Present        |
| WT8401  | SEQ0938            | 331   | 6                | 19      | IdE2 Mac family protein (PF09028) | Present        |
| WT8501  | SEQ0938            | 204   | 4                | 11      | IdE2 Mac family protein (PF09028) | Present        |
| WT9202  | FNE                | 221   | 5                | 13      | Truncated fibronectin binding protein (PF08341) | Present        |
| WT9202  | SEQ0882            | 93    | 3                | 14      | DNA/RNA non-specific endonuclease | Present        |
| WT9403  | SEQ0520            | 556   | 10               | 41      | Hydrolase/esterase (PF07059) | Present        |
| Prt0301 | SEQ1171            | 165   | 4                | 25      | Sortase A (PF04203) | Signal anchor |
| Prt1103 | SEQ1800            | 133   | 3                | 36      | Unknown function, no conserved domains. Restricted distribution within streptococci; position shifted compared to mutant WT2101 | Present        |
| Prt1202 | SEQ1919            | 221   | 3                | 6       | OppA olipopeptide binding lipoprotein (PF00496) | Lipoprotein    |
| Prt2101 | SEQ0408            | 139   | 2                | 26      | 3OS ribosomal protein S6 (PF01230) | No             |
| Prt2301 | SEQ1919            | 86    | 3                | 6       | OppA olipopeptide binding lipoprotein (PF00496) | Lipoprotein    |

a  Spot marked in ESI, Fig. S4. b As annotated in Holden et al., Mascot score. c Number of non-redundant peptides identified for each protein. d Percent amino acid coverage of entire protein. e As determined from Uniprot annotation, BlastP and PFAM analysis.

*S. equi* ΔprtM138–213 mutant we cannot speculate whether this construct is likely to have a native-like conformation and functionality. However, it is notable that the sequence deletion removes not only the majority of the parvulin domain of SEQ0694 but also a conserved lysine of the *Firmicutes* PrsA protein N-domains. It is worth reemphasising that the partial deletion in the *S. equi* ΔprtM138–213 mutant is sufficient to cause significant attenuation of virulence in the natural host.†

It was interesting to note that SEQ1657, a cyclophilin PPlase lipoprotein (orthologous to *S. pneumoniae* SlaA and *L. lactis* PpiA) was up-regulated in both the total cell and secreted proteins of the parental strain. Likewise, it was observed that the SEQ1171 sortase is up-regulated in the mutant strain, perhaps suggesting a need to remodel protein localisation within the mutant cell envelope.

As the proteomic data suggested a range of protein functions are likely to be perturbed in strain ΔprtM138–213 including stress responses, we performed several physiological tests. Although the mutant strain grows normally in nutrient rich broth, we observed pleiotropic changes including increased sensitivity to salt stress (ESI,† Table S1) and increased sensitivity to various antibiotics with diverse cellular targets (ESI,† Fig. S5). Increased sensitivity to salt stress has previously been observed in a prsA mutant of *E. faecalis* and a prsaA2 mutant.

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**Note**: The content is presented as extracted text without further processing to maintain readability. For full reference, consult the original publication.
of \textit{L. monocytogenes}. A range of findings have been observed regarding antibiotic susceptibilities of other \textit{prsA} mutants. Similar to our findings, a \textit{prsA}2 mutant of \textit{L. monocytogenes} displayed increased sensitivity to bacitracin, penicillin and vancomycin but not gentamicin\textsuperscript{30} and a mutant in \textit{Staphylococcus aureus} \textit{prsA} showed increased sensitivity to vancomycin.\textsuperscript{45} However, a \textit{prsA} mutant of \textit{E. faecalis} was unaffected in its sensitivity to ampicillin and norflaxin,\textsuperscript{11} in contrast to our findings. Cumulatively, our data suggest a general perturbation in cell envelope function in the \textit{\DeltaprtM}\textsubscript{138-213} mutant, which likely reflects multiple changes in the extracytoplasmic proteome of the mutant (consistent with our proteomic data). This is conclusion is consistent with the pleiotropic effects of \textit{PrsA} mutation in other \textit{Firmicutes}.\textsuperscript{11,28,30,45}

**Conclusions**

The data presented here confirm that rSEQ0694 is a moderately active PPIase, despite lacking conservation of several amino acids previously considered to be significant to the activity of other parvalin PPIases. This observation thus focusses attention on the conserved Asp/Cys identified as likely critical for catalysis. Furthermore, proteomic experiments confirm that loss of the lipoprotein PPIase activity in strain \textit{\DeltaprtM}\textsubscript{138-213} affects multiple cell envelope proteins, including virulence factors, and is likely to generate diverse phenotypic effects. As strain \textit{\DeltaprtM}\textsubscript{138-213} is attenuated,\textsuperscript{19} these findings further suggest that streptococcal PPIases, and PPIases generally,\textsuperscript{7} are interesting targets for novel therapeutic strategies. By analogy with other bacterial PPIases, it would also be of interest to determine whether the N- and C-terminal domains of SEQ0694 possess additional chaperone activities that contribute to post-translocational protein folding.

**Abbreviations**

\textit{\textit{\rho}Na} Paranitroaniline  
PPIase Peptidyl-prolyl isomerase  
rSEQ0694 Recombinant N-terminally His-tagged mature SEQ0694  
rSEQ0694parv Recombinant N-terminally His-tagged parvalin domain of SEQ0694

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