ddcP, *pstB*, and excess D-lactate impact synergism between vancomycin and chlorhexidine against *Enterococcus faecium* 1,231,410

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Running title: Vancomycin and chlorhexidine synergism in VRE

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Abstract

Vancomycin-resistant enterococci (VRE) are important nosocomial pathogens that cause life-threatening infections. To control hospital-associated infections, skin antisepsis and bathing utilizing chlorhexidine is recommended for VRE patients in acute care hospitals. Previously, we reported that exposure to inhibitory chlorhexidine levels induced the expression of vancomycin resistance genes in VanA-type *Enterococcus faecium*. However, vancomycin susceptibility actually increased for VanA-type *E. faecium* in the presence of chlorhexidine. Hence, a synergistic effect of the two antimicrobials was observed. In this study, we used multiple approaches to investigate the mechanism of synergism between chlorhexidine and vancomycin in the VanA-type VRE strain *E. faecium* 1,231,410. We generated clean deletions of 7 of 11 *pbp*, transpeptidase, and carboxypeptidase genes in this strain (*ponA*, *pbpF*, *pbpZ*, *pbpA*, *ddcP*, ldt_{fm}, and *vanY*). Deletion of *ddcP*, encoding a membrane-bound carboxypeptidase, altered the synergism phenotype. Furthermore, using *in vitro* evolution, we isolated a spontaneous synergy escaper mutant and utilized whole genome sequencing to determine that a mutation in *pstB*, encoding an ATPase of phosphate-specific transporters, also altered synergism. Finally, addition of excess D-lactate, but not D-alanine, enhanced synergism. Overall, our work identified factors that alter chlorhexidine-induced vancomycin resensitization in a model VanA-type VRE strain.

53 **Introduction**

54

55 *Enterococcus faecium* are Gram-positive commensal bacteria inhabiting the gastrointestinal
56 tracts of humans and animals (1). The ability to survive in harsh environmental conditions
57 including starvation and desiccation facilitated the emergence of hospital-adapted strains which
58 are resistant to the action of antibiotics and disinfectants (2). Hospital-adapted enterococcal
59 strains have limited treatment options and are typically characterized by high-level resistance to
60 vancomycin, a glycopeptide antibiotic which inhibits the process of peptidoglycan synthesis (3,
61 4). Vancomycin-resistant enterococci (VRE) synthesize peptidoglycan precursors for which
62 vancomycin has low affinity (5-8). Vancomycin resistance in hospital-adapted enterococcal
63 isolates occurs through the horizontal acquisition of resistance genes (9, 10). For VanA-type
64 VRE, vancomycin resistance is conferred and controlled by the activities encoded by the
65 *vanRS, vanHAX*, and *vanYZ* genes.

66

67 Patients in critical care units are frequently bathed or cleansed with chlorhexidine, a cationic cell
68 membrane-targeting antimicrobial, to reduce the occurrence of hospital-associated infections
69 (11-13). Chlorhexidine interacts with the negatively charged phospholipids and proteins on the
70 cell membrane after primary adsorption by the cell (14, 15). Low chlorhexidine levels disrupt the
71 membrane potential and integrity whereas high chlorhexidine levels can cause a complete
72 precipitation of the cytoplasm (16-18). We previously analyzed the transcriptome of the VanA-
73 type vancomycin-resistant strain *E. faecium* 1,231,410 exposed to inhibitory levels of
74 chlorhexidine, and we found that chlorhexidine stress induced the expression of the VanA-type
75 vancomycin resistance genes (19). However, vancomycin MIC actually decreased when
76 chlorhexidine was present in broth microdilution assays (19).

77

78 We previously proposed three models to explain chlorhexidine-induced vancomycin

79 sensitization despite transcriptional activation of VanA-type vancomycin resistance genes by
80 chlorhexidine (19). Vancomycin resistance genes code for the synthesis of alternative
81 peptidoglycan precursors that terminate in D-alanine-D-lactate (D-Ala-D-Lac), for which
82 vancomycin has lower affinity compared to the normal D-alanine-D-alanine (D-Ala-D-Ala).
83 Model 1 is that altered penicillin-binding protein (Pbp) levels in the presence of chlorhexidine
84 prevents D-Ala-D-Lac precursors from being cross-linked. Model 2 proposes that chlorhexidine
85 alters substrate pools for peptidoglycan synthesis, resulting in vancomycin-sensitive termini that
86 are neither D-Ala-D-Ala nor D-Ala-D-Lac. Model 3 is that post-translational regulation of VanX
87 and/or VanY prevents depletion of D-Ala-D-Ala termini from peptidoglycan precursors in the
88 presence of chlorhexidine. In this study, we used targeted gene deletions, *in vitro* evolution, and
89 culture assays in modified media to assess specific features of these models. Overall, we
90 identify two genes, *ddcP* and *pstB*, and one growth condition (excess D-lactate), that alter
91 chlorhexidine-induced vancomycin sensitization in the model VanA-type VRE strain *E. faecium*
92 1,231,410.
93
94 **Materials and Methods**
95
96 **Bacterial strains and growth conditions**. Bacterial strains used in this study are shown in
97 Table 1. *E. faecium* was cultured at 37°C on brain heart infusion (BHI) agar or in broth without
98 agitation unless otherwise stated. *Escherichia coli* was cultured at 37°C in lysogeny broth (LB)
99 broth with shaking at 225 rpm or on LB with 1.5% agar unless otherwise stated. The
100 chlorhexidine product used for all experiments was Hibiclens (4% wt/vol chlorhexidine gluconate
101 with 4% isopropyl alcohol). We refer to Hibiclens as H-CHG in this study. Antibiotics were added
102 at the following concentrations: vancomycin, 50 µg/ml for *E. faecium*, and chloramphenicol, 15
103 µg/ml for *E. coli*.
104

105 **Table 1. Bacterial strains and plasmids used in the study.**

Strain or plasmid	Description	Reference
Bacterial strains		
E. faecium 1,231,410	Clade A clinical isolate from skin and soft tissue infection; VanA-type VRE	(20)
PB411	*E. faecium* 1,231,410 Δ*pbpF* (EFTG_02258)	This study
PB412	*E. faecium* 1,231,410 Δ*ddcP* (EFTG_01253)	This study
PB413	*E. faecium* 1,231,410 Δ*vanY* (EFTG_02039)	This study
PB414	*E. faecium* 1,231,410 Δ*ldtfm* (EFTG_02461)	This study
PB416	*E. faecium* 1,231,410 Δ*ponA* (EFTG_00370)	This study
PB417	*E. faecium* 1,231,410 Δ*pbpZ* (EFTG_01189)	This study
PB418	*E. faecium* 1,231,410 Δ*ddcP* Δ*vanY*	This study
PB419	*E. faecium* 1,231,410 Δ*pbpA* (EFTG_02132); marked deletion with *tetL*	This study
MI111	*E. faecium* PB412 with reconstituted *ddcP*	This study
MI112	*E. faecium* 1,231,410 Δ*ddcP* Δ*ldtfm*	This study
SE101	Synergy escaper mutant; has Ser199Leu substitution in EFTG_01173	This study
PB430	*E. faecium* 410 Δ*pst* transporter (EFTG_01170-74)	This study
PB431	SE101 Δ*pst* transporter (EFTG_01170-74)	This study
Plasmids		
pHA101	Markerless, counterselectable exchange plasmid; confers chloramphenicol resistance (Cam^R)	(19)
pPB401	pHA101 containing a 2.028-kb EcoRI/EcoRI-digested fragment flanking upstream and downstream of *E. faecium* 410 *pbpF* (EFTG_02258), Cam^R	This study
pPB402	pHA101 containing a 2.019-kb EcoRI/EcoRI-digested fragment flanking upstream and downstream of fragment flanking upstream and downstream of *E. faecium* 410 *ddcP* (EFTG_01253), Cam^R	This study
pPB403	pHA101 containing a 2.010-kb EcoRI/EcoRI-digested fragment flanking upstream and downstream of *E. faecium* 410 *vanY* (EFTG_02039), Cam^R	This study
pPB404	pHA101 containing a 2.010-kb EcoRI/EcoRI-digested fragment flanking upstream and downstream of *E. faecium* 410 *ldtfm (*EFTG_02461), Cam^R	This study
pPB406	pHA101 containing a 2.028-kb EcoRI/EcoRI-digested fragment flanking upstream and downstream of *E. faecium* 410 *ponA (*EFTG_00370), Cam^R	This study
pPB407	pHA101 containing a 2.028-kb EcoRI/EcoRI-digested fragment flanking upstream and downstream of *E. faecium* 410 *pbpZ (*EFTG_01189), Cam^R	This study
pPB408	pHA101 containing a 4.317-kb fragment containing	This study

	flanking upstream, tetracycline resistance gene (*tetL*), downstream arms of *E. faecium* 410 *pbpA* EFTG_02132, confers tetracycline antibiotic resistance	
pMI101	pHA101 containing a 3.303-kb EcoRI/EcoRI-digested fragment flanking upstream and downstream arms with *ddcP* gene (EFTG_01253), Cam^R	This study
pPB411	pHA101 containing a 2.028-kb EcoRI/EcoRI-digested fragment flanking upstream and downstream of *E. faecium* 410 *pst* transporters (EFTG_01170-74), Cam^R	This study

106

107

108 **Routine molecular biology techniques**. *E. faecium* genomic DNA (gDNA) was isolated using
109 a previously published protocol (21). Electroporation of *E. faecium* was performed as described
110 previously (19). Plasmids were purified using the GeneJET Miniprep kit (Thermo Scientific).
111 DNA fragments were purified using the Purelink PCR purification kit (Invitrogen). *Taq*
112 polymerase (New England Biolabs; NEB) was used for routine PCR reactions. Phusion
113 polymerase (Fisher) was used for cloning applications. Restriction endonucleases (NEB) and T4
114 DNA ligase (NEB) reactions were performed per the manufacturer's instructions. Routine DNA
115 sequencing was performed by the Massachusetts General Hospital DNA core facility (Boston,
116 MA). All genetic constructs were validated by DNA sequencing. Primers used in this study are
117 shown in Table S1.

118

119 **MIC determinations**. The minimum inhibitory concentration (MIC) was defined as the lowest
120 drug concentration at which the OD_{600nm} of the bacterial culture matched the OD_{600nm} of the
121 negative control (uninoculated BHI broth). For this study, we refer to synergy MIC as the
122 vancomycin MIC of enterococci in BHI supplemented with H-CHG. The synergy MIC was
123 determined by slightly modifying our previously published protocol (19). 5 µl of vancomycin
124 stock solution (40 mg/ml in water) was added to 195 µl of BHI supplemented with H-CHG in the
125 first well of a 96-well microtiter plate. Next, 100 µl was transferred to the next well containing

126 100 µl of BHI supplemented with H-CHG to make two-fold serial dilutions of vancomycin drug.
127 Overnight cultures of *E. faecium* were diluted to OD_{600} of 0.01 in fresh BHI, and 5 µl of the
128 diluted culture was used to inoculate the wells of the plate. The OD_{600} of the cultures was
129 measured after 24 h incubation at 37°C. For determining synergy MIC in the presence of D-
130 lactate or D-alanine, D-lactate or D-alanine were solubilized to a final concentration of 0.2 M in
131 BHI and the solutions were filter sterilized. Two-fold serial dilutions of vancomycin were made in
132 BHI supplemented with D-lactate/D-alanine and H-CHG as described above. Fold decrease was
133 calculated by dividing the vancomycin MIC in the absence of H-CHG by the vancomycin MIC in
134 the presence of the highest H-CHG concentration at which visible growth was observed. Each
135 experiment was performed independently at least three times.
136
137 **Deletion of genes in *E. faecium*.** Genes were deleted in-frame utilizing plasmid pHA101 as
138 described previously (19). Briefly, ~1 kb regions upstream and downstream of the target gene
139 were amplified and ligated to pHA101. The sequence of the deletion construct plasmid was
140 verified by Sanger sequencing and introduced into *E. faecium* by electroporation. Temperature
141 shifting at the non-permissible temperature of 42°C and counter-selection with *p*-
142 chlorophenylalanine was followed according to a previously published protocol (22).
143 Presumptive deletion mutants were confirmed by Sanger sequencing of the region of interest
144 followed by Illumina genome sequencing (see below).
145
146 After several unsuccessful attempts to generate an unmarked deletion of *pbpA* in *E. faecium*
147 1,231,410, we introduced a tetracycline resistance marker (*tetL*) between the flanking upstream
148 and downstream arms of the deletion construct to select for deletion mutants. Briefly, *tetL* was
149 amplified from pLT06-*tet* using primers *tetL* For and Rev. The deletion construct was linearized
150 via PCR using Phusion DNA polymerase (Fisher) and primers *pbpA*-linear For and Rev (Table
151 S1). The linearized PCR product was dephosphorylated using Shrimp Alkaline phosphatase

152 (New England Biolabs) per the manufacturer's instructions and then ligated with *tetL* to generate
153 the deletion construct PB408. The deletion construct was propagated in EC1000 and
154 sequenced using Sanger sequencing prior to transformation into *E. faecium* 1,231,410.
155
156 **Complementation of *ddcP* deletion.** The *ddcP* gene was restored to the chromosome of the
157 *E. faecium* 1,231,410 *ddcP* deletion mutant. The *ddcP* gene and ~1 kb regions up- and
158 downstream were amplified from *E. faecium* 1,231,410 wild-type gDNA, and the amplicon was
159 digested and inserted into pHA101. The knock-in plasmid construct (pMI101) was transformed
160 into the *ddcP* deletion mutant by electroporation. The temperature shifting and counter-selection
161 protocol was followed as described previously (22). The chromosomal integration of the gene
162 was confirmed by Sanger sequencing.
163
164 **Growth kinetics of *E. faecium* in the presence of H-CHG and vancomycin**. Overnight
165 cultures of *E. faecium* were diluted to an OD_{600} of 0.01 in fresh, pre-warmed BHI and incubated
166 at 37°C with shaking at 100 rpm. The cultures were grown until OD_{600} reached 0.5 to 0.6.
167 Twenty-five milliliters of the culture were added to equal amounts of pre-warmed BHI containing
168 vancomycin (50 µg/ml) and/or H-CHG (4.9 µg/ml), or only BHI (control). OD_{600} values were then
169 monitored hourly for 6 h, and an OD_{600} reading was taken at the 24 h time point. For some
170 experiments and timepoints, CFU/mL were additionally determined by serial dilution of culture
171 and plating on BHI agar. Growth curves were repeated independently three times. For
172 assessing synergy between vancomycin and glycine, the same experimental design was used,
173 except that H-CHG was replaced with 0.2 M glycine.
174
175 **Isolation of *E. faecium* 1,231,410 synergy escaper mutant.** An *E. faecium* 1,231,410 wild-
176 type culture treated with vancomycin and H-CHG was incubated for 24 h, when turbidity was
177 observed. The recovered culture was used as an inoculum for a second growth curve

178 experiment with vancomycin and H-CHG. OD_{600} values were monitored for 6 h, and at the end
179 of 6 h, the cultures were cryopreserved at -80°C. The stocked populations were struck on BHI
180 agar, and the synergy MIC was determined for well-isolated colonies using the broth
181 microdilution assay described above. Colonies with elevated synergy MIC as compared to the
182 parental *E. faecium* 1,231,410 strain were passaged three times in BHI broth and the synergy
183 MICs determined again. A strain with a stably elevated synergy MIC was isolated; this strain is
184 referred to as SE101.
185
186 **Genome sequencing and analysis.** SE101 gDNA was isolated according to a previously
187 published protocol (21) and sequenced with Illumina technology at Molecular Research LP
188 (Shallowater, Texas). Paired end, 2x150 reads were obtained. For the analyses, sequence
189 reads were assembled locally to the *E. faecium* 1,231,410 draft reference genome (GenBank
190 accession number NZ_ACBA00000000.1) using default parameters in CLC Genomics
191 Workbench (Qiagen). Polymorphisms in the resequencing assemblies were detected using
192 basic variant mapping using default settings with a minimum variant frequency of 50%. To
193 detect transposon/IS element hopping, the assembly parameters were changed to global
194 instead of local alignment, and regions with sequential polymorphisms were manually analyzed
195 for potential transposon/IS element hopping. Sanger sequencing was utilized to confirm
196 polymorphisms.
197
198 To confirm deletion mutants, gDNA was isolated as above and sequenced with Illumina
199 technology at the UT-Dallas Genome Core (for deletion mutants Δ*pbpF,* Δ*ddcP,* Δ*vanY,* Δ*ldtfm,*
200 Δ*ponA,* Δ*ddcP* Δ*vanY,* Δ*ddcP* Δ*ldtfm,* and the Δ*pbpA* marked deletion with *tetL*) or the Microbial
201 Genome Sequencing Center in Pittsburgh, PA (for the Δ*pbpZ* mutant). Paired end, 2x75 reads
202 and 2x150 reads were obtained, respectively. For the analyses, sequence reads were
203 assembled locally to the *E. faecium* 1,231,410 draft reference genome as above. Average

204 coverage of the reference genome ranged from 88-245X across all mutants analyzed. The
205 absence of the gene of interest was confirmed for each presumptive deletion mutant by
206 manually analyzing the read assembly at the location of the gene.
207
208 **Phosphate levels measurement.** A commercially available kit (Sigma MAK030) and previously
209 published protocol (23, 24) was utilized to measure intracellular inorganic phosphate (P_i) levels
210 at five time points (OD_{600} from 0.4-0.5, 0.6-0.7, 0.7-0.8, 0.8-0.9, 1.0-1.5) from *E. faecium*
211 1,231,410 and SE101 cultures. The phosphate levels were normalized by CFU and five
212 independent trials were performed.
213
214 **Accession number.** Raw Illumina sequencing reads generated in this study are available in the
215 Sequence Read Archive under the accession numbers SRP113791 (for strain SE101) and
216 PRJNA657813 (for confirmation of deletion mutants).
217
218 **Results and Discussion**
219
220 **Addition of D-lactate enhances chlorhexidine-induced vancomycin sensitization.** It was
221 previously observed that culture supplementation with 0.2 M of glycine or select D-amino acids
222 (including D-methionine, D-serine, D-alanine, or D-phenylalanine) increased VRE susceptibility
223 to vancomycin (25). Consistent with this, Aart et al reported that excess D-Ala substrate
224 competes with D-Lac, thereby increasing the ratio of cell wall termini ending at D-Ala and the
225 efficacy of vancomycin against *Streptomyces* and *E. faecium* (26). We reasoned that if H-CHG
226 stress resulted in an alteration of substrate pools and therefore vancomycin-sensitive termini
227 that are neither D-Ala-D-Ala nor D-Ala-D-Lac (Model 2), an excess of D-lactate could compete
228 with this alternative pathway, thereby increasing the number of D-Ala-D-Lac termini and
229 resulting in loss of synergism between vancomycin and H-CHG.

230

231 To test this, synergy assays were performed with *E. faecium* 1,231,410 in the presence of 0.2 M
232 D-lactate or D-alanine (Table 2). Addition of D-lactate to BHI broth lacking H-CHG resulted in a
233 4-fold increase in vancomycin MIC (Table 2), demonstrating that excess D-lactate does result in
234 reduced vancomycin susceptibility. However, and counter to our expectations, in the presence
235 of both D-lactate and H-CHG, the H-CHG-induced vancomycin resensitization phenotype was
236 enhanced (Table 2). This result suggests that the synergism phenotype is dependent upon D-
237 Ala-D-Lac termini and is enhanced by increased abundance of D-Ala-D-Lac termini. As
238 expected based on the results of Aart et al (26), vancomycin MIC decreased in the presence of
239 D-alanine, and we observed only a 2-fold additional MIC decrease in the presence of both D-
240 alanine and H-CHG (Table 2).

241

242 **Table 2. Median vancomycin MICs in *E. faecium* 1,231,410.**

	Vancomycin MIC (µg/ml)[a]		
H-CHG (µg/ml)[b]	**BHI**	**BHI + 0.2 M D-Lactate**	**BHI + 0.2 M D-Alanine**
0	250	1000	7.8
1.2	62.5	1.0	3.9
2.4	0.2	No growth	No growth
4.9	No growth	No growth	No growth

243

244 [a]Vancomycin MICs (µg/ml) at 24 h post-inoculation from at least three independent
245 experiments.

246 [b]4.9 µg/ml H-CHG is the MIC for *E. faecium* 1,231,410; 1.2 µg/ml H-CHG and 2.4 µg/ml H-CHG
247 are 1/4X MIC and 1/2X MIC, respectively.
248
249
250 **Deletion of *ddcP* alters the synergism phenotype.** The enterococcal cell wall is a multi-
251 layered network and is characterized by the presence of peptidoglycan, teichoic acid, and
252 polysaccharides (27, 28). The main component of the cell wall is peptidoglycan, which is a
253 mesh-like structure consisting of parallel glycan chains cross-linked by amino acids (27). The
254 glycan chains consist of two alternating amino sugars, N-acetylglucosamine (GlcNAc) and N-
255 acetylmuramic acid (MurNAc), connected by β-1,4 linkages (29-31). In *E. faecium*, each
256 MurNAc sugar is linked to short stem pentapeptides (L-alanine[1]-D-isoglutamic acid[2]-L-lysine[3]-D-
257 alanine[4]-D-alanine[5]), which alternate between L- and D-amino acids (30, 32). The MurNAc and
258 GlcNAc glycan sugars are synthesized as a UDP (Uridine diphosphate) derivative in a step-wise
259 fashion in the cytosol (33). Next, MurNAc sugars containing short peptides are transferred to a
260 lipid carrier Lipid I (C_{55}-undecaprenol) (34, 35) and added to UDP-derivative GlcNAc to build a
261 disaccharide, GlcNAc-MurNAc-pentapeptide-C_{55} pyrophosphate, also known as Lipid II (33, 34).
262 Lipid II units are translocated from the cytosol to the outer side of the cell membrane (36) and
263 polymerized through an ordered rate of two processes, transglycosylation (condensation of
264 linear glycan chains) and transpeptidation (cross-linking between carboxyl group of one
265 pentapeptide and amino acid of an adjacent pentapeptide). The disaccharide units are
266 integrated into the growing peptidoglycan layers to form the cell wall (37, 38) and the lipid carrier
267 is recycled back into the cytosol.
268
269 Two classes of penicillin-binding proteins (Pbps) mediate the transpeptidation process (39-41).
270 Class A Pbps (encoded by *ponA*, *pbpF,* and *pbpZ*) are bifunctional, multimodular, high-
271 molecular mass proteins, and catalyze both transpeptidation and transglycosylation reactions.

272 Class B Pbps (encoded by *pbpB*, *pbpA,* and *pbp5*) are monofunctional, low-molecular mass
273 proteins, and catalyze only transpeptidation reactions. Class A and B Pbps mediate 4,3 cross-
274 links (D,D-transpeptidation) between cell wall precursors and these cross-links constitute the
275 majority of the mature cell wall (38). However, 3,3 cross-links are also present in the
276 enterococcal cell wall. The combined activities of DdcP or DdcY (D,D-carboxypeptidase) and
277 the L,D transpeptidase Ldt_{fm} can bypass conventional D,D-transpeptidation and mediate 3,3
278 cross-linking (42-44). DdcP and/or DdcY generates tetrapeptides and reduces the availability of
279 pentapeptide precursors by trimming the terminal D-Ala. Next, Ldt_{fm} mediates cross-links
280 between these cell wall termini.
281
282 To determine whether these factors contribute to vancomycin-chlorhexidine synergism against
283 VRE (Model 1), we deleted 6 of 9 of these genes in *E. faecium* 1,231,410 (Table 1). Our
284 presumptive *pbpB*, *pbp5*, and *ddcY* deletion mutants could not be confirmed by genome
285 sequencing. We utilized growth curves to assess phenotypes of the deletion mutants in the
286 presence and absence of vancomycin and H-CHG. For these experiments, vancomycin (50
287 µg/ml) and H-CHG (4.9 µg/ml) were added to exponentially growing *E. faecium* cultures; a no-
288 drug control was also performed. As shown in Fig. 1A, the OD_{600} of *E. faecium* 1,231,410 wild-
289 type cultures decreased after addition of vancomycin and H-CHG, consistent with cell lysis.
290 After 24 h, the cultures treated with vancomycin and H-CHG were visibly turbid, indicating that
291 *E. faecium* can recover from the effects of the antimicrobials in this experimental condition.
292
293
294 **Figure 1. A Δ*ddcP* mutant has an altered vancomycin/H-CHG synergy phenotype.** Optical
295 density (OD_{600nm}) of (A) *E. faecium* 1,231,410 wild-type (*E. faecium* 410), (B) the *ddcP* deletion
296 mutant, and (C) the *ddcP* complemented strain with and without vancomycin and H-CHG
297 treatment. *E. faecium* was cultured in BHI broth until the OD_{600} reached 0.6, as described in

298 materials and methods. Equal volumes of cultures were split into BHI (control; red circles) or
299 BHI containing vancomycin (50 µg/ml) and H-CHG (4.9 µg/ml) (blue squares). OD_{600} values
300 were monitored for 6 h. Error bars indicate standard deviations from n=3 independent
301 experiments. Significance was assessed using the one-tailed Student's *t*-test. * denotes *P*-value
302 < 0.05. Stars indicate significant differences between vancomycin- and H-CHG-treated cultures
303 in panel B versus A, and in panel C versus B. Note that growth curve of *E. faecium* 410 wild-
304 type in the presence of vancomycin and chlorhexidine from Fig. 1A has been shown again in
305 Fig. S1A for comparison with the *pbp* deletion mutants.
306
307
308 The growth phenotypes of the Δ*pbpF*, Δ*ponA*, Δ*pbpZ*, Δ*pbpA,* and Δldt_{fm} deletion mutants, as
309 measured by OD_{600} values, were comparable to the parental strain (Fig. S1). The Δ*ddcP* mutant
310 had a different phenotype from the wild-type strain (Fig. 1B). After treatment with vancomycin
311 and H-CHG, the OD_{600} values for the *ddcP* deletion mutant did not decrease. The OD_{600} values
312 were significantly different between the wild-type and the Δ*ddcP* mutant for all time points post-
313 H-CHG and vancomycin addition (*P*-value < 0.05, one-tailed Student's *t* test). The Δ*ddcP*
314 mutant was complemented by restoration of the *ddcP* gene in *cis*. OD_{600} values of the
315 complemented strain in the presence of vancomycin and H-CHG were similar to the wild-type
316 (Fig. 1C). No statistically significant differences in OD_{600} values were observed between the
317 wild-type and the *ddcP* complemented strain in the presence of vancomycin and H-CHG.
318
319 In separate experiments, we assessed both the OD_{600} and viability of wild-type and Δ*ddcP*
320 cultures for 3 hours post-treatment with vancomycin and H-CHG. Optical density values
321 significantly differed between the two strains post-treatment; however, CFU/mL values did not
322 (Fig. S2). These results suggest that *ddcP* deletion does not alter the mechanism by which
323 vancomycin/H-CHG kills *E. faecium*, but rather whether the dead cells lyse.

324

325 **The Δ*ddcP* mutant has altered susceptibility to vancomycin-glycine synergy.** Synergism
326 between glycine and vancomycin was previously reported for VRE (25). We carried out growth
327 curves in the presence of vancomycin (50 µg/ml) and 0.2 M glycine. A lytic effect was observed
328 for the wild-type strain cultured with vancomycin and glycine, with the most pronounced effect
329 observed at the 24 h time point (Fig. 2A). However, this lytic effect was not observed for the
330 Δ*ddcP* mutant (*P*-value < 0.05, assessed by one-tailed Student's *t*-test) (Fig. 2B). Together with
331 our results in Figure 1 and Figure S2, these results indicate that DdcP activity weakens the cell
332 wall under antimicrobial stress by reducing the availability of cell wall pentapeptide precursors,
333 contributing to cell lysis. This suggests that *ddcP* expression in cells in the presence of CHX and
334 vancomycin antimicrobials contributes to increased cell lysis and synergism between the two
335 antimicrobials.

336

337

338 **Figure 2. A Δ*ddcP* mutant has reduced susceptibility to vancomycin/glycine synergy.** (A)
339 *E. faecium* 410 wild-type and (B) *ddcP* deletion mutant cultures were grown at 37°C in BHI until
340 OD_{600} reached 0.6 as described in materials and methods. Equal volumes of cultures were split
341 into BHI (control; red circles) or BHI containing vancomycin (50 µg/ml) and glycine (0.2 M)
342 (green squares). OD_{600} values were monitored for 6 h and a reading at 24 h was recorded. Error
343 bars indicate standard deviations from n=3 independent experiments. Significance was
344 assessed using the one-tailed Student's *t*-test. * denotes *P*-value < 0.05. Stars indicate
345 significant differences between vancomycin- and glycine-treated cultures in panel B versus A.

346

347

348 **A *vanY$_A$* mutant does not have an altered synergy phenotype.** Previously, Kristich et al
349 investigated the genetic basis of synergism between vancomycin and cephalosporins (a class of

350 β-lactam antibiotics) in the VanB-type VRE strain *E. faecalis* V583 (45). The synergism was
351 mediated by $VanY_B$, a carboxypeptidase that reduces the availability of precursors ending at D-
352 Ala-D-Ala by trimming the terminal D-Ala, thereby eliminating the target of vancomycin. In the
353 absence of $vanY_B$, cross-linking of cell wall precursors was mediated by low-affinity Pbps and
354 synergism between vancomycin and cephalosporins was lost (45). To determine whether $vanY_A$
355 contributed to vancomycin-chlorhexidine synergism against VRE, which is a component of our
356 Model 3, we deleted $vanY_A$ in *E. faecium* 1,231,410. We observed no effect on the synergy
357 phenotype as assessed by OD_{600} values (Fig. S1C). Moreover, deletion of *ddcP* in a Δ*vanY*
358 background did not further enhance the phenotype of a Δ*ddcP* mutant (Fig. S2E).
359
360 ***E. faecium* 1,231,410 can escape from vancomycin-chlorhexidine synergy.** We observed
361 the growth kinetics of *E. faecium* 1,231,410 cultures exposed to no, either, or both 50 µg/ml
362 vancomycin and 4.9 µg/ml H-CHG over a two-day growth curve experiment. As shown in Fig.
363 3A, cultures exposed to vancomycin were growth-inhibited for the first 2.5 h after exposure, and
364 after 2.5 h, OD_{600} began to increase, consistent with the induction of vancomycin resistance
365 genes and synthesis of modified cell walls, as previously observed (46, 47). The cultures
366 exposed to H-CHG were also temporarily growth-inhibited. Consistent with the experiments
367 shown in Fig. 1A, the OD_{600} of cultures exposed to both vancomycin and H-CHG declined, and
368 after 24 h, the cultures recovered.
369
370
371 **Figure 3. *E. faecium* 1,231,410 can adapt to vancomycin/H-CHG synergy.** The growth
372 kinetics of *E. faecium* 410 in the presence of vancomycin and H-CHG were observed over a
373 two-day (40 h) growth curve. Panel (A) Representative OD_{600} of *E. faecium* 410 after treatment
374 with 0X (control; red circles), vancomycin (orange squares), H-CHG (green triangles) or
375 vancomycin and H-CHG (inverted blue triangles). *E. faecium* culture was grown at 37°C in BHI

376 until OD_{600} reached 0.6 and equal volumes of cultures were split into BHI with different
377 antimicrobials (shown by arrow) as described in materials and methods. OD_{600} values were
378 monitored for 6 h and after 24 h, the vancomycin and H-CHG-treated recovered culture (circled
379 and indicated with dashed arrow) was used as an inoculum to repeat the growth curve (shown
380 in panel B).
381
382
383 The next day, the recovered culture (from the vancomycin + H-CHG growth curve) was used as
384 inoculum to repeat the growth curve experiment (Fig. 3B). Interestingly, the growth inhibition
385 phenotypes observed for the first growth curve experiment were not observed in this second
386 passage. Most strikingly, cell lysis was no longer observed for the vancomycin- and
387 chlorhexidine-treated culture. This is an important observation since it indicates that synergy
388 mutant(s) that do not lyse in the presence of vancomycin and H-CHG can readily emerge.
389
390 **A synergy escape mutant has a mutation in *pstB*.** We colony-purified a synergy escaper
391 mutant (SE101) from the second growth curve cycle, as described in the materials and
392 methods. The growth kinetics of SE101 in the presence of vancomycin and H-CHG confirmed
393 that the synergism phenotype is altered in this strain (Fig. 4A and B). SE101 was initially
394 growth-inhibited in the presence of vancomycin and H-CHG, but after 3 h, OD_{600} values began
395 to increase, unlike what is observed for the wild-type. Significant differences in OD_{600} values
396 were observed for SE101 compared to the wild-type for time points 3 h after addition of
397 vancomycin and H-CHG (P-value < 0.05 using one-tailed Student's t test).
398
399
400 **Figure 4. Mutations in the phosphate-specific transport (*pst*) operon result in escape**
401 **from vancomycin-H-CHG synergy.** Growth of (A) *E. faecium* 410 wild-type, (B) SE101, (C) *E.*

402 *faecium* 410Δ*pst*, and (D) SE101Δ*pst*. *E. faecium* was cultured in BHI until the OD_{600} reached
403 0.6. Equal volumes of cultures were split into BHI (control; red circles) or BHI containing
404 vancomycin (50 µg/ml) and H-CHG (4.9 µg/ml) (blue squares). OD_{600} values were monitored for
405 6 h and the 24 h time point was recorded. Error bars indicate standard deviations from n=3
406 independent experiments. Significance was assessed using the one-tailed Student's *t*-test. *
407 denotes *P*-value < 0.05. Stars indicate significant differences between vancomycin- and H-
408 CHG-treated cultures in panel B versus A, in panel C versus A, and in panel D versus B.
409
410
411 Utilizing whole genome sequencing, we identified a mutation conferring a S199L substitution in
412 PstB (EFTG_01173) in SE101. As a result of this substitution, the protein is predicted to fold into
413 a beta-strand instead of a coil (48). The *pst* (phosphate-specific transport) operon has been well
414 characterized in *E. coli* and consists of *pstSCAB* and *phoU* (a regulator). In phosphate-
415 starvation conditions, inorganic phosphate (Pi) binds PstS and is released into the cytoplasm by
416 the inner membrane channel formed by PstA-PstC. PstB energizes this channel by hydrolyzing
417 ATP (49). The *pst* system and antimicrobial susceptibility has been previously linked in *E.*
418 *faecium*. We identified a non-synonymous substitution in *phoU,* a negative regulator of the *pst*
419 operon*,* in a chlorhexidine-adapted *E. faecium* 1,231,410 derivative that had reduced
420 chlorhexidine and daptomycin susceptibilities and decreased intracellular Pi levels (23).
421
422 We quantified the levels of intracellular inorganic phosphate (Pi) in the wild-type strain and in
423 SE101 under routine culture conditions. However, the levels were not significantly different for
424 any time point assayed (Fig. S3).
425
426 To investigate the function of the *pstB* mutation further, we deleted the complete *pst* transport
427 system (EFTG_01170-74) in SE101 and in the *E. faecium* 1,231,410 wild-type. The growth

428 observed in the presence of vancomycin and H-CHG for the SE101Δ*pst* deletion mutant was
429 significantly different as compared to SE101 (Fig. 4B and D*; P*-value < 0.05 using one-tailed
430 Student's *t* test). Specifically, unlike SE101, the OD_{600} values did not increase for the
431 SE101Δ*pst* deletion mutant after 3 h in the presence of vancomycin and H-CHG. Conversely,
432 deletion of the *pst* transport system from the wild-type strain did not substantially alter OD_{600}
433 values in response vancomycin and H-CHG (Fig. 4A and C). We conclude that the *pstB*
434 mutation in SE101 confers protection from killing by vancomycin and H-CHG co-treatment by an
435 as yet undetermined mechanism, allowing cells to grow in the presence of the two drugs (Fig.
436 4B).
437
438 **Conclusions and perspective.** We previously reported that *E. faecium* 1,231,410 exhibits
439 increased susceptibility to vancomycin in the presence of chlorhexidine (19). The goal of the
440 current study was to identify molecular contributors to this phenotype. The long-term goal is to
441 use this information to identify less toxic compounds that could be compounded with
442 vancomycin to exploit this vulnerability. That said, products incorporating chlorhexidine with
443 antibiotics have been previously reported. Synergism between vancomycin and chlorhexidine
444 was previously reported in methicillin-resistant *Staphylococcus aureus*, where chitosan-based
445 sponges were utilized for localized delivery of these two synergistic compounds that inhibited *S.*
446 *aureus* growth for 21 days (50). Another study exploited synergism between chlorhexidine and
447 β-lactam antibiotics and synthesized hybrid organic salts (GUMBOS), which were effective
448 against clinical isolates of Gram-positive and Gram-negative bacteria (51).
449
450 In our previous report, we proposed three models that are not mutually exclusive that could
451 explain this phenotype. The models are reiterated here. Model 1 is that altered Pbp levels in the
452 presence of chlorhexidine prevent D-Ala-D-Lac precursors from being cross-linked. Model 2
453 proposes that the chlorhexidine stress response alters substrate pools for peptidoglycan

454 synthesis, resulting in vancomycin-sensitive termini that are neither D-Ala-D-Ala nor D-Ala-D-
455 Lac. Finally, model 3 is that post-translational regulation of VanX and/or VanY prevents
456 depletion of D-Ala-D-Ala termini from peptidoglycan precursors in the presence of chlorhexidine,
457 thereby causing cells to be sensitive to vancomycin. In terms of Model 2, the results of the D-
458 lactate amendment study (Table 3) indicate that D-Ala-D-Lac termini (and therefore, induction of
459 the vancomycin resistance genes) are required for the synergy phenotype. Model 3 is not
460 supported by our observation that $vanY_A$ deletion has no impact on the synergy phenotype (Fig.
461 S1), but $vanX_A$ remains to be investigated, and therefore this model has not been fully
462 assessed.
463
464 Growth analyses of *E. faecium* deletion mutants provide some support for Model 1. Upon *ddcP*
465 deletion, which is predicted to result in increased availability of pentapeptide precursors for
466 cross-linking, *E. faecium* 1,231,410 cells maintained susceptibility to the synergistic action of
467 vancomycin and chlorhexidine, but the cells did not lyse. These results suggest that *ddcP*
468 contributes to weakening of the cell wall in the presence of the two drugs. Our previously
469 published transcriptomic study identified up to 5-fold induction of *ddcP* in *E. faecium* 1,231,410
470 cultures treated with the MIC of H-CHG for 15 minutes, as compared to untreated cultures (19).
471 It is possible that in the presence of H-CHG, DdcP actively trims the terminal D-Ala from
472 peptidoglycan precursors and generates tetrapeptides. At the same time, in the presence of
473 vancomycin, the combined activities of the vancomycin resistance genes result in pentapeptides
474 terminating in D-Lac. The relative availability of penta- and tetrapeptides with chemically
475 different termini likely impacts the overall efficiency of cross-linking and the strength of the cell
476 wall. Since all Pbps do not have the same affinity for tetra- versus pentapeptides, unacceptable
477 precursors for transpeptidation are synthesized in the presence of both vancomycin and
478 chlorhexidine, and the cells lyse. However, complicating this explanation, we did not observe
479 any difference in growth phenotype between the L,D transpeptidase (ldt_{fm}) deletion mutant and

480 the wild-type in the presence of vancomycin and H-CHG (Fig. S1F and G). As reported
481 previously, activity of Ldt_{fm} is dependent on availability of tetrapeptides (42, 43). If (and how)
482 Ldt_{fm} activity changes in the presence of vancomycin and H-CHG remains to be elucidated. A
483 critical set of future experiments that are relevant to both Models 1 and 2 will be to analyze
484 cytoplasmic peptidoglycan precursor pools and mature peptidoglycan structures in *E. faecium*
485 wild-type and *ddcP* mutant cultures exposed to vancomycin and chlorhexidine. This analysis
486 would allow us to analyze the relative balance of tetra- versus pentapeptide termini, as well as
487 their chemical compositions. Moreover, more detailed assessments of cell viability and structure
488 would also be useful, including live/dead staining and electron microscopy.
489
490 We also found that synergy escaper mutants (i.e., cells that failed to lyse) arose after 24 h of
491 exposure to both vancomycin and chlorhexidine. A spontaneous non-synonymous substitution
492 in *pstB* conferred a survival advantage in the presence of the two antimicrobials. However, the
493 exact mechanism(s) of how the Pst system impacts antimicrobial susceptibility in *E. faecium* is
494 unknown. Critical experiments for the future are to analyze Pi levels under stressed conditions
495 (i.e., in the presence of vancomycin and chlorhexidine), and to perform analysis of cytoplasmic
496 peptidoglycan precursor pools and mature peptidoglycan structures, as described above.
497
498 Overall, our study highlights the complexity of the enterococcal cell wall stress response in
499 response to combination antimicrobial therapy and identifies a novel contributor (*pstB*) to this
500 response. We additionally present a collection of deletion mutants, validated by genome
501 sequencing, that are of use for future studies of *E. faecium* cell wall biology.
502
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504
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508
509
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646
647

648 **Supplemental Figures and Tables**

649

650 **Figure S1. Representative optical density (OD_{600}) of (A) *E. faecium* 410 wild-type, (B)**
651 **Δ*pbpZ*, (C) Δ*vanY*, (D) Δ*ponA,* (E) Δ*ddcP* Δ*vanY*, (F) Δ*ldt*$_{fm}$, (G) Δ*ddcP* Δ*ldt*$_{fm}$, (H) Δ*pbpF*,**
652 **and (I) Δ*pbpA* after vancomycin and chlorhexidine treatment.** *E. faecium* was cultured at
653 37°C in BHI broth until the OD_{600} reached 0.6 as described in the materials and methods. Equal
654 volumes of culture were split into BHI containing 0X (control; red circles) or vancomycin and
655 chlorhexidine (Van and H-CHG; blue squares). OD_{600} values were monitored for 6 h. Error bars

656 indicate standard deviations from three independent experiments.

657

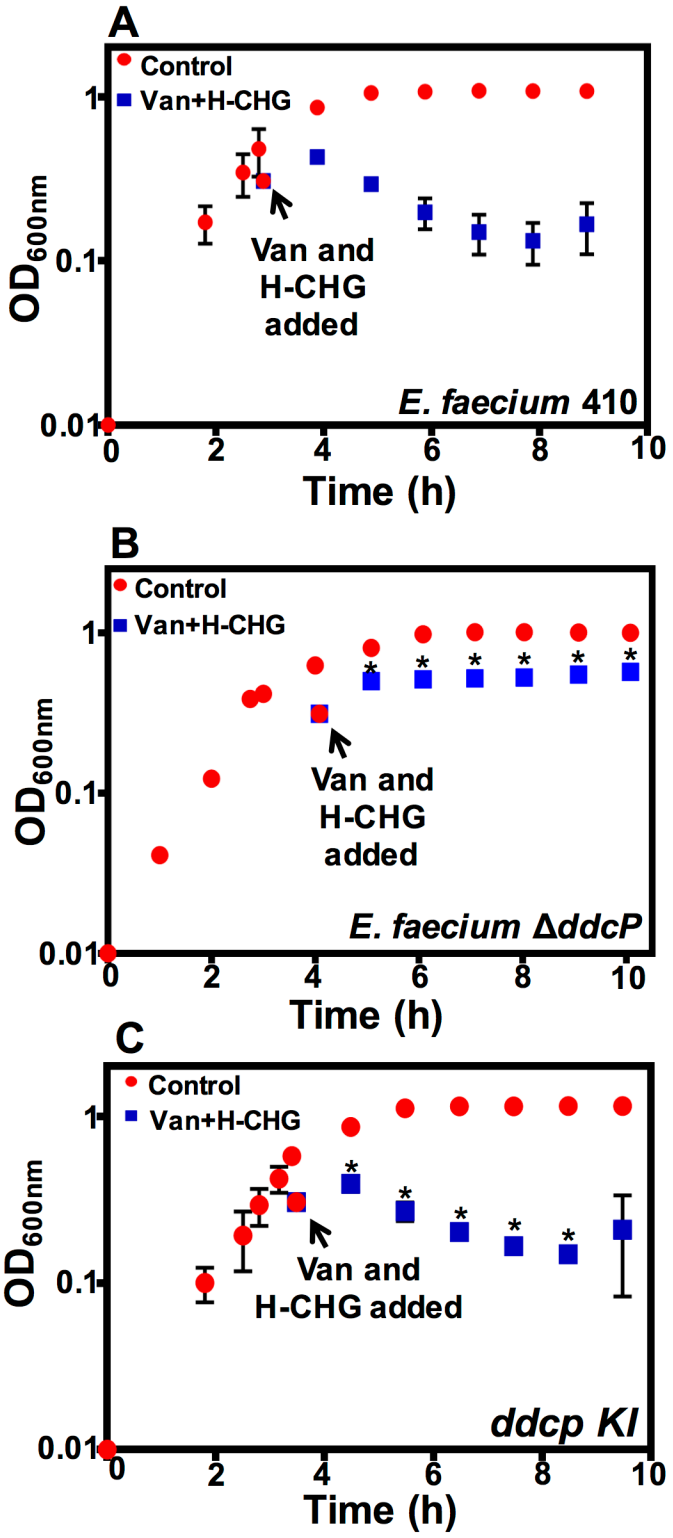
658 **Figure S2. A Δ*ddcP* mutant dies but does not lyse in the presence of vancomycin and H-**
659 **CHG.** Optical density (OD_{600nm}) (A) and CFU/mL (B) of *E. faecium* 1,231,410 wild-type (*E.*
660 *faecium* 410) and the *ddcP* deletion mutant with ("treated") and without ("control") vancomycin
661 and H-CHG treatment. *E. faecium* was cultured in BHI broth until the OD_{600} reached 0.6, as
662 described in materials and methods. Equal volumes of cultures were split into BHI or BHI
663 containing vancomycin (50 µg/ml) and H-CHG (4.9 µg/ml). OD_{600} values and CFU/mL were
664 monitored for 3 h. Error bars indicate standard deviations from n=3 independent experiments.
665 Significance was assessed using the one-tailed Student's *t*-test. * denotes *P*-value < 0.05. Stars
666 indicate significant differences between vancomycin- and H-CHG-treated cultures.

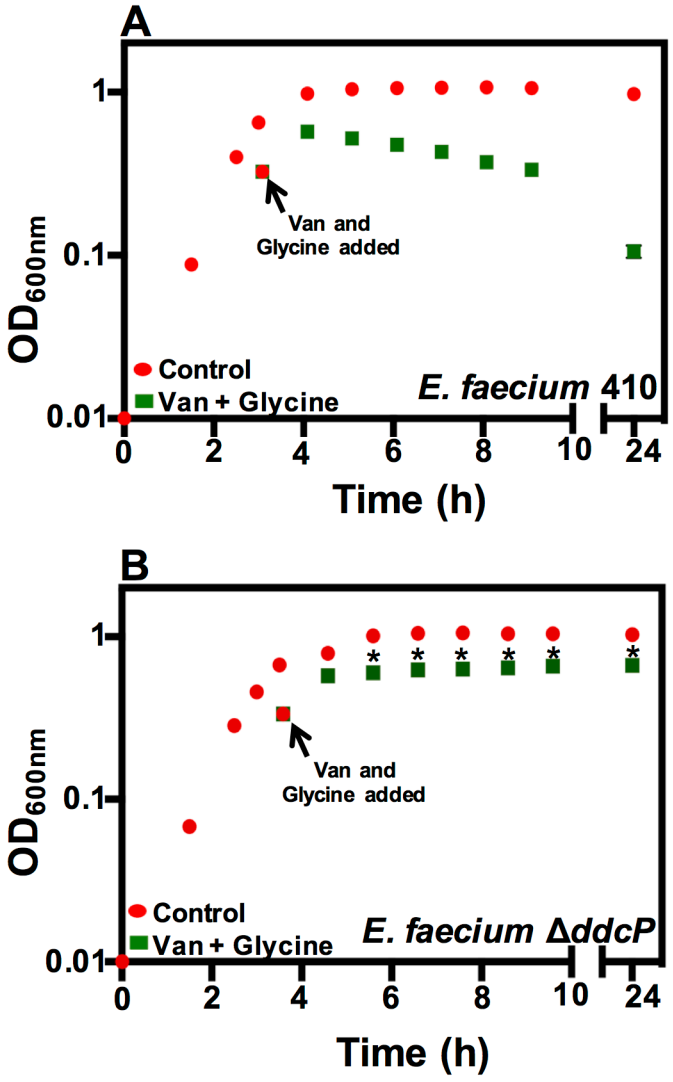
667

668 **Figure S3. Quantification of intracellular organic phosphate (Pi) levels in *E. faecium***
669 **1,231,410 wild-type and SE101 synergy escaper mutant**. Intracellular Pi levels were
670 measured for both strains at different growth time points (OD_{600} 0.4-1.0) as described in
671 materials and methods. The levels (pmoles) were normalized using CFU count. Standard
672 deviation was calculated from n=5 independent experiments and significance value was
673 calculated using one-tailed Student's *t* test. Time points: 1, OD_{600} 0.4-0.5; 2, OD_{600} 0.6-0.7; 3,
674 OD_{600} 0.7-0.8; 4, OD_{600} 0.8-0.9; OD_{600} 1.0-1.5.

675

676 **Table S1. List of primers used in the study.**


A
Control
Van+H-CHG
Van and
H-CHG
added
E. faecium 410
OD600nm
Time (h)
B
Control
Van+H-CHG
Van and
H-CHG
added
E. faecium ΔddcP
OD600nm
Time (h)
C
Control
Van+H-CHG
Van and
H-CHG added
ddcp KI
OD600nm
Time (h)


A
1
0.1
0.01
OD600nm
Van and
Glycine added
Control
Van + Glycine
E. faecium 410
0
2
4
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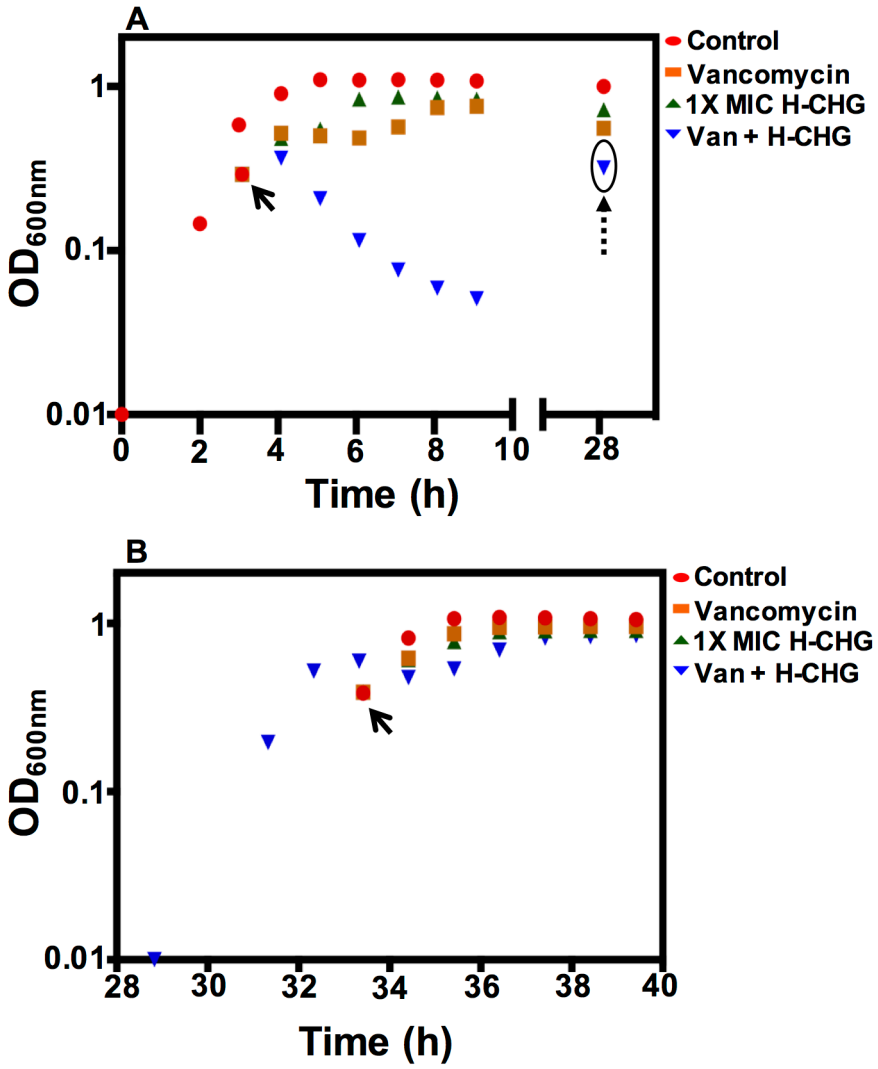
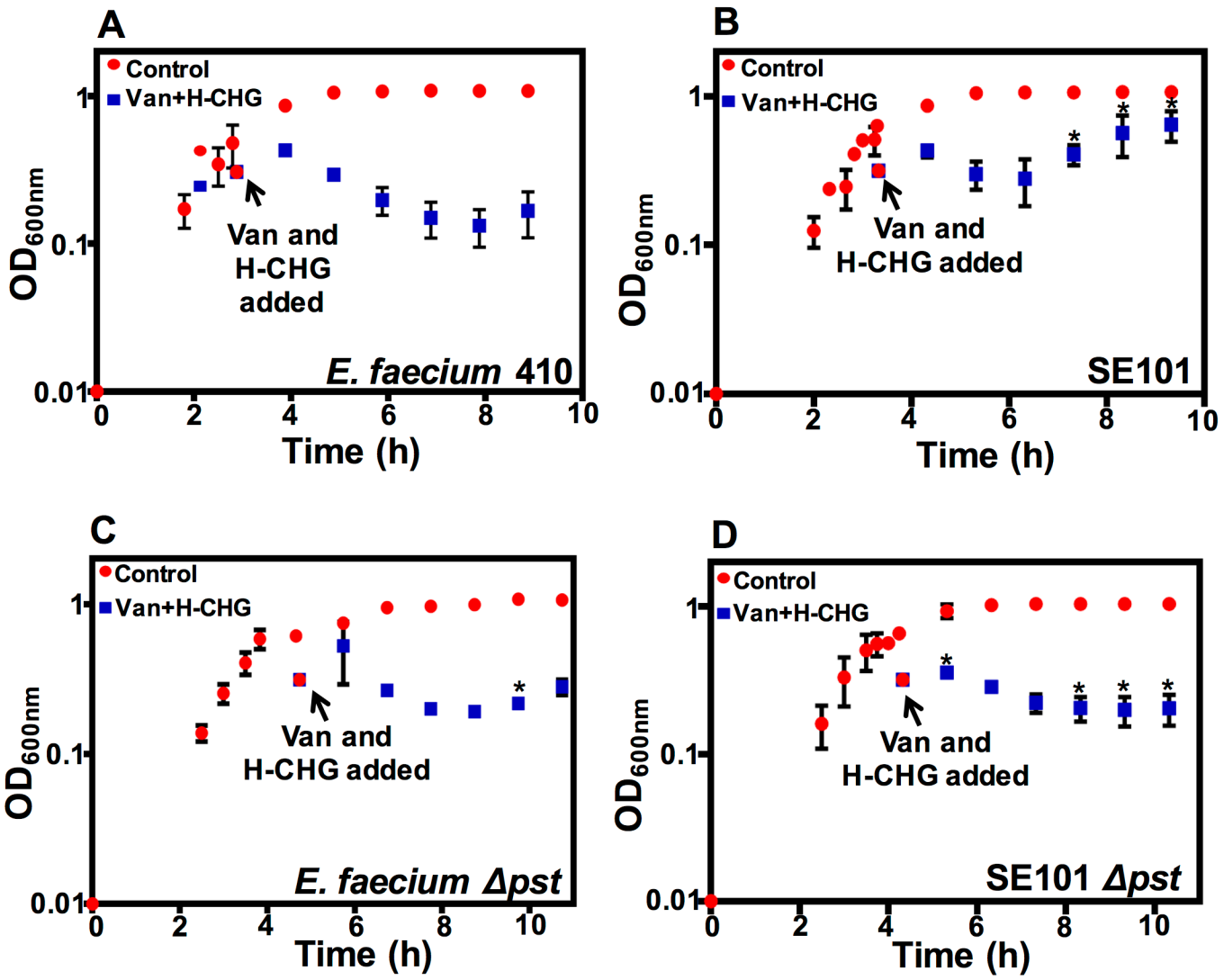
8
10
24
Time (h)
B
1
0.1
0.01
OD600nm
Van and
Glycine added
Control
Van + Glycine
E. faecium ΔddcP
0
2
4
6
8
10
24
Time (h)


A
Control
Vancomycin
1X MIC H-CHG
Van + H-CHG
OD600nm
1
0.1
0.01
0
2
4
6
8
10
28
Time (h)
B
Control
Vancomycin
1X MIC H-CHG
Van + H-CHG
OD600nm
1
0.1
0.01
28
30
32
34
36
38
40
Time (h)


A
Control
Van+H-CHG
Van and
H-CHG
added
E. faecium 410
OD600nm
Time (h)
B
Control
Van+H-CHG
Van and
H-CHG added
SE101
OD600nm
Time (h)
C
Control
Van+H-CHG
Van and
H-CHG added
E. faecium Δpst
OD600nm
Time (h)
D
Control
Van+H-CHG
Van and
H-CHG added
SE101 Δpst
OD600nm
Time (h)

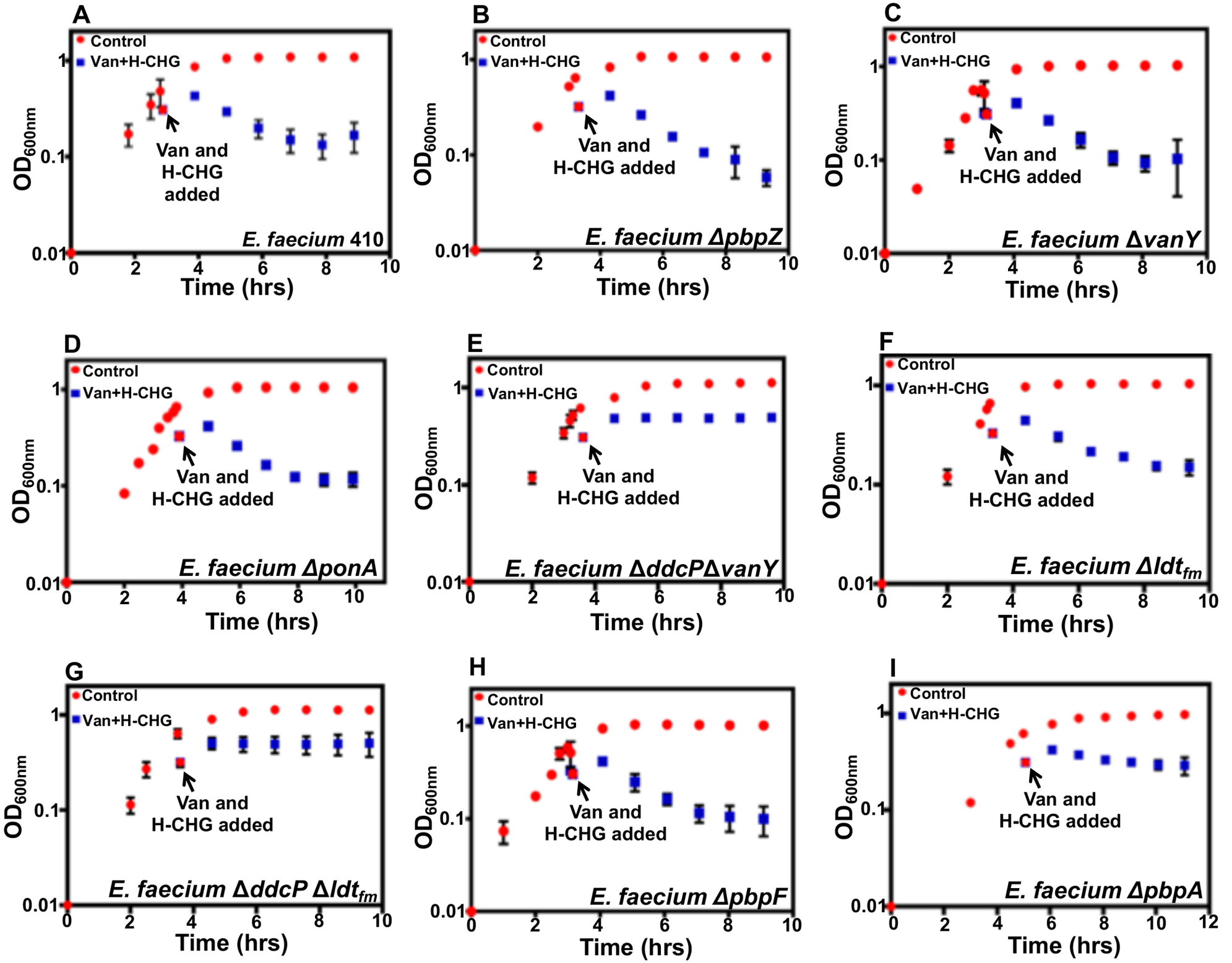
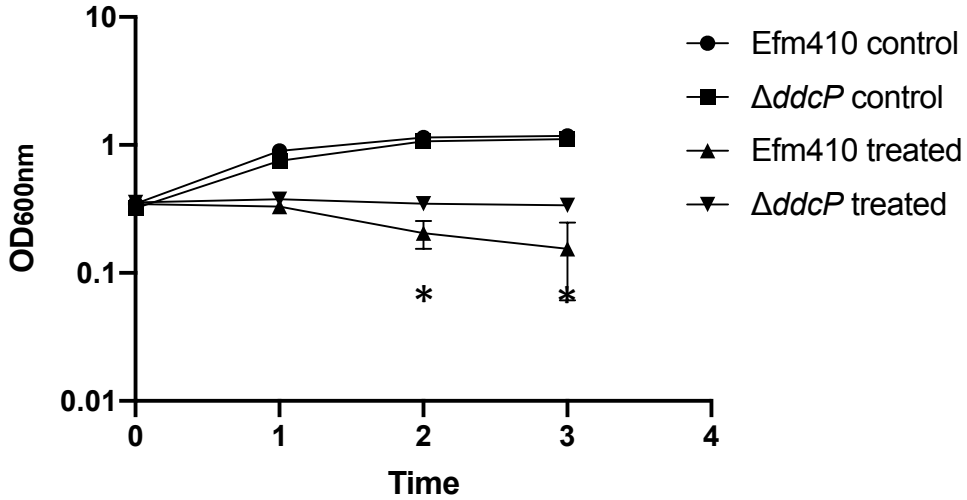


Figure S1. Representative optical density (OD_{600}) of (A) *E. faecium* 410 wild-type, (B) Δ*pbpZ*, (C) Δ*vanY*, (D) Δ*ponA*, (E) Δ*ddcP* Δ *vanY*, (F) Δ*ldtfm*, (G) Δ*ddcP* Δldt_{fm}, (H) Δ*pbpF*, and (I) Δ*pbpA* after vancomycin and chlorhexidine treatment. *E. faecium* culture was grown at 37°C in BHI until OD_{600} reached 0.6 as described in materials and methods. Equal volumes of cultures were split into BHI containing 0X (control; red circles) or vancomycin and chlorhexidine (Van and H-CHG; blue squares). OD_{600} values were monitored for 6 hr. Error bars indicate standard deviations from n=3 independent experiments.



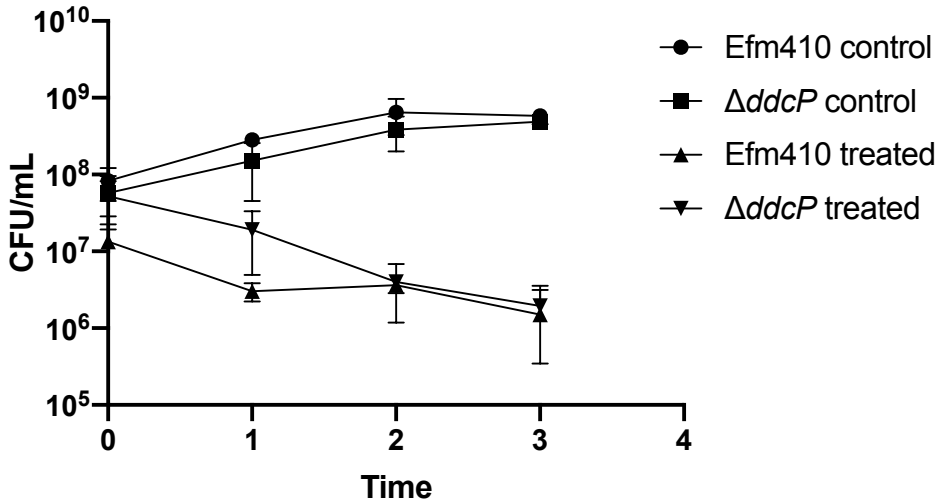


Figure S2. A Δ*ddcP* mutant dies but does not lyse in the presence of vancomycin and H-CHG. Optical density (OD_{600nm}) (A) and CFU/mL (B) of *E. faecium* 1,231,410 wild-type (*E. faecium* 410) and the *ddcP* deletion mutant with ("treated") and without ("control") vancomycin and H-CHG treatment. *E. faecium* was cultured in BHI broth until the OD_{600} reached 0.6, as described in materials and methods. Equal volumes of cultures were split into BHI or BHI containing vancomycin (50 µg/ml) and H-CHG (4.9 µg/ml). OD_{600} values and CFU/mL were monitored for 3 h. Error bars indicate standard deviations from n=3 independent experiments. Significance was assessed using the one-tailed Student's *t*-test. * denotes *P*-value < 0.05. Stars indicate significant differences between vancomycin- and H-CHG-treated cultures.

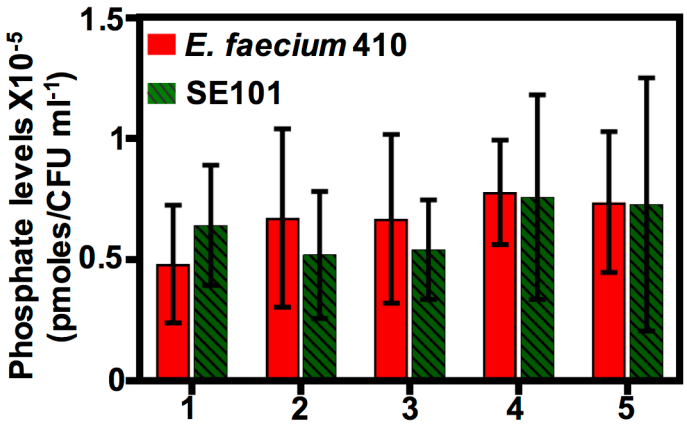


Figure S2. Quantification of intracellular organic phosphate (Pi) levels in *E. faecium* 410 wild-type and SE101 synergy escaper mutant. Intracellular Pi levels were measured for both strains at different growth time points (OD_{600} 0.4-1.0) as described in materials and methods. The levels (pmoles) were normalized using CFU count. Standard deviation was calculated from n=5 independent experiments and significance value was calculated using one-tailed Student's *t* test. Time points: 1, OD_{600} 0.4-0.5; 2, OD_{600} 0.6-0.7; 3, OD_{600} 0.7-0.8; 4, OD_{600} 0.8-0.9; OD_{600} 1.0-1.5.

Table S1. Primers used in the study

Primer name	Sequence
***pbpF* deletion**	
pbpF flanking Arm1_BamHI For	ATGCAT**GGATCC**ATGGAGCATCAGTCGTTCAGCTGT
pbpF flanking Arm1_Sph1 Rev	ATGCAT**GCATGC**AAAATCCATTTGCTTCTTCTCCTG
pbpF flanking Arm2_Sph1 For	ATGCAT**GCATGC**GGAGAGTAGCCCCTTTGAAAACGA
pbpF flanking Arm2_BamHI Rev	ATGCAT**GGATCC**GGCAACAAGCTGTCTGGTGGCCAA
pbpF screening For	GCAGGAAGAAAACACTCTTTCACT
pbpF screening Rev	CGTTCGATTTGATTCGCGCT
ddcP deletion	
ddcP flanking Arm1_EcoRI For	ATGCAT**GAATTC**CGCCACCTGTCAGTTCAGATCCCA
ddcP flanking Arm1_Sph1 Rev	ATGCAT**GCATGC**TATGGACATATCCGATCTCCTTGT
ddcP flanking Arm2_Sph1 For	ATGCAT**GCATGC**TTGTTTTAATTGAACAAAAAGAAA
ddcP flanking Arm2_EcoRI Rev	ATGCAT**GAATTC**TTGTTCCATGGCATATTGTTTCAT
ddcP screening For	AAACGACCGCTAACCTTCCA
ddcP screening Rev	CGCAAACGTCCATGTACTGC
***vanY* deletion**	
vanY flanking Arm1_BamHI For	ATGCAT**GGATCC**CTAAATATGCCACTTGGGATA
vanY flanking Arm1_Sph1 Rev	ATGCAT**GCATGC**CTTCTTCATTTTCAGTCTCCT
vanY flanking Arm2_Sph1 For	ATGCAT**GCATGC**AGGAGGTAAGGATGGCGGAAT
vanY flanking Arm2_BamHI Rev	ATGCAT**GGATCC**GTAGTTTATTACTCTTTAGCG
pbpF screening For	AGCTTGTACCAATGGGGAGC
pbpF screening Rev	TCAGTCCAAGAAAGCCTCCA
***ldtfm* deletion**	
ldtfm flanking Arm1_BamHI For	ATGCAT**GGATCC**TGTCTCACGCTTTGGCATTTA
ldtfm flanking Arm1_Sph1 Rev	ATGCAT**GCATGC**TCTTGTCATATCGACAACTCC
ldtfm flanking Arm2_Sph1 For	ATGCAT**GCATGC**GTCTTCTAACAAAAATAATAT
ldtfm flanking Arm2_BamHI rev	ATGCAT**GGATCC**TGGACGAACACCTATGTTCCA
ldtfm screening For	TACATTGGTGCACCTGCTGT
ldtfm screening Rev	GATGTATTAGAGGCGGGGGC
***ponA* deletion**	
ponA flanking Arm1_BamHI For	ATGCAT**GGATCC**TTCCCTTCATTCCAGTTATTA
ponA flanking Arm1_Xba1 Rev	ATGCAT**TCTAGA**AGTTTGTTCATTTGCCATTCT
ponA flanking Arm2_Xba1 For	ATGCAT**TCTAGA**GCAAATGACCATACACCATCCAGC
ponA flanking Arm2_BamHI rev	ATGCAT**GGATCC**TTCTTTAATTGCAAATAAATGTAT
ponA screening For	GGGACGCCCAAAAGGAAAAA
ponA screening Rev	AGATCACACATGTATATGCTGGA
***pbpZ* deletion**	
pbpZ flanking Arm1_Xba1 For	ATGCAT**TCTAGA**GCGTGTCGAATCCGATTGTTCCAA
pbpZ flanking Arm1_Sph1 Rev	ATGCAT**GCATGC**AAGGGTCACCTCAACTAATGGTTT
pbpZ flanking Arm2_Sph1 For	ATGCAT**GCATGC**GATGATTGATTTAATAGAATACAC
pbpZ flanking Arm2_Xba1 Rev	ATGCAT**TCTAGA**GCTAAGCAAGTGGACGGCGTGATC
pbpZ screening For	CATGCTGACGTGTGAGCCTA
pbpZ screening Rev	GCTGCATTTTGTTCACCACC
***pbpA* deletion**	
pbpA flanking Arm1_BamHI For	ATGCAT**GGATCC**AAAAATCGGTTTTCAAAGTCT
pbpA flanking Arm1_Sph1 Rev	ATGCAT**GCATGC**TTTTTTCATAAAATCTTTCAT
pbpA flanking Arm2_Sph1 For	ATGCAT**GCATGC**GCAAAATAAAAAAGAGGTCGTGAA
pbpA flanking Arm2_BamHI1 Rev	ATGCAT**GGATCC**ACAATTTTTGTCACAACCTTTTTT
pbpA screening For	GTAGTCGCATTAGCCGAGCT

pbpA screening Rev	TCTCGGTATGAAGTCAAATTTAAGCA

For tetracycline marker

tetL For	[Phos]GACCGATGATGAAGAAAAGAATTTGAAAC
tetL Rev	[Phos]CTGTTATAAAAAAAGGATCAATTTTGAACTCTC
pbpA-linear For	GCAAAATAAAAAAGAGGTCGTGAA
pbpA-linear Rev	TTTTTTCATAAAATCTTTCAT

***ddcP* complementation**

ddcP flanking Arm1_EcoRI For	ATGCAT**GAATTC**CGCCACCTGTCAGTTCAGATCCCA
ddcP flanking Arm1_EcoRI Rev	ATGCAT**GAATTC**TTGTTCCATGGCATATTGTTTCAT

***pst* transporter deletion**

pst flanking Arm1_BamHI For	ATGCAT**GGATCC**CCTTGCAAAACCGTTTTTTGATGG
pst flanking Arm1_Sph1 Rev	ATGCAT**GCATGC**TAATTTAAGTTTTTTCATTAGAAA
pst flanking Arm2_Sph1 For	ATGCAT**GCATGC**TCAGGTCGATTTGGATAAGGAGGA
pst flanking Arm2_BamHI Rev	ATGCAT**GGATCC**TGAAGTAAGCACACAAATAAAAAA
pst screening For	TGTCCTTTTCTAACGGGGCC
pst screening Rev	CACGAACTGACTTGTGCACG

Mutation confirmation

Transporter EFTG_01173 check for	GTGTTTCTGTTTCGGCTGGC
Transporter EFTG_01173 check rev	TTGTCATGTTGAGGCCTCCG