DcaP-Family Porins are Required for Carboxylic Acid Catabolism in *Acinetobacter baumannii*

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ABSTRACT

Acinetobacter baumannii is a pathogen of concern and a leading cause of multidrug-resistant healthcare-associated infections. The *A. baumannii* outer membrane is a barrier to antimicrobials and host defenses but must also allow essential nutrients to permeate. Here, we investigate the functional importance of the putative DcaP-family outer membrane porins, which include a proposed vaccine target in *A. baumannii*. All *A. baumannii* genomes surveyed encode multiple DcaP family porins, which we classify in four classes based on protein sequence phylogeny (DcaP1-4). DcaP proteins encoded by species in other genera could not be mapped to these DcaP classes and phylogenetic analysis suggests DcaP1-4 proteins diversified within *Acinetobacter*. Phenotypic array assays and additional experiments show that DcaP3 was necessary for growth on multiple di- and tri-carboxylic acids as sole carbon sources, including citric acid and tricarballylic acid. Finally, a mutant lacking all DcaP proteins was attenuated in the liver and spleen in a mouse model of bloodstream infection and complemented by expression of DcaP3. These findings provide insight on how *A. baumannii* acquires nutrients through the outer membrane barrier and show DcaP3 is important during infection in specific host niches, validating its potential as a therapeutic target.

30 **INTRODUCTION**

31 *Acinetobacter baumannii* is a pathogen of critical concern and a major cause of
32 healthcare-associated infections. Isolates of *A. baumannii* are often multidrug resistant (MDR)
33 or extensively drug resistant (XDR) and exhibit resistance to first and last line antibiotics, such
34 as meropenem and colistin, respectively (1). The Centers for Disease Control and the World
35 Health Organization have therefore identified *A. baumannii* as an urgent public health threat,
36 calling for new avenues of treatment (2–4). The bacterial cell envelope is the primary barrier
37 from the environment and protects bacteria from environmental stress including antibiotics and
38 host defenses; however, the cell envelope must also allow acquisition of essential nutrients and
39 cofactors (5,6). The outer membrane (OM) of *A. baumannii* is thought to be less permeable
40 compared to other Gram-negative bacteria such as *E. coli*, contributing to intrinsic antibiotic
41 resistance (7). How small molecule nutrients required for growth transit the impermeable OM in
42 *A. baumannii* is incompletely understood.

43 The OM of *A. baumannii* is an asymmetric lipid bilayer where the inner leaflet is
44 composed of glycerophospholipids and the outer leaflet of lipooligosaccharides (LOS) (5,8,9).
45 The OM bilayer is occupied by proteins that serve a variety of functions, including nutrient influx.
46 Nutrients typically pass through the OM via active transport by TonB-dependent transporters or
47 passive diffusion through porins which are transmembrane channels that allow passage of small
48 molecules (6,10). The primary porin in *A. baumannii* is OmpA, which shows slow molecular
49 transport in liposome swelling assays, contributing to the low permeability barrier of the OM (11–
50 13). However, the primary function of OmpA is thought to be structural, providing a physical
51 tether between the OM and the peptidoglycan cell wall in *A. baumannii* and other species
52 (14,15). *A. baumannii* encodes multiple other porins including CarO, an OM porin that
53 selectively allows influx of ornithine and other basic amino acids (16), and the Occ family porins,
54 responsible for the influx of compounds like benzoate, hydroxycinnamate, and other aromatic
55 molecules (17–19). The protein DcaP is a predicted OM porin widely distributed across

56 *Acinetobacter* species named for its localization within a genetic locus for utilization of
57 dicarboxylic acids (*dca*) (20). Notably, a DcaP family protein is among the most abundant OM
58 proteins in *A. baumannii* during rat and mouse infections (21). Due to this fact, multiple groups
59 have studied a DcaP-like protein as a promising vaccine candidate for protection against *A.*
60 *baumannii* infection (21–25). However, the biological role of DcaP family proteins remains
61 unclear.

62 First identified in Parke *et al*. as part of the dicarboxylic acid catabolic operon of
63 *Acinetobacter baylyi* ADP1, *dcaP* (dicarboxylic acid porin) and DcaP-like proteins were thought
64 to be specific to the Moraxellaceae family (20). The structure for one DcaP family protein has
65 been solved, presenting as a homo-trimeric 16-stranded beta-barrel protein with an extended
66 periplasmic N-terminus that forms a coiled coil (21). Due to the genetic localization and
67 induction of expression with the dicarboxylic acid adipate, *A. baylyi* DcaP-like proteins were
68 proposed to be nonspecific porins that facilitate the uptake of dicarboxylic acids (20); however, a
69 role for DcaP-like proteins in carboxylic acid catabolism has not been reported. Molecular
70 dynamics and electrophysiology studies determined a DcaP-like protein to have an affinity for
71 anionic compounds as substrates, such as the clinically relevant β-lactamase inhibitor
72 sulbactam (21). In other studies, DcaP-like proteins have been implicated in biofilm formation
73 and mucin catabolism (26,27). Here, we describe four classes of DcaP-like proteins in
74 *Acinetobacter* and investigate their role in carbon source utilization.
75

76 **RESULTS**

77 *Acinetobacter spp. encode multiple DcaP-family porins*

78 The first DcaP was described in *A. baylyi* as part of a dicarboxylic acid catabolic operon
79 (20), and DcaP-like proteins have been identified in various *A. baumannii* clinical isolates and
80 type-strains (21,23). Proteins designated DcaP-like in *A. baumannii* ATCC 17978 are
81 homologous to *A. baylyi* DcaP, sharing ~30-35% amino acid identity by Clustal Omega multiple

82 sequence alignment (28). However, given the abundance of DcaP-like proteins within individual
83 *Acinetobacter* genomes, we hypothesized that these proteins could be further classified based
84 on protein sequence. Using DcaP and DcaP-like sequences from a set of deduplicated *A.*
85 *baumannii* genomes, four distinct classes of DcaP-like proteins were identified that cluster
86 independently, including the original DcaP which we display as DcaP1 (Fig. 1A, S1A). We next
87 determined the distribution of DcaP-like proteins across the *Acinetobacter* genus. Using a set of
88 250 deduplicated *Acinetobacter* genomes, most of which were *A. baumannii*, DcaP proteins
89 were shown to be widely conserved across the genus (Fig. S1B). Additionally, *Acinetobacter*
90 species within the *A. calcoaceticus/baumannii* (*acb*) complex/clade of pathogenic *Acinetobacter*
91 appeared to be enriched for having multiple DcaP proteins compared to non-pathogenic
92 *Acinetobacter* species (Fig. S1B). Among the *A. baumannii* genomes, over 130 of the strains
93 encode four *dcaP* genes (Fig. 1B). In fact, no *A. baumannii* genome analyzed encoded fewer
94 than two *dcaP* genes (Fig. 1B). To determine if the *dcaP* genes were equally distributed across
95 the species, the number of each DcaP subfamily were tallied for each genome and organized
96 based on how many total DcaP proteins were present. The four classes of DcaP proteins were
97 equally likely to be encoded in a given *A. baumannii* genome (Fig. 1B). For example, in most
98 cases where a genome encodes four DcaP proteins, it was most likely to have one of each
99 variant. Alternatively, in a genome encoding five DcaP proteins, DcaP2 was most likely to be
100 duplicated. These data suggest that DcaP proteins are encoded across the *Acinetobacter*
101 genus, and enriched in pathogenic *Acinetobacter,* including *A. baumannii*.
102
103 *DcaP proteins from other bacterial species are distinct from Acinetobacter DcaP proteins*
104 To investigate the evolutionary history of DcaP proteins in *Acinetobacter* and determine if
105 DcaP diversified within *Acinetobacter* or across phyla, orthologues in other bacterial phyla were
106 identified through KEGG. Bacterial phyla were selected for further analysis if the DcaP-like
107 protein was encoded in more than half of the genomes for a given genus (29,30). A rooted

108 phylogenomic tree was generated to demonstrate the evolutionary distance between
109 *Acinetobacter* and the bacteria containing a DcaP orthologue (Fig. 2A). Orthologues of DcaP
110 proteins were found in distantly related organisms, such as *Shewanella spp.* and *Xanthomonas*
111 *spp.,* albeit generally in fewer numbers (Fig. 2A). These DcaP orthologues could not be further
112 classified into one of the four DcaP classes defined in *A. baumannii*. This suggests that the four
113 DcaP classes of proteins defined here are unique to *Acinetobacter spp*. To better understand
114 the relationship between *Acinetobacter* DcaP proteins and proteins designated DcaP-like from
115 distantly related species, an unrooted tree of protein sequences was generated. This analysis
116 revealed that DcaP proteins from AB5075, the included reference *A. baumannii* strain which
117 encodes DcaP1-4, were more similar to each other than to non-*Acinetobacter* DcaP proteins
118 (Fig. 2B). This suggests that diversification of the four DcaP classes defined here occurred
119 within *Acinetobacter*. In contrast to *A. baumannii*, multiple DcaP-like proteins encoded in other
120 organisms were sequence divergent, such as in *Pseudoxanthomonas daejeonensis*,
121 *Stenotrophomonas spp*., *Shewanella psychrotolerans*, and *Marinobacter spp.* (Fig 2B).
122 Comparison of the species phylogeny and DcaP protein phylogeny suggest there may have
123 been occurrences of horizontal gene transfer in other species outside *Acinetobacter*. Overall,
124 these data suggest that DcaP-like proteins are encoded by species across Proteobacteria and
125 that DcaP diversification has occurred within the *Acinetobacter* clade.
126
127 *DcaP family porins are necessary for growth on select di- and tri-carboxylic acids*
128 Next, we hypothesized that the DcaP-family porins are involved in small molecule
129 uptake. One study suggested that DcaP3 may translocate the clinically relevant beta-lactamase
130 inhibitor sulbactam based on electrophysiology and applied field simulation data (21).
131 Sulbactam is a therapeutic often used in combination with beta-lactam antibiotics like ampicillin
132 for bacteria with beta-lactam resistance. Many *A. baumannii* isolates are intrinsically resistant to
133 ampicillin due to the expression of beta-lactamases and sulbactam has been shown to

134 resensitize resistant isolates to beta-lactam antibiotics (31,32). We reasoned that if DcaP
135 proteins facilitated sulbactam entry, a ΔΔΔ*dcaP* mutant would exclude sulbactam from entering
136 the cell and result increased resistance to the beta-lactam ampicillin while a wild-type strain
137 would exhibit a re-sensitization to ampicillin. However, the wild-type and the ΔΔΔ*dcaP* mutant
138 strains exhibited similar sensitivities to ampicillin/sulbactam treatment (Fig. S2). These data
139 suggest that DcaP proteins are not required for sulbactam activity.
140 We next hypothesized that DcaP porins may be important for growth on certain nutrient
141 sources such as dicarboxylic acids as previously suggested (20). The growth of wild-type and
142 ΔΔΔ*dcaP* strains were compared using the high-throughput Biolog PM system to screen for
143 carbon source usage. Multiple compounds were identified on which wildtype was able to grow
144 but ΔΔΔ*dcaP* had a defect, and compounds where ΔΔΔ*dcaP* grew more than wildtype (Fig. 3A-
145 B). Many of the compounds in which WT grew better than ΔΔΔ*dcaP* were carboxylic acids,
146 including simple carboxylic acids, hydroxy carboxylic acids, and sugar acids (Fig. 3A-B).
147 Conversely, compounds in which the mutant outgrew WT were largely amino acids and their
148 derivatives (Fig. 3A-B). These data suggest that DcaP porins may allow the influx of carboxylic
149 acid-containing compounds, as previously predicted (20).
150
151 *DcaP3 is important for growth on multiple carboxylic acid carbon sources*
152 To verify the Biolog results and further determine specificity of the DcaP classes, growth
153 curves using ΔΔΔ*dcaP,* Δ*dcaP1*Δ*dcaP2*, Δ*dcaP1*Δ*dcaP3*, and Δ*dcaP2*Δ*dcaP3* and the carboxylic
154 acids as sole carbon sources were performed. Mutants lacking DcaP3 were defective for growth
155 on citric acid, tricarballylic acid, and mucic acid compared to the wild-type strain (Fig. 4A). We
156 were unable to identify conditions in which DcaP1 or DcaP2 were required for growth.
157 Complementation experiments showed that DcaP3 expression was sufficient to restore growth
158 on these substrates to near wild-type levels (Fig. 4B). Similarly, a single Δ*dcaP3* mutation

159 conferred a defect in growth on citric acid, tricarballylic acid, and mucic acid, whereas single
160 mutants of Δ*dcaP1* or Δ*dcaP2* showed no defect (Fig. S3).
161 A recent study in *A. baylyi* found that tricarballylic acid metabolism is closely linked with
162 the metabolism of *cis*- and *trans*-aconitic acid (33). The genetic organization of the tricarballylic
163 acid catabolic genes are conserved in *A. baumannii* compared to *A. baylyi* (Fig. 4C). Since the
164 data thus far suggest DcaP3 is necessary for growth on tricarballylic acid, we hypothesized that
165 DcaP3 may also be important for *cis*- and *trans*-aconitic acid growth. Mutants lacking DcaP3
166 had a defect for growth on both *cis*- and *trans*-aconitic acid (Fig. 4A). Complementing DcaP3 in
167 the chromosome of the triple mutant ΔΔΔ*dcaP* restored growth to near wild-type-like levels,
168 confirming the role of DcaP3 in growth on these carbon sources (Fig. 4B). Finally, the Δ*dcaP3*
169 single mutant had a defect in growth on both *cis*- and *trans*-aconitic acid compared to wildtype
170 (Fig. S3). To highlight the similarities in the carbon sources in which DcaP3 is important for
171 growth, the chemical structures for each carbon source are outlined in Fig. 4D. Taken together,
172 these data suggest that DcaP3 is important for growth using multiple di- and tri-carboxylic acids
173 as sole carbon sources.
174
175 *DcaP4 complements ΔdcaP3 for growth on carboxylic acids*
176 Thus far, experiments were performed with *A. baumannii* ATCC 17978 which does not
177 encode DcaP4; thus, the potential role for DcaP4 in growth using carboxylic acids was unclear.
178 *A. baylyi* can grow on citric acid and tricarballylic acid and does not encode DcaP3 but rather
179 DcaP1, DcaP2, and DcaP4 (33). We hypothesized that DcaP4 could be also allow influx of
180 carboxylic acids. To test this, the DcaP4 from *A. baumannii* AB5075, which shares 77% amino
181 acid identity to *A. baylyi* DcaP4, was expressed from the 17978 DcaP3 promoter in the
182 ΔΔΔ*dcaP A. baumannii* mutant. Consistent with previous observations, the ΔΔΔ*dcaP* mutant was
183 unable to grow using citric acid, tricarballylic acid, mucic acid, or *cis*- and *trans*-aconitic acid

184 (Fig. 5). Growth was restored to the ΔΔΔ*dcaP* mutant by expressing DcaP4 chromosomally from
185 the DcaP3 promoter, suggesting that DcaP4 and DcaP3 have overlapping functions in some *A.*
186 *baumannii* strains (Fig. 5).
187
188 *DcaP3 is required for growth on di- and tri- carboxylic acids in a clinical isolate*
189 To test if DcaP3 is important for growth on di- and tri-carboxylic acids in a more recent
190 clinical isolate, a Δ*dcaP3* mutant was generated in the more recent clinical isolate AB5075 and
191 similar growth curves were performed (34). Mutants lacking *dcaP3* were defective for growth on
192 citric acid, tricarballylic acid, mucic acid, and *cis*- and *trans*-aconitic acid compared to wild-type
193 (Fig. 6). This suggests that the requirement for DcaP3 for growth on select carboxylic acids as
194 sole carbon sources is conserved among *A. baumannii* isolates.
195
196 *DcaP3 is required for virulence in the liver and spleen during bloodstream infection of mice*
197 Carbon source utilization can be a critical determinant of pathogenesis for *A. baumannii*
198 and other bacterial species in different host niches (35,36). Therefore, we sought to determine if
199 DcaP function is important for *A. baumannii* pathogenesis. To test this, murine bloodstream
200 infections were performed, co-inoculating wild-type and the ΔΔΔ*dcaP* mutant or wild-type and
201 the ΔΔΔ*dcaP* mutant complemented with DcaP3. We hypothesized that there may be a host
202 niche in which DcaP proteins are important for *A. baumannii* replication, leading to a defect for
203 ΔΔΔ*dcaP* compared to wildtype. There was no defect of the ΔΔΔ*dcaP* mutant compared to
204 wildtype in lung, kidney, or heart (Fig. 7A). By contrast, there was a defect for the ΔΔΔ*dcaP*
205 mutant compared to wildtype in the spleen and liver (Fig. 7A). The defect in the spleen and liver
206 was reversed by complementing *dcaP3* in the chromosome of the ΔΔΔ*dcaP* mutant, showing
207 DcaP3 is important for replication in the liver and spleen (Fig. 7B). Together these data suggest
208 that carboxylic acid permeability by DcaP3 is important in specific host niches during infection.
209

210 **DISCUSSION**

211 The OM protects *A. baumannii* from antimicrobials and other host stresses but must
212 permit influx of nutrients essential for replication. How nutrients pass through the *A. baumannii*
213 OM is not well understood. Here, we designate classes of a family of predicted porins, DcaP1-4,
214 that are widely distributed across *Acinetobacter spp.* and show DcaP3 or DcaP4 are required for
215 growth on multiple carboxylic acids.

216 DcaP-like porins have been identified in genetic screens for biofilm formation,
217 desiccation, and mucin catabolism, largely referred to as DcaP-like proteins without further
218 distinction (26,27,37–39). We show that *A. baumannii* DcaP-like proteins can be grouped into
219 four classes based on protein sequence (Fig. 1A, S1A). The presence of DcaP-encoding genes
220 is conserved among *Acinetobacter* spp, and particularly in *A. baumannii* and the *acb* complex
221 (Fig. 1B, Fig. S1B). While DcaP proteins can be found in distantly related organisms (Fig. 2A),
222 the DcaP1-4 classes we define in *A. baumannii* cluster together (Fig. 2B). These findings
223 suggest DcaP1-4 diversified within the *Acinetobacter* clade.

224 Antibiotic resistance in *A. baumannii* is a critical public health problem due to the
225 emergence of XDR isolates. Various porins in *A. baumannii* have been implicated in the uptake
226 of toxic molecules including antibiotics (12,40–42). DcaP3 was proposed to allow entry for the
227 beta-lactamase inhibitor sulbactam (21). Here, we show encoding DcaP-like proteins has no
228 impact on sensitivity to ampicillin in the presence of sulbactam under the conditions tested (Fig.
229 S2). These data suggest DcaP-like proteins may not be required for function of sulbactam.

230 The transport of essential nutrients across the cell envelope is incompletely understood
231 in *A. baumannii*. In general, *A. baumannii* utilizes organic acids and amino acids as carbon
232 sources and cannot utilize sugars such as glucose (35). Accordingly, multiple OM channels
233 have been identified that are important for growth on specific carbon sources including ornithine,
234 arginine, glutamic acid, and benzoic acid (16–19,43). One study in ATCC 19606 found that
235 DcaP1 (*A1S_1380*) was upregulated in the presence of mucin, suggesting DcaP1 may play a

236 role in the influx of mucin components (26). In a Biolog screen, we identified multiple carboxylic
237 acid carbon sources that supported significantly more growth of the wildtype compared to the
238 ΔΔΔ*dcaP* mutant (Fig. 3), suggesting DcaP-family proteins are important for their diffusion
239 through the OM.

240 The data suggest DcaP3 is responsible for the influx of carboxylic acid carbon sources
241 citric acid, mucic acid, tricarballylic acid, and *cis*- and *trans*- aconitic acid in *A. baumannii* ATCC
242 17978, as mutants lacking DcaP3 show decreased growth on these substrates (Fig. 4A-B, S3).
243 However, the Δ*dcaP3* mutant grew more than the ΔΔΔ*dcaP* mutant in ATCC 17978, suggesting
244 DcaP1 or DcaP2 may play a minor role in growth with these carbon sources (Fig. S3). Citric
245 acid is an intermediate of the tricarboxylic acid (TCA) cycle, a ubiquitous pathway for energy
246 generation. Despite this, many bacteria cannot utilize citric acid as a carbon source and how
247 citric acid permeates the OM is unknown (44). Mutants in *P. aeruginosa* OpdH were defective
248 for growth on *cis*-aconitic acid, but not on citric acid, suggesting they encode other citric acid
249 transporters (45,46). A ΔΔΔ*dcaP* mutant displayed a strong defect for growth on citric acid that
250 can be rescued by complementing with DcaP3 or DcaP4 (Fig. 4A, 4B, Fig. 5). Therefore,
251 encoding multiple porins for OM citric acid passage may be conserved across bacterial genera.

252 Mucic acid, or galactaric acid, is a sugar acid derived from the oxidation of galactose and
253 is unrelated to mucin. Mucic acid is not typically found in the host; but, some antibiotic
254 treatments result in increased mucic acid in the human gut (47–49). However, only a subset of
255 *A. baumannii* strains, including ATCC 17978, encode the D-galactaric acid dehydrogenase
256 required for growth on mucic acid (50). The digestive tract is a reservoir for *A. baumannii*
257 colonization that increases the potential for infection and transmission and *A. baumannii* ATCC
258 17978 can asymptomatically colonize the mouse gut (51–56). Thus, mucic acid may be used as
259 carbon source by some *A. baumannii* in the inflamed gut. Our data suggest that DcaP3 or
260 DcaP4 are important for growth on mucic acid.

261 The catabolism of *cis*- and *trans*-aconitic acid has been described in *A. baylyi*, and the
262 catabolism of tricarballylic acid in *A. baylyi* and *Salmonella* (33,57,58). However, the OM porin
263 required for growth on these carbon sources in *Acinetobacter* is unknown. Our data suggest that
264 DcaP3 or DcaP4 are important for growth on tricarballylic acid, and *cis*- and *trans*-aconitic acid.
265 Taken together, our data suggests that DcaP3 and DcaP4 are the major porins for passive
266 transport of specific carboxylic acid carbon sources.

267 The requirement for DcaP3 in growth on select di- and tri-carboxylic acids is conserved
268 in the more recent clinical isolate *A. baumannii* AB5075, as a Δ*dcaP3* mutant has reduced
269 growth in these conditions (Fig. 6). However, this was surprising as *A. baumannii* AB5075
270 encodes all four DcaP proteins, including DcaP4, which complemented growth in an *A.*
271 *baumannii* ATCC 17978 ΔΔΔ*dcaP* mutant (Fig. 5). We speculate that *dcaP4* may not be
272 expressed under these conditions.

273 During infection, bacteria must scavenge nutrients from the host to replicate. The *A.*
274 *baumannii* ATCC 17978 ΔΔΔ*dcaP* mutant had a defect compared to wildtype in the mouse liver
275 and spleen that was complemented by expression of *dcaP3* (Fig. 7A-B). This suggests DcaP3
276 passive import of carboxylic acid carbon sources is important for pathogenesis in the liver and
277 spleen. Alternatively, DcaP3 may play another role in pathogenesis. For example, porins in *A.*
278 *baumannii* have demonstrated roles for the adhesion or invasion of eukaryotic cells (13,59–62).
279 DcaP3 is the DcaP-like protein that is a proposed vaccine candidate (21–25). These data
280 suggest that neutralizing DcaP3 may also promote *A. baumannii* clearance.

281 In summary, we further classify a family of porins previously termed DcaP-like into four
282 classes in *Acinetobacter* spp. This classification allows for the differentiation between DcaP-like
283 proteins and the potential to determine individual functions for DcaP1-4 in *Acinetobacter* spp.
284 DcaP3 was critically important for growth on citric acid, tricarballylic acid, mucic acid, and *cis*-
285 and *trans*-aconitic acid as sole carbon sources. A ΔΔΔ*dcaP* mutant was attenuated in a
286 competitive murine systemic infection and complemented by expression of DcaP3, suggesting a

287 role for DcaP3 in pathogenesis and validating its potential as a therapeutic target. Our data
288 therefore provides a deeper understanding of how *A. baumannii* acquires nutrients including in
289 the host.
290
291
292 **MATERIALS AND METHODS**
293 Bacterial strain construction and growth
294 All bacterial strains and plasmids used in this study are listed in Tables S1 and S2,
295 respectively. The wild-type strain was *A. baumannii* ATCC 17978VU or AB5075 (63).
296 Oligonucleotides are listed in Table S3 and were purchased from Integrated DNA Technologies
297 (Coralville, IA). Strains were grown in Luria-Bertani lysogeny broth (LB; Miller) or on LB with
298 1.5% (wt/vol) agar unless indicated otherwise. Antibiotics were used at the following
299 concentrations: carbenicillin (Carb), 75 mg/L; kanamycin (Kan), 40 mg/L; chloramphenicol, 15
300 mg/L; hygromycin (Hyg) 300 mg/L. For deletion constructs, 1000 bp of 3' and 5' flanking DNA to
301 the gene of interest was amplified using Q5 High Fidelity 2x Master Mix [New England Biolabs
302 (NEB), Ipswich, MA] from *A. baumannii* ATCC 17978VU or AB5075. The vector pFLP2 was
303 digested with BamHI and KpnI restriction enzymes (NEB, Ipswitch, MA) and gel purified. The
304 kanamycin or hygromycin cassette was amplified from pKD4. Fragments were ligated together
305 using HiFi ligation mix (NEB, Ipswitch, MA), transformed into chemically competent *E. coli*
306 DH5α, and plated to selective media. Transformants were confirmed to contain the insert by
307 PCR. To generate the knockout strains, a triparental conjugation using helper *E. coli* strain
308 HB101 containing pRK2013 was performed. Single-crossover merodiploids containing the
309 integrated pFLP2 vector were chosen based on a Kan^R $Carb^R$ or Hyg^R and sucrose-sensitive
310 (10% w/v; Suc^S) phenotype. Putative merodiploids displaying were verified by PCR.
311 Merodiploids were then grown on LB agar, resuspended, and plated to LB agar or LB agar with

312 10% sucrose to select for colonies with the second crossover event. Colonies were then
313 screened for a Kan^R $Carb^S$ Suc^R or Hyg^R Suc^S phenotype. Mutants were confirmed via PCR.
314 For chromosomal integration constructs, DNA from ATCC 17978VU or AB5075 was
315 amplified using Q5 High Fidelity 2x Master Mix (NEB, Ipswich, MA). The mTn7 pKNOCK vector
316 was digested with BamHI and KpnI prior to ligation using HiFi ligation mix (NEB, Ipswitch, MA)
317 and transformation into chemically competent *E. coli* DH5α λ*pir116*$^+$. To generate
318 chromosomally integrated mTn7 constructs, a modified four-way parental mating was performed
319 using helper *E. coli* strain HB101 containing pRK2013 and *E. coli* DH5α containing pTNS2 (64).
320 Colonies were screened by PCR for integration into the correct chromosomal locus at the *att*
321 site. All plasmid constructs were verified by whole plasmid sequencing before transforming into
322 *A. baumannii* (Plasmidsaurus, South San Francisco, CA).
323
324 Phylogenetic tree construction
325 To identify DcaP orthologs and classify them into hierarchical orthogroups (HOGs),
326 OrthoFinder v2.5.5 was used (65). Two datasets were analyzed: (i) a 253-strain dataset
327 including 235 *A. baumannii* strains deduplicated as previously described (66); (ii) a 28-species
328 dataset that included multiple *Acinetobacter* and a broader range of gammaproteobacteria
329 rooted by one alphaproteobacterial. The protein accession numbers and genome accession
330 numbers are listed in Table S4.
331 Non-Acinetobacter species were selected based on the conservation of DcaP orthologs
332 across the genus or species indicated by KEGG. Specific organisms were selected to portray a
333 representative distribution of DcaP orthologs across bacteria, a group of 22 species. The
334 FastTree v2.1.11-derived (67), manually rooted species tree was used as an input for
335 OrthoFinder HOG inference (65,68), ensuring accurate classification of gene duplication and
336 speciation events. The resulting DcaP classifications were visualized and annotated in iTOL

337 (69). To infer a species phylogeny, a set of 120 universal bacterial marker genes (Bac120) was
338 identified from each proteome using HMMER3 (hmmsearch, v3.3), following the methodology
339 described in Parks *et al*. 2018 (70). The majority of species had only one significant hit for each
340 of the 120 protein HMMs; if a species had more than one hit, the best-scoring hit for that marker
341 was extracted.

342 Each of the 120 marker proteins was independently aligned to its respective HMM profile
343 using hmmalign (HMMER v3.3). Alignments were trimmed to remove poorly aligned regions and
344 concatenated into a single concatenated supermatrix for each species. To improve alignment
345 quality, columns were filtered based on the following criteria: (i) highly gapped regions (>80%
346 gaps) were removed; (ii) completely homogenous columns were excluded to reduce
347 redundancy.

348 Maximum likelihood species trees were inferred from the filtered concatenated alignment
349 using FastTree v2.1.11, with the LG model of amino acid evolution. The resulting unrooted trees
350 were manually rooted and annotated in iTOL using *Brevundimonas subvibrioides* or *E.coli* as
351 outgroups for the smaller and larger datasets.

352

353 <u>DcaP protein phylogeny</u>

354 DcaP homologs were extracted from their respective proteomes by selecting sequences
355 within the DcaP HOG at the root of all *Acinetobacter* species in the 255-species dataset in
356 Orthofinder. To ensure consistent domain identification, sequences were aligned to the Pfam
357 Hidden Markov Model (HMM) PF19577.4, corresponding to the DcaP OM protein family.
358 Alignments were trimmed to remove poorly aligned residues prior to phylogenetic inference. A
359 maximum likelihood phylogenetic tree was constructed using FastTree v2.1.11 with the LG
360 model of amino acid evolution. The inferred clusters were identical to OrthoFinder's DcaP
361 subfamilies, except for a small cluster of DcaP proteins that OrthoFinder grouped with DcaP1,
362 while FastTree grouped the same cluster with DcaP3.

363 To identify putative orthologs of DcaP proteins from the 22 species identified above and
364 *A. baumannii* AB5075, proteomes from genomic assemblies were downloaded from the NCBI
365 Datasets database. Two complementary approaches were employed to verify orthology. First,
366 HMMER v3.4 was used to search each proteome with the Pfam profile HMM PF19577,
367 corresponding to the DcaP protein family. Significant hits were retained as candidate DcaP
368 homologs. To independently assess orthology and reconstruct gene relationships, OrthoFinder
369 v2.5.5 was run on all 23 proteomes, which also produced a rooted gene tree for the DcaP
370 family. The resulting DcaP sequences were realigned to the PF19577 HMM using hmmalign,
371 and poorly aligned or unaligned amino acids were trimmed. A maximum likelihood phylogeny
372 was then inferred using RAxML v8.2.12, under the LG amino acid substitution model.
373 Amino acid sequence alignment and percent identity were determined using the Clustal
374 Omega program (28).
375
376
377 Carbon source utilization screen using Biolog plates
378 Plates PM1 and PM2A were obtained from Biolog for carbon source utilization testing. A
379 110 μL aliquot of defined M9 minimal media lacking carbon was dispensed into every well and
380 resuspended. Then, 100 μL was transferred from the Biolog plates into sterile flat-bottom 96-
381 well plates. Overnight bacterial cultures were diluted 100-fold in sterile PBS before 1 μL of
382 diluted culture was inoculated into every well. Plates were incubated at 37°C with shaking and
383 growth was monitored by optical density at 600 nm (OD_{600}) in an EPOCH2 or SynergyH1 BioTek
384 plate reader (Winooski, VT). Background absorbance was subtracted before area under the
385 curve calculations for each isolate and each compound were calculated and the difference
386 between wildtype and ΔΔΔ*dcaP* was analyzed. Compounds were included if any isolate of
387 either wildtype or ΔΔΔ*dcaP* reached an OD_{600} of 0.15 or higher.

388

389 Growth curve analyses

390 M9 minimal medium without glucose was supplemented 0.1X Vishniac's trace minerals
391 (71) with the specified carbon source at a concentration to maintain the carbon equivalency of a
392 4-carbon compound at 16.5 mM. Cultures were inoculated with a single bacterial colony and
393 grown in 3 mL LB media overnight at 37°C with shaking at 180 rpm for 8-16 hours. Growth
394 curves were performed by diluting overnight cultures 100-fold in sterile PBS and inoculating 1
395 μL diluted culture into 99 μL media in a 96-well flat bottom plate. Growth was monitored as
396 described above.

397

398 Murine bloodstream infection

399 Six-week-old female ND4 Swiss Webster mice were purchased from Envigo/Harlan
400 Laboratory. Mice were boarded in a temperature-controlled environment with 14:10 h light:dark
401 cycles and food and water were provided as needed. Mice were acclimated to the facility for 1
402 week prior to infection. Mice were anesthetized with isoflurane and inoculated retro-orbitally with
403 approximately 3×10^8 CFU in a 50 μL bacterial suspension of a 1:1 mixture of *A.*
404 *baumannii* ATCC 17978VU wildtype and ΔΔΔ*dcaP* mutant or ΔΔΔ*dcaP*+*dcaP3*. For wildtype
405 versus ΔΔΔ*dcaP,* 5 of the mice were infected with wild-type ATCC 17978VU and 5 were infected
406 with ATCC 17978 mTn7(Carb^R). All mice infected with the complement strain were infected with
407 ATCC 17978VU. The inoculum dose was determined by serial dilution and plating on selective
408 agar media. Mice were euthanized at 24 h post infection by CO_2 asphyxiation, and the organs
409 were excised aseptically. Tissues were homogenized in PBS using a Bullet Blender (Next
410 Advance, Troy, NY), and all samples were serially diluted and plated on LB and LB with
411 carbenicillin or kanamycin selective agar plates for bacterial enumeration. All animal care
412 protocols were approved by the University of Illinois Chicago Institutional Animal Care and Use

Committee (IACUC; protocol number 23–119) in accordance with the Animal Care Policies of UIC, the Animal Welfare Act, the National Institutes of Health, and the American Veterinary Medical Association (AVMA). Animals were humanely euthanized consistent with the AVMA guidelines.

Data reporting, statistical analysis, and figure preparation

Each measurement was taken from a distinct biological sample (e.g., bacterial culture from a single colony or an individual mouse). Data processing and statistical analyses were performed using Microsoft Excel 16.98 and GraphPad Prism 10.4.2. Statistical tests used are indicated in each figure legend. Figures were prepared in Adobe Illustrator 25.2.3.

Author contributions

H.R.N. – project conceptualization, methodology, data collection, data analysis, and writing. J.D.W – bioinformatics, data analysis, and writing. L.D.P. – project conceptualization, methodology, data analysis, writing, funding, and resources.

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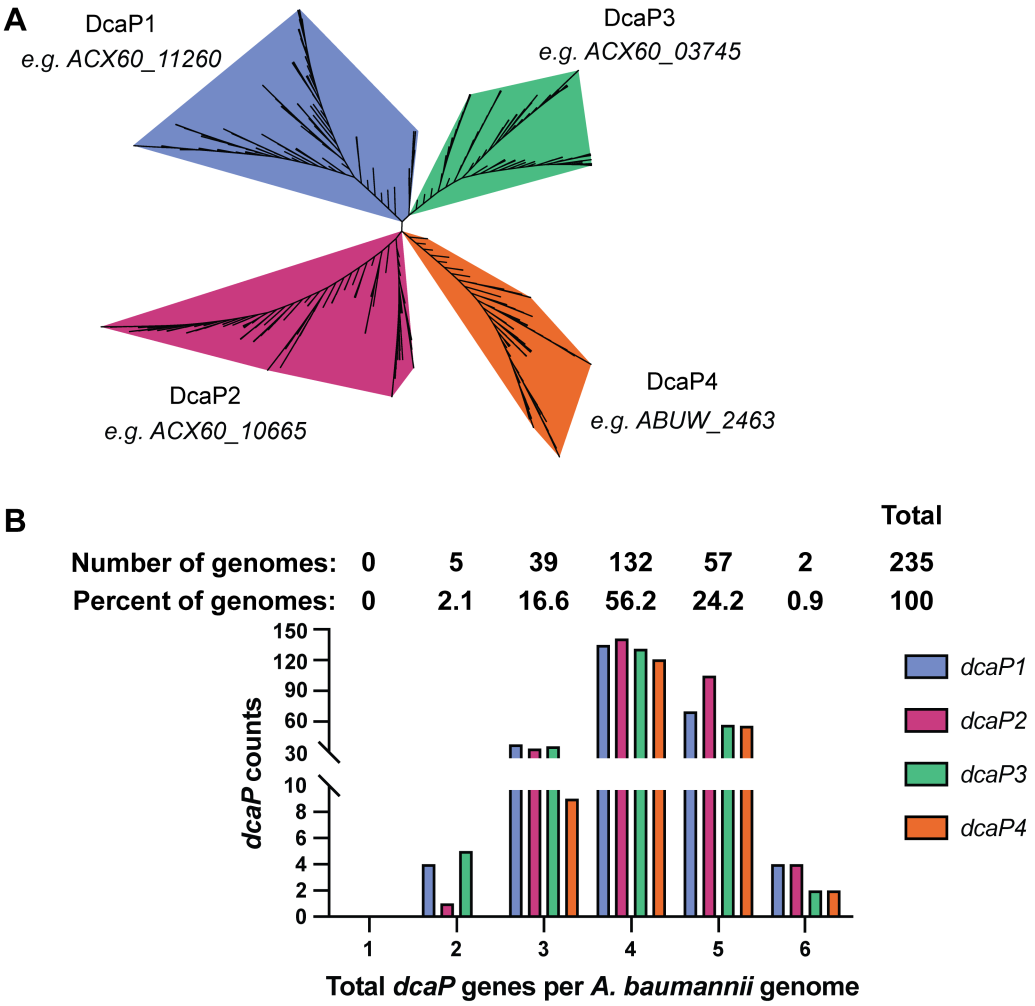
638

639 **FIGURES**



640
641 **Figure 1. *A. baumannii* DcaP proteins cluster in four classes and are widely distributed**
642 **among *Acinetobacter*. (A)** An unrooted tree of DcaP protein sequences from 255
643 *Acinetobacter* genomes (235 *A. baumannii* genomes). **(B)** Manual counts and distribution of
644 individual DcaP proteins binned by the total number of DcaP proteins in an *A. baumannii*
645 genome.
646

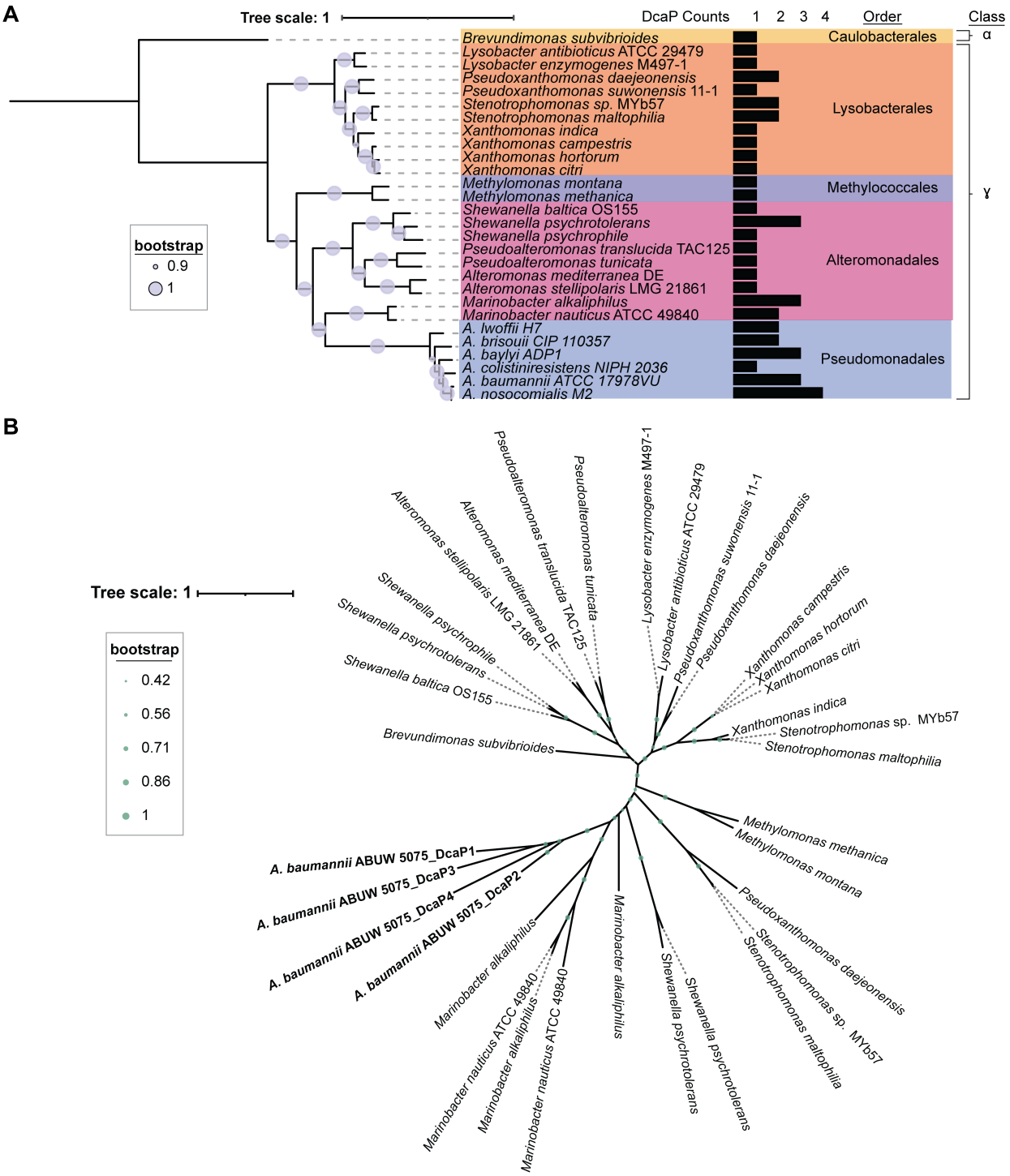


Figure 2. *A. baumannii* DcaP-family proteins cluster together compared to non-*Acinetobacter* DcaP proteins. (A) A rooted tree of DcaP containing species outside of *Acinetobacter* and some *Acinetobacter spp.* depicting class, order, and number of encoded DcaP proteins. **(B)** An unrooted tree of DcaP protein sequences from non-*Acinetobacter* species with AB5075 as the *A. baumannii* reference. Tree scale in amino acid substitutions.

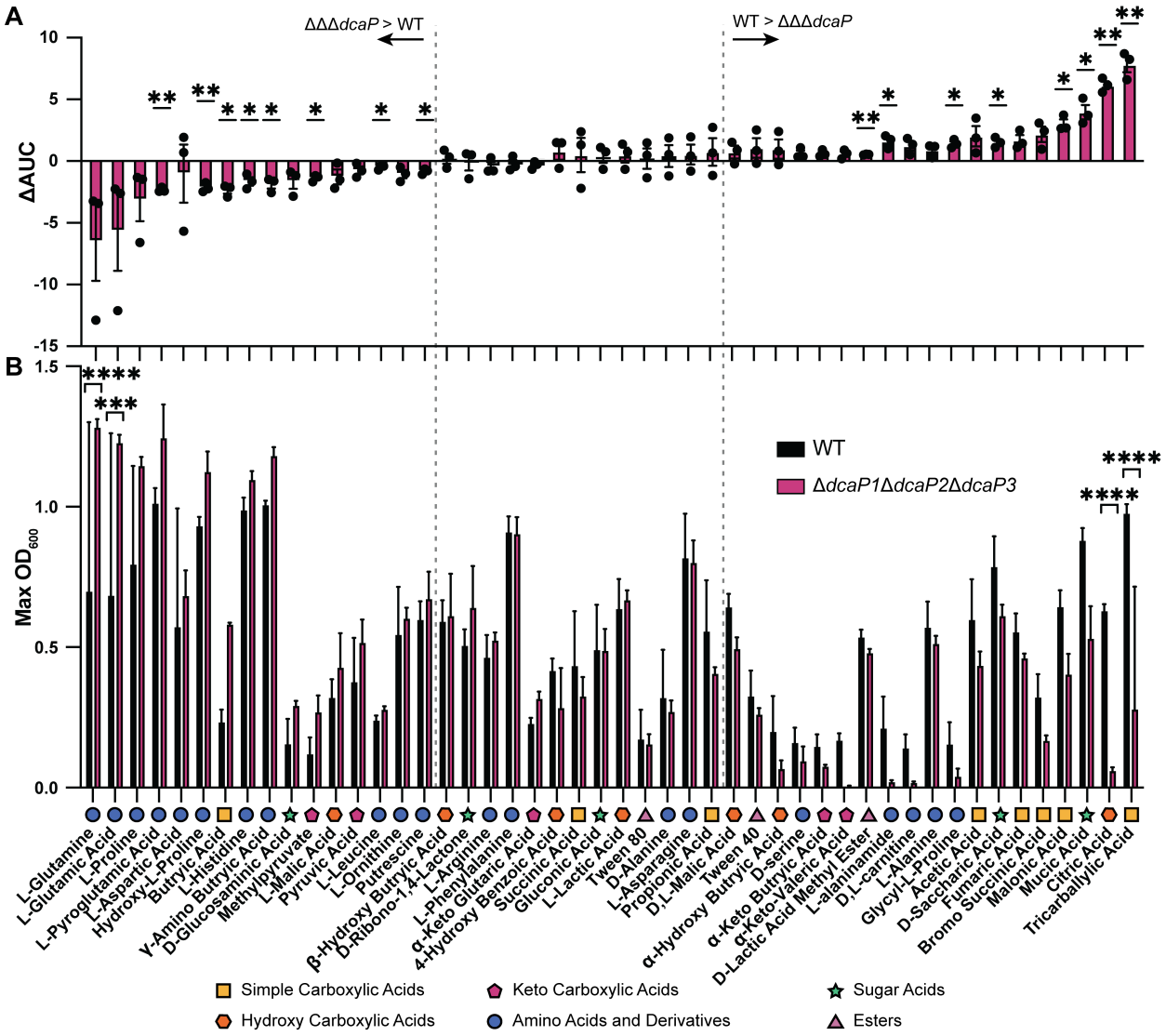


Figure 3. Wild-type *A. baumannii* grows better than ΔΔΔ*dcaP* mutant on certain di- and tricarboxylic acids as sole carbon sources. Biolog plates PM1 and PM2a were resuspended in M9 minimal media without a carbon source and inoculated with either WT or the ΔΔΔ*dcaP* mutant. (**A**) Difference in area under the curve (ΔAUC) was calculated for WT – ΔΔΔ*dcaP* mutant. Each point is from one experiment with 1 biological replicate per strain. Significance is by one sample t-test compared to 0. (**B**) Maximum optical density at 600 nm (OD_{600}) is shown. Significance is by two-way ANOVA with Sidak's multiple comparisons. Experiments were conducted three times with an n=1 for a total of n=3. Data are mean +/- SD. *$P < 0.05$, **$P < 0.01$, ***P < 0.001, ****P < 0.0001

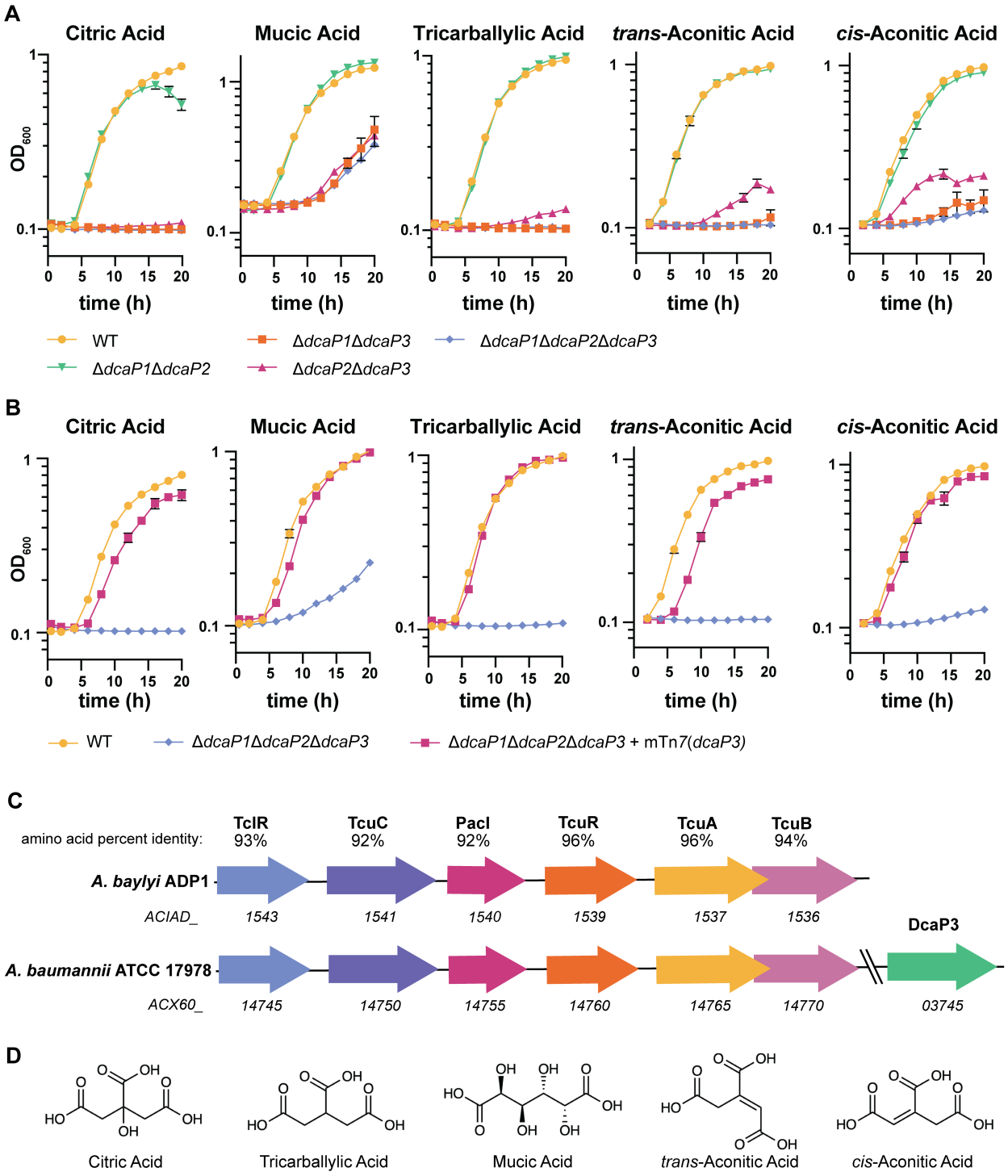
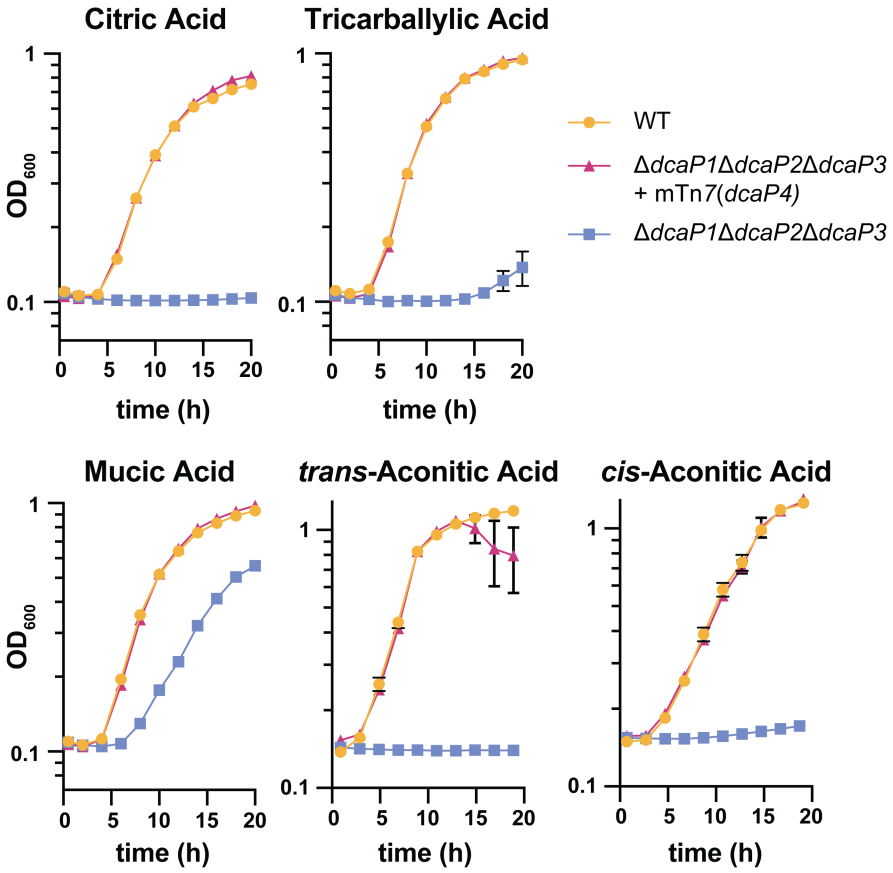
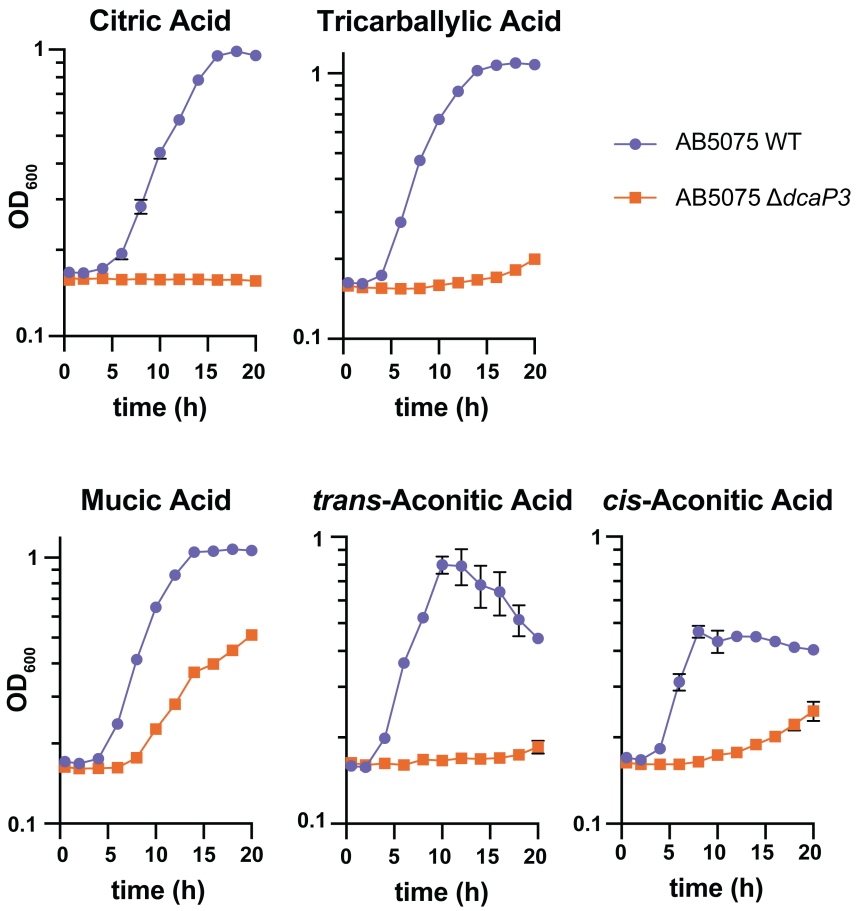


Figure 4. DcaP3 is important for growth on the carboxylic acid carbon sources citric acid, tricarballylic acid, mucic acid, and *cis*- and *trans*- aconitic acid. (A) Wildtype, double, and the triple ΔΔΔ*dcaP* mutants were grown in M9 media with the indicated compound as the sole carbon source. Optical density at 600 nm (OD_{600}) is shown. **(B)** Wildtype, the ΔΔΔ*dcaP* mutant, and the ΔΔΔ*dcaP* mutant complemented with *dcaP3* were grown on the indicated compound as the sole carbon source. **(C)** The genetic organization of the *tcu* metabolic locus and *dcaP3* in *A. baumannii* ATCC 17978. **(D)** The chemical structures of the relevant carbon source compounds. Data are mean +/- SEM and n=3. Experiments were repeated twice with similar results.



674
675 **Figure 5. *A. baumannii* AB5075 DcaP4 complements growth of *A. baumannii* ATCC 17978**
676 **Δ*dcaP1-3* on citric acid, tricarballylic acid, mucic acid, and *cis*- and *trans*-aconitic acid.**
677 Wildtype, the ΔΔΔ*dcaP* mutant, and the ΔΔΔ*dcaP* mutant complemented with *dcaP4* were grown
678 in M9 media with the indicated compound as the sole carbon source. Optical density at 600 nm
679 (OD_{600}) is shown. Data are mean +/- SEM and n=3. Experiments were repeated twice with
680 similar results.
681



682
683 **Figure 6. *A. baumannii* AB5075 Δ*dcaP3* is defective for growth on citric acid, tricarballylic**
684 **acid, mucic acid, and *cis*- and *trans*-aconitic acid.** *A. baumannii* AB5075 wild-type and
685 Δ*dcaP3* mutant strains were grown in M9 media with the indicated compound as the sole
686 carbon source. Optical density at 600 nm (OD_{600}) is shown. Data are mean +/- SEM and n=3.
687 Experiments were repeated twice with similar results.
688

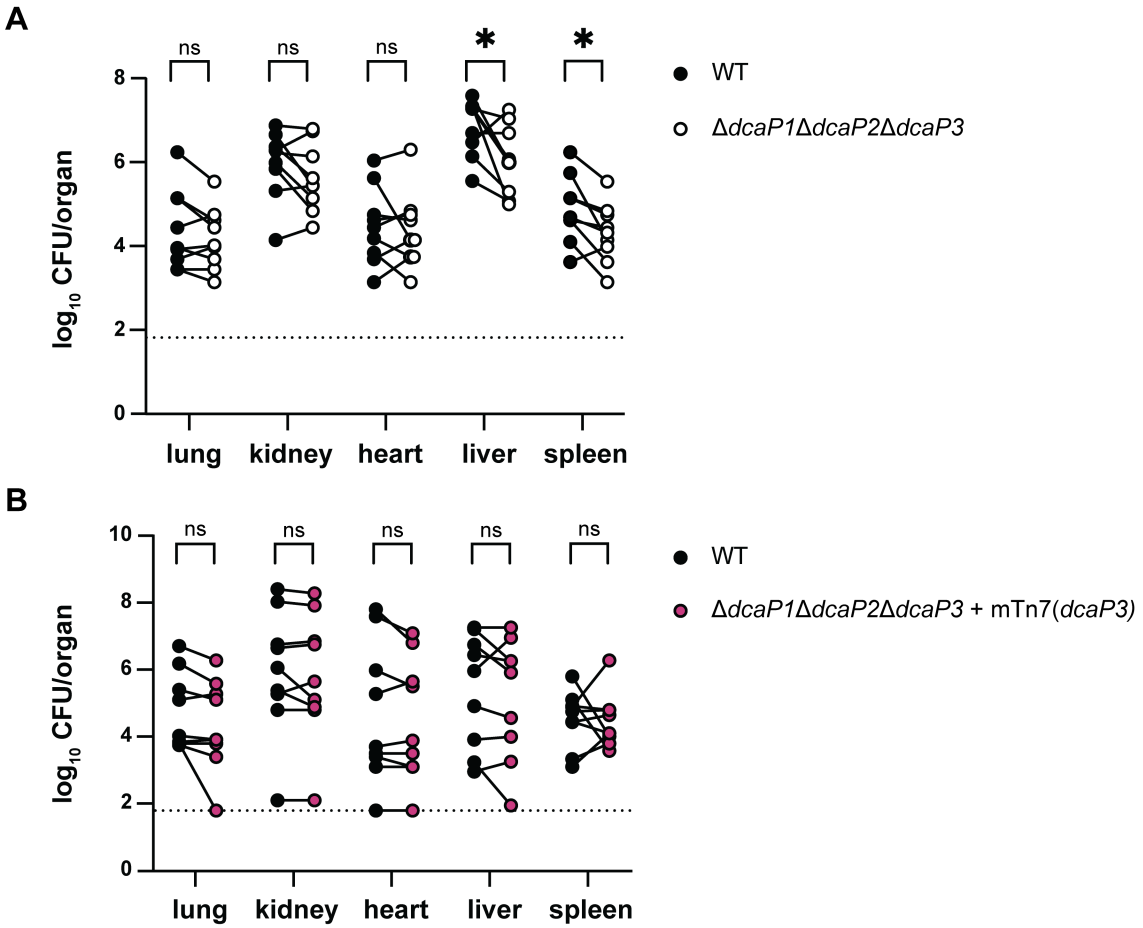


Figure 7. DcaP3 is important for infecting the liver and spleen in a model of bloodstream infection. (A-B) Wild-type and the indicated strains were retro-orbitally inoculated into Swiss Webster mice in a 1:1 ratio. At 24 h post-infection, organs were harvested and bacterial CFU were enumerated. The dotted lines indicate the limit of detection. Each point represents one strain enumerated from one mouse; n=9-10. Data are combined from two experiments. Statistics are Wilcoxon non-parametric test. *$P < 0.05$.