



### Colistin- phage combinations decrease antibiotic resistance in *A. baumannii* via changes in envelope architecture

Journal:	<i>Emerging Microbes &amp; Infections</i>
Manuscript ID	TEMI-2021-0922.R1
Manuscript Type:	Research Article
Date Submitted by the Author:	n/a
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Keywords:	phage therapy, Phage, Phage Resistance, Colistin Resistance, Virulence
Abstract:	Multidrug-resistant bacterial infections are becoming increasingly common, with only few last-resort antibiotics such as colistin for clinical therapy. An alternative therapeutic strategy gaining momentum is phage therapy, which has the advantage of not being affected by bacterial resistance to antibiotics. However, a major challenge in phage therapy is the rapid emergence of phage-resistant bacteria. In this work, our main aim was to understand the mechanisms of phage-resistance used by the

	<p>top priority pathogen <i>Acinetobacter baumannii</i>. We isolated the novel phage Phab24, capable of infecting colistin-sensitive and -resistant strains of <i>A. baumannii</i>. After co-incubating Phab24 with its hosts, we obtained phage-resistant mutants which were characterised on both genotypic and phenotypic levels. Using whole genome sequencing, we identified phage-resistant strains that displayed mutations in genes that alter the architecture of the bacterial envelope at two levels: the capsule and the outer membrane. Using an adsorption assay, we confirmed that phage Phab24 uses the bacterial capsule as its primary receptor, with the outer membrane possibly serving as the secondary receptor. Interestingly, the phage-resistant isolates were less virulent compared to the parental strains in a <i>Galleria mellonella</i> infection model. Most importantly, we observed that phage-resistant bacteria that evolved in the absence of antibiotics exhibited an increased sensitivity to colistin, even though the antibiotic resistance mechanism per se remained unaltered. This increase in antibiotic sensitivity is a direct consequence of the phage-resistance mechanism, and could potentially be exploited in the clinical setting.</p>

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# **Colistin- phage combinations decrease antibiotic resistance in *A. baumannii* via changes in envelope architecture**

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**ABSTRACT:** Multidrug-resistant bacterial infections are becoming increasingly common, with only few last-resort antibiotics such as colistin for clinical therapy. An alternative therapeutic strategy gaining momentum is phage therapy, which has the advantage of not being affected by bacterial resistance to antibiotics. However, a major challenge in phage therapy is the rapid emergence of phage-resistant bacteria. In this work, our main aim was to understand the mechanisms of phage-resistance used by the top priority pathogen *Acinetobacter baumannii*. We isolated the novel phage Phab24, capable of infecting colistin-sensitive and -resistant strains of *A. baumannii*. After co-incubating Phab24 with its hosts, we obtained phage-resistant mutants which were characterised on both genotypic and phenotypic levels. Using whole genome sequencing, we identified phage-resistant strains that displayed mutations in genes that alter the architecture of the bacterial envelope at two levels: the capsule and the outer membrane. Using an adsorption assay, we confirmed that phage Phab24 uses the bacterial capsule as its primary receptor, with the outer membrane possibly serving as the secondary receptor. Interestingly, the phage-resistant isolates were less virulent compared to the parental strains in a *Galleria mellonella* infection model. Most importantly, we observed that phage-resistant bacteria that evolved in the absence of antibiotics exhibited an increased sensitivity to colistin, even though the antibiotic resistance mechanism per se remained unaltered. This increase in antibiotic sensitivity is a direct consequence of the phage-resistance mechanism, and could potentially be exploited in the clinical setting.

**Running title:** Phage resistance in colistin resistant *A. baumannii*

**Keywords:** Phage; Phage Therapy; Phage-resistance; Phage Adsorption; Colistin Resistance; Antibiotic Resensitisation; Virulence;

**Introduction:**

Antimicrobial resistance (AMR) is a global concern. The overuse of antibiotics in human medicine and the misuse of even last resort antimicrobial compounds such as colistin in agriculture, is contributing to the increasing number of antibiotic resistant bacterial pathogens [1]. Molecular mechanisms of resistance have evolved for most antibiotics, which are then quickly distributed throughout bacterial populations by horizontal gene transfer. This is primarily mediated by plasmids and integrative and conjugative elements, ICEs [2-4]. At the same time, the slow and expensive discovery process and clinical development of antimicrobial compounds together with the lack of monetary incentives have resulted in continuously decreasing numbers of effective drugs to treat bacterial infections [5, 6]. Even the last resort antibiotic colistin, often associated with strong renal and neurological side effects, is now being deployed for infections by multidrug resistant pathogens, regaining clinical importance. However, colistin resistance in pathogens is increasing as well.

Phage therapy has emerged as a promising strategy to treat drug resistant bacterial infections, as viruses are not affected by resistance to antimicrobial compounds [7-9]. Phage therapy is the use of lytic phages that have the ability to inactivate pathogens. However, phage-resistance, i.e. the emergence of bacterial mutants that are resistant to a therapeutic phage, is commonly observed [10]. Several solutions have been explored in the past, such as combinational phage-antibiotic therapeutic courses, where synergistic effects are often observed, or the deployment of phage mixtures (“phage cocktails”). Yet, in the majority of clinical trials phage-resistance occurs [11]. Therefore, it is important to understand the mechanisms that enable bacteria to gain resistance to phages and the consequences of selection. In addition, identifying target molecules that facilitate phage

infection and deploying phages that do not bind the same receptors has been proposed to decrease the likelihood of phage-resistance [12].

In order to understand molecular mechanisms of phage-resistance, we investigated a phage-pathogen system consisting of the type strain of *A. baumannii* ATCC17978, and a colistin-resistant mutant derived from the isolate. We employed whole genome sequencing of phage-escape mutants that emerged after co-incubating the novel phage Phab24 that infects both strains. We found that genes abolishing infection are primarily involved in the biogenesis of the envelope of the bacterial host, namely the lipooligosaccharide (LOS) of the outer membrane and capsular polysaccharides. Specifically, phage resistance is mediated by mutations in gene *gtr9*, which is putatively involved in capsule formation, and *gtrOC3*, which plays a role in LOS biosynthesis. While a *gtr9* deletion leads to decreased adsorption, the mutation in the *gtrOC3* gene, by itself, does not alter binding of the phage to the bacterial surface. Gene engineered strains introducing the observed mutations one at a time in the parental strain, and their complementation with the wildtype gene *in trans*, confirmed the role of the genes in phage-resistance. *In vitro* evolution experiments resulted in the selection of escape mutants with decreased antibiotic resistance, with mutations in *gtr9*, and possibly *gtrOC3*, contributing to this effect.

## Results

### Isolation of Phage Phab24 that infects Colistin-Resistant *A. baumannii* Strain XH198

Colistin resistance is mediated by a fundamental change in the bacterial outer membrane composition. A mutation in gene *pmrB* (G315D) results in surface modification of the bacterial envelope, preventing efficient colistin binding and thus mediating resistance to the antibiotic [13-17]. To study phage-resistance of bacteria *in vitro*, we used the colistin resistant *Acinetobacter baumannii* strain XH198 and its non-resistant parental strain ATCC17978. Strain XH198 was obtained by an *in vitro* evolution experiment and exhibits altered LOS molecules, which have also been observed in clinical isolates, rendering colistin ineffective [14]. We isolated several phages that are able to infect both XH198 and ATCC17978. To focus on one particular virus-host system, we selected a phage that we named Phab24, for Phage *Acinetobacter baumannii* number 24 [18] (Figure 1A). Whole genome analysis using the programme PhageAI (<https://phage.ai/>) revealed that bacteriophage Phab24 is virulent (lytic) with a 93.76% prediction confidence [19].

### Isolation and characterisation of phage-resistant bacterial mutants:

We first used the phage-host system of Phab24 and ATCC17978, to study the emergence of phage-resistant bacterial mutants, by co-incubating both in liquid media. Subsequently, bacteria were plated on solid media from which we randomly picked 80 bacterial colonies (R1-R80, genome accession data: Supplemental table 1). Surprisingly, two isolates displayed susceptibility to Phab24, possibly due to persister cells [20], while the remaining 78 were resistant to Phab24. Similarly, from co-incubating Phab24 with XH198, the colistin-resistant derivative of the ATCC reference strain, we isolated 400 colonies at random. Next, we sequenced the whole genome of six of the phage-resistant isolates of ATCC17978 (R5, R10, R22, R23, R39, R70) and nine of XH198 (R81, R83, R86, R115,

R125, R130, R132, R134, R137). Using Breseq [21], we found several point mutations as well as deletions or insertions in genes that might mediate phage-resistance, which were confirmed by PCR and subsequent sequencing (Table 1 and Supplemental table 2). The most common gene to have mutations was *gtrOC3* [22,23], which codes for a putative glycosyltransferase (gtr) present in the type-2 OC locus, responsible for the biosynthesis of the outer core of *A. baumannii*'s lipooligosaccharide. Therein, we observed a single nucleotide deletion or an IS insertion (by the IS701-like element from the ISAbA11 family), indicating parallel emergence of phage resistance. We also found mutations in genes predicted to code for other glycosyltransferases (*gtr1*, AUO97\_06920 and *gtr2*, AUO97\_03485), phosphohydrolase *phoH* (AUO97\_03925) and the putative ABC transporter *abcT* (AUO97\_07355). While we found many mutations in genes that were later identified to be irrelevant for phage-resistance, we also identified two types of mutations (a frameshift or an insertion) in the glycosyltransferase gene *gtr9* (AUO97\_06900), which is found in the type-3 capsule biosynthesis (K) locus.

To demonstrate that the mutations indeed render a strain non-susceptible, we constructed several plasmids encoding the wildtype genes in the *A. baumannii* shuttle vector pYMAb2-hygR [24,25]. We then introduced the episomal elements into the phage-resistant (R) mutants. The expression of the wildtype genes of the LOS biosynthesis protein *gtrOC3* (e.g. in R1) as well as of *gtr9* (e.g. in R7) did restore phage sensitivity, unless they were both present in the strain (e.g. strain R5) (Table 1). Some phage-resistant isolates could not be complemented by wildtype genes coding for some of the mutations we observed, e.g. the membrane transport protein *abcT* (AUO97\_07355) *phoH* (AUO97\_03925), or *actP* (AUO97\_05550). This indicates the presence of additional, as of yet unidentified, mutations that confer resistance (Supplemental table 2).



Due to the obvious complexity of the resistance mechanisms, we decided to focus on *gtrOC3* and *gtr9*. To demonstrate the role of these genes in phage susceptibility, in addition to complementation *in trans*, we engineered the mutations into the parental *A. baumannii* strain (ATCC17978), or created knock-out mutants of genes. When mutations were introduced into the gene coding for *gtrOC3*, the bacterium was rendered “immune” to phage Phab24 (Figure 1B). Similarly, a reconstructed mutant in which the *gtr9* gene was deleted could not be infected by the phage, clearly demonstrating the role of these two genes in phage susceptibility. Both reconstructed mutants could be infected by Phab24 when the complementing wildtype genes are expressed *in trans*, from plasmids (Figure 1B and C).

### **Attachment of Phab24 to the surface of phage-resistant mutants**

As the mutations found in *gtrOC3* and *gtr9* code for putative proteins involved in LOS and capsule formation, respectively, we concluded that the surface of the phage-resistant mutants may exhibit modifications compared to the wildtype. Changes on the surface of mutant strains might therefore lead to a reduction in binding of phages to bacteria. We therefore performed binding assays to assess the quantity of phages that bind to the bacterial envelope. To this end, we co-incubated Phab24 with the phage-resistant mutants and controls for 20 minutes and subsequently determined the phage titre left in the supernatant (Figure 2). The positive control, strain ATCC17978, was able to reduce the free-phage titre by a factor of more than 1000-fold, while the negative controls (no bacteria or *A. baumannii* strain XH194 resistant to Phab24 infection) resulted in only a minor reduction in the number of phage particles in the supernatant. Interestingly, Phab24 bound ATCC17978 with an apparent binding affinity higher than XH198. The *gtr9* knockout on the backbone of ATCC17978 showed reduced bacteriophage binding, similar to the negative controls. Expectedly, upon complementation with the wildtype *gtr9* gene *in trans*, binding of

Phab24 was restored to a level comparable to parental ATCC17978. Interestingly, the *gtrOC3* knockout and its derivative complemented with wildtype *gtrOC3* both bound Phab24 avidly just like the parental ATCC17978 strain. In summary, phage Phab24 is able to bind to most phage-resistant strains, with the exception of *gtr9* mutants, and those with double mutations in *gtr9* and *gtrOC3*, suggesting the bacterial capsule is the primary receptor used by the phage (Figure 2B).

### **The bacterial envelope is altered in both the LOS (*gtrOC3*) and capsule (*gtr9*) mutants**

LPS, or LOS in the case of *A. baumannii*, often serves as a co-receptor in phage binding [26]. As a disruption in the gene coding for a LOS biosynthesis protein (*gtrOC3*) was observed, we determined if the mutations in the isolated strains lead to a change in LOS composition. Mass spectrometry of isolated lipid A, obtained using the hot aqueous phenol extraction method, was performed to compare the reconstructed mutants (on the ATCC17978 backbone) with the ATCC17978 control (Figure 3B and A, respectively). In addition, we analysed samples of the plasmid-complemented strain that allows the expression of *gtrOC3* *in trans*. Previously, it was established that the mass/charge (m/z) ratio of *A. baumannii* lipid A is featured as a prominent peak at 1,910, which was identified as a singly deprotonated lipid A structure that contains two phosphate groups and seven acyl chains (i.e., diphosphoryl hepta-acylated lipid A). In our experiments, this peak was observed in all samples (Figure 3A-C). While the mass spectrum of the KO strain (Figure 3B) shows molecules with m/z values of 1,910 and smaller, the reference spectrum (Figure 3A) exhibits several additional small peaks larger than 2,000. These higher molecular weight peaks are more prominent in the plasmid-complemented strain (Figure 3C). While the identification of molecules that lead to the occurrence of these peaks with higher m/z values is still outstanding, they possibly represent modified Lipid A molecules. As these

peaks are clearly absent from the baseline spectrum recorded in the KO strain sample (Figure 3B), it may be reasonable to conclude that the disruption in *gtrOC3* results in a modification in the bacterial surface structure. The gene disruption might ultimately prevent the incorporation of one or more types of modified LOS molecules into the bacterial envelope which -when absent- abolish Phab24 phage binding [15, 27].

As *gtr9* is found in the K locus, and therefore is involved in the formation of the bacterial capsule, we isolated the oligosaccharides of both the reconstructed *gtr9* mutant and the parental strain ATCC17978, and compared them using mass spectrometry. Perhaps unexpectedly, we did not observe any additional presence or absence of peaks in the spectra across 180-3200 m/z (Supplemental Fig. 1, 2, 3). While ratio and intensity varied for some peaks, there is no indication of the absence of specific polysaccharides, or the presence of others, in the *gtr9* mutant. Because the relative quantity of the polysaccharides cannot be firmly established through mass spectrometry, we attempted to determine such differences using SDS PAGE gels, which allow a separation of molecules based on size, while also allowing a quantitative analysis. Here, we observed that the genetically engineered *gtr9* mutants of ATCC17978 or of XH198 exhibited a massive reduction in material on the gel compared to the complemented strains (and the reference strains) where *gtr9* was expressed *in trans* (Figure 3D, E). A gel with Alcian blue, which stains acidic polysaccharides, shows that the *gtr9* mutants of both ATCC17978 and XH198 contain almost undetectable amounts of material, while the plasmid-complemented strains are similar to the wildtype level. In addition to large molecular weight bands, we also observe small molecule components which are stained by Alcian blue (Fig. 3D), but also by silver ions (Fig. 3E). As silver staining allows the sensitive detection of lipids and proteins but not of the saccharides (and polypeptides can be excluded due to the preparation which includes a Proteinase K digestion step), the smaller molecules possibly

indicate the presence of lipid-saccharide conjugates in the samples, which again, are absent in the *gtr9* mutants. Although the mass spectrometry data did not indicate any changes in saccharide composition, the quantitative method of size-separated oligosaccharides on gels suggests that the bacterial envelope surface of the *gtr9* mutant is different from that of the *A. baumannii* reference strain.

### **Changes in cell morphology and capsule formation in phage-escape mutants.**

On the molecular level, we could confirm that the composition of the cell envelope is different in the *gtrOC3* mutant while we found no indication for a qualitative change in the *gtr9* mutant, although the mutant appears to produce substantially less exopolysaccharides. However, we pursued further evidence before conclusively asserting that the surface structure of the cells is altered by the mutations. We first employed Transmission electron microscopy on thin sections of resin-embedded cells with inconclusive results (Supplemental Figure 4). We then used Scanning Electron Microscopy where, both ATCC17978 and XH198 cells, appear similarly smooth and rod-shaped. A similar morphology could be observed in the case of cells containing the *gtrOC3* mutant; when complemented *in trans* by the functional gene, a slightly more “shrivelled” -possibly desiccated- structure was observed. A very even, smooth surface was seen when the *gtr9* mutant was complemented with the functional gene *in trans* while the surface of the *gtr9* mutant itself appeared less smooth. In addition, the cells of the *gtr9* mutant appear more rounded and adherent to each other, forming clusters (Figure 4). We also observed the formation of mucoid-like strings in preparations of the *gtr9* mutant which were absent in all other samples (not shown).

The observed clustering and appearance of “slime” on the surface of the *gtr9* mutant may be caused by altered exopolysaccharide production and/or biofilm formation. We therefore

assessed the production of these materials by growing bacteria on a solid surface for three days, washing them off, and testing the capacity of the produced material to retain the crystal violet dye. Here, we observed that dye retention, which is commonly used to determine the extent of biofilm formation in the lab setting, was most pronounced in the colistin resistant strain XH198, but remained low in all other strains (Figure 5A). Compared to the reference strain ATCC17978, the *gtr9* mutant showed reduced biofilm formation (~42 % reduction compared to ATCC17978), while plasmid complementation led to a slight increase in biofilm (~117% of that of ATCC17978) (Figure 5A). In the case of the *gtrOC3* mutant, no significant difference in biofilm formation between the complemented or non-complemented strains was observed. Thus, the “mucoid” appearance and aggregation observed in SEM preparations of the cells in the *gtr9* mutant cannot be explained by the formation of biofilms. Interestingly, we observed the formation of highly fragile membranous structures in the multi-well plates for this mutant that, however, did not retain the dye, and were washed away easily (Supplemental Figure 5A). In addition to the formation of biofilms we also employed crystal violet staining of capsules of planktonic cells. Biofilms are usually formed when bacteria are incubated for a long duration and allowed to sediment and form clusters. If cells are incubated for shorter times with shaking, biofilm formation does not occur. It is reasonable to assume that the amount of dye that is retained by the capsule correlates with the quantity of material present for the dye to embed in (i.e. more dye is retained by thicker, more extensive capsules) and/ or the density of the packing of the capsule material (i.e. released quicker if the material is less compact). The ATCC17978 strain retained substantially more dye compared to the *gtr9* mutant while a complementation results in the same levels observed for the reference strain (Figure 5B). One interpretation is that the *gtr9* mutant strain can absorb less dye due to a smaller capsule which would correlate with the results of the capsular material

separated on SDS gels (Figure 3). The *gtrOC3* mutant exhibits slightly more absorption of the dye, while the complemented strain shows levels identical to ATCC17978.

### **Capsule (*gtr9*) and LOS (*gtrOC3*) biosynthesis mutants are less virulent *in vivo***

The extended bacterial surface structure, which includes capsules and LPS/LOS molecules, often contributes to bacterial virulence [28-31]. We therefore investigated how the genes that conferred phage-resistance would impact the virulence of the phage-escape mutants. To this end, we used the insect larva model *Galleria mellonella*, to assess the virulence of the reference strains (ATCC17978, XH198), compared to the single gene mutant strains (*gtr9*, *gtrOC3*), and those complemented *in trans*. The mutation in *gtrOC3* impacts the virulence of the strain only to a small extent, with slightly increased survival rates compared to ATCC17978 (Figure 6). In contrast, the *gtr9* KO strain had a significantly reduced virulence, demonstrating the importance of *gtr9* on the pathogenicity of *A. baumannii*. When the *gtr9* mutant strain was complemented with a plasmid expressing the wildtype gene under a constitutive promoter, the virulence was significantly increased compared to ATCC17978, possibly due to a higher expression level. Similarly, albeit to a lesser extent, virulence of the strain with the *gtrOC3* mutation increased when the wildtype gene was expressed *in trans*.

### **Phage-resistance mutations in *gtr9* decrease colistin resistance**

Specific alterations in outer membrane composition are the molecular basis for colistin resistance. We found that phage Phab24 binds to surface exposed molecules of ATCC17978 and XH198, and resistance is mediated by altered envelope structures. To answer the question if phage- and antibiotic-resistance mechanisms impact each other, we performed experiments testing the combination of Phab24 with colistin against our strains. During phage therapy, antibiotics are often used in combination with therapeutic phages,

as synergistic effects of phage-antibiotic combinations have often been observed [32,33]. In our case, increasing concentrations of phage reduced the apparent MIC of colistin (Figure 7A). One explanation to this observation is that phage-resistant mutants show a higher sensitivity to colistin. To address this hypothesis, we investigated if phage-resistant bacteria show higher sensitivity to colistin, testing colony survival of XH198 cultures grown in the absence of colistin but in the absence or presence Phab24 (MOI of 1) (Figure 7B and C, respectively). The numbers of colony forming units (CFUs) were subsequently determined on media with different amounts of colistin. Interestingly, we observed that the number of CFU decreases with increasing colistin concentration, regardless of whether or not the bacteria were co-incubated with Phab24. In the absence of Phab24, the ratio of bacterial colonies dropped by  $\sim 1/4$  to  $\sim 3/4$  when colistin was present compared to the number of colonies that grew on plates without colistin (Fig. 7B). However, in the presence of Phab24, the ratio of CFUs was reduced to less than 0.01% compared to the count when colistin was absent (Fig. 7C). This observation might indicate that the selection for phage-resistance leads to the mutations which in turn increase the sensitivity to colistin.

To investigate this finding in more detail, we tested the MIC of individual phage-resistant XH198 mutants (Figure 7D). Resistance levels varied widely from 64 to 0.5 mg/L (Supplemental Table 3). The correlation between the observed reduction in colistin resistance with phage resistance is far from trivial. Colistin resistance in the parental strain XH198 is mediated by a mutation in gene *pmrB* (G315D), which remained unchanged (data not shown). Therefore, the molecular basis for increased sensitivity possibly lies in other mutations found in the strains, including those in *gtr9* or *gtrOC3*. Thus, we tested the impact of *gtr9* and *gtrOC3* on the sensitivity to colistin.

We first tested XH198-derived phage resistant isolates with *gtrOC3* mutations, R518 and R587, where we observed a colistin MIC of 2 mg/L. Both strains can be complemented with a plasmid-encoded *gtrOC3*, which then allows infection by Phab24, increasing the MIC to 64 mg/L (Figure 7D). While the strains may have additional mutations, this might be an indication that the *gtrOC3* mutation increases colistin sensitivity. However, unexpectedly, the genetic deletion of the entire *gtrOC3* gene in XH198 (a knock-out) apparently does not result in a reduction in colistin resistance. We then tested the reconstructed *gtr9* mutant on the backbone of XH198, which showed strongly increased sensitivity to colistin, from 64 mg/L to 8 mg/L (Figure 7D). The complementation *in trans* using a plasmid-encoded wildtype *gtr9* restored the high resistance level to colistin. Similarly, mutants containing *gtr9* mutations exhibiting various degrees of colistin sensitivity, displayed the high level of resistance when complemented e.g. R130 from 4 mg/L (without plasmid), to 64 mg/L (with plasmid).

## Discussion

Bacterial phage susceptibility rests on several mechanisms, one of which is binding to receptors and co-receptors. In our work, we have established the role of two genes in permitting the infection of *A. baumannii* strain ATCC17978 and its colistin-resistant derivative, XH198, by phage Phab24. One gene has a putative function in the biogenesis of *A. baumannii* LOS, and is found in the type-2 outer core locus (OCL2), the glycosyltransferase *gtrOC3* [34]. The second gene, also a glycosyltransferase, *gtr9* (found in the K locus), is involved in the biosynthesis of capsular polysaccharides [34].

Previous work has shown that capsular molecules can serve as phage receptors [35-38], a finding our study is able to confirm. Phage-resistant isolates that displayed mutations in *gtr9* did not permit efficient binding or infection by Phab24. These mutations may either



lead to the production of altered surface receptors to which the phage cannot bind, or perhaps abolish the production of the cognate receptor. Surprisingly, we found that binding is unaltered in strains displaying mutations in *gtrOC3*, yet infection does not occur, which contrasts previous reports [12,39]. However, these strains did contain an intact copy of *gtr9*. Our results suggest a model where Phab24 uses *A. baumannii*'s capsular polysaccharides, in whose production *gtr9* is involved, as a primary receptor, whereas a specific type of LOS molecule, absent in *gtrOC3* mutants, acts as a co-receptor, possibly required to then trigger the release of DNA into the bacterium (Supplemental Figure 6). This simultaneous, or sequential, binding of receptor and co-receptor, essential for the release of DNA into the host, has just been described in *E. coli* [26] but, to the best of our knowledge, not for *A. baumannii*-specific phages.

While a previous study has described phage-resistance caused by capsule loss in *A. baumannii* [12], our work supports phage resistance being able to emerge by alterations of the bacterial surface structure at two levels: the capsule and the LOS of the outer membrane. In the aforementioned study, capsule-deficient phage-escape mutants of *A. baumannii* MDR strains showed a much reduced propensity to form biofilms. In our work, we have also observed a decrease in biofilm formation when investigating the *gtr9* gene knockout in the colistin sensitive reference strain ATCC17978. In addition to the *gtr* gene mutations, we also identified several mutations in genes that were later found not to be responsible for phage resistance. These included the membrane protein *abcT*, *actP* and *phoH*. Genetically engineered mutants were still susceptible to Phab24 while plasmid complementation experiments with *abcT*, *actT*, or *phoH* mutants (containing additional mutations rendering the strains phage-resistant), did not affect infection.

Our study also showed that the two mutations in *gtr9* and *gtrOC3* which conferred phage-resistance resulted in decreased virulence in our *in vivo* model. Similar to our findings, it has been shown that phage escape mutants often show attenuated pathogenicity which, in some instances, is directly attributed to the bacterial envelope modifications that serve as the basis for phage resistance [39, 41-44]. Although we investigated only a limited number of colistin resistant *A. baumannii* strains due to the limited host range of Phab24, increasing evidence indicates that phage-resistance can be accompanied by “trade-off” mechanisms that result in decreased virulence and increased susceptibility to antibiotics [45].

The use of colistin as the last resort for the treatment of MDR infections, has been increasing over the years. The mechanism of action of the antibiotic remains to be fully elucidated, but it has been shown that colistin binds to LPS (or: LOS) and causes the deterioration of the membrane structure with the antibiotic acting detergent-like, resulting in an osmotic disruption of the cell and ultimately, death [46,47]. However, colistin resistance is on the rise, often mediated by genomic mutations in *pmr* genes [13]. Other mutations involve the *lpx* genes that are often identified in *in vitro* evolution experiments; in contrast to *pmrB* used in this study, *lpx* gene mutations can lead to increased sensitivity to vancomycin [48,49]. In clinical practice, patients receiving phage therapy have accessed it for compassionate, or last resort, use. In these patients, therapeutic bacteriophages are commonly deployed in addition to the antibiotic therapy they might be receiving. This is often done despite the fact that the bacteria may be displaying resistance to the used antibiotics *in vitro*. The rationale behind this approach is the often observed phage-antibiotic synergy; a phenomenon that is also supported by our observations [11, 32, 50-52]. In our work, we saw a decrease in apparent MIC when colistin was used in combination with phage Phab24. We also confirmed that emerging phage-resistant

bacterial clones often exhibited increased levels of antibiotic sensitivity. We hypothesise that the loss of the capsule facilitates the diffusion and ultimately the insertion into the membrane as the absence of the capsule material might allow diffusion of the colistin molecule to the membrane directly without having to cross the capsule barrier (Figure 8). Our findings could potentially be leveraged in the clinical setting, where being able to reduce the doses and duration of colistin treatment a patient receives, could prevent the emergence of its severe side effects [53]. A potential limitation of our study is that we evaluated the impact of phage resistance only for a single colistin resistant bacterial strain. However, our work adds to the mounting evidence that phage resistance often results in fundamental changes in bacteria that can lead to reduced virulence or antibiotic resensitization [38,54,55]. Our work provides experimental data that elucidates the phage resistance mediated molecular mechanism, resulting in increased colistin susceptibility in *A. baumannii*, one of the most dangerous MDR pathogens.

## **Acknowledgements**

We thank Mark Toleman (University of Cardiff) for critically reading the manuscript, Jeremy Barr (Monash University) and Nick Scott (University of Melbourne) for helpful discussions. We thank Belinda Loh who has obtained no financial compensation nor salary for her work.

SL, XH, YY and BL contributed to study conception and design. XW and LZ performed the experiments. XW, SL, BL analysed the data. SL supervised the study. SL and BL wrote the manuscript. All authors approved the final manuscript.

Conflict of Interest: The authors declare no conflict of interest, financial or otherwise, in relation to the work.

## Materials & Methods

Isolation, purification and the genome of phage Phab24 are described elsewhere [18].

GenBank accession number for Phab24 genome: MZ477002.

DNA genome sequencing and analysis. Genomic DNA was extracted using Bacterial genome DNA isolation kit (Biomed, China), sequenced by Illumina HiSeq platform (150-bp paired reads). Breseq was used to identify single point mutations [21].

Gene knockout or replacement, plasmid-derived complementation were performed as described previously: [24]. All primers for cloning and gene replacement are shown in Supplemental Table 4. Briefly, to construct gene knock out strains, primers were designed to bind a sequence about 1kb upstream and 1kb downstream, respectively, of the target gene in ATCC17978. A PCR fragment was obtained which was then cloned into the suicide plasmid pMo130-hygR by seamless cloning (Gibson assembly) (Biomed Biotech, Beijing, China), transformed into chemically competent DH5 $\alpha$  cells (Vazyme, Nanjing, China), and selected on LB plates supplemented with 100 mg/L hygromycin. Sequenced “positive” plasmids were then introduced into *A. baumannii* strains using electrotransformation. After two crossovers, positive colonies that survived on 10% sucrose plates were screened by colony PCR and finally verified by subsequent Sanger sequencing. For testing complementation, the target genes were amplified via PCR using primers designed using the Gibson assembly principle (seamless cloning) and then inserted into the *A. baumannii* shuttle vector pYMAb2-hygR, downstream of a constitutional promotor. Primers for confirming mutations identified from the whole genome were designed and used for PCR amplification with subsequent Sanger sequencing to confirm mutations or insertions (Supplemental Table 4).

Determination of bacterial growth rates was performed as described previously [56] with the following modifications for experiments that included phages: An MOI of 5 of a high-titre preparation was added to the culture with a negligible dilution.

Transmission electron microscopy was performed as described previously [47]. Micrographs were obtained with a JEOL JEM1010 at 80 kV. Scanning Electron Microscopy as described here: [24].

Phage adsorption. Adsorption was measured indirectly by quantifying free phage in solution. Overnight bacterial culture was diluted in LB and bacteria at  $8 \times 10^9/\text{mL}$  were incubated with Phab24 at  $2 \times 10^9/\text{mL}$  at  $4^\circ\text{C}$  for 20 minutes. Cells were pelleted by centrifugation, before the supernatant was serially diluted and non-adsorbed phages quantified by spot titre.

Laboratory evolution experiment: The soft-agar overlay technique was used to obtain phage resistant colonies which are purified three times by re-streaking, after co-incubation of ATCC17978 (or XH198) with Phab24 (MOI = 1) for 3 hours at  $37^\circ\text{C}$ .

Colistin MIC according to the CLSI 2020 antibiogram performance standards ([www.clsi.org](http://www.clsi.org)), was determined by the broth-dilution method as described previously [57].

Lipid A isolation and structural characterisation: Lipid A isolation was performed as previously described [58] which was used for MALDI-TOF MS.

Surface polysaccharide extraction were purified by hot aqueous phenol extraction according to a previously described protocol [59].

Biofilm assays were performed as described previously: [60]. Each sample was done five times, with 3 independent experiments.

Crystal Violet (CV) retention assay of planktonic cells: Overnight cultures were diluted in LB media to OD600 = 1. 1 mL of diluted culture was centrifuged and cells were washed with PBS, then resuspended. CV was added (final 0.01% w/v), vortexed and incubated for 10 minutes. Cells were washed 3 times, before being destained with 2 mL of 95% ethanol for 10 minutes. Cell-free supernatant was then transferred into spectroscopic cuvettes and absorbance is measured at 540 nm.

*Galleria mellonella* infection model. Larvae survival assay was performed as previously described [61]. Ten larvae per group.

Checkerboard Assay was performed as described previously: [32].  $4 \times 10^4$  bacteria, with MOI: 5000, 500, 50, 5, 0.5, 0.05, 0.005.

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## Figure legends

### Figure 1: Phage Phab24 and effect on *A. baumannii* strain growth dynamics. (A)

Transmission electron micrograph of Phab24 (negative staining). Phage Phab24 belongs to Myoviridae which have contractile tails (as seen on the rightside virion). Bar: 200 nm.

(B) Growth curves of the *A. baumannii* reference strain ATCC17978 and phage-resistant reconstructed strains with introduced genomic mutations in the putative capsular biosynthesis gene *gtr9* or in the putative LOS biogenesis gene *gtrOC3*, and their plasmid-complementations (*::gtr9* and *::gtrOC3*) in the presence or absence of phage Phab24. (C) Spot testing of Phab24 on agar containing either phage-resistant or susceptible strains.

### Figure 2: Attachment assay of Phab24 to bacteria. Titre of free phages detected in

media after incubation with (A) reference strain ATCC17978, colistin resistant derivate XH198, the *gtr9* and *gtrOC3* genetically engineered strains ( $\Delta$ ), and their complementations (*::*); and (B) Phab24 phage-resistant colonies, “R”, derived from ATCC17978. Control: phage Phab24 incubated without bacteria. XH194: bacterial strain that is colistin resistant and is not infected by Phab24.

**Figure 3: Composition of the bacterial envelope in parental and phage-resistant *A. baumannii*.** (A to C) Mass spectrometry (positive mode) analysis of lipid A isolated using aqueous phenol extraction from (A) Wildtype strain ATCC17978, (B) Phab24 resistant, genetically introduced reconstructed *gtrOC3* gene mutant on ATCC17978, (C) Plasmid complemented Phab24 resistant strain. (D and E) SDS-PAGE gel of isolated capsular polysaccharides stained with (D) Alcian blue, which allows the detection of acidic polysaccharides, and (E) silver staining, which detects lipids and proteins/peptides.

**Figure 4: Surface structure of bacterial cell envelope.** Scanning Electron Microscopy. *ΔgtrOC3*: knock-out of *gtrOC3* gene in the ATCC17978. *ΔgtrOC3::gtrOC3*: knock-out of *gtrOC3* gene which was complemented with the wildtype *gtrOC3* gene *in trans*. *Δgtr9*: knock-out of *gtr9* gene in the ATCC17978. *Δgtr9::gtr9*: knock-out of *gtr9* gene which was complemented with the wildtype *gtr9* gene *in trans*.

**Figure 5: Biofilm formation and capsular stain.** (A) Biofilm formation assessed by the ability to retain crystal violet (CV) dye. Strains were incubated for 72 hours in multi well plates without shaking. (B) Capsule stain of planktonic cells incubated for 8 hours with shaking. Cells were stained with CV to determine the ability of the bacterial capsule to retain the dye. Ethanol was used to destain the capsule and release the CV dye which was then detected by measuring absorbance at 540nm.

**Figure 6: *In vivo* virulence tests of *A. baumannii* strains and the Phab24 resistant isolates.** Survival of *G. melonella* larvae over 120 h after injection with (A) 10<sup>6</sup> colony forming units (CFU), (B) 10<sup>7</sup> CFU, and (C) 10<sup>8</sup> CFU of *A. baumannii* strains. Each group consisted of 10 larvae. Shown is a representative experiment of 4 independent repeats.

**Figure 7: Colistin and Phage resistance.** (A) Synergy of colistin with/without phage Phab24. Co-incubation of different numbers of Phab24 (MOI) at different concentrations of colistin (mg/L) at constant cell numbers. Each circle represents an independent experiment. (B and C) Colistin-resistance levels of emerged phage-resistant colonies. Colony count of XH198 incubated for 3 h in the absence of colistin or on colistin plates with different antibiotic concentrations (B) in the absence of phage, and (C) in the presence of Phab24. (D) Colistin MIC of selected Phab24 resistant isolates. Top panel shows if the strain can be infected by Phab24, indicating successful complementation of a mutated gene. The control, strain XH198, exhibits a MIC of 64 mg/L. Phage-resistant isolates displayed reduced levels of resistance varying from 16 - 1 mg/L, except for one strain (R81). The reconstructed *gtr9* mutant shows an increased sensitivity to colistin compared to the reference strain XH198, while plasmid complementation with the wildtype gene fully restores the high level of resistance. The genetic deletion of the entire *gtrOC3* gene in XH198 appears does not result in a reduction in colistin resistance. However, strains with mutations that lead to a truncated *gtrOC3* gene product increase colistin sensitivity by 32-fold (R518, R587).

**Figure 8: Model of binding of Phab24 to ATCC17978/ XH198 and *gtr9* mutants.** Phages can bind to the capsule surrounding the cell (top, light blue) as well as to LOS molecules anchored in the outer membrane (OM). In the case of cells in which *gtr9* is disrupted or mutated, phage particles are able to bind to the cells via the LOS molecules (bottom). When the capsule is missing, colistin (CST) is able to bind to the OM more easily as the absence of a barrier facilitates diffusion to the membrane. IM: inner membrane; EPS: Extracellular polymeric substance.

**Table 1:** Resistant strains and mutations conveying phage resistance and outcome of wildtype gene complementations *in trans*. Mutations were either detected by whole genome sequencing (strains R5, R10, R22, R23, R39, R70, R81, R83, R86, R115, R125, R130, R132, R134, R137), or screened for using mutation-specific primers.

## Supplemental Materials

**Supplemental Figure 1,2,3: Composition of the bacterial envelope.** (1) Mass spectra with m/z values from 180 to 750 of polysaccharides isolated from the wildtype strain ATCC17978, or the Phab24 resistant, genetically engineered (reconstructed) *gtr9* gene mutant on ATCC17978. (2) Mass spectra with m/z values from 750 to 1500 of polysaccharides isolated from the wildtype strain ATCC17978, or the Phab24 resistant, genetically engineered (reconstructed) *gtr9* gene mutant on ATCC17978. (3) Mass spectra with m/z values from 1500 to 2300 of polysaccharides isolated from the wildtype strain ATCC17978, or the Phab24 resistant, genetically engineered (reconstructed) *gtr9* gene mutant on ATCC17978.

**Supplemental Figure 4: Surface structure of bacterial cell envelope.** Thin sections of bacterial cells visualised by TEM. Two pictures representative of cells were chosen for each cell type.  $\Delta gtr9$ : knock-out of *gtr9* gene in the ATCC reference strain.  $\Delta gtrOC3$ : knock-out of *gtrOC3* gene in the ATCC reference strain.

**Supplemental Figure 5: Membraneous structures and cell aggregation observed during experimental protocols using the ATCC17978 *gtr9* KO mutant:** (Top) Biofilm Assay (Bottom) Capsular staining.

**Supplemental Figure 6: Model of binding of Phab24 to ATCC17978/ XH198 and *gtr9* mutants.** Phages bind to the capsule surrounding the cell (top, light blue) as well as to LOS molecules anchored in the outer membrane (OM). In the case of cells in which *gtr9* is disrupted or mutated, phage particles are able to bind to the cells via the LOS molecules (bottom). Colistin (CST) diffusion and insertion into the membrane is facilitated by the absence of capsule material, thus decreasing the concentration of the antibiotic to be effective. IM: inner membrane; EPS: Extracellular polymeric substance.

**Supplemental Table 1:** NCBI SRA accession numbers of whole genome sequences of the phage-resistant strains of *A. baumannii* isolated in this study.

**Supplemental Table 2:** A selection of Phage-resistant isolates with gene mutations that are not responsible for phage resistance. The mutations conveying resistance are indicated (unless unknown). Last column (right): Negative outcome of wildtype gene complementations in trans indicate that resistance is not mediated by these genes. Mutations were either detected by whole genome sequencing and confirmed by PCR (strains R5, R10, R22, R23, R39, R70, R81, R83, R86, R115, R125, R130, R132, R134, R137), or screened for using gene-specific primers.

**Supplemental Table 3:** Colistin MIC values of phage resistant isolates (individual strains) derived from XH198 determined by micro broth dilution method.

**Supplemental Table 4:** Primers used in this study.

**TABLE 1** Identified mutations in phage-resistant isolates and complementation tests.

A selection of phage Phab24 resistant strains and mutations conveying resistance, and outcome of wildtype gene complementations *in trans*. Mutations were either detected by whole genome sequencing and confirmed by PCR (strains R5, R10, R22, R23, R39, R70, R81, R83, R86, R115, R125, R130, R132, R134, R137), or screened for using gene-specific primers.

Resistant Isolate	Mutation	Putative gene function	Complementation	
			Yes	No
R1	<i>abcT</i> (A1844T, p.Glu615Val)	ABC transporter		<i>abcT</i>
R1	<i>actP</i> (A1144G, p.Thr382Ala)	acetate permease		<i>actP</i>
R1	<i>gtrOC3</i> (IS4 family insertion)	LPS/ LOS biosynthesis	<i>gtrOC3</i>	
R1	<i>phoH</i> (1011nt, 103th A loss)	phosphohydrolase		<i>phoH</i>
R1	<i>decT</i> (753nt, G233A, p.Thr78Met)	di-trans,poly-cis-decaprenylcistransferase		
R1	<i>dcaP</i> (1332nt, G395T, p.Pro132Glu)	DcaP-like protein		
R1	<i>Udp</i> (720nt, T35C, p.Leu 12 Ser)	UDP-2,3-diacylglucosamine diphosphatase		
R2	<i>abcT</i> (A1844T, p.Glu615Val)	ABC transporter		<i>abcT</i>
R2	<i>actP</i> (A1144G, p.Thr382Ala)	acetate permease		<i>actP</i>
R2	<i>gtrOC3</i> ( 535 <sup>th</sup> A loss, p.Asn179Ile fs Ter7)	LPS/ LOS biosynthesis	<i>gtrOC3</i>	
R2	<i>phoH</i> (1011nt, 103th A loss)	phosphohydrolase		<i>phoH</i>
R2	<i>decT</i> (753nt, G233A, p.Thr78Met)	di-trans,poly-cis-decaprenylcistransferase		
R2	<i>dcaP</i> (1332nt, G395T, p.Pro132Glu)	DcaP-like protein		
R2	<i>Udp</i> (720nt, T35C, p.Leu 12 Ser)	UDP-2,3-diacylglucosamine diphosphatase		
R5	<i>gtr9</i> (IS4 insertion)	Capsule biosynthesis		<i>gtr9</i>
R5	<i>abcT</i> (A1844T, p.Glu615Val)	ABC transporter		<i>abcT</i>

Resistant Isolate	Mutation	Putative gene function	Complementation	
			Yes	No
R5	<i>actP</i> (A1144G, p.Thr382Ala)	acetate permease		<i>actP</i>
R5	<i>gtrOC3</i> ( 535 <sup>th</sup> A loss, p.Asn179Ile fs Ter7)	LPS/ LOS biosynthesis		<i>gtrOC3</i>
R5	<i>phoH</i> (1011nt, 103th A loss)	phosphohydrolase		<i>phoH</i>
R5	<i>decT</i> (753nt, G233A, p.Thr78Met)	di-trans,poly-cis-decaprenylcistransferase		
R5	<i>dcaP</i> (1332nt, G395T, p.Pro132Glu)	DcaP-like protein		
R5	<i>Udp</i> (720nt, T35C, p.Leu 12 Ser)	UDP-2,3-diacylglucosamine diphosphatase		
R6	<i>abcT</i> (A1844T, p.Glu615Val)	ABC transporter		<i>abcT</i>
R6	<i>actP</i> (A1144G, p.Thr382Ala)	an acetate permease		<i>actP</i>
R6	<i>phoH</i> (1011nt, 103th A loss)	phosphohydrolase		<i>phoH</i>
R6	<i>decT</i> (753nt, G233A, p.Thr78Met)	di-trans,poly-cis-decaprenylcistransferase		
R6	<i>dcaP</i> (1332nt, G395T, p.Pro132Glu)	DcaP-like protein		
R6	<i>Udp</i> (720nt, T35C, p.Leu 12 Ser)	UDP-2,3-diacylglucosamine diphosphatase		
R7	<i>gtr9</i> (IS5 insertion)	Capsule biosynthesis	<i>gtr9</i>	
R7	<i>abcT</i> (A1844T, p.Glu615Val)	ABC transporter		<i>abcT</i>
R7	<i>actP</i> (A1144G, p.Thr382Ala)	an acetate permease		<i>actP</i>
R7	<i>phoH</i> (1011nt, 103th A loss)	phosphohydrolase		<i>phoH</i>
R7	<i>decT</i> (753nt, G233A, p.Thr78Met)	di-trans,poly-cis-decaprenylcistransferase		
R7	<i>dcaP</i> (1332nt, G395T, p.Pro132Glu)	DcaP-like protein		
R7	<i>Udp</i> (720nt, T35C, p.Leu 12 Ser)	UDP-2,3-diacylglucosamine		



Resistant Isolate	Mutation	Putative gene function	Complementation	
			Yes	No
R8	<i>abcT</i> (A1844T, p.Glu615Val)	ABC transporter		<i>abcT</i>
R8	<i>actP</i> (A1144G, p.Thr382Ala)	an acetate permease		<i>actP</i>
R8	<i>gtrOC3</i> (535 <sup>th</sup> A loss, p.Asn179Ile fs Ter7)	LPS/ LOS biosynthesis	<i>gtrOC3</i>	
R8	<i>phoH</i> (1011nt, 103th A loss)	phosphohydrolase		<i>phoH</i>
R8	<i>decT</i> (753nt, G233A, p.Thr78Met)	di-trans,poly-cis-decaprenylcistransferase		
R8	<i>dcaP</i> (1332nt, G395T, p.Pro132Glu)	DcaP-like protein		
R8	<i>Udp</i> (720nt, T35C, p.Leu 12 Ser)	UDP-2,3-diacylglucosamine diphosphatase		
R10	<i>gtr9</i> (559 <sup>th</sup> T loss, p. Leu187Tyr fs Ter3)	Capsule biosynthesis	<i>gtr9</i>	
R10	<i>abcT</i> (A1844T, p.Glu615Val)	ABC transporter		<i>abcT</i>
R10	<i>actP</i> (A1144G, p.Thr382Ala)	an acetate permease		<i>actP</i>
R10	<i>phoH</i> (1011nt, 103th A loss)	phosphohydrolase		
R10	<i>decT</i> (753nt, G233A, p.Thr78Met)	di-trans,poly-cis-decaprenylcistransferase		
R10	<i>dcaP</i> (1332nt, G395T, p.Pro132Glu)	DcaP-like protein		
R10	<i>Udp</i> (720nt, T35C, p.Leu 12 Ser)	UDP-2,3-diacylglucosamine diphosphatase		
R10	<i>isoS</i> (1698nt, 655 <sup>th</sup> T loss, p.Ser 219 Pro fs Ter23)	2-isopropylmalate synthase		
R10	<i>LptD</i> (2439nt, 2395 <sup>th</sup> G to T, p.Val 799 Phe)	LPS- assembly protein		
R10	long-chain fatty acid--CoA ligase (1680nt,1240 <sup>th</sup> T to A, p.Phe 414 Ile)	long-chain fatty acid--CoA ligase		
R12	<i>abcT</i> (1A1844T, p.Glu615Val)	ABC transporter		<i>abcT</i>
R12	<i>actP</i> (A1144G, p.Thr382Ala)	an acetate permease		<i>actP</i>

Resistant Isolate	Mutation	Putative gene function	Complementation	
			Yes	No
R12	<i>gtrOC3</i> (535 <sup>th</sup> A loss, p.Asn179Ile fs Ter7)	LPS/ LOS biosynthesis	<i>gtrOC3</i>	
R12	<i>phoH</i> (1011nt, 103th A loss)	phosphohydrolase		<i>phoH</i>
R12	<i>decT</i> (753nt, G233A, p.Thr78Met)	di-trans,poly-cis-decaprenylcistransferase		
R12	<i>dcaP</i> (1332nt, G395T, p.Pro132Glu)	DcaP-like protein		
R12	<i>Udp</i> (720nt, T35C, p.Leu 12 Ser)	UDP-2,3-diacylglucosamine diphosphatase		
R13	No PCR product of <i>gtr9</i>	Capsule biosynthesis		<i>gtr9</i>
R13	<i>abcT</i> (A1844T, p.Glu615Val)	ABC transporter		<i>abcT</i>
R13	<i>actP</i> (A1144G, p.Thr382Ala)	an acetate permease		<i>actP</i>
R13	<i>phoH</i> (1011nt, 103th A loss)	phosphohydrolase		<i>phoH</i>
R13	<i>decT</i> (753nt, G233A, p.Thr78Met)	di-trans,poly-cis-decaprenylcistransferase		
R13	<i>dcaP</i> (1332nt, G395T, p.Pro132Glu)	DcaP-like protein		
R13	<i>Udp</i> (720nt, T35C, p.Leu 12 Ser)	UDP-2,3-diacylglucosamine diphosphatase		
R28	<i>gtr9</i> (transposase insertion)	Capsule biosynthesis		<i>gtr9</i>
R33	<i>gtr9</i> (IS5 insertion)	Capsule biosynthesis		<i>gtr9</i>
R35	<i>gtrOC3</i> (535 <sup>th</sup> A loss, p.Asn179Ile fs Ter7)	LPS/ LOS biosynthesis	<i>gtrOC3</i>	
R39	<i>gtrOC3</i> (535 <sup>th</sup> A loss, p.Asn179Ile fs Ter7)	LPS/ LOS biosynthesis	<i>gtrOC3</i>	
R54	<i>gtr9</i> (transposase insertion)	Capsule biosynthesis		<i>gtr9</i>
R78	<i>gtrOC3</i> (IS5 family insertion)	LPS/ LOS biosynthesis	<i>gtrOC3</i>	
<i>gtr9</i> KO	Markerless knock out the entire <i>gtr9</i> on the background of ATCC17978	Capsule biosynthesis	<i>gtr9</i>	

Resistant Isolate	Mutation	Putative gene function	Complementation	
			Yes	No
<i>gtrOC3</i> -delta A	Substitute for the wild type <i>gtrOC3</i> on the background of ATCC17978	LPS/ LOS biosynthesis	<i>gtrOC3</i>	
R81	<i>gtr9</i> (transposase insertion)	Capsule biosynthesis	<i>gtr9</i>	
R83	No PCR product of <i>gtr9</i>	Capsule biosynthesis		<i>gtr9</i>
R86	<i>gtr9</i> (transposase insertion)	Capsule biosynthesis	<i>gtr9</i>	
R115	<i>gtr9</i> (transposase insertion)	Capsule biosynthesis	<i>gtr9</i>	
R125	<i>gtr1</i> (448th A loss, p. Met 150 Cys fs Ter22)	Glycosyltransferase		<i>gtr1</i>
R130	<i>gtr9</i> (transposase insertion)	Capsule biosynthesis	<i>gtr9</i>	
R132	<i>gtr9</i> (transposase insertion)	Capsule biosynthesis		<i>gtr9</i>
R132	<i>gtr1</i> (448th A loss, p. Met 150 Cys fs Ter22)	Glycosyltransferase		<i>gtr1</i>
R134	<i>gtr9</i> (transposase insertion)	Capsule biosynthesis	<i>gtr9</i>	
XH198 <i>gtr9</i> KO	Markerless knock out the entire <i>gtr9</i> on the background of XH198	Capsule biosynthesis	<i>gtr9</i>	
XH198 <i>gtrOC3</i> -KO	Markerless knock out the entire <i>gtrOC3</i> on the background of XH198	LPS/ LOS biosynthesis	<i>gtrOC3</i>	
R518	<i>gtrOC3</i> (535 <sup>th</sup> A loss, p.Asn179Ile fs Ter7)	LPS/ LOS biosynthesis	<i>gtrOC3</i>	
R587	<i>gtrOC3</i> (535 <sup>th</sup> A loss, p.Asn179Ile fs Ter7)	LPS/ LOS biosynthesis	<i>gtrOC3</i>	

Yes: After the transformation of the corresponding plasmid which contains the WT gene, the R variant can get infected by Phab24.

No: After the transformation of the corresponding plasmid which contains the WT gene, the R variant cannot get infected by Phab24.

R1-R80 are Phab24 escape mutants from ATCC17978.

R81-R587 are Phab24 escape variants from XH198.

Based on the NCBI accession number CP018664.1, ATCC17978:

AUO97\_06900, *gtr9*, 828nt

AUO97\_07355, *abcT*, 1932nt

AUO97\_05550, *actP*, 1716nt

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AUO97\_03485, *gtrOC3*, 768nt

AUO97\_03925, *phoH*, 1011nt.

AUO97\_06920, *gtr1*, 1164nt

AUO97\_09800, 2-isopropylmalate synthase, 1698nt

AUO97\_15295, LPS assembly protein *LptD*, 2439nt

AUO97\_06215, long-chain fatty acid--CoA ligase, 1680nt

Interestingly, the *phoH* of the WT or ATCC17978 used for Sanger sequencing has 1012nt, while the *phoH* of CP018664.1 has 1011nt, the same as the mutated R variants. Maybe that is the reason why the *phoH* is annotated as the pseudogene.

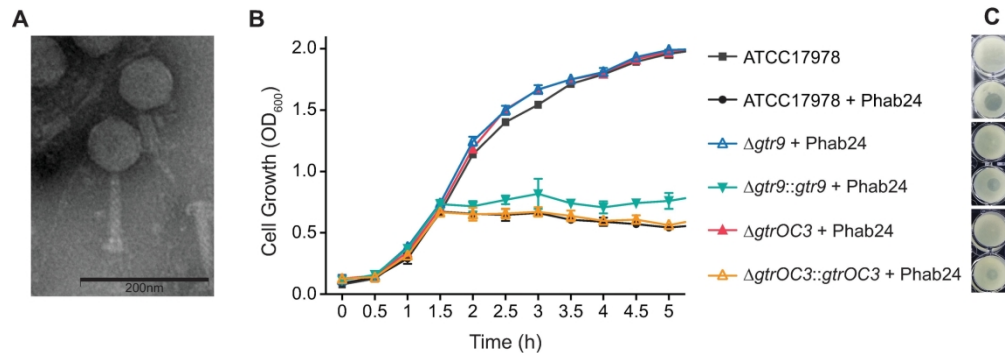
**Figure 1**

Figure 1: Phage Phab24 and effect on *A. baumannii* strain growth dynamics. (A) Transmission electron micrograph of Phab24 (negative staining). Phage Phab24 belongs to Myoviridae which have contractile tails (as seen on the rightside virion). Bar: 200 nm. (B) Growth curves of the *A. baumannii* reference strain ATCC17978 and phage-resistant reconstructed strains with introduced genomic mutations in the putative capsular biosynthesis gene *gtr9* or in the putative LOS biogenesis gene *gtrOC3*, and their plasmid-complementations (*::gtr9* and *::gtrOC3*) in the presence or absence of phage Phab24. (C) Spot testing of Phab24 on agar containing either phage-resistant or susceptible strains.

196x82mm (300 x 300 DPI)

Figure 2

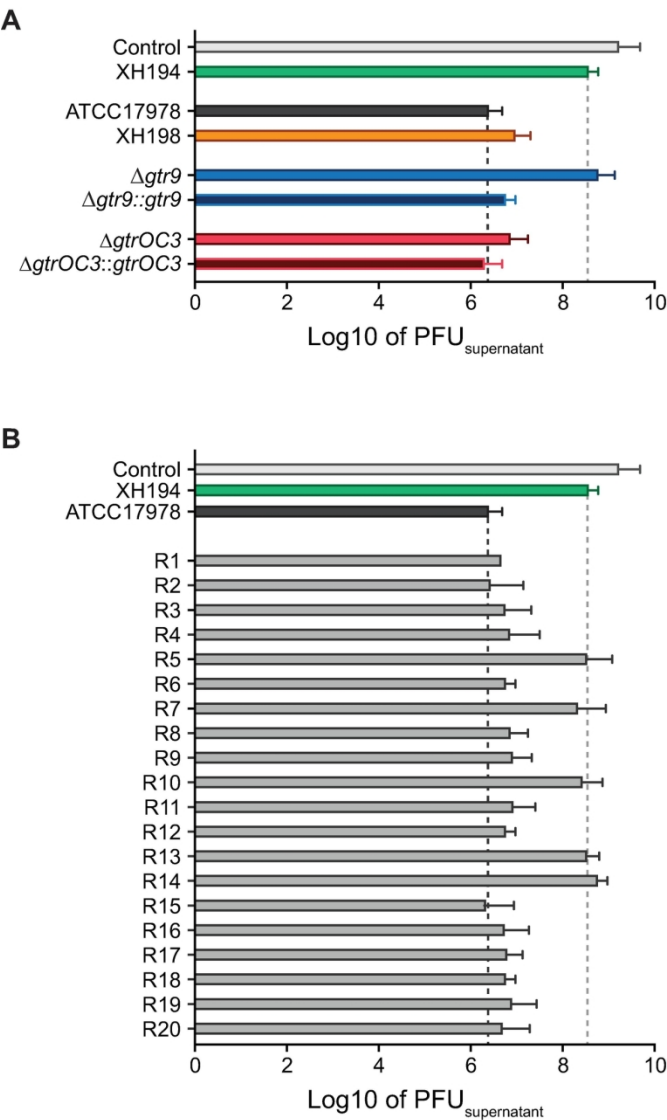


Figure 2: Attachment assay of Phab24 to bacteria. Titre of free phages detected in media after incubation with (A) reference strain ATCC17978, colistin resistant derivate XH198, the *gtr9* and *gtrOC3* genetically engineered strains ( $\Delta$ ), and their complementations ( $::$ ); and (B) Phab24 phage-resistant colonies, "R", derived from ATCC17978. Control: phage Phab24 incubated without bacteria. XH194: bacterial strain that is colistin resistant and is not infected by Phab24.

110x198mm (300 x 300 DPI)

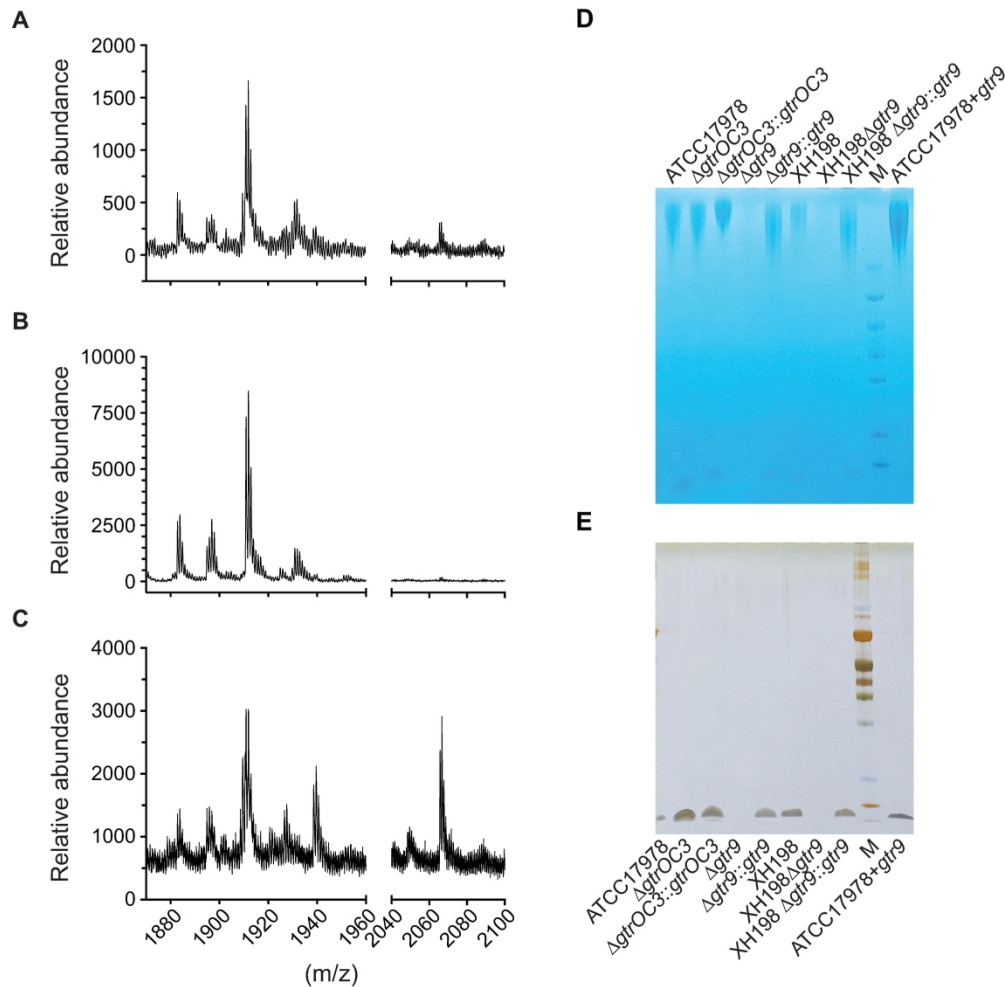
**Figure 3**

Figure 3: Composition of the bacterial envelope in parental and phage-resistant *A. baumannii*. (A to C) Mass spectrometry (positive mode) analysis of lipid A isolated using aqueous phenol extraction from (A) Wildtype strain ATCC17978, (B) Phab24 resistant, genetically introduced reconstructed gtrOC3 gene mutant on ATCC17978, (C) Plasmid complemented Phab24 resistant strain. (D and E) SDS-PAGE gel of isolated capsular polysaccharides stained with (D) Alcian blue, which allows the detection of acidic polysaccharides, and (E) silver staining, which detects lipids and proteins/peptides.

193x206mm (300 x 300 DPI)

Figure 4

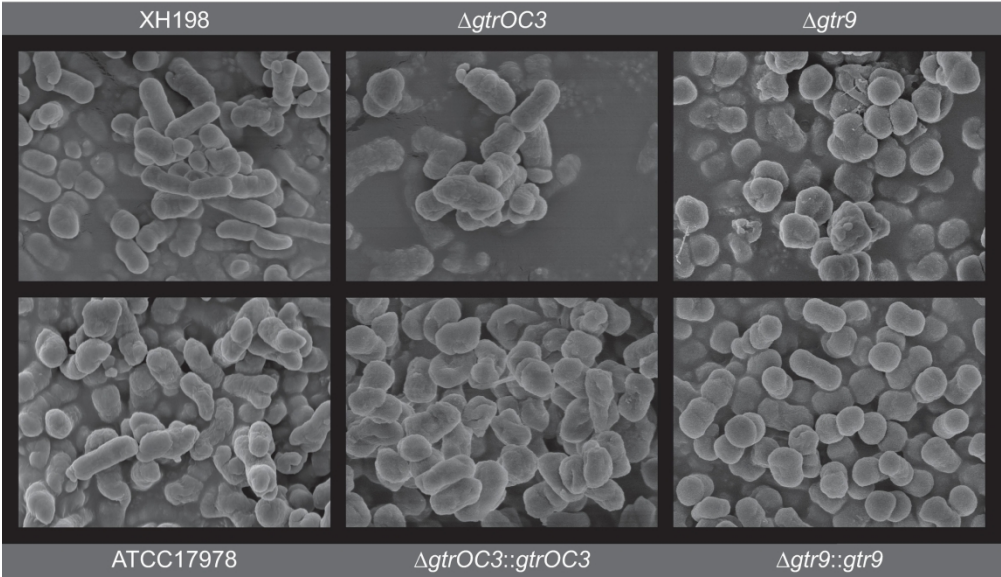


Figure 4: Surface structure of bacterial cell envelope. Scanning Electron Microscopy. ΔgtrOC3: knock-out of gtrOC3 gene in the ATCC17978. ΔgtrOC3::gtrOC3: knock-out of gtrOC3 gene which was complemented with the wildtype gtrOC3 gene in trans. Δgtr9: knock-out of gtr9 gene in the ATCC17978. Δgtr9::gtr9: knock-out of gtr9 gene which was complemented with the wildtype gtr9 gene in trans.

213x136mm (300 x 300 DPI)



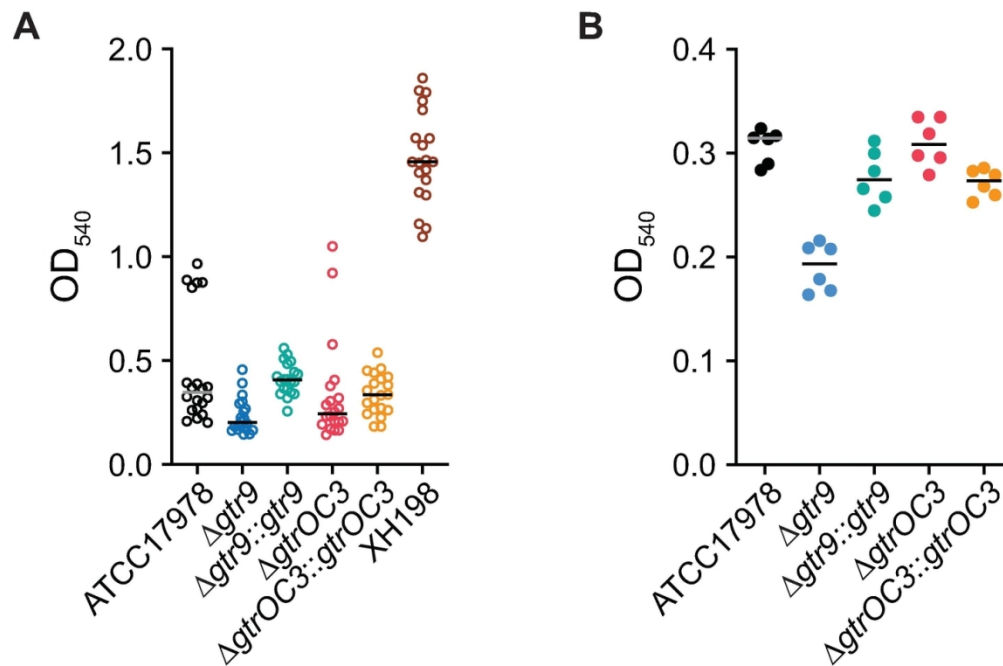
**Figure 5**

Figure 5: Biofilm formation and capsular stain. (A) Biofilm formation assessed by the ability to retain crystal violet (CV) dye. Strains were incubated for 72 hours in multi well plates without shaking. (B) Capsule stain of planktonic cells incubated for 8 hours with shaking. Cells were stained with CV to determine the ability of the bacterial capsule to retain the dye. Ethanol was used to destain the capsule and release the CV dye which was then detected by measuring absorbance at 540nm.

122x94mm (300 x 300 DPI)

Figure 6

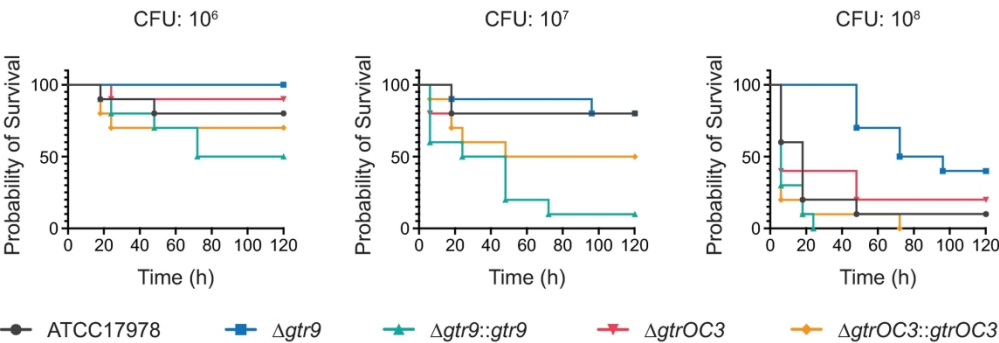


Figure 6: In vivo virulence tests of *A. baumannii* strains and the Phab24 resistant isolates. Survival of *Galleria melonella* larvae over 120 h after injection with (A)  $10^6$  colony forming units (CFU), (B)  $10^7$  CFU, and (C)  $10^8$  CFU of *A. baumannii* strains. Each group consisted of 10 larvae. Shown is a representative experiment of 4 independent repeats.

185x89mm (300 x 300 DPI)

Figure 7

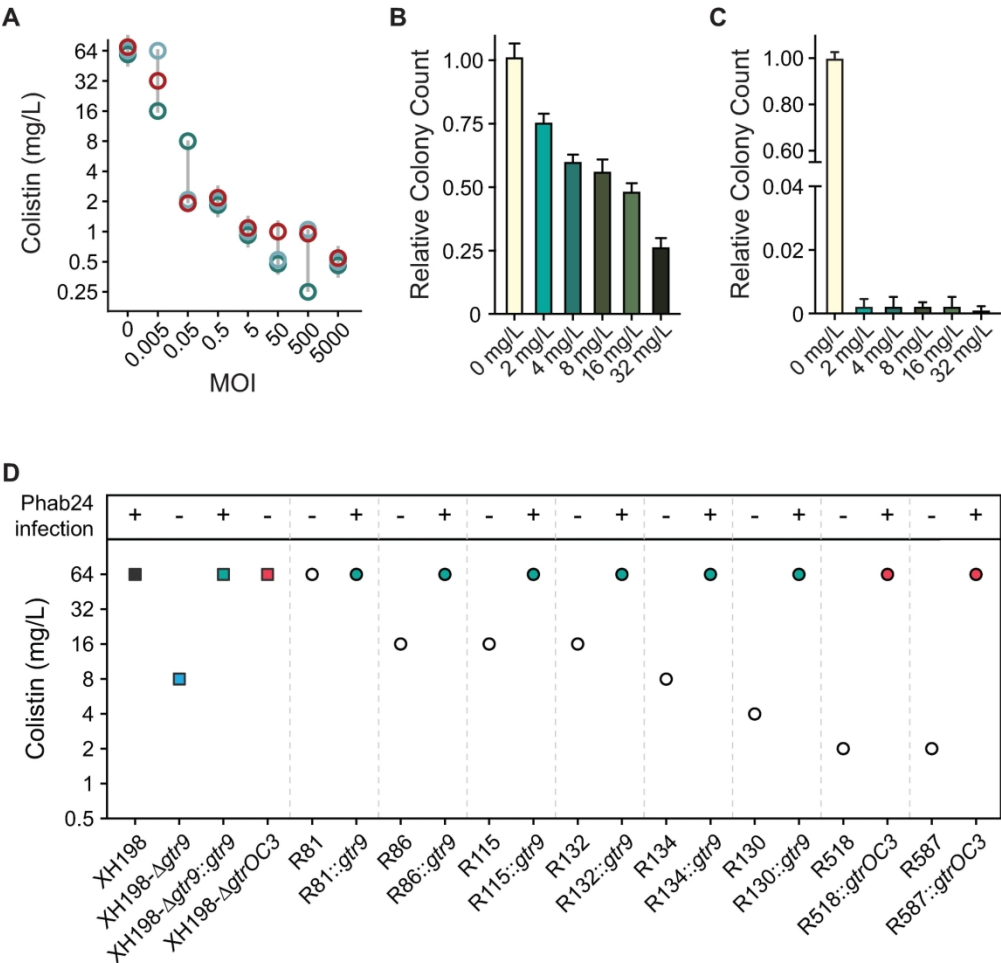


Figure 7: Colistin and Phage resistance. (A) Synergy of colistin with/without phage Phab24. Co-incubation of different numbers of Phab24 (MOI) at different concentrations of colistin (mg/L) at constant cell numbers. Each circle represents an independent experiment. (B and C) Colistin-resistance levels of emerged phage-resistant colonies. Colony count of XH198 incubated for 3 h in the absence of colistin or on colistin plates with different antibiotic concentrations (B) in the absence of phage, and (C) in the presence of Phab24. (D) Colistin MIC of selected Phab24 resistant isolates. Top panel shows if the strain can be infected by Phab24, indicating successful complementation of a mutated gene. The control, strain XH198, exhibits a MIC of 64 mg/L. Phage-resistant isolates displayed reduced levels of resistance varying from 16 - 1 mg/L, except for one strain (R81). The reconstructed gtr9 mutant shows an increased sensitivity to colistin compared to the reference strain XH198, while plasmid complementation with the wildtype gene fully restores the high level of resistance. The genetic deletion of the entire gtrOC3 gene in XH198 appears does not result in a reduction in colistin resistance. However, strains with mutations that lead to a truncated gtrOC3 gene product increase colistin sensitivity by 32-fold (R518, R587).

182x188mm (300 x 300 DPI)

Figure 7

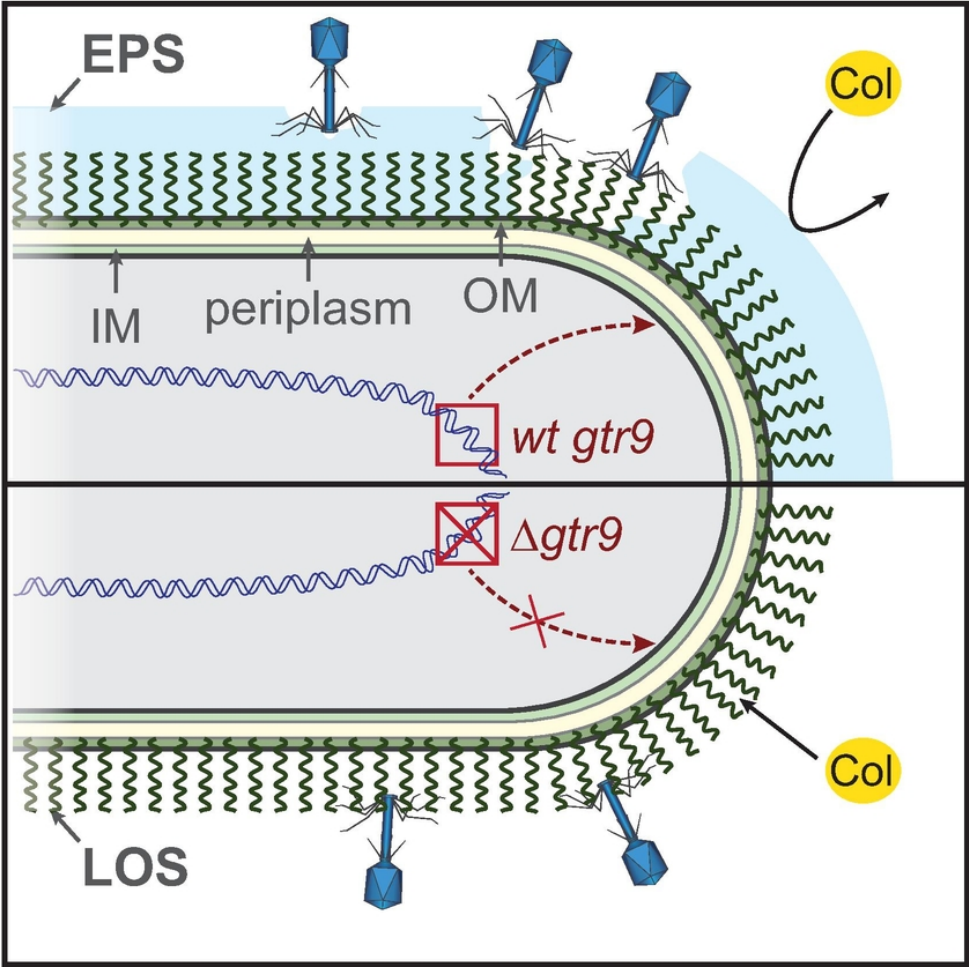


Figure 8: Model of binding of Phab24 to ATCC17978/ XH198 and gtr9 mutants. Phages can bind to the capsule surrounding the cell (top, light blue) as well as to LOS molecules anchored in the outer membrane (OM). In the case of cells in which gtr9 is disrupted or mutated, phage particles are able to bind to the cells via the LOS molecules (bottom). When the capsule is missing, colistin (CST) is able to bind to the OM more easily as the absence of a barrier facilitates diffusion to the membrane. IM: inner membrane; EPS: Extracellular polymeric substance.

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**Supplemental Table 3:** Colistin MIC values of phage resistant isolates (individual strains)

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derived from XH198 determined by micro broth dilution method.

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**Supplemental Table 4:** Primers used in this study.

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Accession	Strain/ Name	Organism	Tax ID	URL	SRA
SAMN22216671	R2	<i>Acinetobacter baumannii</i>	470	<a href="https://www.ncbi.nlm.nih.gov/biosample/22216671">https://www.ncbi.nlm.nih.gov/biosample/22216671</a>	SRS10528705
SAMN22216672	R5	<i>Acinetobacter baumannii</i>	470	<a href="https://www.ncbi.nlm.nih.gov/biosample/22216672">https://www.ncbi.nlm.nih.gov/biosample/22216672</a>	SRS10528706
SAMN22216673	R10	<i>Acinetobacter baumannii</i>	470	<a href="https://www.ncbi.nlm.nih.gov/biosample/22216673">https://www.ncbi.nlm.nih.gov/biosample/22216673</a>	SRS10528714
SAMN22216674	R13	<i>Acinetobacter baumannii</i>	470	<a href="https://www.ncbi.nlm.nih.gov/biosample/22216674">https://www.ncbi.nlm.nih.gov/biosample/22216674</a>	SRS10528715
SAMN22216675	R22	<i>Acinetobacter baumannii</i>	470	<a href="https://www.ncbi.nlm.nih.gov/biosample/22216675">https://www.ncbi.nlm.nih.gov/biosample/22216675</a>	SRS10528716
SAMN22216676	R23	<i>Acinetobacter baumannii</i>	470	<a href="https://www.ncbi.nlm.nih.gov/biosample/22216676">https://www.ncbi.nlm.nih.gov/biosample/22216676</a>	SRS10528717
SAMN22216677	R39	<i>Acinetobacter baumannii</i>	470	<a href="https://www.ncbi.nlm.nih.gov/biosample/22216677">https://www.ncbi.nlm.nih.gov/biosample/22216677</a>	SRS10528718
SAMN22216678	R70	<i>Acinetobacter baumannii</i>	470	<a href="https://www.ncbi.nlm.nih.gov/biosample/22216678">https://www.ncbi.nlm.nih.gov/biosample/22216678</a>	SRS10528719
SAMN22216679	R81	<i>Acinetobacter baumannii</i>	470	<a href="https://www.ncbi.nlm.nih.gov/biosample/22216679">https://www.ncbi.nlm.nih.gov/biosample/22216679</a>	SRS10528720
SAMN22216680	R83	<i>Acinetobacter baumannii</i>	470	<a href="https://www.ncbi.nlm.nih.gov/biosample/22216680">https://www.ncbi.nlm.nih.gov/biosample/22216680</a>	SRS10528721
SAMN22216681	R86	<i>Acinetobacter baumannii</i>	470	<a href="https://www.ncbi.nlm.nih.gov/biosample/22216681">https://www.ncbi.nlm.nih.gov/biosample/22216681</a>	SRS10528707
SAMN22216682	R115	<i>Acinetobacter baumannii</i>	470	<a href="https://www.ncbi.nlm.nih.gov/biosample/22216682">https://www.ncbi.nlm.nih.gov/biosample/22216682</a>	SRS10528708
SAMN22216683	R125	<i>Acinetobacter baumannii</i>	470	<a href="https://www.ncbi.nlm.nih.gov/biosample/22216683">https://www.ncbi.nlm.nih.gov/biosample/22216683</a>	SRS10528709
SAMN22216684	R130	<i>Acinetobacter baumannii</i>	470	<a href="https://www.ncbi.nlm.nih.gov/biosample/22216684">https://www.ncbi.nlm.nih.gov/biosample/22216684</a>	SRS10528710

Accession	Strain/ Name	Organism	Tax ID	URL	SRA
SAMN22216685	R132	<i>Acinetobacter baumannii</i>	470	<a href="https://www.ncbi.nlm.nih.gov/biosample/22216685">https://www.ncbi.nlm.nih.gov/biosample/22216685</a>	SRS10528711
SAMN22216686	R134	<i>Acinetobacter baumannii</i>	470	<a href="https://www.ncbi.nlm.nih.gov/biosample/22216686">https://www.ncbi.nlm.nih.gov/biosample/22216686</a>	SRS10528712
SAMN22216687	R137	<i>Acinetobacter baumannii</i>	470	<a href="https://www.ncbi.nlm.nih.gov/biosample/22216687">https://www.ncbi.nlm.nih.gov/biosample/22216687</a>	SRS10528713

SUPPLEMENTARY TABLE 1

## SUPPLEMENTARY TABLE 2

A selection of Phage-resistant isolates with gene mutations that are not responsible for phage resistance. The mutations conveying resistance are indicated (unless unknown). Last column (right): Negative outcome of wildtype gene complementations *in trans* indicate that resistance is not mediated by these genes. Mutations were either detected by whole genome sequencing and confirmed by PCR (strains R5, R10, R22, R23, R39, R70, R81, R83, R86, R115, R125, R130, R132, R134, R137), or screened for using gene-specific primers.

Resistant Isolate	Gene mutation responsible for phage infection	Mutation	Putative gene function	Un-successful complementation with gene
R1	<i>gtrOC3</i>	<i>abcT</i> (A1844T, p.Glu615Val)	ABC transporter	<i>abcT</i>
		<i>actP</i> (A1144G, p.Thr382Ala)	acetate permease	<i>actP</i>
		<i>phoH</i> (1011nt, 103th A loss)	phosphohydrolase	<i>phoH</i>
		<i>decT</i> (753nt, G233A, p.Thr78Met)	di-trans,poly-cis-decaprenylcistransferase	NA
		<i>dcaP</i> (1332nt, G395T, p.Pro132Glu)	DcaP-like protein	NA
		<i>Udp</i> (720nt, T35C, p.Leu 12 Ser)	UDP-2,3-diacylglucosamine diphosphatase	NA
R2	<i>gtrOC3</i>	<i>abcT</i> (A1844T, p.Glu615Val)	ABC transporter	<i>abcT</i>
		<i>actP</i> (A1144G, p.Thr382Ala)	acetate permease	<i>actP</i>
		<i>phoH</i> (1011nt, 103th A loss)	phosphohydrolase	<i>phoH</i>
		<i>decT</i> (753nt, G233A, p.Thr78Met)	di-trans,poly-cis-decaprenylcistransferase	NA



Resistant Isolate	Gene mutation responsible for phage infection	Mutation	Putative gene function	Un-successful complementation with gene
		<i>dcaP</i> (1332nt, G395T, p.Pro132Glu)	DcaP-like protein	NA
		<i>Udp</i> (720nt, T35C, p.Leu 12 Ser)	UDP-2,3-diacetylglucosamine diphosphatase	NA
R5	<i>gtr9</i>	<i>abcT</i> (A1844T, p.Glu615Val)	ABC transporter	<i>abcT</i>
		<i>actP</i> (A1144G, p.Thr382Ala)	acetate permease	<i>actP</i>
		<i>phoH</i> (1011nt, 103th A loss)	phosphohydrolase	<i>phoH</i>
		<i>decT</i> (753nt, G233A, p.Thr78Met)	di-trans,poly-cis-decaprenylcistransferase	NA
		<i>dcaP</i> (1332nt, G395T, p.Pro132Glu)	DcaP-like protein	NA
		<i>Udp</i> (720nt, T35C, p.Leu 12 Ser)	UDP-2,3-diacetylglucosamine diphosphatase	NA
R6	Unknown	<i>abcT</i> (A1844T, p.Glu615Val)	ABC transporter	<i>abcT</i>
		<i>actP</i> (A1144G, p.Thr382Ala)	an acetate permease	<i>actP</i>
		<i>phoH</i> (1011nt, 103th A loss)	phosphohydrolase	<i>phoH</i>
		<i>decT</i> (753nt, G233A, p.Thr78Met)	di-trans,poly-cis-decaprenylcistransferase	NA
		<i>dcaP</i> (1332nt, G395T, p.Pro132Glu)	DcaP-like protein	NA

Resistant Isolate	Gene mutation responsible for phage infection	Mutation	Putative gene function	Un-successful complementation with gene
		<i>Udp</i> (720nt, T35C, p.Leu 12 Ser)	UDP-2,3-diacylglucosamine diphosphatase	NA
R7	<i>gtr9</i>	<i>abcT</i> (A1844T, p.Glu615Val)	ABC transporter	<i>abcT</i>
		<i>actP</i> (A1144G, p.Thr382Ala)	an acetate permease	<i>actP</i>
		<i>phoH</i> (1011nt, 103th A loss)	phosphohydrolase	<i>phoH</i>
		<i>decT</i> (753nt, G233A, p.Thr78Met)	di-trans,poly-cis-decaprenylcistransferase	NA
		<i>dcaP</i> (1332nt, G395T, p.Pro132Glu)	DcaP-like protein	NA
		<i>Udp</i> (720nt, T35C, p.Leu 12 Ser)	UDP-2,3-diacylglucosamine diphosphatase	NA
R8	<i>gtrOC3</i>	<i>abcT</i> (A1844T, p.Glu615Val)	ABC transporter	<i>abcT</i>
		<i>actP</i> (A1144G, p.Thr382Ala)	an acetate permease	<i>actP</i>
		<i>phoH</i> (1011nt, 103th A loss)	phosphohydrolase	<i>phoH</i>
		<i>decT</i> (753nt, G233A, p.Thr78Met)	di-trans,poly-cis-decaprenylcistransferase	NA
		<i>dcaP</i> (1332nt, G395T, p.Pro132Glu)	DcaP-like protein	NA
		<i>Udp</i> (720nt, T35C, p.Leu 12 Ser)	UDP-2,3-diacylglucosamine diphosphatase	NA

Resistant Isolate	Gene mutation responsible for phage infection	Mutation	Putative gene function	Un-successful complementa tion with gene
R10	<i>gtr9</i>	<i>abcT</i> (A1844T, p.Glu615Val)	ABC transporter	<i>abcT</i>
		<i>actP</i> (A1144G, p.Thr382Ala)	an acetate permease	<i>actP</i>
		<i>phoH</i> (1011nt, 103th A loss)	phosphohydrolase	NA
		<i>decT</i> (753nt, G233A, p.Thr78Met)	di-trans,poly-cis-decaprenylcistransferase	NA
		<i>dcaP</i> (1332nt, G395T, p.Pro132Glu)	DcaP-like protein	NA
		<i>Udp</i> (720nt, T35C, p.Leu 12 Ser)	UDP-2,3-diacylglucosamine diphosphatase	NA
		<i>isoS</i> (1698nt, 655 <sup>th</sup> T loss, p.Ser 219 Pro fs Ter23)	2-isopropylmalate synthase	NA
		<i>LptD</i> (2439nt, 2395 <sup>th</sup> G to T, p.Val 799 Phe)	LPS- assembly protein	NA
		long-chain fatty acid--CoA ligase (1680nt,1240 <sup>th</sup> T to A, p.Phe 414 Ile)	long-chain fatty acid--CoA ligase	NA
R12	<i>gtrOC3</i>	<i>abcT</i> (1A1844T, p.Glu615Val)	ABC transporter	<i>abcT</i>
		<i>actP</i> (A1144G, p.Thr382Ala)	an acetate permease	<i>actP</i>
		<i>phoH</i> (1011nt, 103th A loss)	phosphohydrolase	<i>phoH</i>
		<i>decT</i> (753nt, G233A, p.Thr78Met)	di-trans,poly-cis-decaprenylcistransferase	NA

Resistant Isolate	Gene mutation responsible for phage infection	Mutation	Putative gene function	Un-successful complementation with gene
		<i>dcaP</i> (1332nt, G395T, p.Pro132Glu)	DcaP-like protein	NA
		<i>Udp</i> (720nt, T35C, p.Leu 12 Ser)	UDP-2,3-diacylglucosamine diphosphatase	NA
R13	Unknown, (not <i>gtr9</i> )	<i>abcT</i> (A1844T, p.Glu615Val)	ABC transporter	<i>abcT</i>
		<i>actP</i> (A1144G, p.Thr382Ala)	an acetate permease	<i>actP</i>
		<i>phoH</i> (1011nt, 103th A loss)	phosphohydrolase	<i>phoH</i>
		<i>decT</i> (753nt, G233A, p.Thr78Met)	di-trans,poly-cis-decaprenylcistransferase	NA
		<i>dcaP</i> (1332nt, G395T, p.Pro132Glu)	DcaP-like protein	NA
		<i>Udp</i> (720nt, T35C, p.Leu 12 Ser)	UDP-2,3-diacylglucosamine diphosphatase	NA
R125	Unknown	<i>glyT</i> (448th A loss, p. Met 150 Cys fs Ter22)	Glycosyltransferase	<i>glyT</i>
R132	Unknown, (not <i>gtr9</i> )	<i>glyT</i> (448th A loss, p. Met 150 Cys fs Ter22)	Glycosyltransferase	<i>glyT</i>

NA: No complementation attempted.

R1-R80 are Phab24 escape mutants from ATCC17978.

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2 R81-R587 are Phab24 escape variants from XH198.  
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4 Based on the NCBI accession number CP018664.1, ATCC17978:  
5  
6  
7  
8 AUO97-07355, *abcT*, 1932nt  
9  
10  
11 APP30310.1, *actP*, 1716nt  
12  
13  
14  
15 AUO97-03925, *phoH*, 1011nt.  
16  
17  
18 AUO97-06920, *gtr1*, 1164nt  
19  
20  
21 AUO97-09800, 2-isopropylmalate synthase, 1698nt  
22  
23  
24 AUO97-15295, LPS assembly protein *LptD*, 2439nt  
25  
26  
27 AUO97-06215, long-chain fatty acid--CoA ligase, 1680nt  
28  
29  
30  
31 Interestingly, the *phoH* of the WT or ATCC17978 used for Sanger sequencing has 1012nt, while  
32 the *phoH* of CP018664.1 has 1011nt, the same as the mutated R variants.  
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	Colistin MIC	µP24 sensi	pmrB mutation	gtrI mutation
1				
2				
3				
4				
5	R588	0.25	–	No verification
6	R515	0.5	–	No verification
7	R567	0.5	–	No verification
8	R573	0.5	–	No verification
9	R584	0.5	–	No verification
10	R544	1	–	No verification
11	R571	1	–	No verification
12	R703	1	–	No verification
13	R83	2	–	p.Gly 315 Asp NO
14	R506	2	–	No verification
15	R518	2	–	No verification
16	R536	2	–	No verification
17	R545	2	–	No verification
18	R587	2	–	No verification
19	R701	2	–	No verification
20	R130	4	–	p.Gly 315 Asp NO
21	R505	4	–	No verification
22	R523	4	–	No verification
23	R527	4	–	No verification
24	R558	4	–	No verification
25	R580	4	–	No verification
26	R125	8	–	p.Gly 315 Asp p. Met 150 Cys fs Ter22
27	R134	8	–	p.Gly 315 Asp NO
28	R504	8	–	p.Gly 315 Asp No verification
29	R522	8	–	No verification
30	R524	8	–	No verification
31	R533	8	–	No verification
32	R577	8	–	No verification
33	R596	8	–	No verification
34	R86	16	–	p.Gly 315 Asp NO
35	R115	16	–	p.Gly 315 Asp NO
36	R132	16	–	p.Gly 315 Asp p. Met 150 Cys fs Ter22
37	R528	16	–	p.Gly 315 Asp No verification
38	R537	16	–	No verification
39	R551	16	–	No verification
40	R564	16	–	No verification
41	R569	16	–	No verification
42	R572	16	–	No verification
43	R589	16	–	No verification
44	R590	16	–	No verification
45	R705	16	–	No verification
46	R710	16	–	No verification
47	R549	32	–	No verification
48	R552	32	–	No verification

1					
2					
3	R556	32	–	No verification	No verification
4	R565	32	–	No verification	No verification
5	R570	32	–	No verification	No verification
6	R575	32	–	No verification	No verification
7	R576	32	–	No verification	No verification
8	R578	32	–	No verification	No verification
9	R81	64	–	p.Gly 315 Asp	NO
10	R553	64	–	No verification	No verification
11	R568	64	–	No verification	No verification
12	R707	64	–	No verification	No verification
13	R501	>64	–	p.Gly 315 Asp	No verification
14	R502	>64	–	No verification	No verification
15	R509	>64	–	No verification	No verification
16	R511	>64	–	No verification	No verification
17	R514	>64	–	No verification	No verification
18	R516	>64	–	No verification	No verification
19	R519	>64	–	No verification	No verification
20	R520	>64	–	No verification	No verification
21	R531	>64	–	No verification	No verification
22	R535	>64	–	No verification	No verification
23	R550	>64	–	No verification	No verification
24	R555	>64	–	No verification	No verification
25	R557	>64	–	No verification	No verification
26	R559	>64	–	No verification	No verification
27	R560	>64	–	No verification	No verification
28	R561	>64	–	No verification	No verification
29	R562	>64	–	No verification	No verification
30	R574	>64	–	No verification	No verification
31	R581	>64	–	No verification	No verification
32	R582	>64	–	No verification	No verification
33	R585	>64	–	No verification	No verification
34	R591	>64	–	No verification	No verification
35	R593	>64	–	No verification	No verification
36	R594	>64	–	No verification	No verification
37	R702	>64	–	No verification	No verification
38	R704	>64	–	No verification	No verification
39	R706	>64	–	No verification	No verification
40	R708	>64	–	No verification	No verification
41	R709	>64	–	No verification	No verification
42	R711	>64	–	No verification	No verification

Minus refers to resistance to P24  
pmrB: AU097-RS02735, Two-component system sensor histidine kinase  
gtrI: AU097-RS06920, Glycosyltransferase  
gtrOC3: AU097-RS03485, LPS/ LOS biosynthesis

gtr9: AU097-RS06900, Amylovoran biosynthesis

traL: AU0970RS06930, Polysaccharide biosynthesis protein or Translocase

**No verification** refers to no PCR screen

**NO** refers to no related gene mutation via PCR screen

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1			
2			
3	gtrOC3 mutation	gtr9 mutation	traL mutation
4	No verification	No verification	No verification
5	No verification	No verification	No verification
6	No verification	No verification	No verification
7	No verification	No verification	No verification
8	NO	No verification	No verification
9	No verification	No verification	No verification
10	No verification	No verification	No verification
11	No verification	No verification	No verification
12	No verification	No verification	No verification
13	No verification	No verification	No verification
14	No verification	No verification	No verification
15	No verification	No PCR product of gtr9	NO
16	No verification	No verification	No verification
17	p.Asn179 Ile fs Ter7	NO	No verification
18	No verification	No verification	No verification
19	NO	No verification	No verification
20	p.Asn179 Ile fs Ter7	NO	No verification
21	No verification	No verification	No verification
22	No verification	transposase insertion	NO
23	NO	No verification	No verification
24	No verification	No verification	No verification
25	No verification	No verification	No verification
26	No verification	No verification	No verification
27	No verification	No verification	No verification
28	No verification	No verification	No verification
29	No verification	No verification	No verification
30	No verification	No verification	No verification
31	No verification	NO	NO
32	No verification	transposase insertion	NO
33	No verification	No verification	No verification
34	NO	p.Gln234Ter1	No verification
35	No verification	No verification	No verification
36	No verification	No verification	No verification
37	No verification	No verification	No verification
38	No verification	No verification	No verification
39	No verification	No verification	No verification
40	NO	No verification	No verification
41	No verification	transposase insertion	NO
42	No verification	transposase insertion	NO
43	No verification	transposase insertion	NO
44	No verification	No verification	No verification
45	No verification	No verification	No verification
46	No verification	No verification	No verification
47	NO	No verification	No verification
48	No verification	No verification	No verification
49	No verification	No verification	No verification
50	No verification	No verification	No verification
51	No verification	No verification	No verification
52	No verification	No verification	No verification
53	No verification	No verification	No verification
54	NO	No verification	No verification
55	No verification	No verification	No verification
56	No verification	No verification	No verification
57	No verification	No verification	No verification
58	NO	No verification	No verification
59	No verification	No verification	No verification
60	No verification	No verification	No verification



# SUPPLEMENTARY TABLE 4

Primer names and sequences used for the study:

Primer sequences for mutation screening of *abcT* /*actP* /*phoH* /*gtrOC3* /*gtr9*.

abcT-F	TCTGTGTATGGCAACCCTTAAGAT
abcT-R	TGGTACACGGTGGCAAATGT
actP-F	GCAAACCCGATTGATGCCTT
actP-R	ACAAGACCAACTACGCCACC
pho-F	CTCGTGCGTACTGGATTGGT
pho-R	CCTGGAACTGAATAAACTGGAGC
lps-F	CTCACCAAGACTGGCAGGG
lps-R	ATTCCAACGACTACGGGCAA
AmsE-F	GAAATGACTATGTCTACTAAACGCTTCA
AmsE-R	TAAAAATCTGGATTGAAAAGGTTTTAG

Primer sequences for fragment amplification and insertion into NotI and BamHI digested pYMAb2-hygR

1ABCT-F	agcaaatgggtcgcgatccATGATTCAATTTGACCAAGTTTCTT
1ABCT-R	gtggtgctcgagtgcgccgcTTAGTTTTCAAATGAGGCTTCCATT
2lps-F	agcaaatgggtcgcgatccATGAATAAAATTCCATGTAGTGTTT
2lps-R	gtggtgctcgagtgcgccgcCTACTTATTTTTATCTTTATTCATC
3phoHF	tggtggtgctcgagtgcgccgcTTATACAAGTTCAATAATATCAATAGTAGGCG
3phoHR	cagcaaatgggtcgcgatccATGTGGAACCCAAATTCAATCAT
4act-F	agcaaatgggtcgcgatccATGAAATGGAATTCATTAAGCGA
4act-R	gtggtgctcgagtgcgccgcTTAGTGGTCTGATGCACCAGAA
5AmsE-F	agcaaatgggtcgcgatccATGTTTTCTGTATTAAGTTCTATTT
5AmsE-R	gtggtgctcgagtgcgccgcTCATTTTTTAATATCTTTACGAAG

Sequencing primers for the reconstructed expression plasmid pYMAb2-hygR

seqP-F	CAGCCATCATCATCATCATC
seqP-R	TTATTGCTCAGCGGTGGCAG

Primer sequences for the amplification the upstream ~900bp and downstream 900bp of *gtrOC3*, for subsequent insertion into NotI and BamHI digested suicide plasmid pM0130-hygR for markerless and seamless knock-out of the *gtrOC3* gene:

Up-F	tgacctgacctgagcgccgcAAACCTTGAGTATCTCCAATTTTCAG
Up-R	aggacgttataagttGCAAGCTATGAAAATTGTTTCAGGTATT
Dw-F	atattcatagcttgcAACTTATAACGTCCTTTAGCAAGGG
Dw-R	gcatgcatctagagggatccACCCAGAGCAAGCTGTAAAAGTA

Primer sequences for the amplification the upstream ~900bp and downstream 900bp of *gtr9*, for subsequent insertion into NotI and BamHI digested suicide plasmid pM0130-hygR for markerless and seamless knock-out of the *gtr9* gene:

amsE1	tgacctgacctgagcgccgcTAGAGTGGTTTCCAACCTCAAAGTTA
amsE2	gaaggataaattttGTGAATGAAAATATGAAGCGTTTAGTAGA
amsE3	catattttcattcacAAAAATTTATCCTTCTAAAACCTTTTCAATCCA
amsE4	gcatgcatctagagggatccGATAATGTAGAAGTAATTGCTTTAT

Primer sequences for amplification the upstream ~900bp and downstream 900bp of *abcT /actP /phoH*, inserted into NotI and BamHI digested suicide plasmid pM0130-hygR aiming to generate a markerless and seamless replacement of the wild type *abcT /actP /phoH*.

Rep ABC-T Fw	GCTGACCTGACCTGAGCGGCCGCGTAACTTGAATGAGTGCATGGCC
Rep ABC-T Rv	CGCATGCATCTAGAGGGATCCATCTCAGAAGGAATAGGTTGGGC

Rep act-P Fw	GCTGACCTGACCTGAGCGGCCGCTAGGCGTGTGCTTGATATATTGTAAA
Rep act-P Rv	CGCATGCATCTAGAGGGATCCGATAATTGCAATAACGGCAAGAAT
Rep phoP Fw	GCTGACCTGACCTGAGCGGCCGCTAACCATGGTTTATCTTGAGGTAAGT C
Rep phoP Rv	CGCATGCATCTAGAGGGATCCCTATCACACAGCGATGCAAGTTTA

Primer sequences for screening the mutation in *pmrB* (G315D):

pmrBF	TCACGCTCTTGTTTCATGT
pmrBR	GTGCATTATTCATTAAAAAACG

Note: Working names for primers do not reflect the gene nomenclature as presented in the manuscript. LPS: *gtrOC3*; *amsE*: *gtr9*