Evolution of Colistin Resistance in the Klebsiella pneumoniae Complex Follows Multiple Evolutionary Trajectories with Variable Effects on Fitness and Virulence Characteristics

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Evolution of colistin resistance in the *Klebsiella pneumoniae* complex follows multiple evolutionary trajectories with variable effects on fitness and virulence characteristics.

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Running title: colistin resistance in *Klebsiella*

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Abstract

The increasing prevalence of multidrug-resistant *Klebsiella pneumoniae* has led to a resurgence in the use of colistin as last-resort drug. Colistin is a cationic antibiotic that selectively acts on Gram-negative bacteria through electrostatic interactions with anionic phosphate groups of the lipid A moiety of lipopolysaccharides (LPS). Colistin resistance in *K. pneumoniae* is mediated through loss of these phosphate groups, their modification by cationic groups, and by the hydroxylation of acyl-groups of lipid A. Here, we study the *in vitro* evolutionary trajectories towards colistin resistance in four clinical *K. pneumoniae* complex strains and their impact on fitness and virulence characteristics.

Through population sequencing during *in vitro* evolution, we found that colistin resistance develops through a combination of single nucleotide polymorphisms, insertion and deletions, and the integration of insertion sequence elements, affecting genes associated with LPS biosynthesis and modification, and capsule structures. Colistin resistance decreased the maximum growth rate of one *K. pneumoniae sensu stricto* strain, but not in the other three *K. pneumoniae* complex strains. Colistin-resistant strains had lipid A modified through hydroxylation, palmitoylation, and L-Ara4N addition. *K. pneumoniae sensu stricto* strains exhibited cross-resistance to LL-37, in contrast to the *K. variicola* subsp. *variicola* strain. Virulence, as determined in a *Caenorhabditis elegans* survival assay, was increased in two colistin-resistant strains.

Our study suggests that nosocomial *K. pneumoniae* complex strains can rapidly develop colistin resistance through diverse evolutionary trajectories upon exposure to colistin. This effectively shortens the lifespan of this last-resort antibiotic for the treatment of infections with multidrug-resistant *Klebsiella*.

Introduction

Klebsiella pneumoniae is a Gram-negative opportunistic pathogen and a leading cause of hospital-associated infections such as pneumonia, surgical site infections, and urinary tract infections. *K. pneumoniae* may also asymptomatically colonize the skin, upper respiratory tract, and digestive tract of healthy individuals (1, 2). The *K. pneumoniae* complex is genetically diverse, with different phylogroups within the complex corresponding to different species and sub-species, each occupying specific niches (1, 2). The *K. pneumoniae sensu strico* and *K. quasipneumoniae* phylogroups are associated with human intestinal carriage, whilst the *K. variicola* phylogroup is associated with plants and bovines (1, 3). Of all strains isolated from human infections and typed as *K. pneumoniae*, the majority is *K. pneumoniae sensu stricto*, but *K. variicola* and *K. quasipneumoniae* have also been found to cause infections in patients and are frequently misidentified as *K. pneumoniae* (4, 5). Although infections with strains from the *K. variicola* phylogroup are relatively rare, they have been associated with the highest mortality rate within the *K. pneumoniae* complex (3).

In recent years, *K. pneumoniae* complex strains have rapidly emerged as multidrug-resistant pathogens through acquisition of resistance to third-generation cephalosporins, fluoroquinolones, and aminoglycosides, and have increasingly become resistant to carbapenems through the acquisition of carbapenemases (6–9). The increasing prevalence of multidrug resistance within the *K. pneumoniae* complex, and the lack of development of novel antibiotic classes effective against Gram-negative bacteria, have limited the available therapeutic options against multidrug-resistant *K. pneumoniae* complex strains. These limitations have prompted the resurgence in the use of the antibiotic colistin in treatment of infections by *K. pneumoniae* complex strains (10–12). After its introduction into clinical practice in the 1950s, colistin fell into disuse in human medicine in the 1970s because of the neuro- and nephrotoxic side effects associated with its use and the development of safer classes of antibiotics. Due to the emergence

multidrug-resistant Gram-negative opportunistic pathogens, like *K. pneumoniae*, it has recently regained clinical relevance as a last-line antibiotic (13).

Colistin (polymyxin E) is a cationic, amphipathic molecule composed of a fatty acid chain linked to a non-ribosomally synthesized decapeptide (14, 15). The mechanism of action of colistin relies on the selective presence of the negatively charged lipopolysaccharides (LPS) in the membranes of Gram-negative bacteria. The negative charges of LPS are carried by the anionic phosphate groups of the lipid A moiety of LPS, which enable colistin to bind through electrostatic interactions (14). Insertion of colistin into the outer membrane leads to membrane permeabilization. The subsequent destabilization of the cytoplasmic membrane, where LPS is present after synthesis in the cytoplasm while awaiting transport to the outer membrane, ultimately leads to cell death (14, 16, 17).

The increased use of colistin to treat infections with multidrug-resistant Gram-negative bacteria, especially in low- and middle-income countries (12), and the use of colistin in livestock farming, either therapeutically to treat enteric infections or as a growth promoter (18), has led to a rise in colistin resistance in *K. pneumoniae* from clinical, veterinary, and environmental sources (9, 18, 19). Colistin resistance in *K. pneumoniae* complex strains is mostly mediated through decoration of lipid A with cationic groups, to counteract the electrostatic interactions between colistin and lipid A (14). These modifications can be the result of point mutations and insertion-deletions (indels) in chromosomally located genes (including *phoPQ*, *pmrAB*, and *crrAB*) resulting in amino acid substitutions, insertions, and deletions in the proteins encoded by these genes (20–23). In addition, the acquisition of mobile genetic elements carrying a member of the *mcr*-gene family may also lead to lipid A modification (23, 24). In *K. pneumoniae*, the inactivation of *mgrB* encoding an negative regulator of the two-component regulatory system PhoPQ, through the insertion of an insertion sequence (IS) element, or a mutation leading to the formation of a premature stop codon, is a particularly frequently observed colistin resistance mechanism (25–29). Other mechanisms of

colistin resistance in *K. pneumoniae* include the upregulated expression of efflux pumps (30, 31), changes in LPS production (20, 32), and the overproduction of capsular polysaccharides (33, 34).

Upon infection the innate immune system will attempt to neutralize invading bacteria. The cellular components of the innate immune system can detect Gram-negative bacteria through the presence of LPS (35). Activated immune cells can kill bacteria and will attempt to kill them by unleashing bactericidal components including the antimicrobial peptide LL-37. Similar to colistin, LL-37 relies on electrostatic interactions with LPS for its mechanism of action (36). Modifications to LPS may influence the efficacy of bactericidal components, and may thus result in altered virulence by reducing the effectiveness of these components (35–37). Modifications capable of affecting the efficiency of the immune system include neutralization of the anionic charges carried by lipid A, and changes in acylation of lipid A (35, 38, 39). These changes are mediated through the PhoPQ and PmrAB two-component regulatory systems. Notably, colistin resistance is mediated through the same modifications and two-component regulatory systems. The development of colistin resistance may thus also affect virulence characteristics.

To better understand the mechanisms and consequences of colistin resistance in *K. pneumoniae* complex strains, we determined the evolutionary trajectories of three *K. pneumoniae sensu stricto* strains and one *K. variicola* subsp. *variicola* strain towards colistin resistance in an *in vitro* evolution experiment, and determined how colistin resistance impacted fitness, LPS modifications, and virulence characteristics.

Materials and Methods

Ethical statement

The colistin-susceptible *K. pneumoniae* complex strains used in this study were isolated as part of routine diagnostic procedures, which did not require consent or ethical approval by an institutional review board.

Bacterial strains, growth conditions, and chemicals

The colistin-susceptible KP209, KP040, KP257, and KV402 strains were retrospectively, obtained from the diagnostic laboratory of the University Medical Center Utrecht in Utrecht, the Netherlands. In initial routine diagnostic procedures, they were identified as *K. pneumoniae sensu stricto* by matrix-assisted laser desorption–ionisation time-of-flight (MALDI-TOF) on a Bruker microflex system (Leiderdorp, The Netherlands). Colistin susceptibility testing of the clinical isolates was initially performed on a BD Phoenix automated identification and susceptibility testing system (Becton Dickinson, Vianen, The Netherlands). All strains were grown either in lysogeny broth (LB; Oxoid, Landsmeer, The Netherlands) with agitation at 300 rpm, or on LB agar, at 37°C, unless otherwise specified. Colistin sulphate was obtained from Duchefa Biochemie (Haarlem, The Netherlands).

Determination of minimal inhibitory concentration of colistin

Minimal inhibitory concentrations (MICs) to colistin were determined as described previously (40) in line with the recommendations from the joint Clinical & Laboratory Standards Institute and European

Committee on Antimicrobial Susceptibility Testing (EUCAST) Polymyxin Breakpoints Working Group (http://www.eucast.org/fileadmin/src/media/PDFs/EUCAST_files/General_documents/Recommendations_for_MIC_determination_of_colistin_March_2016.pdf). In short, colistin susceptibility testing was performed using BBL™ Mueller Hinton II (cation-adjusted) broth (MHCAB; Becton Dickinson), untreated Nunc 96-wells round bottom polystyrene plates (Thermo Fisher Scientific, Landsmeer, The Netherlands), and Breathe-Easy sealing membranes (Sigma-Aldrich, Zwijndrecht, The Netherlands). The MIC was observed after stationary, overnight growth at 37°C, and was determined to be the lowest concentration where no visible growth was observed. The breakpoint value for colistin resistance of an MIC > 2 µg/ml was obtained from EUCAST (http://www.eucast.org/clinical_breakpoints/).

In vitro evolution of colistin resistance

The nosocomial, colistin-susceptible *K. pneumoniae* strains were evolved towards colistin resistance by culturing in increasing colistin concentrations over a period of 5-7 days. As we used LB as medium for the *in vitro* evolution, we first determined the colistin MICs in this medium (as outlined above) and subsequently grew each strain in 1 ml LB with initial colistin concentrations of 1- and 2-times the MIC. After overnight growth, 1 µl of the cultures with the highest concentration of colistin that had visible growth were used to propagate a fresh culture by inoculating 1 ml of fresh LB, supplemented with the same or twice the concentration of colistin in which growth was observed in the previous day's culture (Supplemental Figure S1). This process was repeated for 5-7 days. Each overnight culture was stored at -80°C in 20% glycerol.

Genomic DNA isolation and whole-genome sequencing

Genomic DNA was isolated using the Wizard Genomic DNA purification kit (Promega, Leiden, The Netherlands) according to the manufacturer's instructions. DNA concentrations were measured with the Qubit 2.0 fluorometer and the Qubit dsDNA Broad Range Assay kit (Life Technologies, Bleiswijk, The Netherlands).

Illumina sequence libraries of genomic DNA were prepared using the Nextera XT kit (Illumina, San Diego, CA) according to the manufacturer's instructions, and sequenced on an Illumina MiSeq system with a 500-cycle (2 × 250 bp) MiSeq v2 reagent kit (Illumina). MinION library preparation for barcoded 2D long-read sequencing was performed using the SQK-LSK208 kit (Oxford Nanopore Technologies, Oxford, England, United Kingdom), according to the manufacturer's instructions, with G-tube (Covaris, Woburn, Massachusetts, United States of America) shearing of chromosomal DNA for 2 x 120 seconds at 1500 *g*. The libraries were sequenced on a MinION sequencer (Oxford Nanopore Technologies) through a SpotON Flow Cell Mk I (R9.4; Oxford Nanopore Technologies).

Genome assembly and annotation

The quality of the Illumina sequencing data was assessed using FastQC v0.11.5 (https://github.com/s-andrews/FastQC). Illumina sequencing reads were trimmed for quality using nesoni v0.115 (https://github.com/Victorian-Bioinformatics-Consortium/nesoni) using standard settings with the exception of a minimum read length of 100 nucleotides. MinION reads in FastQ format were extracted from Metrichor base-called FAST5-files using Poretools (41). *De novo* hybrid genome assembly of the colistin-susceptible strains was performed with Illumina and Oxford Nanopore data as described previously (42). Genome annotation was performed using Prokka (43).

Phylogenetic analysis, MLST typing, and identification of antibiotic resistance genes

To generate a core genome phylogeny, Illumina/Oxford Nanopore hybrid genome assemblies were aligned using ParSNP v1.2 (37) with 37 publicly available *Klebsiella pneumoniae* complex genomes that cover all phylogroups of the *K. pneumoniae* complex (2). To include the genome of *K. africanensis* strain 38679, we assembled the genome from raw reads, by processing the raw sequence reads using Nesoni with standard settings, except for minimum read length (75 nucleotides), and subsequent assembly by SPAdes with kmers 21, 33, 55, 77 and the "careful" options turned on.

Figtree was used to visualize and midpoint root the phylogenetic tree (http://tree.bio.ed.ac.uk/). MLST typing was performed using the mlst package v2.10 (https://github.com/tseemann/mlst). Genome assemblies of colistin-susceptible strains were assessed for antibiotic resistance genes by ResFinder 3.1 through standard settings (44).

Determination of SNPs and indels between axenic colistin-susceptible and colistin-resistant strain pairs.

Read-mapping of Nesoni-filtered reads of evolved strains to the genomes of the isogenic colistin-susceptible parental strains was performed using Bowtie2 (45). SNP and indel-calling was performed using SAMtools 0.1.18 using the following settings: Qscore ≥ 50, mapping quality ≥ 30, a mapping depth ≥ 10 reads, a consensus of ≥ 75% to support a call, and ≥ 1 read in each direction supporting a mutation, as previously described (46). To correct for potential assembly errors, we also performed the SNP and indel-calling procedure by mapping the reads of the reference isolates against their own assemblies. SNPs and indels found in the reference-versus-reference comparison were ignored in query-versus-reference comparisons. Synonymous mutations were excluded from further analyses. SNPs and indels were manually linked to genes in the assembly.

192

193 **Determination of location of IS elements in genomes**

194 To determine which IS elements were present in the genomes of colistin-susceptible strains, we
195 analysed the Illumina/Oxford Nanopore hybrid genome assemblies using ISfinder (47). Per genome, the IS
196 elements with an E-value < 1e-50 were selected for further study. If multiple distinct IS elements were
197 called at the same position, the element with the highest sequence identity was selected to represent that
198 position.

199 To detect changes in the position of the identified IS elements, we analysed the genomic assemblies
200 of the isogenic colistin-susceptible and colistin-resistant strain pairs through ISMapper (48). To maximize
201 the ability of ISMapper to detect IS elements in our sequencing data, the obtained nucleotide sequences of
202 the IS elements in the genome were used as input, and the --cutoff flag of ISMapper was set to 1, whilst
203 other settings remained unchanged. The results were inspected for IS elements that had different positions
204 between the colistin-susceptible, and colistin-resistant strains. Insertion of IS elements was confirmed
205 through PCRs, using DreamTaq Green PCR Master Mix (Thermo Fisher Scientific) and primers spanning
206 the IS insertion site (Supplemental Table S1) and subsequent Sanger sequencing of the PCR product by
207 Macrogen (Amsterdam, The Netherlands).

208

209 **SNP and indel calling in evolving populations.**

210 To track the genomic changes within the growing cultures under the selective pressure of increasing
211 colistin concentrations, genomic DNA was isolated from the 5-7 overnight cultures of each *in vitro*
212 evolution experiment and sequenced on the Illumina MiSeq platform as described above. SNPs and indels
213 were called as before, with each call supported by at least 25% of reads. Once identified in one or more

populations, the abundance of the specific SNPs and indels were then quantified manually for all individual populations of the *in vitro* evolution experiment. Mutations called within 150 bp of a contig end were filtered out, as previously recommended (49). Identified SNPs and indels were manually linked to genes in the genome assembly, and inspected for synonymous versus non-synonymous mutations. Non-coding mutations were included in subsequent analyses, while synonymous mutations were excluded.

Determination of growth rate

To determine the maximum specific growth rate, a Bioscreen C instrument (Oy Growth Curves AB, Helsinki, Finland) was used. Overnight cultures were used to inoculate 200 µl fresh LB medium 1:1000. Incubation was set at 37°C with continuous shaking. Growth was observed by measuring the absorbance at 600 nm every 7.5 minutes. Each experiment was performed in triplicate.

MALDI-TOF analysis of lipid A structures

Isolation of lipid A molecules and subsequent analysis by negative-ion matrix-assisted laser desorption–ionisation time-of-flight (MALDI-TOF) mass spectrometry was performed as previously described (29, 50, 51). Briefly, *K. pneumoniae* strains were grown in LB (Oxoid) and the lipid A was purified from stationary cultures using the ammonium hydroxide/isobutyric acid isolation method described earlier (52). Mass spectrometry analysis were performed on a Bruker autoflex® speed TOF/TOF mass spectrometer in negative reflective mode with delayed extraction using as matrix an equal volume of dihydroxybenzoic acid matrix (Sigma-Aldrich) dissolved in (1:2) acetonitrile-0.1% trifluoroacetic acid. The ion-accelerating voltage was set at 20 kV. Each spectrum was an average of 300 shots. A peptide calibration standard (Bruker) was used to calibrate the MALDI-TOF. Further calibration for lipid A analysis was

performed externally using lipid A extracted from *Escherichia coli* strain MG1655 grown in LB medium at 37°C.

LL-37 survival assay

In order to test the susceptibility of the *K. pneumoniae* strains to LL-37, we adapted previously described protocols (53). An overnight broth culture was diluted to a concentration of $2.5x10^6$ CFU/ml in 25% LB and incubated with or without the addition of 50 µg/ml LL-37 (AnaSpec Inc, Fermont, California, United States of America) for 90 minutes at 37°C with agitation at 300 rpm in sterile round-bottom 96-well plates (Greiner Bio-One, Alphen aan den Rijn, The Netherlands). After incubation, samples were serially diluted in PBS and plated on LB agar plates. CFUs were counted after overnight incubation at 37°C.

***Caenorhabditis elegans* virulence assays**

Caenorhabditis elegans strain CF512 (*rrf-3*(*b26*) *II*; *fem-1*(*hc17*) *IV*), which has a temperature-sensitive reproduction defect, was obtained from the Caenorhabditis Genetics Center at the University of Minnesota, Twin Cities (http://www.cgc.cbs.umn.edu/). CF512 nematodes were maintained at 20°C on Nematode Growth Medium (NGM) agar plates seeded with *E. coli* OP50 (54), and placed on fresh plates at least once per week. For seeding of NGM plates, mid-exponential phase cultures were used. After reaching mid-exponential phase, the cells were washed with PBS, and 1 x 10^6 CFU were spread on NGM plates, after which the bacterial lawns were grown overnight at 37°C.

To quantify bacterial virulence, *C. elegans* CF512 lifespan assays were performed with synchronized nematodes according to a previously described protocol (55). For synchronization, nematodes and eggs were collected from a NGM plate in ice-cold filter-sterilized M9 medium, and washed by spinning

at 1500 x *g* for 30 seconds (56). Nematodes were destructed by vigorous vortexing in hypochlorite solution (25 mM NaOH, 1.28% sodium hypochlorite) for two minutes, after which the reaction was stopped by the addition of M9 medium. Eggs were allowed to hatch on NGM plates seeded with *E. coli* OP50 for 6-8 hours at 20°C, after which they were placed at 25°C to avoid progeny. After 48 hours, L3-L4 nematodes were placed on NGM plates (n=40 per plate) seeded with bacterial strains. Plates were scored for live nematodes. Nematodes were considered dead when they did not show spontaneous movement or a response to external stimuli.

Statistical analysis

Statistical analyses were performed using the parametric one-way ANOVA test with a Dunnett's test for multiple comparisons (for the determination of maximum growth rates), the non-parametric Mann-Whitney test was used (for the LL-37 survival assay), and the Mantel-Cox log-rank test (for the *C. elegans* assays). Statistical significance was defined as a p-value < 0.05 for all tests. Statistical analyses were performed using GraphPad Prism 6 software (GraphPad Software, San Diego, California, United States of America).

Data availability

Sequence data of both the Illumina short-read, and the Oxford Nanopore long-read sequencing has been deposited in the European Nucleotide Archive (accession number PRJEB29521).

Results

The colistin-susceptible *K. pneumoniae* complex strains have a diverse genetic background

The four clinical isolates used in this study were obtained from pus, faecal, or urine samples through routine diagnostic procedures in September 2013. All four strains were initially typed as *K. pneumoniae sensu stricto* through routine diagnostic procedures using MALDI-TOF. The susceptibility to colistin of these strains, previously determined in routine diagnostic procedures, was confirmed through antibiotic susceptibility testing using broth microdilution (Figure 1A).

The sequenced genomes of the colistin-susceptible strains were screened for acquired antibiotic resistance genes through ResFinder 3.1 (Figure 1B). None of the nosocomial strains was determined to carry one of the *mcr*-genes. Between two and five acquired antibiotic resistance genes were observed in the genome assemblies, encoding resistance to beta-lactams, quinolones, and fosfomycin.

To accurately identify the phylogenetic position of these nosocomial strains within the *K. pneumoniae* complex, a phylogenetic tree was generated based on the Illumina/Oxford Nanopore hybrid genome assemblies of the colistin-susceptible strains, and 37 publicly available genomes covering all phylogroups in the *K. pneumoniae* complex (2). Based on a 1.3 Mbp core-genome alignment, the phylogenetic tree showed that strains KP209, KP040, and KP257 clustered in the *K. pneumoniae sensu stricto* (KpI) phylogroup (Figure 1C). Strain KV402 clustered in the *K. variicola* subsp. *variicola* (KpIII) phylogroup, even though it had been typed as *K. pneumoniae sensu stricto* through MALDI-TOF during initial routine diagnostic procedures.

Colistin resistance emerges through multiple evolutionary trajectories in the *K. pneumoniae* complex

To understand the evolutionary trajectories through which the *K. pneumoniae* complex strains evolved resistance towards colistin, we deep-sequenced each overnight culture during growth in increasing concentrations of colistin (Supplemental Table S2), and identified SNP, indels and excision/integration events of IS elements.

We observed the rapid emergence and fixation of several mutations (Figure 2) in the presence of colistin. In three populations (KP209, KP257, and KV402), these mutations occurred in the genes encoding the PhoPQ two-component regulatory system after one day of culturing (Supplemental Table S3). In the KP040 population, we observed the integration of an IS*5* element (Supplemental Table S4, Supplemental Data 1) in the promoter region of both the *crrAB* operon and the divergently transcribed *crrC* gene. In addition, an intergenic SNP (located in promoter regions of *ecpR* or *phnC*) in KP040 became fixed in the population on the first day of culturing. Both EcpR and PhnC have not previously been associated with colistin resistance. Although other mutations, in other locations, also occurred during the first day of culturing, these mutations failed to become fixed in the population, and were either lost on subsequent days, or did not change in abundance over time.

On subsequent days of the *in vitro* evolution experiment, novel mutations in the populations were associated with additional increases in MIC of colistin. New SNPs that were fixed in the populations were observed in *phoQ* (KP209 (day 5), and KV402 (day 6)), and *pmrB* (KP209 (day4)). In KP257, a SNP in *lptD* was first observed on day 3, and was then fixed in the population. The *lptD* gene encodes a barrel-shaped transporter that transports LPS onto the outer leaflet of the outer membrane (57). Mutations in genes located in the capsule synthesis locus (K-locus) were also detected. In KV402 a 13 bp deletion was observed in *wcaJ* from day 3 onwards, leading to a premature stop-codon. In KP040 a new insertion of IS*102*, inactivating *wzc* was observed from day 4. In addition, a 12 bp insertion in the gene encoding the Rho transcription termination factor was observed in KP040. We did not observe any mutations in the *mgrB* gene in these *in vitro* evolution experiments.

K. pneumoniae can rapidly develop colistin resistance without loss of fitness.

To enable a further characterisation of the impact of the evolution of colistin resistance on fitness and virulence characteristics, we isolated a single, random colony on non-selective medium from each day of the *in vitro* evolution experiments. The genome sequences of the axenic strains of the last day of the *in vitro* evolution experiments were determined by Illumina sequencing. SNPs, indels and IS element insertions were identified in these strains in comparison with the colistin-susceptible parental strain. After combining these data with the population sequencing data described above, we determined the presence of these mutations in the axenic strains isolated after each day of the *in vitro* evolution experiment by targeted PCRs and Sanger sequencing of the amplicons. We were thus able to correlate the occurrence of mutations with increases in the MIC of colistin (determined in MHCAB) in each strain.

All four strains developed levels of resistance to colistin above the breakpoint value (2 µg/ml) after one overnight incubation of the colistin-susceptible (MIC ≤2 µg/ml) strain in the presence of the antibiotic (Figure 2). The initial mutations in *phoPQ* were associated with an increase in MIC in strains KP209 (32 µg/ml), KP257 (128 µg/ml), and KV402 (32 µg/ml) (Figure 2). The integration of the IS*5* element in the promoter region of *crrAB* and *crrC*, and the appearance of an intergenic SNP between *ecpR* and *phnC*, also occur simultaneously with an increase in the MIC of colistin (4 µg/ml). The additional SNP in *phoQ* in KP209 was not associated with an increase in the MIC of colistin (256 µg/ml). Integration of IS*102* in *wzc* of the K-locus, as well as the 12-bp insertion in the gene encoding the transcription termination factor Rho, was associated with an additional increase in the MIC of colistin (128 µg/ml) in strain KP040. The SNP in *lptD* in strain KP257 did not lead to a meaningful increase in the MIC of colistin (256 µg/ml). The culture isolated from the last day of the KV402 *in vitro* evolution experiments had a SNP in *yciM* (Supplemental Table S5), encoding a negative regulator of LPS biosynthesis (20), but this did not contribute to a further

reduced susceptibility to colistin. Because of the random nature of picking single isolates from their populations, some mutations identified by population sequencing were not recapitulated in the axenic strains and *vice versa* (Fig. 2, Supplemental Table S5).

The measurement of the maximum growth rate as a proxy for general fitness of the axenic strains isolated on the different days of the *in vitro* evolution experiment showed that the increase in MIC of colistin to values above 2 µg/ml after one overnight incubation, did not negatively affect the maximum growth rate for strains KP209, KP040, and KV402. Only the initial increase in MIC of colistin in strain KP257 had a negative impact on the maximum growth rate, decreasing the maximum growth rate by 37% (Figure 3). Over time, the maximum growth rates of strains KP209 and KV402 decreased 13.4% and 9.5%, respectively, compared to the maximum growth rate of the colistin-susceptible strain. In strain KP040, an increase of 10.0% in maximum growth rate was observed during the course of the *in vitro* evolution experiment.

Colistin-resistant *K. pneumoniae* complex strains have lipid A that is modified through hydroxylation, palmitoylation and addition of 4-amino-4-deoxy-L-arabinose (L-Ara4N)

To determine the modifications to lipid A in the colistin-resistant strains, we performed MALDI-TOF analysis on lipid A isolated from the colistin-susceptible strain, and the axenic strain of the last day of the *in vitro* evolution experiments. The MALDI-TOF spectra of lipid A isolated from colistin-susceptible strains (Figure 4A), showed a dominant peak from hexa-acylated lipid A (mass-to-charge ratio (*m/z*) 1824), corresponding to two glucosamines, two phosphates, four 3-OH-C_{14} and two C_{14} acyl chains (50). Additional minor peaks in the MALDI-TOF spectrum of the susceptible strains could be observed at *m/z* 1840, corresponding to the hydroxylation (*m/z* 16) of one of the C_{14} acyl-groups

of hexa-acylated lipid A (*m/z* 1824), and at *m/z* 2063 (in KP209 and KP257), corresponding to a hepta-acylated lipid A, with an additional acylation of lipid A (*m/z* 1824) with a palmitoyl group (*m/z* 239).

All the MALDI-TOF spectra of lipid A isolated from colistin-resistant strains show additional peaks (Figure 4B), indicating the modification of their lipid A. In the spectra of colistin-resistant KP209 and KV402, lipid A *m/z* 1955 was observed, indicating addition of L-Ara4N (*m/z* 131) to the hexa-acylated lipid A *m/z* 1824. In colistin-resistant KV402 lipid A *m/z* 1850 was observed, consistent with hexa-acylated lipid A *m/z* 1824 with one C_{16} acyl chain (Figure 4C). The peak at *m/z* 1866 in the MALDI-TOF spectra of colistin-resistant KP040 and KP257 was consistent with hydroxylation of lipid A *m/z* 1850.

Development of colistin resistance is associated with increased LL-37 resistance and virulence in a *C. elegans* survival model.

To determine the impact of colistin resistance resistance on virulence characteristics of the *K. pneumoniae* complex strains, we first determined the susceptibility of the strains to the human cathelicidin antimicrobial peptide LL-37. We observed that three of the four colistin-resistant strains (KP209, KP040, and KP257) showed a decreased susceptibility to killing by LL-37 compared to their colistin-susceptible parental strains (Figure 5). In contrast, development of colistin resistance in strain KV402 did not affect susceptibility to LL-37.

To investigate the possible consequences of colistin resistance on virulence, we exposed the nematode *C. elegans* strain CF512 to the colistin-susceptible/resistant strain pairs. *C. elegans* had a decreased lifespan on a lawn of colistin-resistant KP209 (Figure 6) and KP040, compared to their colistin-susceptible strains. Survival of *C. elegans* was not affected by growth on colistin-resistant strains derived from KP257 and KV402, compared to the colistin-susceptible parental strains.

Discussion

Colistin plays a pivotal role in public health due to its last-resort status for treatment of infections with multidrug-resistant Gram-negative bacteria. The increasing number of reports of *K. pneumoniae* strains that have acquired resistance to multiple antibiotics, including colistin, is thus a cause for increasing concern (7–9, 58). In this study, we aimed to study the potential to evolve colistin resistance in clinical *K. pneumoniae* isolates. Due to the difficulties in generating targeted mutants in these multidrug-resistant clinical isolates, we were limited to *in vitro* evolution experiments to identify mutations associated with colistin resistance. We observed the swift development of colistin resistance through diverse evolutionary trajectories. Development of colistin resistance had no, or only a minor, impact on maximum growth rate in three out of four *in vitro* evolution experiments performed here. This suggests that colistin may rapidly lose its effectiveness in the treatment of infections caused by multidrug-resistant *K. pneumoniae* complex strains as fitness costs associated with colistin resistance seem limited.

We observe that mutations associated with an increase in MIC of colistin seem confined to genes from functional groups involved in the synthesis and modification of LPS, and the synthesis of capsular polysaccharides, which are both important surface-associated structures. In the genes encoding the PhoPQ two-component regulatory system, which have a role in regulating modifications of LPS and contribute to colistin resistance in Enterobacteriaceae (21, 59), we found variations in both PhoP (a D191N substitution), and PhoQ (a G385S substitution, and a 12-bp deletion). The G385S PhoQ substitution has previously been described in a colistin-resistant clinical *K. pneumoniae* strain (60). We also found that a novel integration of an IS*5* element in the promoter region associated with the genes encoding CrrAB and CrrC coincides with increase in MIC of colistin. The IS*5* element can influence the transcriptional activity of the genes located near its integration site (61). The activity of PmrAB may be influenced by CrrAB through CrrC (22, 62). In line with previous observations, in which insertions of IS elements were associated with

414 resistance to colistin, we hypothesize that the insertion of IS5 may lead to increased expression of CrrAB
415 and/or CrrC, and thus cause colistin resistance (28).

416 We observed that the inactivation of *wzc* of the K-locus, by the IS*102* element coincides with an
417 increase in the MIC of colistin. In *E. coli*, Wzc is involved in the synthesis and export of extracellular
418 polysaccharides containing colanic acid (63), but also the phosphorylation of other endogenous proteins
419 (64). Wzc has previously been hypothesised to be involved in colistin resistance in *E. coli*, and it may act
420 similarly in *K. pneumoniae* (64–66). The loss of Wzc may potentially cause colistin resistance through two
421 mechanisms. A reduction in the export of colanic acid units (the building blocks of *K. pneumoniae* capsule),
422 can lead to the accumulation of colanic acid metabolic intermediates, including UDP-glucuronic acid. This
423 accumulation has been hypothesised to lead to an increased flux towards biosynthesis of UDP-L-Ara4N,
424 resulting in the modification of lipid A with L-Ara4N (67). Alternatively, the absence or reduction of
425 negatively charged colanic acid residues on the cell surface could lower local concentrations of positively
426 charged colistin molecules, thereby reducing damage to the outer membrane (67). Further studies are
427 needed to fully characterize the interplay between the *Klebsiella* capsule and colistin resistance. In addition
428 to the inactivation of *wzc*, we observed a 12-bp insertion in the highly-conserved *rho* gene, encoding the
429 transcription termination factor Rho. Rho has not been previously linked to colistin resistance, but
430 mutations in *rho* may have pleiotropic effects on transcription (68), which could influence the expression
431 of genes involved in, or may compensate for fitness costs caused by colistin resistance.

432 Notably, we did not find any alterations in *mgrB*, which is an otherwise important mechanism
433 through which colistin resistance may occur in nosocomial *K. pneumoniae* complex strains (20, 25–27, 69).
434 Nevertheless colistin-resistant clinical *K. pneumoniae* isolates without mutations in *mgrB* are also
435 frequently encountered (60, 62, 70–73). We can only speculate on the reasons for the absence of *mgrB*
436 mutations in our *in vitro* evolution experiments. The relatively short duration of this experiment performed
437 with a limited number of strains, likely implies that we have not covered all potential colistin resistance

mechanisms in *K. pneumoniae*. Due to these limitations and the lack of replicate experiments, we cannot make any conclusions on the repeatability or the need for a specific order in these mutational pathways.

The impact of developing colistin resistance through the observed mutations might extend past the inability to treat the infection through antibiotic therapy, as we show in this study that modifications to lipid A may reduce the susceptibility to antimicrobial peptides and increase virulence. However, the mechanisms behind the differential effects on virulence of colistin resistance in the *K. pneumoniae* complex are not fully understood and are deserving of further study. A single *K. variicola* isolate was included in this study. While *K. variicola* can cause life-threatening infections in immunocompromised individuals (5), it remains currently understudied. Additional studies into the mechanisms of colistin resistance and their impact on fitness and virulence may be warranted in this species.

The emergence and spread of colistin resistance could complicate future treatments of infections caused by multidrug-resistant Gram-negative bacteria. Our study indicates that in the *K. pneumoniae* complex multiple evolutionary trajectories towards colistin resistance exist, without negatively impacting fitness or virulence characteristics. Our data highlight the remarkable adaptive abilities of strains in the *K. pneumoniae* complex, which makes them a nosocomial pathogen of considerable importance. Future studies may lead to the development of novel therapeutics to specifically target colistin resistance mechanisms, which may be essential to lengthen the clinical lifespan of colistin as a last-resort drug in treatment of *K. pneumoniae* infections.

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Competing interests

The authors have declared that no competing interests exist.

Author contributions

A.B.J., D.J.D. and G.M. performed experiments and analysed data. A.B.J. and M.R.C.R performed bioinformatic analyses. S.H.M.R., J.A.B., and W.v.S designed experiments. A.B.J., M.J.M.B, S.H.M.R.,

R.J.L.W., J.A.B. and W.v.S. wrote the manuscript. All authors reviewed and approved the manuscript prior to submission.

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Figure and table legends

Figure 1

***K. pneumoniae* complex strains: metadata, presence of antibiotic resistance genes, and core-genome phylogenetic analysis. A)** Overview of the isolates used in this study, including the date and source of isolation, MLST type, and the initial MIC determined. MLST typing of strain KV402 resulted in an incomplete MLST profile, so no conclusive ST could be assigned. NA, not applicable. **B)** Antibiotic resistance genes detected in *K. pneumoniae* complex strains sequenced as part of this study. Classes of antibiotic resistance genes are indicated as follow: BLA, beta-lactam resistance genes; QLN, quinolone resistance genes; FOS, fosfomycin resistance genes. The strains did not carry acquired colistin resistance genes of the *mcr*-family. **C)** Midpoint-rooted phylogenetic tree representing the 1.3-Mbp core-genome alignment of 41 *K. pneumoniae* complex. Taxonomic phylogroups of the *K. pneumoniae* complex (2) are indicated along the branches. The strains used in this study are highlighted in red.

Figure 2

Population analysis of mutations during *in vitro* evolution in the presence of colistin. For each strain, and each day of the *in vitro* evolution experiment (performed in LB), the positions that have mutated compared to the colistin-susceptible strain are indicated. For SNPs and indels, the number of reads supporting a mutation at a given location was used to estimate the abundance of the mutation. Novel integrations of IS elements are also indicated. For mutations not located in a coding sequence, nearby coding sequences are indicated. Mutations and IS element integrations observed in the axenic, strain isolated daily from each population are indicated by a blue border. The MIC of colistin (determined in MHCAB) for each axenic strain isolated from the *in vitro* evolution population is indicated. The MIC

values represent the mode from three independent experiments performed in duplo. Hyp. protein: hypothetical protein.

Figure 3

Maximum growth rate of colistin resistant evolved strains. Optical density at 600 nm (OD_{600}) was measured every 7.5 minutes during growth in LB. Representative data of three individual experiments, performed in triplicate are shown. Mean and standard deviations are shown. A parametric one-way ANOVA with Dunnett's multiple correction was used for the statistical analysis of the differences in growth rates between the axenic strains isolated from each day of the *in vitro* evolution experiment and the colistin-susceptible parental strain. Outcomes of the statistical analysis are indicated by asterisks: $p < 0.05$ (*), < 0.01 (**), <0.001 (***), or <0.0001 (****).

Figure 4

Lipid A modifications in colistin-susceptible and colistin-resistant strains. MALDI-TOF spectra showing the mass-to-charge (m/z) ratio values of the isolated lipid A from (A) colistin-susceptible, and (B) colistin-resistant axenic strains, isolated from the cultures of the last day of the *in vitro* evolution experiment. C) Proposed chemical structures of lipid A-moieties corresponding to the observed m/z-values in the MALDI-TOF spectra. Modifications relative to the unmodified hexa-acylated lipid A corresponding to m/z value 1824 are depicted in red. Hydroxylation of an acyl-chain adds 16 to the m/z ratio, 4-amino-4-deoxy-L-arabinose adds 131, acylation with palmitate adds 239.

Figure 5

Susceptibility of colistin-susceptible and colistin-resistant strains to the human cathelicidin LL-37. Strains were incubated for 90 minutes in 25% LB at 37ºC with or without the addition of 50 µg/ml LL-37. Viability was assessed by determination of the number of colony-forming units. The non-parametric Mann-Whitney test was used as statistical test and significance was defined as a p-value of < 0.05 (*), < 0.01 (**), <0.001 (***), or <0.0001 (****).

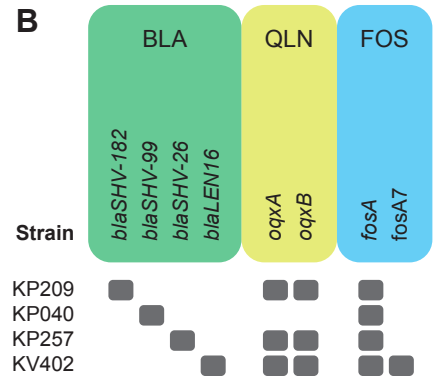
Figure 6

Survival of *C. elegans* on lawns of *K. pneumoniae* colistin-susceptible and colistin-resistant strains complex strains. *C. elegans* CF512 were kept on a lawn of colistin-susceptible (green) and colistin-resistant (red) *K. pneumoniae* complex strains. Survival was scored over a period of 15 days. The data represent three independent experiments in which a total of 129 (in colistin-susceptible KP209), 118 (colistin-resistant KP209), 106 (colistin-suscptible KP040), 127 (colistin-resistant KP040), 127 (colistin-susceptible KP257), 131 (colistin-resistant KP257), 100 (colistin-susceptible KP402), and 102 (colistin-resistant KP402) *C. elegans* nematodes were used. Statistical significance according to Mantel-Cox log-rank test is indicated. Statistical significance was defined as a p-value < 0.05.

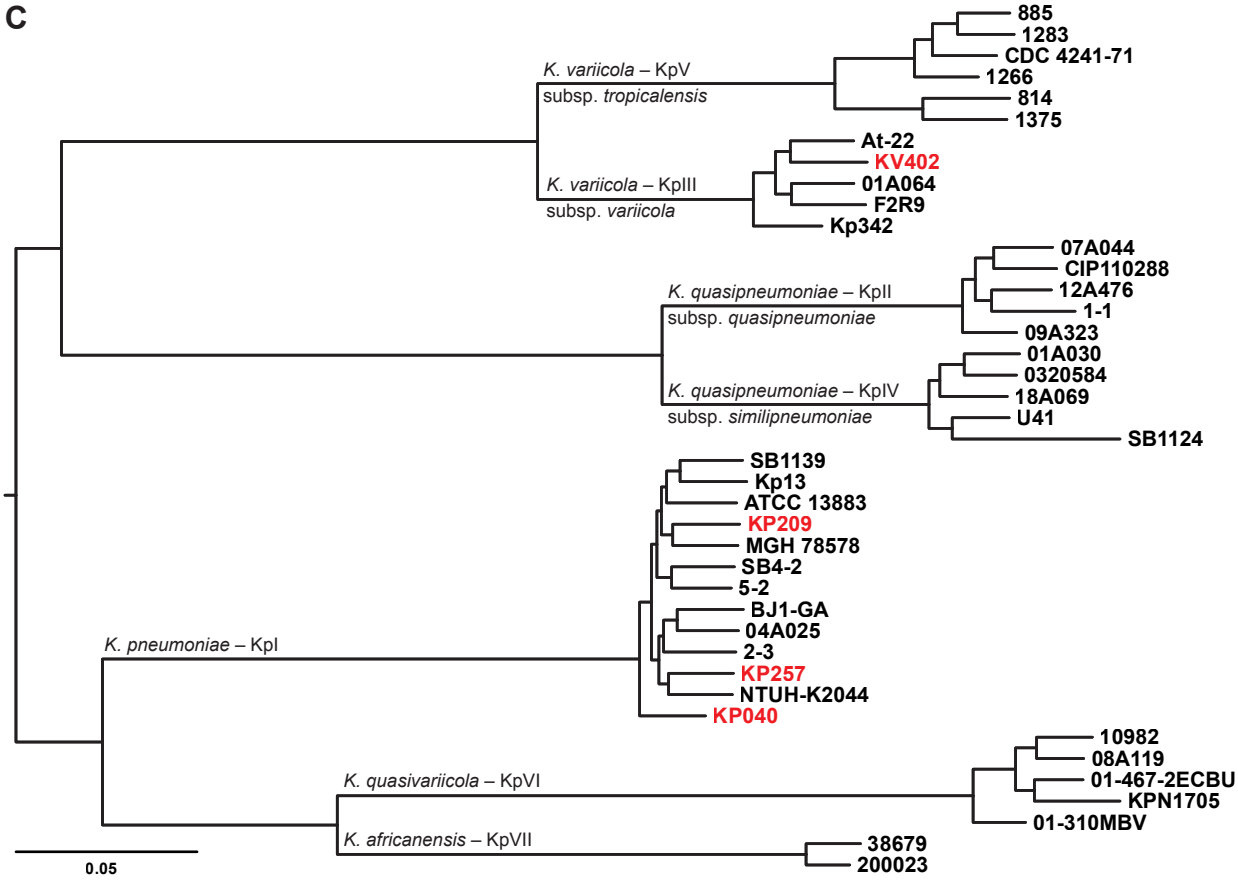
A

Strain	Date of isolation	Isolation source	MLST type	MIC of colistin (mg/L)	Reference
KP209	17-09-2013	Urine	11	0.5	This study
KP040	09-09-2013	Faeces	10	1	This study
KP257	27-09-2013	Pus	3030	1	This study
KV402	19-09-2013	Urine	NA	0.5	This study

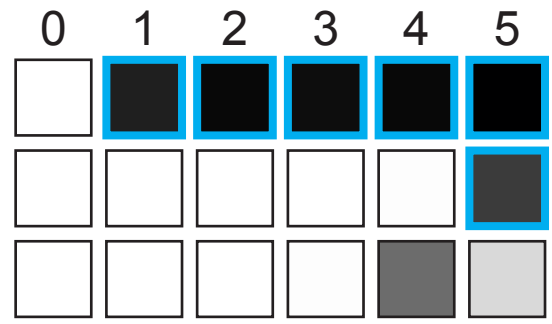
B



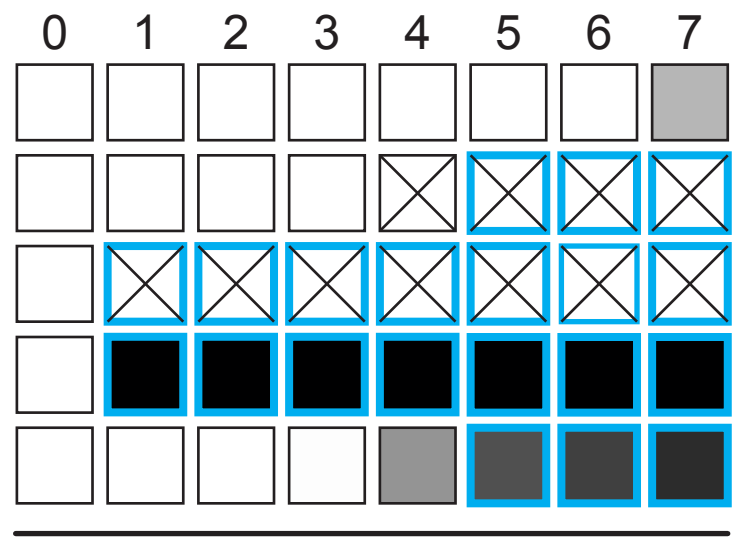
C



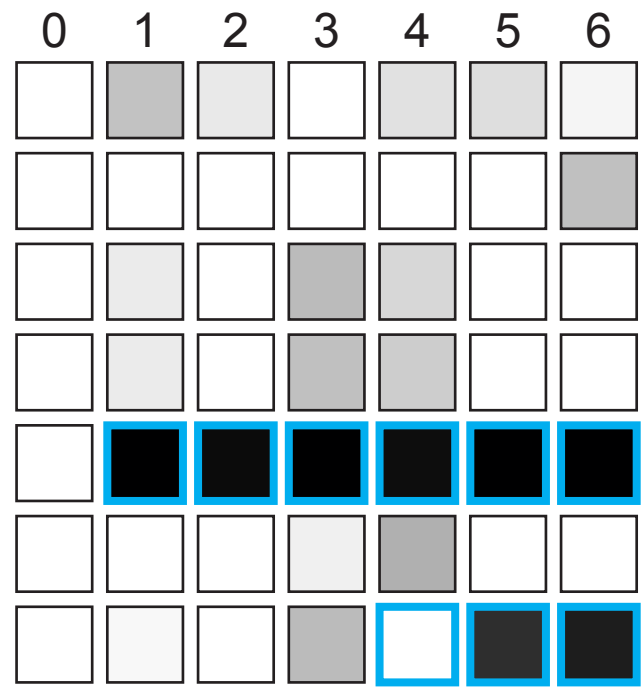
KP209



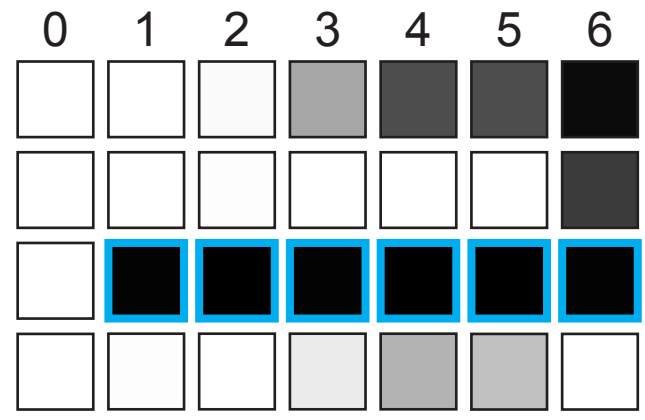
KP040

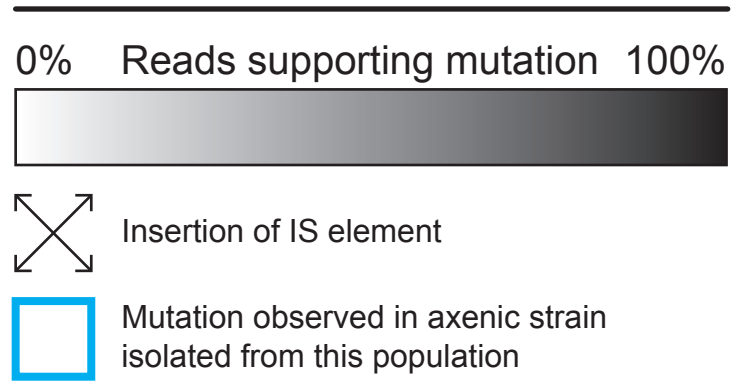


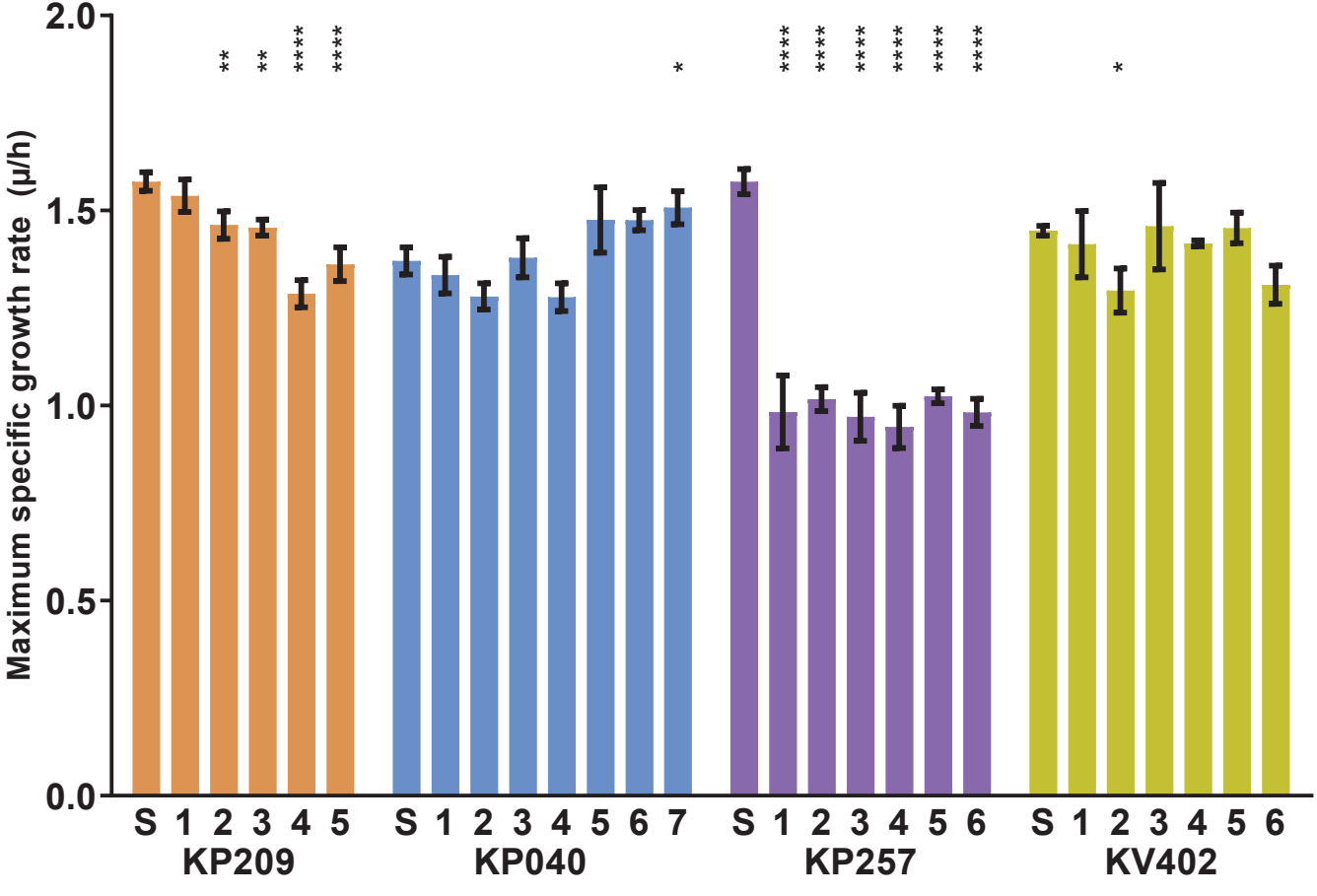
KP257



KV402






Maximum specific growth rate (μ/h)
2.0
1.5
1.0
0.5
0.0
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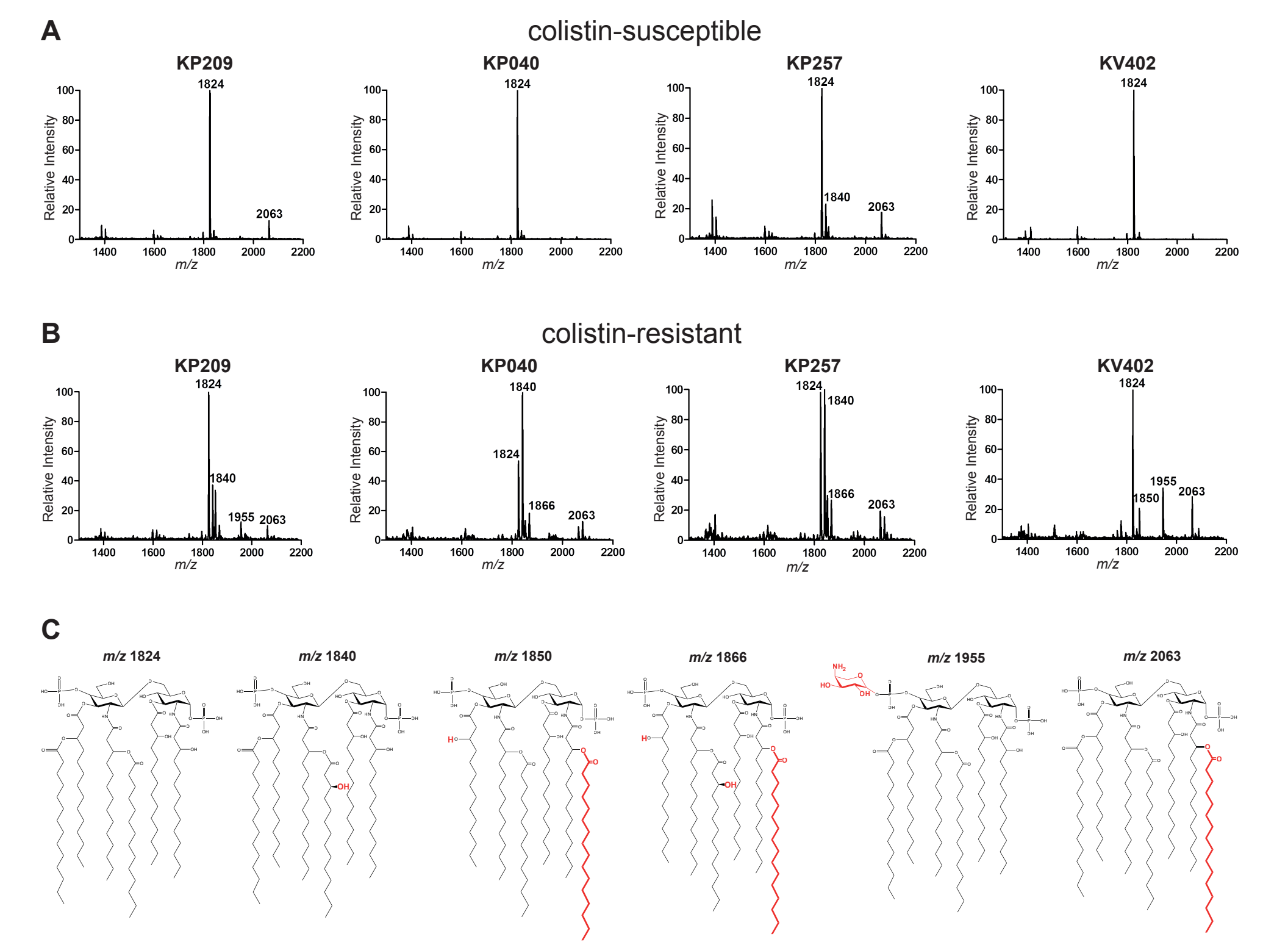
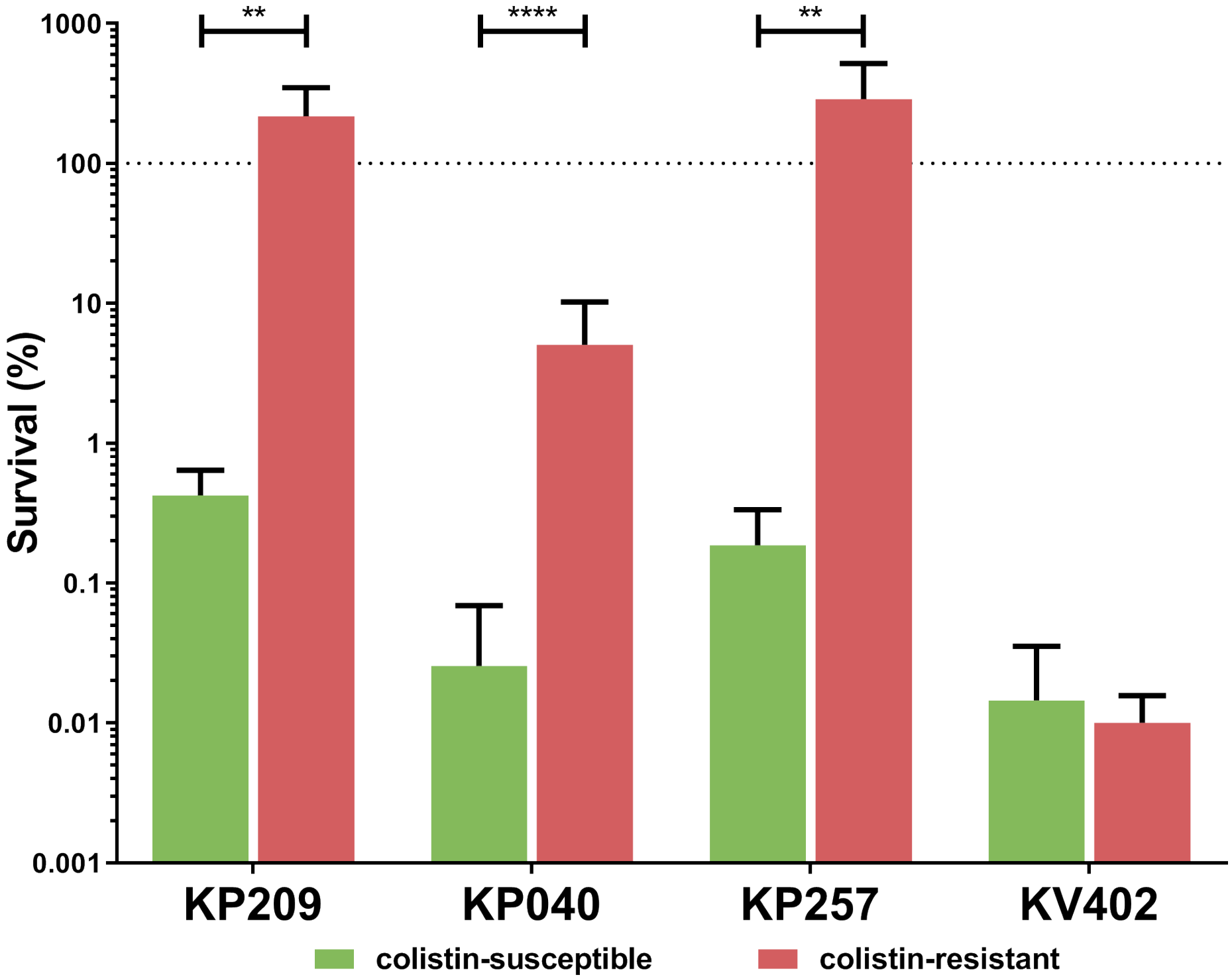
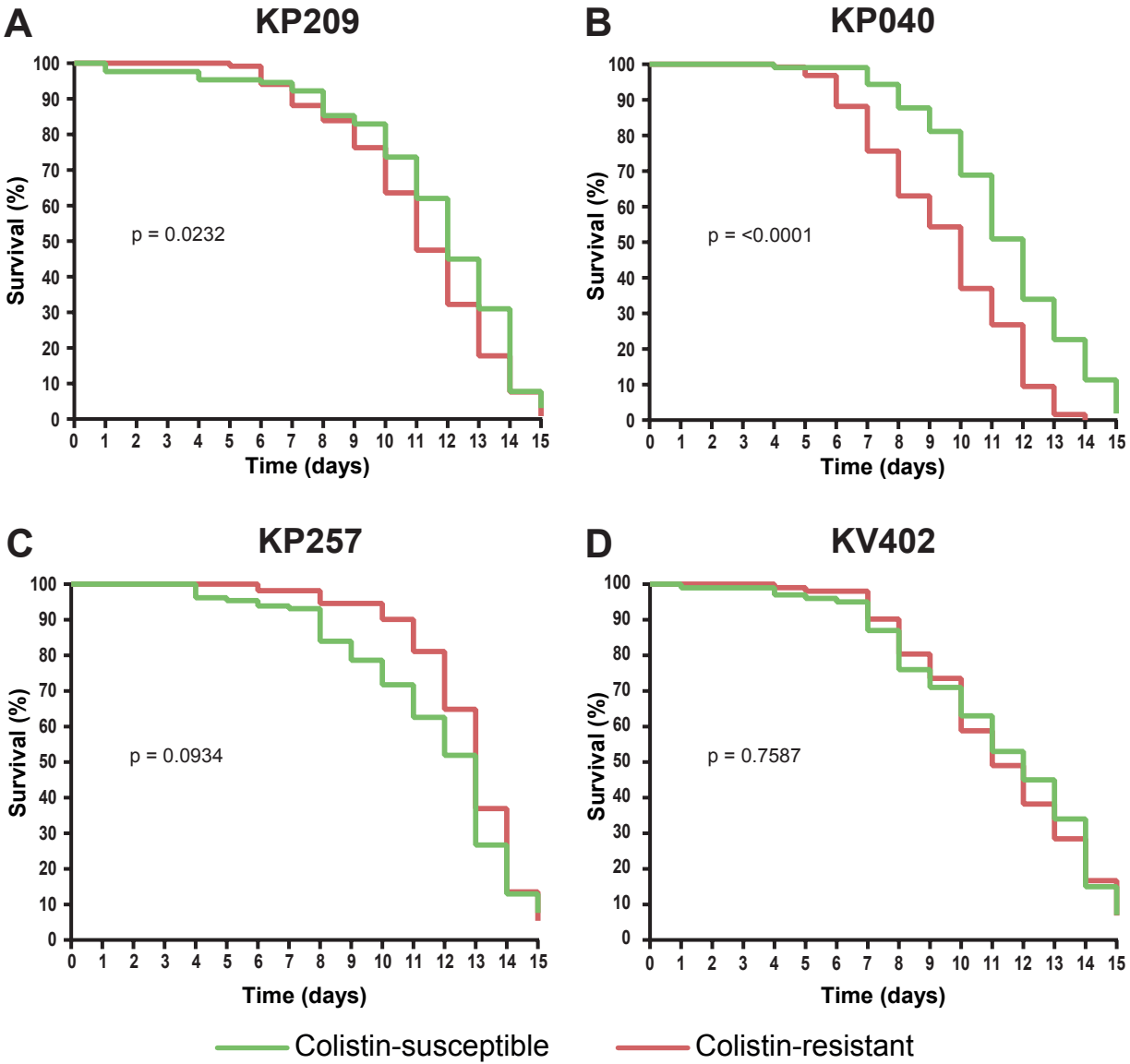
****
*
****
****
****
****
****
****
*
S 1 2 3 4 5
S 1 2 3 4 5 6 7
S 1 2 3 4 5 6
S 1 2 3 4 5 6
KP209
KP040
KP257
KV402


A
colistin-susceptible
KP209
KP040
KP257
KV402
Relative Intensity
m/z
1824
2063
1840
B
colistin-resistant
1955
1866
1850
C
m/z 1824
m/z 1840
m/z 1850
m/z 1866
m/z 1955
m/z 2063


**
****
**
1000
100
10
1
0.1
0.01
0.001
Survival (%)
KP209
KP040
KP257
KV402
colistin-susceptible
colistin-resistant


A
KP209
B
KP040
C
KP257
D
KV402
Survival (%)
Time (days)
p = 0.0232
p = <0.0001
p = 0.0934
p = 0.7587
Colistin-susceptible
Colistin-resistant