

McCarthy, AJ; Martin, P; Cloup, E; Stabler, R; Oswald, E; Taylor, PW; (2015) The Genotoxin Colibactin is a Determinant of Virulence in *Escherichia coli* K1 Experimental Neonatal Systemic Infection. *Infection and Immunity* , 83 (9) pp. 3704-3711.

ARTICLE

The Genotoxin Colibactin is a Determinant of Virulence in *Escherichia coli* K1 Experimental Neonatal Systemic Infection

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Running Head: Colibactin in neonatal *E. coli* infection

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Abstract

Escherichia coli expressing the K1 capsule are a major cause of sepsis and meningitis in human neonates. The development of these diseases is dependent on the expression of a range of virulence factors, many of which remain uncharacterised. Here, we show that all but one of 34 *E. coli* K1 neonatal isolates carry *clbA* and *clbP*, genes contained within the *pks* pathogenicity island and required for the synthesis of colibactin, a polyketide-peptide genotoxin that causes genomic instability in eukaryotic cells by induction of double-strand breaks in DNA. Inactivation of *clbA* and *clbP* in *E. coli* A192PP, a virulent strain of serotype O18:K1 that colonizes the gastrointestinal tract and translocates to the blood compartment with very high frequency in experimental infection of the neonatal rat, significantly reduced the capacity of A192PP to colonize the gut, engender double-strand breaks in DNA and cause invasive, lethal disease. Mutation of *clbA*, which encodes a pleiotropic enzyme also involved in siderophore synthesis, impacted virulence to a greater extent than mutation of *clbP*, encoding an enzyme specific to colibactin synthesis. Restoration of colibactin gene function by complementation re-established the fully virulent phenotype. We conclude that colibactin contributes to the capacity of *E. coli* K1 to colonise the neonatal gastrointestinal tract and to cause invasive disease in the susceptible neonate.

Introduction

Escherichia coli isolates belonging to phylogenetic group B2 are found with increasing frequency in the feces of healthy individuals from high-income countries (1) and are responsible for a range of extraintestinal infections that include those of the urinary tract, sepsis, pneumonia and neonatal meningitis (2). These extraintestinal pathogenic *E. coli* (ExPEC) strains carry genes encoding a diverse range of virulence determinants that promote colonization, invasion, survival in the blood compartment and the capacity to evade host defences and damage the host (3). These virulence-enhancing genes tend to cluster on pathogenicity islands, genomic elements that facilitate dissemination by horizontal gene transfer (4). The *pks* genomic island is found in 30-40% of *E. coli* B2 strains and codes for the production of colibactin, a polyketide-peptide genotoxin of as-yet unknown chemical structure that causes double-strand (ds) breaks in DNA, leading to cell cycle arrest, chromosome instability and increased lymphopenia in septic rodents (5-8). Carriage of the *pks* island is linked to long-term persistence in the gastrointestinal (GI) tract (9) and *pks* – bearing strains represent a high-virulence subset within the B2 group (6). The 54kb *pks* island encodes nonribosomal peptide synthetases, polyketide synthetases and hybrid synthetases, in addition to accessory, tailoring and editing enzymes; the *clbA* gene encodes a phosphopantetheinyl transferase required for colibactin synthesis and *clbP* specifies a D-amino peptidase involved in colibactin maturation (10, 11). The *pks* island also contributes to the synthesis of siderophores by virtue of the broad substrate specificity of ClbA, impacting iron acquisition and the ability to survive in the blood compartment (12).

The *pks* island was initially identified in an *E. coli* isolate from a case of neonatal bacterial meningitis (NBM) (6). *E. coli* is a leading cause of NBM and neonatal sepsis (13-15); these life-threatening conditions arise following vertical transmission of the bacteria from mother to infant during or shortly after birth and the large majority express the anti-phagocytic polysialic acid K1 capsule (16). Data from human infections is sparse, but studies using rat models of infection indicate that *E. coli* K1 strains initially colonize the GI tract of the

neonatal rat and subsequently enter the blood circulation *via* the mesenteric lymphatic system, causing severe systemic infection with a high likelihood of central nervous system (CNS) involvement and local inflammation (17-21), much as in human infections. The neonatal rat model adopted for these studies replicates the strong age-dependency characteristic of the human condition; systemic infection appears to be related to the capacity of the colonizing bacteria to translocate across the immature GI tract of the newborn (18, 21). Neuropathogenic strains of *E. coli* K1 have arisen by clonal expansion (22) and although they are not generally responsible for systemic infection in post-neonatal infants and adults, constitute a group of highly virulent opportunistic pathogens for susceptible neonates. We therefore examined the extent of involvement of colibactin production in the pathogenesis of neonatal *E. coli* K1 systemic infection by determining the degree of *pks* carriage in clinical isolates and the impact of mutation of *clbA* and *clbP* in the course of infection in a rat model of neonatal infection. The data indicate that colibactin and siderophore synthesis has a substantial impact on GI tract colonization and the capacity of *pks*-positive *E. coli* K1 to cause invasive disease.

METHODS

Bacterial strains

E. coli O18:K1 strain A192PP was derived from septicemia isolate *E. coli* A192 (22) by two rounds of passage through neonatal rat pups, with bacterial recovery from the blood (23). Thirty four isolates of *E. coli* K1 from neonatal blood, obtained between 2001 and 2014 at Great Ormond Street Hospital, London, were kindly provided by Professor Nigel Kline and Ms Elaine Cloutman-Green (Institute of Child Health, University College London). The presence of K1 capsule was confirmed with K1-specific bacteriophage K1E (24). Inactivation of *E. coli* A192PP genes was undertaken using bacteriophage λ Red recombinase as described (25). The mutants employed are shown in Table 1. For complementation, *clbA* was cloned into plasmid pASK75 (26), and *clbP* into plasmid pBRSK (10) (Table 1): *clbA::kan* and *clbP::kan* alleles were amplified by PCR from chromosomal DNA of

SP15*clbA::kan* and SP15*clbP::kan* using primers *clbA-F/clbA-R* and *clbP-F/clbP-R*, respectively, and were used to transform strain A192PP (*clbA-F*: CAG ATA CAC AGA TAC CAT TCA; *clbA-R*: CTA GAT TAT CCG TGG CGA TTC; *clbP-F*: GTG AAC TGA GCG AAA TAT TGG CTA ATC; *clbP-R*: TTA CTC ATC GTC CCA CTC CTT GTT G). The allelic exchanges were confirmed by PCR.

Identification of *pks* island

Strains were screened by PCR for the presence of *clbA* and *clbP* genes representative of the *pks* island. PCR reactions were performed using HotStart Taq kit (QIAGEN, Limburg, Netherlands) in 25 µl containing 1 pmol F and R primers, 1 x buffer, 1 x HotStart Taq Buffer Mix, 1 µl DNA and dH₂O. Reactions were heated to 95°C for 15 min, followed by 35 cycles at 95°C for 30 s, 60°C for 30 s and 72°C for 90 s, followed by one cycle of 72°C for 10 min. PCR products were detected following separation by electrophoresis using 1.5% agarose gels.

Genome sequencing

Bacteria were grown overnight in Mueller-Hinton broth at 37°C using an orbital incubator (200 orbits min). Genomic DNA was extracted from 1 ml of culture using QIAamp DNA mini kit (QIAGEN). Sequencing library preparation was carried out with Illumina Nextera XT according to the manufacturer's instructions. Mi-Seq sequencing (2 x 151 bp) was carried out following the manufacturer's standard protocols (Illumina Inc, USA). Sequencing reads were quality controlled using Trimmomatic (26). Nucleotide sequence of the A192PP genome has been deposited in the European Nucleotide Archive (<http://www.ebi.ac.uk/ena/>; accession number PRJEB9141). *pks* islands were identified in *E. coli* genomes by BLAST analysis of the *pks* element in IHE3034 (AM229678). *pks* islands and their insertion sites from nine *E. coli* genomes were compared using the Artemis Comparison Tool (27). Fastq

files for A192PP were mapped against the IHE3034 *pks* element using the Burrows-Wheeler Aligner software package (28).

Colibactin production

Colibactin induces senescence and consequent megalocytosis in cultured eukaryotic cells, manifest as progressive enlargement of the cell body and nucleus and the absence of mitosis. We quantified the extent of colibactin-induced megalocytosis using a methylene blue binding assay (12). *E. coli* strains were added to HeLa cells cultivated as described above at multiplicities of infection (MOIs) of between 12 and 400, co-cultured for 4 h and washed. Cells were then incubated for 72 h with cell culture medium containing 200 µg/ml gentamicin followed by staining with methylene blue. Dye binding was determined spectrophotometrically at OD₆₆₀.

Genotoxicity assay

The capacity of colibactin to engender ds DNA breaks was determined in HeLa cells by γ-H2AX immunofluorescence analysis (5, 29); this assay monitors the phosphorylation of histone H2AX, a sensitive marker of ds DNA breaks. HeLa cells (1.5 × 10⁴ cells in 200 µl Dulbecco's modified Eagle's medium supplemented with 10% fetal calf serum, 80 µg/ml gentamicin and 0.1 unit/ml bovine insulin) were dispensed into 96-well cell culture plates. After incubation at 37°C in a 5% CO₂ atmosphere for 24 h, the cells were washed and incubated with bacteria at MOIs of 20 to 100 bacteria per cell. After 5 h infection at 37°C in 5% CO₂, cells were washed 3 times with Hank's Balanced Salts Solution and incubated at 37°C in cell culture medium for 20 h with 200 µg/ml gentamicin. Cells were fixed in the plate with 4% paraformaldehyde and processed as previously described (12). Rabbit monoclonal anti-γ-H2AX antibody #9718 (Cell Signaling Technology Inc, Danvers MA) was diluted 1:500 in blocking solution and incubated for 2 h at room temperature. IRDyeTM 800CW-conjugated goat anti-rabbit secondary antibody was diluted 1:100 in blocking solution and incubated for 1 h. RedDot2 (Biotium) was used for DNA labelling. DNA and γ-H2AX were

visualized using an Odyssey Infrared Imaging Scanner (Li-Cor ScienceTec, Les Ulis, France) using 680 nm and 800 nm channels for RedDot2 and IRDyeTM800 respectively. Relative fluorescence units for γ -H2AX per cell (as determined by γ -H2AX divided by DNA content) were divided by vehicle controls to determine percentage change in phosphorylation of H2AX levels relative to control. All experiments were carried out in triplicate.

Colonization and infection of neonatal rats

Animal experiments were approved by the Ethical Committee of the UCL School of Pharmacy and the UK Home Office (HO) and were conducted under HO Project Licence PPL 80/2243. The procedure has been described in detail (30). Briefly, all members of a litter (12 pups) of two-day-old (P2) Wistar rat pups (Harlan UK) were fed 20 μ l of mid-logarithmic phase *E. coli* ($2-6 \times 10^6$ CFU) from an Eppendorf micropipette. GI tract colonization was determined by culture of perianal swabs on MacConkey agar; bacteremia was detected by MacConkey agar culture of blood taken *post mortem*. Disease progression was determined by daily evaluation of symptoms of systemic infection (28). After sacrifice, samples from the proximal small intestine (SI), mid-SI, distal SI, colon, blood, mesenteric lymph nodes (MLN), liver, kidney and spleen were excised aseptically, transferred to ice-cold phosphate buffered saline (PBS) and homogenized. Bacteria were quantified by serial dilution culture on MacConkey agar and *E. coli* K1 confirmed with bacteriophage K1E.

Immunohistochemical evaluation of tissue sections

The entire GI tract was recovered immediately after culling of rat pups and 2 cm segments of the mid-SI removed as previously described (30). Tissues were placed in 10% formalin for 24 h, embedded in paraffin and 5 μ m sections cut. Dewaxed sections were subjected to antigen retrieval in 0.1 M trypsin for 6 min at 37°C, then in 10 mM sodium citrate buffer (pH

6.0) for 30 min at 94°C. After peroxidase blocking (DAKO S2023) for 5 min, sections were incubated with protein block reagent (2.5% normal goat serum) for 20 min and then with the monoclonal rabbit anti-γH2AX antibody #9718 (Cell Signaling Technology Inc, Danvers MA) at a dilution of 1:400 for 1 h. The slides were washed with Envision flex buffer (DAKO K8000) for 5 min, and then incubated with the polymer-peroxidase conjugate (DAKO, K4061) for 30 min. After a second wash, chromogenic development was performed for 5 min with 3,3'-diaminobenzidine (DAKO, K3468). The tissues were counterstained with haematoxylin. Histological images were transformed into digital microscopic images with the Panoramic 250 Flash II scanning system (3DHISTECH, Budapest, Hungary).

RESULTS

The *pks* island is widely distributed amongst neonatal *E. coli* K1 isolates

E. coli A192PP displays a high level of virulence in the rodent model of systemic infection (23); lethal infection in susceptible neonatal pups occurs following translocation across the small intestine, with evidence that the invading bacteria adopt a transcellular route across the epithelium (21). *E. coli* K1 virulence factors enabling colonization and invasion have not been elucidated in unambiguous fashion and we therefore examined A192PP for the presence of genes associated with the *pks* island; PCR indicated that the strain carried *clbA* and *clbP*. The presence of the *pks* island was confirmed by whole-genome sequencing of A192PP; the strain carries all genes required for colibactin production and the island contains no single nucleotide polymorphisms that distinguish it from the island found in O18:K1:H7 ExPEC strain IHE3034; similar observations were made with regard to the other sequences we interrogated. We then examined 34 *E. coli* K1 neonatal isolates for the presence of *clbA* and *clbP*; all but one isolate carried these two genes.

Neonatal *E. coli* K1 isolates elicit genotoxic effects *in vitro*

Seven neonatal *E. coli* K1 *pks*⁺ isolates were randomly selected and their capacity to elicit genotoxic effects in HeLa co-cultures was determined; in all cases, exposure of HeLa cells

to neonatal *E. coli* K1 isolates resulted in megalocytosis, a reliable marker of colibactin-producing group B2 strains (Fig. 1) (31). *E. coli* A192PP also demonstrated the ability to induce megalocytosis in HeLa cell co-culture (Fig. 2B).

Whilst disruption of *clbA* and *clbP* in *E. coli* A192PP did not affect growth kinetics in batch culture (Fig. 2A), induction of megalocytosis was not evident when HeLa cells were exposed to A192PP Δ *clbA::kan* and A192PP Δ *clbP::kan* derivatives of *E. coli* A192PP (Fig. 2B).

Further, in contrast to the parent strain, A192PP Δ *clbA::kan* and A192PP Δ *clbP::kan* did not induce ds DNA breaks in HeLa cells (Fig. 2C). This functionality was restored when *clbA* and *clbP* were introduced on plasmid vectors (Fig. 2C), and the capacity of the complemented strains to induce γ -H2AX was comparable to the progenitor A192PP.

Colibactin contributes to the virulence of *E. coli* K1 strain A192PP

E. coli A192PP, Δ *clbA::kan* and Δ *clbP::kan* mutants and the complemented strains were examined for their capacity to induce lethal effects in a rat model of neonatal *E. coli* K1 systemic infection. We have previously established that two-day-old (P2) rat pups are exquisitely susceptible to lethal infection following oral introduction of *E. coli* A192PP (23). Over a period of one week (P2-P9) the pups become progressively more resistant to infection, but not colonization, as a result of rapid maturation of the neonatal GI tract (21, 32). In susceptible animals, *E. coli* A192PP cells begin to enter the blood circulation around 24 h after GI tract colonization becomes apparent and within seven days all animals in an infected litter succumb to a highly disseminated infection. GI colonization of *E. coli* A192PP is stable in quantitative aspects over the period of investigation (21, 23). Here, P2 neonates became efficiently colonized in the GI tract by *E. coli* A192PP and all derivatives within 24-48 h of administration and remained colonized for the duration of the experiment. As expected, *E. coli* A192PP produced lethal infection in all colonized pups (Fig. 3) and although a proportion of pups colonized with A192PP Δ *clbA::kan* (Figure 3A) and A192PP Δ *clbP::kan* (Fig. 3B) did not survive, the overall lethal effect as a result of these mutations was significantly attenuated. Thus, disruption of *clbA* increased survival by 50% and of *clbP* by

30%. Introduction of an intact *clbA* gene restored the lethal effect whilst enhanced lethality over *E. coli* A192PP was found when the *clbP* gene was complemented using plasmid pBRSK.*clbP*.

Colibactin influences colonization of, and induces genotoxic effects in, the neonatal GI tract

Current evidence suggests that the likely site of translocation of *E. coli* K1 from GI lumen to the blood compartment is the small intestine (21), with the proximal and mid-section of this region as the most likely loci of colonization preceding systemic invasion. At both sites, inactivation of *clbA* and *clbP* in *E. coli* A192PP resulted in a significantly lower population of colonizing bacteria (Fig. 4). With A192PP Δ *clbA*::*kan* and A192PP Δ *clbP*::*kan*, significantly fewer viable bacteria were recovered from the blood compared to the parent strain and fewer bacteria were recovered from the major organs of bacterial clearance but, with the exception of the spleen, following infection with the *clbP* mutant these did not reach levels of statistical significance (Fig. 4). We also examined the possibility that GI-colonizing *E. coli* A192PP engendered ds DNA breaks in enterocytes lining the mid-SI. We therefore obtained mid-SI sections from P2 pups 48 h and 72 h after oral administration of *E. coli* A192PP strains and assessed DNA damage by monitoring phosphorylation of histone γ -H2AX, a sensitive marker of ds DNA breaks (33), with monoclonal rabbit anti- γ -H2AX antibody. There was evidence of extensive ds DNA breaks in cells lining the mid-SI lumen from pups exposed to A192PP, but not to A192PP Δ *clbA*::*kan* and A192PP Δ *clbP*::*kan* mutants or the negative control (Fig. 5A). At 48 h and 72 h after colonization, dsDNA breaks were found in, respectively, 35.7% and 33.6% of cells lining the mid-SI lumen of pups exposed to *E. coli* A192PP, significantly more than in the cells from pups exposed to A192PP Δ *clbA*::*kan* and A192PP Δ *clbP*::*kan* mutants ($P < 0.01$ and $P < 0.001$ at 48 and 72 hours respectively; ANOVA) (Fig. 5B).

DISCUSSION

The blood isolate *E. coli* A192 efficiently (100%) colonized the GI tract of neonatal rats but elicited bacteremia in only 25-35% of colonized animals (18, 32), whereas the passaged derivative A192PP caused invasive disease in essentially all pups colonized at P2 (23, 32). GI tract colonization of P2 pups by *E. coli* A192PP was accompanied by extensive replication of A192PP to yield steady-state populations of 10^7 - 10^8 /g within 24 h (21). A similar degree of clonal expansion was noted at 24 h in this study, particularly in the proximal and mid-SI; inactivation of both *clbA* and *clbP* gave rise to a statistically significant, five- to tenfold reduction in the size of the colonizing population in these regions of the GI tract (Fig. 4). It is likely that the capacity of potential neuropathogens to colonise the neonate in numbers sufficient to permit their translocation to the blood compartment during the first few days of life represents a key determinant of outcome, although very little experimental or epidemiological data is available to assess the relative importance of quantitative aspects of early gastrointestinal colonisation in either naturally occurring or experimental infections. However, these reductions in colonization are concomitant with a reduced capacity to cause bacteremia and death (Fig. 3). In this context, it is known that colonization with A192PP induces massive down-regulation of *tff2* encoding Trefoil factor 2, a compact protein involved in assembly and maturation of the mucin layer that keeps luminal bacteria away from the enterocyte surface (21, 33).

Colibactin production has a substantial impact on the capacity of A192PP to cause lethal infection (Fig. 3) following invasion of the blood compartment (Fig. 4), providing a practical demonstration that the *pks* island is associated with bacteremia (6, 9, 12). In line with previous observations (5, 7), we found that *pks* carriage elicits ds DNA breaks in cultured cells. DNA ds cleavage is also manifest in gut epithelial cells (Fig. 5) during the period (48-72 h) of translocation from GI lumen to the blood compartment (21). The blood bioburden of *E. coli* A192PP Δ *clbA::kan* was significantly lower than that achieved by A192PP Δ *clbP::kan* 24 h after colonization (Fig. 4). ClbA impacts on colibactin and siderophore synthesis, whilst ClbP is involved only in colibactin synthesis (12), suggesting that low-molecular-weight iron

chelators may also play a significant role in the invasive potential of *E. coli* K1 infection in the neonatal rat. We have previously shown that mutation of *clbA* impacts siderophore biosynthesis when the *entD* gene (present in *E. coli* A192PP) is inactivated (12), emphasizing that the *clbA* mutation has the potential to engender pleiotropic effects on siderophore and colibactin biosynthesis, even in the presence of a functional *entD* gene. We therefore hypothesize that A192PP Δ *clbA::kan*, compromised with regard to colibactin biosynthesis, also displays altered siderophore production, which could contribute to the decreased virulence of the *clbA* mutant compared to the *clbP* mutant. It should be borne in mind, however, that siderophore production *in vitro* does not inform on the levels of synthesis of the chelator during colonization and invasion of infected animals.

Colibactin requires cell-bacterium contact in order to elicit genotoxic effects (5). We have recently obtained as-yet unpublished histological and immunohistochemical evidence that A192PP comes into close proximity to enterocytes lining the GI tract, adopts a transcellular route across the epithelial barrier and gains access to the circulation *via* the mesenteric lymphatic system. The observations reported here provide additional evidence for this mode of translocation, as it is likely that DNA strand breakage occurs predominantly either during close-proximity colonisation with, or after internalization of, *pks*-carrying bacteria. Colibactin-mediated DNA damage leads to activation of DNA damage repair pathways that will promote the accumulation of mutations with long-term health consequences for the host if exposure to the genotoxin persists (7). More transient exposure leads to anaphase bridges, chromosomal abnormalities and senescence in dividing cells (7, 34). Recently, it has been demonstrated, using a mother-to-offspring transmission model, that colibactin-producing *E. coli* strains impair intestinal permeability to low-molecular-weight molecules and impact oral tolerance (35). We will determine if A192PP colonization impacts on the permeability of the gut to micromolecules, macromolecules and particulates in order to reconcile transient or

long-term DNA damage with an enhanced capacity to translocate across the gut epithelium. Additional processes associated with colibactin production remain to be established.

In summary, this is the first report to show that colibactin production contributes to the capacity of *E. coli* to cause systemic lethal infections in experimental models that follow that natural pathway to infection. Moreover, our findings indicate that the *pks* island is widely distributed amongst neonatal *E. coli* K1 isolates, suggesting that this virulence factor has an important role to play in invasive disease in susceptible neonates. Additional processes associated with colibactin production remain to be established.

Acknowledgments. This work was supported by research grant MR/K018396/1 from the Medical Research Council. This work was also supported by research grant ANR-13-BSV1-0028-01 from the Agence Nationale de la Recherche and the platform Aninfimip, an EquipEx ('Equipement d'Excellence') supported by the French government through the Investments for the Future program (ANR-11-EQPX-0003). The National Institute for Health Research University College London Hospitals Biomedical Research Centre provided further support.

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Figure Legends

FIG 1 Production of colibactin by *E. coli* A192PP and derivatives determined by methylene blue staining (OD₆₆₀) of HeLa cells exposed to the bacteria indicated; MOI, multiplicity of infection, compared to non-exposed control (C).

FIG 2 Colibactin production by *E. coli* A192PP induces genotoxic effects. (A), Growth of *E. coli* strains A192PP, A192PP Δ *clbA*::*kan* and A192PP Δ *clbP*::*kan* in MH broth at 37°C (200 orbits min); \pm 1 SD, *n*=3. (B), Production of colibactin by *E. coli* A192PP and derivatives determined by methylene blue staining (OD₆₆₀) of HeLa cells exposed to the bacteria indicated; MOI, multiplicity of infection, compared to non-exposed control. (C), Quantification of double-strand (ds) DNA breaks induced by *E. coli* A192PP and derivatives; A192PP Δ *clbA*::*kan*+pASK75.*clbA* and A192PP Δ *clbP*::*kan*+pBRSK.*clbP* are complemented derivatives of A192PP Δ *clbA*::*kan* and A192PP Δ *clbP*::*kan* respectively. HeLa cells were incubated with the concentrations of bacteria indicated and ds breaks quantified by

determination of γ -H2AX. Z-test was used to determine significant differences of means and standard errors between A192PP and A192PP Δ *clbA*, A192PP and A192PP Δ *clbA*+pASK75.*clbA*, A192PP Δ *clbA* and A192PP Δ *clbA*+pASK75.*clbA*, A192PP and A192PP Δ *clbP*, A192PP Δ *clbP* and A192PP Δ *clbA*+pBRSK.*clbP*, and A192PP Δ *clbA*+pASK75.*clbA* and A192PP Δ *clbA*+pBRSK.*clbP* (all $P < 0.001$). There were no significant differences between A192PP Δ *clbA* and A192PP Δ *clbP*, and A192PP and A192PP Δ *clbP*+pBRSK.*clbP*.

FIG 3 Colibactin genes are required for expression of full virulence in the rat model of neonatal systemic infection. Survival of P2 rats colonized with *E. coli* K1 A192PP and (A) A192PP Δ *clbA* or (B) A192PP Δ *clbP*. GI tract colonization was established by manual feeding of $2-6 \times 10^6$ CFU. For A, A192PP $n=24$, A192PP Δ *clbA*::*kan* $n=24$, A192PP Δ *clbA*::*kan*+pASK75 $n=12$, A192PP Δ *clbA*::*kan* +pASK75.*clbA* $n=12$; for B, A192PP $n=36$, A192PP Δ *clbP*::*kan* $n=36$, A192PP Δ *clbP*::*kan*+pBRSK $n=12$, A192PP Δ *clbP*::*kan*+pBRSK.*clbP* $n=12$; log-rank (Mantel-Cox) test: ns, non-significant, * $P < 0.05$, ** $P < 0.01$.

FIG 4 Colibactin genes influence the degree of GI tract colonization and blood and organ dissemination of *E. coli* A192PP in the susceptible P2 neonatal rat. Tissues were removed 24 h after colonization and CFU/g of tissue determined by plating on MacConkey agar: *E. coli* A192PP colonies were detected using K1-specific bacteriophage; mutants were selected on medium containing 50 μ g/ml kanamycin. SI, small intestine. For (A), A192PP $n=18$, A192PP Δ *clbP*::*kan* ($n=18$); for (B), A192PP $n=17$, A192PP Δ *clbP*::*kan* ($n=17$); Student's *t* test: ns, non-significant, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

FIG 5 *E. coli* A192PP induces double-strand (ds) DNA breaks in epithelial cells of the mid-SI. P2 rats were colonized with *E. coli* A192PP, A192PP Δ *clbA*::*kan* or A192PP Δ *clbP*::*kan* by feeding from an Eppendorf pipette; controls (uninfected group) were fed MH broth. Animals were sacrificed at 48 h ($n=6$) or 72 h ($n=6$) after administration of the colonizing bacteria or

broth. Sections of the mid-SI were embedded in paraffin and stained for γ H2AX (brown), a biomarker for breaks in ds DNA, and counterstained with haematoxylin. (A), Representative mid-SI sections. Scale bar 100 μ m. (B), Quantification of ds DNA breaks in mid-SI sections. Groups of 6 rats were analyzed, mean \pm SD; one-way ANOVA with Tukey's multiple comparison test, * P <0.05, ** P <0.01, *** P <0.001.

Table 1. Strains and plasmids used in this study

| Strains | Genotype or phenotype | Source |
|---|---|------------|
| A192PP | 018:K1:H7; virulent in rat model of neonatal meningitis | [23] |
| A192PP Δ <i>clbA::kan</i> | <i>clbA</i> mutant of A192PP; Kan ^R | This study |
| A192PP Δ <i>clbA::kan</i> + pASK75 | <i>clbA</i> mutant of A192PP carrying pASK75 <i>clbA</i> ⁺ ; Kan ^R , Amp ^R | This study |
| A192PP Δ <i>clbA::kan</i> + pASK75. <i>clbA</i> | <i>clbA</i> mutant of A192PP carrying pASK75; Kan ^R , Amp ^R | This study |
| A192PP Δ <i>clbP::kan</i> | <i>clbP</i> mutant of A192PP; Kan ^R | This study |
| A192PP Δ <i>clbP::kan</i> + pBRSK | <i>clbP</i> mutant of A192PP carrying pBRSK; Kan ^R , Amp ^R | This study |
| A192PP Δ <i>clbP::kan</i> + pBRSK. <i>clbP</i> | <i>clbP</i> mutant of A192PP carrying pBRSK <i>clbP</i> ⁺ ; Kan ^R , Amp ^R | This study |
| | | |
| Plasmids | | |
| pASK75. <i>clbA</i> | Plasmid carrying <i>clbA</i> gene; Amp ^r | [25] |

| | | |
|--------------------|-----------------------------------|------------|
| pBRSK. <i>clbP</i> | Plasmid carrying <i>clbP</i> gene | This study |
|--------------------|-----------------------------------|------------|