



Molecular Analysis of *bla*_{KPC-2}-Harboring Plasmids: Tn4401a Interplasmid Transposition and Tn4401a-Carrying ColRNAI Plasmid Mobilization from *Klebsiella pneumoniae* to *Citrobacter europaeus* and *Morganella morganii* in a Single Patient

Kayoko Sugita,^{a,c}  Kotaro Aoki,^b Kohji Komori,^a Tatsuya Nagasawa,^a  Yoshikazu Ishii,^{a,b} Satoshi Iwata,^{d,e} Kazuhiro Tateda^{a,b}

^aDepartment of Microbiology and Infectious Diseases, Toho University Graduate School of Medicine, Tokyo, Japan

^bDepartment of Microbiology and Infectious Diseases, Toho University School of Medicine, Tokyo, Japan

^cDepartment of Microbiology and Immunology, Keio University School of Medicine, Tokyo, Japan

^dDepartment of Infectious Diseases, Keio University School of Medicine, Tokyo, Japan

^eDepartment of Infectious Diseases, National Cancer Center Hospital, Tokyo, Japan

ABSTRACT The spread of *Klebsiella pneumoniae* carbapenemase (KPC)-producing *Enterobacteriales* is a public health concern. KPC-encoding *bla*_{KPC} is predominantly spread by strains of a particular phylogenetic lineage, clonal group 258, but can also be spread by horizontal transfer of *bla*_{KPC}-carrying plasmids. Here, we report the transfer of a *bla*_{KPC-2}-harboring plasmid via mobilization from *K. pneumoniae* to *Citrobacter freundii* complex and *Morganella morganii* strains in a single patient. We performed draft whole-genome sequencing to analyze 20 carbapenemase-producing *Enterobacteriales* strains (15 of *K. pneumoniae*, two of *C. freundii* complex, and three of *M. morganii*) and all *K. pneumoniae* strains using MiSeq and/or MinION isolated from a patient who was hospitalized in New York and Montreal before returning to Japan. All strains harbored *bla*_{KPC-2}-containing Tn4401a. The 15 *K. pneumoniae* strains each belonged to sequence type 258 and harbored a Tn4401a-carrying multireplicon-type plasmid, IncN and IncR (IncN+R). Three of these *K. pneumoniae* strains also possessed a Tn4401a-carrying ColRNAI plasmid, suggesting that Tn4401a underwent interplasmid transposition. Of these three ColRNAI plasmids, two and one were identical to plasmids harbored by two *Citrobacter europaeus* and three *M. morganii* strains, respectively. The Tn4401a-carrying ColRNAI plasmids were each 23,753 bp long and incapable of conjugal transfer via their own genes alone, but they mobilized during the conjugal transfer of Tn4401a-carrying IncN+R plasmids in *K. pneumoniae*. Interplasmid transposition of Tn4401a from an IncN+R plasmid to a ColRNAI plasmid in *K. pneumoniae* and mobilization of Tn4401a-carrying ColRNAI plasmids contributed to the acquisition of *bla*_{KPC-2} in *C. europaeus* and *M. morganii*.

IMPORTANCE Plasmid transfer plays an important role in the interspecies spread of carbapenemase genes, including the *Klebsiella pneumoniae* carbapenemase (KPC)-coding gene, *bla*_{KPC}. We conducted whole-genome sequencing (WGS) analysis and transmission experiments to analyze *bla*_{KPC-2}-carrying mobile genetic elements (MGEs) between the *bla*_{KPC-2}-harboring *K. pneumoniae*, *Citrobacter europaeus*, and *Morganella morganii* strains isolated from a single patient. *bla*_{KPC-2} was contained within an MGE, Tn4401a. WGS of *bla*_{KPC-2}-carrying *K. pneumoniae*, *C. europaeus*, and *M. morganii* strains isolated from one patient revealed that Tn4401a-carrying ColRNAI plasmids were generated by plasmid-to-plasmid transfer of Tn4401a from a multireplicon-type IncN and IncR (IncN+R) plasmid in *K. pneumoniae* strains. Tn4401a-carrying ColRNAI plasmids were incapable of conjugal transfer in *C. europaeus* and *M. morganii* but mobilized from *K. pneumoniae* to

Citation Sugita K, Aoki K, Komori K, Nagasawa T, Ishii Y, Iwata S, Tateda K. 2021. Molecular analysis of *bla*_{KPC-2}-harboring plasmids: Tn4401a interplasmid transposition and Tn4401a-carrying ColRNAI plasmid mobilization from *Klebsiella pneumoniae* to *Citrobacter europaeus* and *Morganella morganii* in a single patient. *mSphere* 6:e00850-21. <https://doi.org/10.1128/mSphere.00850-21>.

Editor Mariana Castanheira, JMI Laboratories

Copyright © 2021 Sugita et al. This is an open-access article distributed under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/).

Address correspondence to Yoshikazu Ishii, yishii@med.toho-u.ac.jp.

Received 13 October 2021

Accepted 21 October 2021

Published 3 November 2021

a recipient *Escherichia coli* strain during the conjugal transfer of Tn4401a-carrying IncN+R plasmid. Therefore, Tn4401a-carrying ColRNAI plasmids contributed to the acquisition of *bla*_{KPC-2} in *C. europaeus* and *M. organii*.

KEYWORDS KPC-producing organisms, plasmid, Tn4401a, *bla*_{KPC-2}, WGS

The spread of carbapenemase-producing *Enterobacteriales* (CPE) is a public health concern (1). *Klebsiella pneumoniae* carbapenemase (KPC) genes (*bla*_{KPC}) have now spread worldwide and are particularly prevalent in North and South America, China, Greece, and Israel (1). *K. pneumoniae* strains belonging to clonal group 258 (CG258), including those of sequence type 11 (ST11), ST258, and ST512, are associated with the spread of *bla*_{KPC} (2–8).

The Tn3-family transposon Tn4401 is an important mobile genetic element for carrying *bla*_{KPC} (9–11). To date, nine Tn4401 isoforms have been reported (12–17). The IncF group pKpQIL-like plasmid carrying Tn4401 has been analyzed in detail (18–21). Furthermore, *bla*_{KPC}-carrying Inc plasmids, e.g., IncFIIK1, IncFIIK2, IncFIA, IncN, IncI2, IncX, IncA/C, IncR, and ColE1, have been detected in various ST258 clones (5, 18, 22).

Interstrain and -species horizontal transfer of genes encoding carbapenemases is important for the spread of CPE (23, 24). *bla*_{KPC}-carrying plasmids can be transmitted to other strains or species, resulting in the emergence of new KPC-producing strains (25). In our case study, KPC-type CPE, which are rarely detected in Japan (1), were detected in one patient comprising not only *bla*_{KPC}-positive *K. pneumoniae* but also *bla*_{KPC}-positive *Citrobacter freundii* complex and *Morganella morganii* (Table 1). It was interesting that these KPC-type CPE were detected in a single patient. We hypothesized that interstrain transmission of the plasmid carrying *bla*_{KPC} occurred via a mechanism involving a mobile genetic element in the patient. In the present study, we conducted whole-genome sequencing (WGS) analysis and transmission experiments with Tn4401-carrying plasmids to elucidate the relationship between the *bla*_{KPC-2}-positive *K. pneumoniae*, *C. freundii* complex, and *M. morganii* strains isolated from a single patient.

RESULTS

Antimicrobial susceptibility and carbapenemase genes. Twenty-six ceftazidime-resistant strains (15 *K. pneumoniae*, eight *C. freundii* complex, and three *M. morganii* strains) were isolated from a single patient in a university hospital in Tokyo over 3 months from November 201X to January 201X+1 (Table 1) (for the protection of personal privacy, permission was not obtained from any of the ethics committees to specify the year of isolation in the paper). The patient had been previously hospitalized in New York and Montreal before returning to Japan. All 26 strains were resistant to tazobactam-piperacillin and ceftazidime and were susceptible to amikacin (see Table S1 in the supplemental material). All 15 *K. pneumoniae* and all three *M. morganii* strains were imipenem or meropenem resistant and were determined by PCR to be *bla*_{KPC} positive. Additionally, two of the eight *C. freundii* complex strains with reduced susceptibility to imipenem were determined by PCR to be *bla*_{KPC} positive.

PFGE. All of the strains within each species, including the 15 *K. pneumoniae*, eight *C. freundii* complex (regardless of *bla*_{KPC}-positive or -negative status), and three *M. morganii* strains, were derived from the same clone, as determined by pulsed-field gel electrophoresis (PFGE) (Fig. S1A to C).

Draft and complete WGS. Draft genome sequences were obtained using an Illumina sequencer, MiSeq, for 20 *bla*_{KPC}-positive strains with an average depth of 86.6 (standard deviation [SD], 40.3) (Table S2). Assembled genomes contained an average of 78.7 (SD, 18.9) contigs and an *N*₅₀ value of 176,169 bp (SD, 90,246 bp). Complete genome sequences were obtained using a Nanopore sequencer, MinION, for 15 *bla*_{KPC}-positive *K. pneumoniae* strains with an average depth of 332.0 (SD, 189.3) (Table S2).

Species identification and MLST. The strains identified as *K. pneumoniae*, *C. freundii* complex, and *M. morganii* in the primary biochemical identification were identified as *K. pneumoniae*, *Citrobacter europaeus*, and *M. morganii*, respectively, by their average

TABLE 1 Ceftazidime-resistant CPE isolated from the single patient in this study

Strain ID	Species	Specimen	<i>bla</i> _{KPC-2}	Isolation date (YYYY.MM.DD)
TUM12126	<i>K. pneumoniae</i>	Bile	+	201X.11.8
TUM12127	<i>K. pneumoniae</i>	Bile	+	201X.11.8
TUM12128	<i>K. pneumoniae</i>	Stool	+	201X.11.15
TUM12129	<i>K. pneumoniae</i>	Bile	+	201X.11.22
TUM12130	<i>K. pneumoniae</i>	Bile	+	201X.11.22
TUM12131	<i>K. pneumoniae</i>	Stool	+	201X.12.15
TUM12132	<i>K. pneumoniae</i>	Bile	+	201X.12.22
TUM12133	<i>K. pneumoniae</i>	Bile	+	201X.12.22
TUM12134	<i>K. pneumoniae</i>	Bile	+	201X+1.1.1
TUM12135	<i>K. pneumoniae</i>	Bile	+	201X+1.1.1
TUM12136	<i>K. pneumoniae</i>	Bile	+	201X+1.1.1
TUM12137	<i>K. pneumoniae</i>	Bile	+	201X+1.1.8
TUM12138	<i>K. pneumoniae</i>	Bile	+	201X+1.1.8
TUM12139	<i>K. pneumoniae</i>	Blood	+	201X+1.1.8
TUM12140	<i>K. pneumoniae</i>	Blood	+	201X+1.1.8
TUM12141	<i>C. europaeus</i>	Stool	–	201X.12.15
TUM12142	<i>C. europaeus</i>	Bile	–	201X.12.22
TUM12143	<i>C. europaeus</i>	Bile	–	201X.12.22
TUM12144	<i>C. europaeus</i>	Bile	–	201X+1.1.1
TUM12145	<i>C. europaeus</i>	Bile	–	201X+1.1.1
TUM12146	<i>C. europaeus</i>	Bile	–	201X+1.1.8
TUM12147	<i>C. europaeus</i>	Blood	+	201X+1.1.8
TUM12148	<i>C. europaeus</i>	Blood	+	201X+1.1.8
TUM12149	<i>M. morgani</i>	Bile	+	201X+1.1.1
TUM12150	<i>M. morgani</i>	Bile	+	201X+1.1.8
TUM12151	<i>M. morgani</i>	Blood	+	201X+1.1.15

nucleotide identity (ANI) scores. All of the *K. pneumoniae* strains belonged to ST258. All of the *C. europaeus* strains were ascribed to ST497, which was a newly discovered ST in this study. No multilocus sequence typing (MLST) scheme for *M. morgani* is currently available.

Antimicrobial resistance genes. All of the *bla*_{KPC-2}-positive strains harbored *bla*_{KPC-2} located on Tn4401a. The *K. pneumoniae* strains also possessed *bla*_{OXA-9}, *bla*_{TEM-1}, *aac*(3')-IV, *aph*(4)-Ia, *aadA1*, *aadA2*, *aac*(6')-Ib-cr, and *cmlA1* (Table S1). The *C. europaeus* and *M. morgani* strains possessed *bla*_{KPC-2} and *aac*(6')-Ib-cr (Tables S1 and S3).

Mobile genetic element and plasmid similarity. All 15 of the *K. pneumoniae* strains shared similarly structured IncN- and IncR-type multireplicon (hereafter called IncN+R) plasmids that carried Tn4401a (Fig. S2A and Table S3). These 15 IncN+R plasmids showed 97% to 100% coverage and 99.90% to 100% similarity to each other. In three of these *K. pneumoniae* strains (TUM12137, TUM12139, and TUM12140), two copies of Tn4401a were present on each IncN+R plasmid. No plasmids resembling the Tn4401a-carrying IncN+R multireplicon plasmid harbored by *K. pneumoniae*, represented by pMTY12126_IncN+R from TUM12126, were reported in the GenBank database prior to September 2021. The highest coverage for pMTY12126_IncN+R was 59% for *K. pneumoniae* BWHC1 plasmid unnamed2 (GenBank accession number CP020500.1). The IncN and IncR portions of the multireplicon pMTY12126_IncN+R were similar to plasmid 9 (IncN, GenBank accession number FJ223607.1) and pKPC484 (IncR, GenBank accession number CP008798.1), respectively (Fig. S2B). Plasmid 9 and pKPC484 showed 52% and 55% coverage of the length of pMTY12126_IncN+R, respectively (Fig. S2B). Interestingly, plasmid 9 and pKPC484 each possessed a copy of Tn4401, and pMTY12126_IncN+R was structured such that their copies of Tn4401a merged (Fig. S2B).

In addition, three strains of *K. pneumoniae* (TUM12128, TUM12134, and TUM12135) harbored Tn4401a-carrying ColRNAI plasmids. The Tn4401a-carrying ColRNAI plasmid of *K. pneumoniae* TUM12128 (pMTY12128_ColRNAI) had a structure identical to that of the ColRNAI plasmids of *C. europaeus* TUM12147 (pMTY12147_ColRNAI) and TUM12148 (pMTY12148_ColRNAI) (Fig. S2C). Six *bla*_{KPC-2}-negative *C. europaeus* strains (from TUM12141 to TUM12146) were ColRNAI plasmid-specific PCR (*mobB*) negative.

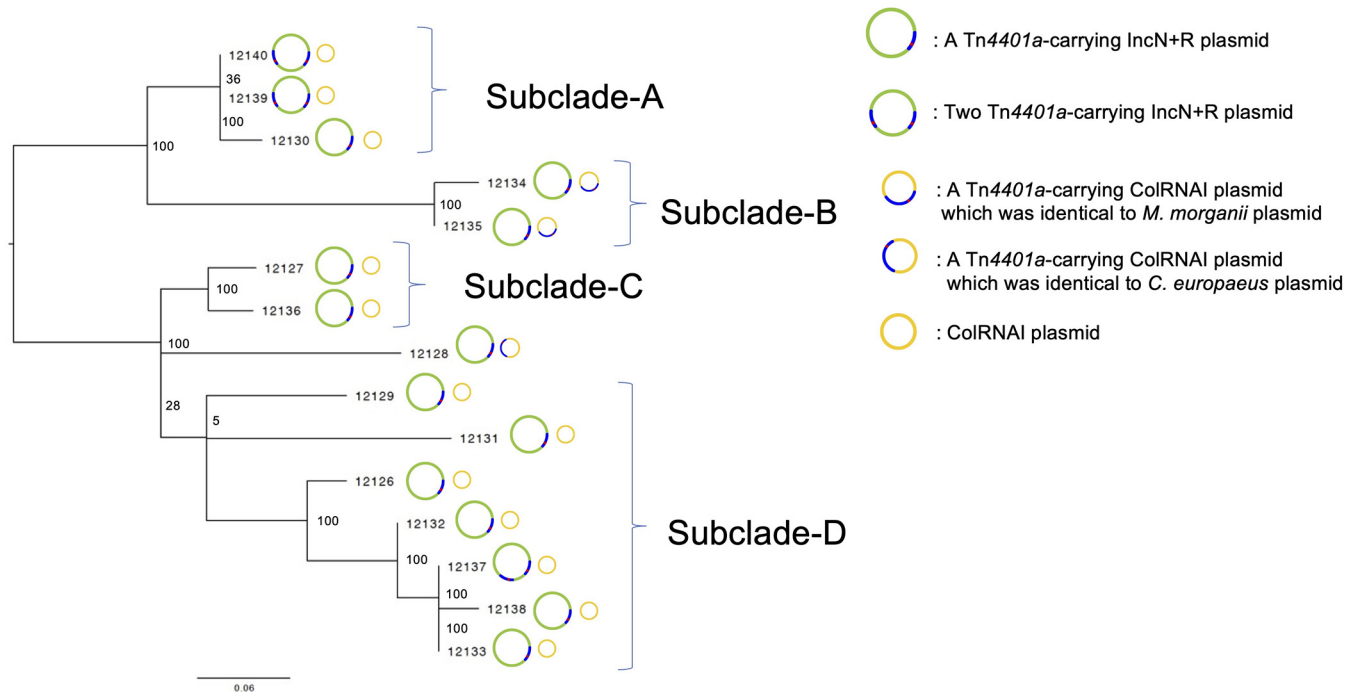


FIG 1 Phylogenetic tree of *bla*_{KPC-2}-positive *Klebsiella pneumoniae* strains. Phylogenetic tree of the 15 *bla*_{KPC-2}-positive *K. pneumoniae* strains and information on their harbored plasmids. The phylogenetic tree was constructed using a maximum-likelihood phylogenetic analysis based on single nucleotide polymorphisms (SNPs) in the core genome and excluding homologous recombination sequences. We used the bootstrap 1,000 times and listed the bootstrap values on the branch. The core-genome region comprised 95.1% (5,130,070/5,394,056 bp) of the genome of the reference strain, *K. pneumoniae* KPNIH1 ST258 (GenBank accession number [NZ_CP008827.1](https://www.ncbi.nlm.nih.gov/nuccore/NZ_CP008827.1)). The scale distance corresponds to the number of SNPs per the core genome, excluding the homologous recombination sequence.

Similarly, the Tn4401a-carrying ColRNAI plasmids of TUM12134 (pMTY12134_ColRNAI) and TUM12135 (pMTY12135_ColRNAI) had structures identical to those of the ColRNAI plasmids of *M. morgani* TUM12149, TUM12150, and TUM12151 (pMTY12149_ColRNAI, pMTY12150_ColRNAI, and pMTY12151_ColRNAI, respectively) (Fig. S2D). The backbone structures of the Tn4401a-carrying ColRNAI plasmids in this study were all identical, the only difference being the Tn4401a insertion site (Fig. S2E). The structures of the Tn4401a-carrying ColRNAI plasmids, pMTY12147_ColRNAI and pMTY12150_ColRNAI, were similar only to that of plasmid 15S (GenBank accession number [FJ223606.1](https://www.ncbi.nlm.nih.gov/nuccore/FJ223606.1)) among the identified plasmids, differing only in the position in which Tn4401a was inserted (Fig. S2F). The coverage of pMTY12147_ColRNAI, pMTY12150_ColRNAI, and plasmid 15S was 100%, with the only difference being the insertion site of Tn4401a. In addition, plasmids with structures that appear to be integrations of the Tn4401a-carrying ColRNAI plasmid into the IncFIB/FII, IncFII, or IncR plasmid are registered in the GenBank database (Fig. S2F).

Core-genome-based SNP analysis of *K. pneumoniae* strains and their Tn4401a-carrying plasmids. Phylogenetic analysis of the 15 *K. pneumoniae* strains from this study and 20 unrelated *bla*_{KPC-2}-positive ST258 *K. pneumoniae* strains isolated overseas for which genomic data are available from the GenBank database (Table S4) revealed that the 15 strains from this study form a cluster (Fig. S3A). The average substitution rate in the core genome was estimated to be 1.32 single nucleotide polymorphisms (SNPs) (95% highest posterior density interval, 0.19 to 2.46 SNPs) per genome per year, and the time of divergence of the 15-strain cluster in this study from the other analyzed strains was estimated to be approximately 100 months (approximately 8 years) before the time when these strains were isolated in a Japanese hospital (Fig. S3A). Phylogenetic analysis of only the 15 *K. pneumoniae* strains from this study showed that these strains can be divided into four subclades (subclades A, B, C, and D) (Fig. 1). The maximum number of SNPs among all 15 strains was 18, and the maximum number of SNPs among each subclade was only two (Fig. S3B). Two of the three strains in

subclade A and one of the seven strains in subclade D harbored two copies of Tn4401a on their IncN+R plasmid (Fig. 1). All strains in subclade B (TUM12134 and TUM12135) and one strain not belonging to a subclade (TUM12128) harbored a ColRNAI plasmid carrying Tn4401a (Fig. 1).

Plasmid transfer and similarity. The Tn4401a-carrying IncN+R plasmids from all except one of the *K. pneumoniae* strains (pMTY12128_IncN+R from TUM12128) were successfully transferred to *Escherichia coli* by conjugation. Interestingly, the pMTY12128_IncN+R plasmid, which was unable to be transferred by conjugation, had an approximately 20-kb inversion in the region of the conjugative transfer-associated gene cluster (Fig. S2A).

MOB-suite software detected the *mobC* gene in all ColRNAI plasmids with or without Tn4401a, which could not be detected by DFAST, and determined it to be a mobilizable plasmid. Conjugative transfer experiments revealed that the pMTY12133_ColRNAI and pMTY12134_ColRNAI plasmids could be successfully mobilized from *K. pneumoniae* TUM12133 and TUM12134, respectively, into *E. coli* via the conjugative transfer of an IncN+R plasmid. Plasmids pMTY12148_ColRNAI and pMTY12151_ColRNAI were also successfully mobilized by transforming the ColRNAI plasmid in *E. coli* harboring a self-transferable IncW plasmid, as we previously reported (*bla*_{IMP-1}-carrying plasmid, pMTY10660_IncW, GenBank accession number [AP018350.1](#)) (26). The *E. coli* harboring a *bla*_{IMP-1}-carrying IncW plasmid and a *bla*_{KPC-2}-carrying ColRNAI plasmid showed resistance to both moxalactam (>4 mg/liter) and aztreonam (>4 mg/liter) on selective agar plates.

DISCUSSION

In this study, we estimated the transposition of Tn4401a from an IncN+R plasmid to a ColRNAI plasmid in *K. pneumoniae* strains and found that the Tn4401a-carrying ColRNAI plasmid mobilized via conjugal plasmid transfer to the recipient. Furthermore, the mobilization of Tn4401a-carrying ColRNAI plasmids was confirmed by the results of *in vitro* conjugation experiments using *E. coli* as the recipient.

The Tn4401a-carrying IncN+R and ColRNAI plasmids that we analyzed were both found to be novel structures with low similarity to plasmids currently registered in the GenBank database. The IncR plasmid has been reported to form a multireplicon with the IncA/C and IncN plasmids (27). To the best of our knowledge, no IncR plasmid with conjugative ability has been reported, and we speculate that the IncN+R plasmid described in this study acquired conjugative ability by forming a multireplicon, as previously reported (28). The Tn4401a-carrying IncN+R plasmid may have acquired conjugative transfer ability by inheriting the *tra* gene from an ancestral IncN plasmid similar to plasmid 9.

The results of a core-genome SNP-based phylogenetic analysis conducted on 15 *bla*_{KPC-2}-positive *K. pneumoniae* strains from this study and representative ST258 strains from the GenBank database suggested that the strains from our patient diverged and evolved independently approximately 8 years prior to their time of isolation (see Fig. S3A in the supplemental material). This result strongly suggests that the patient may have already been carrying *bla*_{KPC-2}-positive ST258 *K. pneumoniae* strains at the time of medical treatment in New York, USA, and/or Montreal, Canada. Tn4401a detected in this study has the same structure as the IncFII-like plasmids pKpQIL (GenBank accession number [GU595196.1](#)) and pNYC (GenBank accession number [EU176011.1](#)) (21). Tn4401 is a transposon belonging to the Tn3 family and has been reported to be actively translocated in bacteria (29).

The WGS analysis of our 15 *K. pneumoniae* strains revealed that Tn4401a replicated on the IncN+R plasmid, leading to the generation over a 3-month period of bacteria harboring two copies, which it replicatively transferred to ColRNAI plasmids (Fig. S2A). Because ColRNAI plasmids carrying *bla*_{KPC-2} were found to be incapable of conjugative transduction themselves due to the lack of conjugative transfer element (*tra*) genes (Fig. S2C), it is likely that the conjugative transduction ability of the IncN+R plasmid helped *K. pneumoniae* to transmit Tn4401a to *C. europaeus* and *M. morgani*. However,

the IncN+R plasmid was not detected in *C. europaeus* or *M. morgani*, suggesting that the plasmid was not adapted to these hosts. Transposition of Tn4401a to ColRNAI must have been essential for the strains of *C. europaeus* and *M. morgani* in this patient to acquire *bla*_{KPC-2}. From the WGS data, we speculate that Tn4401a on the ColRNAI plasmids may have been sourced from an IncN+R plasmid in *K. pneumoniae*; however, to date, we have not experimentally demonstrated that Tn4401 was transferred.

This study revealed novel IncN+R and ColRNAI plasmids carrying Tn4401a. The data suggest that the interplasmid transposition of Tn4401a from an IncN+R plasmid to a ColRNAI plasmid in *K. pneumoniae* and the mobilization of Tn4401a-carrying ColRNAI plasmids contributed to the acquisition of *bla*_{KPC-2} in strains of *C. europaeus* and *M. morgani*.

MATERIALS AND METHODS

Bacterial strains. The bacterial strains used in the present study were isolated from a single patient in a university hospital in Tokyo over the 3-month period from November 201X to January 201X+1. The strains comprised 26 ceftazidime-resistant strains (15 *K. pneumoniae*, eight *C. freundii* complex, and three *M. morgani*) isolated from a patient who was hospitalized in New York and Montreal before returning to Japan. The strains were isolated during routine testing of bile and blood samples using sheep blood agar (Nissui Pharmaceutical Co., Ltd., Tokyo, Japan) and MacConkey II agar (Becton, Dickinson, Franklin Lakes, NJ, USA), and during active surveillance of extended-spectrum cephalosporins or carbapenem-resistant *Enterobacterales* in stool samples using ChromID ESBL agar (bioMérieux, Lyon, France). The patient had received multiple antibiotics, including meropenem, during the previous month.

Ethics. The study protocol was approved by the Ethics Committee of the Toho University School of Medicine (no. 27037 and A17023) and the Keio University School of Medicine (no. 20150090).

Primary bacterial species identification and antimicrobial susceptibility testing. Primary bacterial species identification and antibiotic susceptibility testing were performed with NBPcomb6.23J and Neg MIC6.31J of MicroScan WalkAway Plus (Beckman Coulter, Brea, CA, USA). Strains showing MICs of 4 mg/liter or higher for ceftazidime were judged as potential carbapenemase producers. The MICs were measured using the broth microdilution method in accordance with the CLSI guidelines (M07, 11th edition) (30). The following antimicrobial agents were used for antimicrobial susceptibility testing: piperacillin, ceftazidime, and imipenem (Sigma Chemical, St. Louis, MO, USA); ciprofloxacin (LKT Laboratories, St Paul, MN, USA); aztreonam (Tokyo Chemical Industry Co. Ltd., Tokyo, Japan); tazobactam (Toyama Chemical Co., Ltd., Toyama, Japan); meropenem, amikacin, and gentamicin (Wako Pure Chemical Industries, Ltd., Tokyo, Japan); and ertapenem (Merck & Co., Inc., Kenilworth, NJ, USA). The MIC measurement range was 0.125 to 256 mg/liter. *E. coli* ATCC 25922 and *Pseudomonas aeruginosa* ATCC 27853 were used as quality control strains for antibiotic susceptibility testing. The results were interpreted in accordance with the CLSI guidelines (M100, 31st edition) (31).

Screening carbapenemase genes by PCR. The main carbapenemase genes, *bla*_{KPC}, *bla*_{NDM}, *bla*_{IMP}, *bla*_{VIM}, and *bla*_{OXA-48-like} were screened using conventional PCR (32). Carbapenemase gene-positive strains were used in the following analyses in this study.

PFGE. *K. pneumoniae*, *C. freundii* complex, and *M. morgani* genomic DNAs, in gel-embedded form, were digested with XbaI (TaKaRa Bio, Shiga, Japan). Pulsed-field gel electrophoresis (PFGE) was performed using CHEF Mapper (Bio-Rad, Hercules, CA, USA) in 1× Tris-borate-EDTA (TBE) buffer, along with Lambda Ladder PFG marker (New England Biolabs, Hertfordshire, United Kingdom). Fingerprinting II software (Bio-Rad) was used to analyze the electrophoretic patterns, and the analysis parameters were as follows: the Dice coefficient, the unweighted pair group method with averages, 1% position tolerance, and 1% optimization.

Draft WGS and analysis. DNA was extracted from bacterial cultures, grown in LB medium using phenol-chloroform, and was purified using a QIAamp PCR purification kit (Qiagen, Valencia, CA, USA). DNA libraries were created using the Nextera XT DNA sample preparation kit (Illumina, Inc., San Diego, CA, USA). The DNA libraries were sequenced with the MiSeq platform (Illumina) for paired-end reads of 300 bp using a MiSeq reagent kit v3 600-cycle kit. MiSeq output reads were assembled with SPAdes v3.13.1 (33). Species identification was performed using the ANI with the type strain database gcType (34) and the comparesketch command in the BBMap package (<https://sourceforge.net/projects/bbmap/>) (35). We used a cutoff value of ≥96% (36) of the ANI value compared with the genomic sequences of the type strain for species identification. The DNA Data Bank of Japan Fast Annotation and Submission Tool (DFAST) was used for open reading frame (ORF) and gene annotation (37). ResFinder and Plasmid Finder from the Center for Genomic Epidemiology (<https://cge.cbs.dtu.dk/services/>) were used to detect acquired antimicrobial resistance genes and plasmid replicons. Multilocus sequence typing (MLST) was performed using the PubMLST scheme for *K. pneumoniae* and *Citrobacter* spp. (<https://pubmlst.org/>). *In silico* relaxase typing (MOB typing) was performed with MOB-suite (38).

MinION sequencing and hybrid *de novo* assembly with MiSeq reads. To determine the complete sequences of *bla*_{KPC-2}-carrying plasmids, genomic DNA was sequenced using MinION (Oxford Nanopore Technologies, Oxford, United Kingdom). DNA extraction and library preparation were performed using a NucleoBond AXG 20 column (TaKaRa Bio) combined with NucleoBond buffer set III (TaKaRa Bio) and rapid barcoding kit SQK-RBK004 (Oxford Nanopore Technologies), respectively. MinION flow cell R9.4 (Oxford Nanopore Technologies) was used for sequencing. Basecalling and demultiplexing were performed by Guppy v3.4.1. Hybrid *de novo* assembly, using both MiSeq and MinION reads, was conducted

with Unicycler (39) after the reads were quality trimmed with the Trimmomatic tool (version 0.38) (40) and NanoFilt (41).

Core-genome SNP-based phylogenetic analysis. Core-genome single nucleotide polymorphism (SNP)-based phylogenetic analysis was performed with MiSeq sequencing data. The MiSeq sequencing data were aligned to the genomic sequence of the reference isolate, *K. pneumoniae* KPNIH1 ST258 (GenBank accession number [NZ_CP008827.1](https://www.ncbi.nlm.nih.gov/nuccore/NZ_CP008827.1)), using the Burrows-Wheeler Aligner (BWA) with the “SW” option (42). We constructed a core-genome alignment using SAMtools (version 1.3) mpileup (43), and VarScan (version 2.3.7) mpileup2cns (44) and then a maximum-likelihood tree using PhyML (45). Using this as the starting tree, we inferred homologous recombination events that imported DNA fragments from beyond the phylogenetic clade and constructed a clonal phylogeny with corrected branch lengths using ClonalFrameML (46). The core genome, excluding homologous recombination sequences estimated using ClonalFrameML, was subjected to SNP detection and used for phylogenetic analysis by RAXML (47). We used the bootstrap 1,000 times and the gamma site model (GTR) substitution model. In addition, we estimated the evolutionary rate and timing of phylogenetic divergence of the 15 *K. pneumoniae* strains isolated over 3 months by BEAST (version 2.4.7) (48). BEAST was run for 20 million generations, sampling every 200 states, using the GTR substitution model.

Conjugation experiments. The conjugation experiments were performed by applying the filter mating method. A sodium azide- and rifampin-resistant, lactose-nonfermenting *E. coli* strain (ML4909 with added sodium azide resistance) was used as the recipient (26). Transconjugants were selected on modified Drigalski agar (Eiken Chemical Co., Ltd., Tokyo, Japan) containing both ceftazidime (4 mg/liter) and sodium azide (100 mg/liter; Fujifilm Wako Pure Chemical Corporation, Osaka, Japan). The carriage of *bla*_{KPC-2} by transconjugants was confirmed by PCR (32). Confirmation of the transmitted plasmid replicon type was performed by IncN- and IncR-specific PCR (23, 49).

Mobilization experiments. The procedure applied for confirming that the horizontal transfer to recipient cells occurred by the mobilization modality of a ColRNAI plasmid carrying *bla*_{KPC-2}, which did not appear to be self-transmissible by conjugation, was as follows. First, the test plasmids (*bla*_{KPC-2}-carrying ColRNAI plasmids designated pMTY12148_ColRNAI and pMTY12151_ColRNAI) were introduced by electroporation into *E. coli* cells carrying a conjugative *bla*_{IMP-1}-carrying plasmid (pMTY10660_IncW). The *E. coli* cells were washed three times with ice-cooled sterilized water as a pretreatment for electroporation. The *E. coli* Pulser (Bio-Rad, Munich, Germany) was used at a voltage of 1.5 kV. Second, a conjugation experiment was performed using an *E. coli* strain harboring a *bla*_{IMP-1}-carrying IncW plasmid and a *bla*_{KPC-2}-carrying ColRNAI plasmid as the donor and rifampin-resistant *E. coli* ML4909 as the recipient. If the *bla*_{IMP-1}- and *bla*_{KPC-2}-carrying plasmids were transferred at the same time, mobilization was considered to have occurred. Therefore, the *bla*_{KPC-2}-carrying mobilized cells were selected by their growth on modified Drigalski agar containing the three antibiotics aztreonam (4 mg/liter), moxalactam (4 mg/liter; Shionogi & Co., Ltd., Osaka, Japan), and rifampin (50 mg/liter; Fujifilm Wako Pure Chemical Corporation, Osaka, Japan). Confirmation of the transmitted *bla*_{IMP-1} and *bla*_{KPC-2} genes (32) and ColRNAI plasmid was performed by PCR. Transfer of the ColRNAI plasmid was confirmed by PCR of *mobB*, which is specifically retained by the ColRNAI plasmid. The primers used for this amplification were *mobB*-Fw (5'-ATCTGTTCCGCGATCTCGAC-3') and *mobB*-Rv (5'-CCCCAGTGCCTCAGTACAT-3').

Accession number(s). The draft and whole-genome sequencing data were deposited under the GenBank BioProject accession number [PRJDB11646](https://www.ncbi.nlm.nih.gov/bioproject/PRJDB11646). The accession numbers for each strain and plasmid are shown in Tables S1 and S3 in the supplemental material.

SUPPLEMENTAL MATERIAL

Supplemental material is available online only.

FIG S1, TIF file, 0.5 MB.

FIG S2, TIF file, 1.4 MB.

FIG S3, TIF file, 1.1 MB.

TABLE S1, PDF file, 0.03 MB.

TABLE S2, PDF file, 0.02 MB.

TABLE S3, PDF file, 0.02 MB.

TABLE S4, PDF file, 0.01 MB.

ACKNOWLEDGMENTS

This study was supported by the Ministry of Health, Labour and Welfare, Food Safety Promotion Research Program grant number 30190801.

We thank Edanz for editing a draft of this manuscript.

REFERENCES

- Logan LK, Weinstein RA. 2017. The epidemiology of carbapenem-resistant Enterobacteriaceae: the impact and evolution of a global menace. *J Infect Dis* 215:S28–S36. <https://doi.org/10.1093/infdis/jiw282>.
- Woodford N, Turton JF, Livermore DM. 2011. Multiresistant gram-negative bacteria: the role of high-risk clones in the dissemination of antibiotic resistance. *FEMS Microbiol Rev* 35:736–755. <https://doi.org/10.1111/j.1574-6976.2011.00268.x>.
- Munoz-Price LS, Poirel L, Bonomo RA, Schwaber MJ, Daikos GL, Cormican M, Cornaglia G, Garau J, Gniadkowski M, Hayden MK, Kumarasamy K, Livermore DM, Maya JJ, Nordmann P, Patel JB, Paterson DL, Pitout J,

- Villegas MV, Wang H, Woodford N, Quinn JP. 2013. Clinical epidemiology of the global expansion of *Klebsiella pneumoniae* carbapenemases. *Lancet Infect Dis* 13:785–796. [https://doi.org/10.1016/S1473-3099\(13\)70190-7](https://doi.org/10.1016/S1473-3099(13)70190-7).
4. Mathers AJ, Peirano G, Pitout JDD. 2015. The role of epidemic resistance plasmids and international high-risk clones in the spread of multidrug-resistant Enterobacteriaceae. *Clin Microbiol Rev* 28:565–591. <https://doi.org/10.1128/CMR.00116-14>.
 5. Chen L, Mathema B, Chavda KD, DeLeo FR, Bonomo RA, Kreiswirth BN. 2014. Carbapenemase-producing *Klebsiella pneumoniae*: molecular and genetic decoding. *Trends Microbiol* 22:686–696. <https://doi.org/10.1016/j.tim.2014.09.003>.
 6. Chen L, Mathema B, Pitout JDD, DeLeo FR, Kreiswirth BN. 2014. Epidemic *Klebsiella pneumoniae* ST258 is a hybrid strain. *mBio* 5:e01355-14. <https://doi.org/10.1128/mBio.01355-14>.
 7. Pitout JDD, Nordmann P, Poirel L. 2015. Carbapenemase-producing *Klebsiella pneumoniae*, a key pathogen set for global nosocomial dominance. *Antimicrob Agents Chemother* 59:5873–5884. <https://doi.org/10.1128/AAC.01019-15>.
 8. Wright MS, Perez F, Brinkac L, Jacobs MR, Kaye K, Cober E, van Duin D, Marshall SH, Hujer AM, Rudin SD, Hujer KM, Bonomo RA, Adams MD. 2014. Population structure of KPC-producing *Klebsiella pneumoniae* isolates from midwestern U.S. hospitals. *Antimicrob Agents Chemother* 58:4961–4965. <https://doi.org/10.1128/AAC.00125-14>.
 9. Naas T, Cuzon G, Villegas M-V, Lartigue M-F, Quinn JP, Nordmann P. 2008. Genetic structures at the origin of acquisition of the beta-lactamase *bla*_{KPC} gene. *Antimicrob Agents Chemother* 52:1257–1263. <https://doi.org/10.1128/AAC.01451-07>.
 10. Cuzon G, Naas T, Nordmann P. 2011. Functional characterization of Tn4401, a Tn3-based transposon involved in *bla*_{KPC} gene mobilization. *Antimicrob Agents Chemother* 55:5370–5373. <https://doi.org/10.1128/AAC.05202-11>.
 11. David S, Cohen V, Reuter S, Sheppard AE, Giani T, Parkhill J, European Survey of Carbapenemase-Producing Enterobacteriaceae (EuSCAPE) Working Group, ESCMID Study Group for Epidemiological Markers (ESGEM), Rossolini GM, Feil EJ, Grundmann H, Aanensen DM. 2020. Integrated chromosomal and plasmid sequence analyses reveal diverse modes of carbapenemase gene spread among *Klebsiella pneumoniae*. *Proc Natl Acad Sci U S A* 117:25043–25054. <https://doi.org/10.1073/pnas.2003407117>.
 12. Cheruvanky A, Stoesser N, Sheppard AE, Crook DW, Hoffman PS, Weddle E, Carroll J, Sifri CD, Chai W, Barry K, Ramakrishnan G, Mathers AJ. 2017. Enhanced *Klebsiella pneumoniae* carbapenemase expression from a novel Tn4401 deletion. *Antimicrob Agents Chemother* 61:e00025-17. <https://doi.org/10.1128/AAC.00025-17>.
 13. Araújo BF, Royer S, Campos PA, Ferreira ML, Gonçalves IR, Machado LG, Lincopan N, Fernandes MR, Cerdeira LT, Batista DWDF, Gontijo-Filho PP, Ribas RM. 2018. Insights into a novel Tn4401 deletion (Tn4401i) in a multidrug-resistant *Klebsiella pneumoniae* clinical strain belonging to the high-risk clonal group 258 producing KPC-2. *Int J Antimicrob Agents* 52:525–527. <https://doi.org/10.1016/j.ijantimicag.2018.08.011>.
 14. Chen L, Chavda KD, Mediavilla JR, Jacobs MR, Levi MH, Bonomo RA, Kreiswirth BN. 2012. Partial excision of *bla*_{KPC} from Tn4401 in carbapenem-resistant *Klebsiella pneumoniae*. *Antimicrob Agents Chemother* 56:1635–1638. <https://doi.org/10.1128/AAC.06182-11>.
 15. Bryant KA, Van Schooneveld TC, Thapa I, Bastola D, Williams LO, Safrank TJ, Hinrichs SH, Rupp ME, Fey PD. 2013. KPC-4 is encoded within a truncated Tn4401 in an IncL/M plasmid, pNE1280, isolated from *Enterobacter cloacae* and *Serratia marcescens*. *Antimicrob Agents Chemother* 57:37–41. <https://doi.org/10.1128/AAC.01062-12>.
 16. Pecora ND, Li N, Allard M, Li C, Albano E, Delaney M, Dubois A, Onderdonk AB, Bry L. 2015. Genomically informed surveillance for carbapenem-resistant Enterobacteriaceae in a health care system. *mBio* 6:e01030-15. <https://doi.org/10.1128/mBio.01030-15>.
 17. Baraniak A, Izdebski R, Fiett J, Herda M, Derde LPG, Bonten MJM, Adler A, Carmeli Y, Goossens H, Hryniewicz W, Brun-Buisson C, Gniadkowski M, MOSAR WP2, WP3, and WP5 Study Groups. 2015. KPC-like carbapenemase-producing Enterobacteriaceae colonizing patients in Europe and Israel. *Antimicrob Agents Chemother* 60:1912–1917. <https://doi.org/10.1128/AAC.02756-15>.
 18. Conlan S, Thomas PJ, Deming C, Park M, Lau AF, Dekker JP, Snitkin ES, Clark TA, Luong K, Song Y, Tsai Y-C, Boitano M, Dayal J, Brooks SY, Schmidt B, Young AC, Thomas JW, Bouffard GG, Blakesley RW, NISC Comparative Sequencing Program, Mullikin JC, Korlach J, Henderson DK, Frank KM, Palmore TN, Segre JA. 2014. Single-molecule sequencing to track plasmid diversity of hospital-associated carbapenemase-producing Enterobacteriaceae. *Sci Transl Med* 6:254ra126. <https://doi.org/10.1126/scitranslmed.3009845>.
 19. Stoesser N, Phan HTT, Seale AC, Aiken Z, Thomas S, Smith M, Wyllie D, George R, Sebra R, Mathers AJ, Vaughan A, Peto TEA, Ellington MJ, Hopkins KL, Crook DW, Orlek A, Welfare W, Cawthorne J, Lenney C, Dodgson A, Woodford N, Walker AS, TRACE Investigators' Group. 2020. Genomic epidemiology of complex, multispecies, plasmid-borne *bla*_{KPC} carbapenemase in Enterobacteriales in the United Kingdom from 2009 to 2014. *Antimicrob Agents Chemother* 64:e02244-19. <https://doi.org/10.1128/AAC.02244-19>.
 20. Chen L, Chavda KD, Melano RG, Jacobs MR, Koll B, Hong T, Rojzman AD, Levi MH, Bonomo RA, Kreiswirth BN. 2014. Comparative genomic analysis of KPC-encoding pKpQIL-like plasmids and their distribution in New Jersey and New York hospitals. *Antimicrob Agents Chemother* 58:2871–2877. <https://doi.org/10.1128/AAC.00120-14>.
 21. Leavitt A, Chmelnitsky I, Carmeli Y, Navon-Venezia S. 2010. Complete nucleotide sequence of KPC-3-encoding plasmid pKpQIL in the epidemic *Klebsiella pneumoniae* sequence type 258. *Antimicrob Agents Chemother* 54:4493–4496. <https://doi.org/10.1128/AAC.00175-10>.
 22. He S, Chandler M, Varani AM, Hickman AB, Dekker JP, Dyda F. 2016. Mechanisms of evolution in high-consequence drug resistance plasmids. *mBio* 7:e01987-16. <https://doi.org/10.1128/mBio.01987-16>.
 23. Rozwandowicz M, Brouwer MSM, Fischer J, Wagenaar JA, Gonzalez-Zorn B, Guerra B, Mevius DJ, Hordijk J. 2018. Plasmids carrying antimicrobial resistance genes in Enterobacteriaceae. *J Antimicrob Chemother* 73:1121–1137. <https://doi.org/10.1093/jac/dkx488>.
 24. Hidalgo L, de Been M, Rogers MRC, Schürch AC, Scharringa J, van der Zee A, Bonten MJM, Fluit AC. 2019. Sequence-based epidemiology of an OXA-48 plasmid during a hospital outbreak. *Antimicrob Agents Chemother* 63:e01204-19. <https://doi.org/10.1128/AAC.01204-19>.
 25. Conlan S, Park M, Deming C, Thomas PJ, Young AC, Coleman H, Sison C, NISC Comparative Sequencing Program, Weingarten RA, Lau AF, Dekker JP, Palmore TN, Frank KM, Segre JA. 2016. Plasmid dynamics in KPC-positive *Klebsiella pneumoniae* during long-term patient colonization. *mBio* 7:e00742-16. <https://doi.org/10.1128/mBio.00742-16>.
 26. Aoki K, Harada S, Yahara K, Ishii Y, Motooka D, Nakamura S, Akeda Y, Iida T, Tomono K, Iwata S, Moriya K, Tateda K. 2018. Molecular characterization of IMP-1-producing *Enterobacter cloacae* complex isolates in Tokyo. *Antimicrob Agents Chemother* 62:e02091-17. <https://doi.org/10.1128/AAC.02091-17>.
 27. Papagiannitsis CC, Miriagou V, Giakkoupi P, Tzouveleki LS, Vatopoulos AC. 2013. Characterization of pKP1780, a novel IncR plasmid from the emerging *Klebsiella pneumoniae* ST147, encoding the VIM-1 metallo-β-lactamase. *J Antimicrob Chemother* 68:2259–2262. <https://doi.org/10.1093/jac/dkt196>.
 28. Qu D, Shen Y, Hu L, Jiang X, Yin Z, Gao B, Zhao Y, Yang W, Yang H, Han J, Zhou D. 2019. Comparative analysis of KPC-2-encoding chimera plasmids with multi-replicon IncR:Inc_{pA1763-KPC}:IncN1 or IncFII_{pHN7A8}:Inc_{pA1763-KPC}:IncN1. *Infect Drug Resist* 12:285–296. <https://doi.org/10.2147/IDR.S189168>.
 29. He S, Hickman AB, Varani AM, Siguier P, Chandler M, Dekker JP, Dyda F. 2015. Insertion sequence IS26 reorganizes plasmids in clinically isolated multidrug-resistant bacteria by replicative transposition. *mBio* 6:e00762-15. <https://doi.org/10.1128/mBio.00762-15>.
 30. CLSI. 2018. CLSI M07. Methods for dilution antimicrobial susceptibility tests for bacteria that grow aerobically, 11th ed. Clinical and Laboratory Standards Institute, Wayne, PA.
 31. CLSI. 2021. CLSI M100-ED31:2021. Performance standards for antimicrobial susceptibility testing, 31st ed. Clinical and Laboratory Standards Institute, Wayne, PA.
 32. Doyle D, Peirano G, Lascols C, Lloyd T, Church DL, Pitout JDD. 2012. Laboratory detection of Enterobacteriaceae that produce carbapenemases. *J Clin Microbiol* 50:3877–3880. <https://doi.org/10.1128/JCM.02117-12>.
 33. Bankevich A, Nurk S, Antipov D, Gurevich AA, Dvorkin M, Kulikov AS, Lesin VM, Nikolenko SI, Pham S, Pribelski AD, Pyshkin AV, Sirotkin AV, Vyahhi N, Tesler G, Alekseyev MA, Pevzner PA. 2012. SPAdes: a new genome assembly algorithm and its applications to single-cell sequencing. *J Comput Biol* 19:455–477. <https://doi.org/10.1089/cmb.2012.0021>.
 34. Shi W, Sun Q, Fan G, Hideaki S, Moriya O, Itoh T, Zhou Y, Cai M, Kim S-G, Lee J-S, Sedlacek I, Arahal DR, Lucena T, Kawasaki H, Evtushenko L, Weir BS, Alexander S, Dénes D, Tanasupawat S, Eurwilachit L, Ingsriwang S, Gomez-Gil B, Hazbón MH, Riojas MA, Suwannachart C, Yao S, Vandamme P, Peng F, Chen Z, Liu D, Sun X, Zhang X, Zhou Y, Meng Z, Wu L, Ma J. 2021. gType: a high-quality type strain genome database for microbial phylogenetic and functional research. *Nucleic Acids Res* 49:D694–D705. <https://doi.org/10.1093/nar/gkaa957>.

35. Richter M, Rosselló-Móra R. 2009. Shifting the genomic gold standard for the prokaryotic species definition. *Proc Natl Acad Sci U S A* 106:19126–19131. <https://doi.org/10.1073/pnas.0906412106>.
36. Kim M, Oh H-S, Park S-C, Chun J. 2014. Towards a taxonomic coherence between average nucleotide identity and 16S rRNA gene sequence similarity for species demarcation of prokaryotes. *Int J Syst Evol Microbiol* 64:346–351. <https://doi.org/10.1099/ijs.0.059774-0>.
37. Tanizawa Y, Fujisawa T, Kaminuma E, Nakamura Y, Arita M. 2016. DFAST and DAGA: web-based integrated genome annotation tools and resources. *Biosci Microbiota Food Health* 35:173–184. <https://doi.org/10.12938/bmfh.16-003>.
38. Robertson J, Nash JHE. 2018. MOB-suite: software tools for clustering, reconstruction and typing of plasmids from draft assemblies. *Microb Genom* 4:e000206. <https://doi.org/10.1099/mgen.0.000206>.
39. Wick RR, Judd LM, Gorrie CL, Holt KE. 2017. Unicycler: resolving bacterial genome assemblies from short and long sequencing reads. *PLoS Comput Biol* 13:e1005595. <https://doi.org/10.1371/journal.pcbi.1005595>.
40. Bolger AM, Lohse M, Usadel B. 2014. Trimmomatic: a flexible trimmer for Illumina sequence data. *Bioinformatics* 30:2114–2120. <https://doi.org/10.1093/bioinformatics/btu170>.
41. De Coster W, D’Hert S, Schultz DT, Cruts M, Van Broeckhoven C. 2018. NanoPack: visualizing and processing long-read sequencing data. *Bioinformatics* 34:2666–2669. <https://doi.org/10.1093/bioinformatics/bty149>.
42. Li H, Durbin R. 2009. Fast and accurate short read alignment with Burrows-Wheeler transform. *Bioinformatics* 25:1754–1760. <https://doi.org/10.1093/bioinformatics/btp324>.
43. Li H, Handsaker B, Wysoker A, Fennell T, Ruan J, Homer N, Marth G, Abecasis G, Durbin R, 1000 Genome Project Data Processing Subgroup. 2009. The Sequence Alignment/Map format and SAMtools. *Bioinformatics* 25:2078–2079. <https://doi.org/10.1093/bioinformatics/btp352>.
44. Koboldt DC, Zhang Q, Larson DE, Shen D, McLellan MD, Lin L, Miller CA, Mardis ER, Ding L, Wilson RK. 2012. VarScan 2: somatic mutation and copy number alteration discovery in cancer by exome sequencing. *Genome Res* 22:568–576. <https://doi.org/10.1101/gr.129684.111>.
45. Guindon S, Dufayard J-F, Lefort V, Anisimova M, Hordijk W, Gascuel O. 2010. New algorithms and methods to estimate maximum-likelihood phylogenies: assessing the performance of PhyML 3.0. *Syst Biol* 59:307–321. <https://doi.org/10.1093/sysbio/syq010>.
46. Didelot X, Wilson DJ. 2015. ClonalFrameML: efficient inference of recombination in whole bacterial genomes. *PLoS Comput Biol* 11:e1004041. <https://doi.org/10.1371/journal.pcbi.1004041>.
47. Stamatakis A. 2014. RAxML version 8: a tool for phylogenetic analysis and post-analysis of large phylogenies. *Bioinformatics* 30:1312–1313. <https://doi.org/10.1093/bioinformatics/btu033>.
48. Bouckaert R, Heled J, Kühnert D, Vaughan T, Wu C-H, Xie D, Suchard MA, Rambaut A, Drummond AJ. 2014. BEAST 2: a software platform for Bayesian evolutionary analysis. *PLoS Comput Biol* 10:e1003537. <https://doi.org/10.1371/journal.pcbi.1003537>.
49. García-Fernández A, Fortini D, Veldman K, Mevius D, Carattoli A. 2009. Characterization of plasmids harbouring *qnrS1*, *qnrB2* and *qnrB19* genes in *Salmonella*. *J Antimicrob Chemother* 63:274–281. <https://doi.org/10.1093/jac/dkn470>.