Extended-spectrum $\beta$-lactamase-producing and carbapenemase-producing Enterobacteriaceae

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Abstract

Antimicrobial resistance (AMR) is a global public-health emergency, which threatens the advances made by modern medical care over the past century. The World Health Organization has recently published a global priority list of antibiotic-resistant bacteria, which includes extended-spectrum $\beta$-lactamase-producing Enterobacteriaceae and carbapenemase-producing Enterobacteriaceae. In this review, we highlight the mechanisms of resistance and the genomic epidemiology of these organisms, and the impact of AMR.

INTRODUCTION

The development and introduction of antimicrobials in the 20th century has transformed the delivery of modern medical care. Yet, this ‘antibiotic golden-age’ is ending, threatened by rising rates of antimicrobial resistance (AMR) globally. Enterobacteriaceae, a family encompassing many clinically important bacterial species, exhibits rising levels of AMR. Infection with either extended-spectrum $\beta$-lactamase-producing Enterobacteriaceae (ESBL-E) or carbapenemase-producing Enterobacteriaceae (CPE) is associated with increased mortality rates, time to effective therapy, length of stay and overall healthcare costs [1–8]. The impact of the continued spread of AMR could have repercussions in multiple sectors. In the healthcare sector itself, patient deaths resulting from AMR are projected to reach 10 million annually by 2050, but AMR will also cause losses in the trillions to global economic output [9]. ESBL-E and CPE have spread globally [10, 11], and technologies such as whole-genome sequencing (WGS) are providing detailed insights into their evolution and dissemination. The World Health Organization has recently published a global priority pathogens list to focus attention on the most significantly resistant pathogens. Enterobacteriaceae resistant to third-generation cephalosporins (which includes ESBL-E) and Enterobacteriaceae resistant to carbapenems (CRE) are included within the critical category of this list [12].

ESBL-E

The definition of multidrug resistance is variable [13], but Enterobacteriaceae exhibiting resistance to $\beta$-lactams, extended-spectrum $\beta$-lactams and third-generation cephalosporins are commonly recognized as ESBL-E [11, 14]. Extended-spectrum $\beta$-lactamase (ESBL) mechanisms themselves are classified based on their molecular structure or functional similarities [15, 16] (Table 1). Initially, ESBL-E were predominantly associated with nosocomial outbreaks, with resistance arising from point mutations in plasmid-mediated enzymes such as TEM-1, TEM-2, SHV-1 and OXA-10 [14]. CTX-M enzymes are now predominant. They arose via multiple escape events of chromosomal $\beta$-lactamase-encoding genes (blalab) from Kluyvera spp. [17–19], supported by the presence of transpositional units including ISEcp1 in CTX-M groups 1, 2, 9 and 25 or ISCR1 in groups 2 and 9 [20]. Following initial reports in Europe [21], South America [22] and Japan [23], CTX-M enzymes have disseminated globally [24]. The group 1 enzyme CTX-M-15 is the most frequently identified, and dominates in many countries in Europe [25–30], Asia [31, 32], Africa [33–35] and the USA [36, 37]. Additional CTX-M mechanisms predominate in other locations. For example, the group 9 enzyme CTX-M-14 is the leading mechanism in Escherichia coli in some areas of Korea [38] and South America [39]. Until recently, CTX-M-14 was the major mechanism across China [40–42], but a steady increase in CTX-M-15 has also occurred [43–45].
Genomic epidemiology demonstrates a number of widespread lineages including sequence type (ST)131, ST38, ST405 and ST10 in \textit{E. coli} \cite{46–49}, and ST11, ST14 and ST15 in \textit{Klebsiella pneumoniae} \cite{32, 50, 51}. ST131, an extra-intestinal pathogenic \textit{E. coli}, has undergone massive clonal expansion and is strongly associated with the global dissemination of the \textit{bla}_{CTX-M-15} gene \cite{47, 52, 53}.

WGS has resolved ST131 into three clades, based upon the presence of marker alleles for the type 1 fimbriae, \textit{fimH}. Clade A is associated with \textit{H41}, clade B with \textit{H22} and \textit{H30} is associated with clade C \cite{54–58}. A clade C sublineage is the main driving force in the widespread dissemination of CTX-M-15 and fluoroquinolone resistance (FQR) in ST131 \cite{55, 56, 59}. Clade C is identifiable by FQR mutations in \textit{gyrA} (\textit{gyrA1AB}) and \textit{parC} (\textit{parC1aAB}) genes, whereas clades A and B are predominantly fluoroquinolone susceptible \cite{55}. Further segregation of clade C into C1 and C2 occurs depending upon the presence of \textit{bla}_{CTX-M-15} \cite{56, 59}. Prior to the emergence of C1 and C2, acquisition of elements including the \textit{Gly-phV} genomic island \cite{54} and the \textit{H30} allele \cite{60} helped to prime ST131 for global success. C1 and C2 divergence and the development of FQR mutations is estimated to have occurred in the late 1980s, consistent with the introduction of fluoroquinolones for clinical use \cite{54}. CTX-M-14, CTX-M-27, CTX-M-19, CTX-M-24 and CTX-M-55 have been identified in clade C \cite{59}; however, CTX-M-15 is almost entirely restricted to C2 \cite{55, 56, 59}. Bayesian analysis based upon CTX-M variant distribution also suggests \textit{bla}_{CTX-M-15} emerged in ST131 following the introduction of extended-spectrum cephalosporins into clinical practice \cite{59}.

Plasmid movement between different species and lineages represents a major source of AMR. \textit{bla}_{CTX-M-15}, in ST131 is invariably associated with plasmids of incompatibility group F (IncF) \cite{25, 59, 61}, albeit presence on IncN \cite{64}, IncX \cite{65} and IncI \cite{66} plasmids has also been reported. Specific IncF plasmids have been associated with C2 isolates. This includes those with dual replicons, which complicates plasmid typing and broadens the plasmid host range \cite{67, 68}, additional AMR genes, gene cassettes, toxin/

### Table 1. Classification of \(\beta\)-lactamases

Adapted from Bush and Jacoby, 2010 \cite{16}.

| Ambler molecular class | Bush–Jacoby group | Preferred substrate | Inhibited | Representative enzyme |
|------------------------|-------------------|---------------------|-----------|----------------------|
| A (serine penicillinas) | 2a                | Penicillins         | +         | PCI from \textit{S. aureus} |
|                        | 2b                | Penicillins, narrow-spectrum cephalosporins | +          | TEM-1, TEM-2, SHV-1 |
|                        | 2e                | Penicillins, narrow-spectrum and extended-spectrum cephalosporins | +          | SHV-2 to SHV-6, TEM-3 to TEM-26, CTX-Ms, BEL-1, VEB-1, PER-1 |
|                        | 2r                | Penicillins         | −          | TEM-30, SHV-72, SHV-19 |
|                        | 2c                | Penicillins, carbenicillin | +          | PSE-1 |
|                        | 2e                | Extended-spectrum cephalosporins | +          | FEC-1, CepA |
|                        | 2f                | Penicillins, cephalosporins, carbapenems | +/-       | KPC-2, SME-1, NMC-A |
| B (MBLs)               | 3                 | Most \(\beta\)-lactams including carbapenems | −          | IMP-1, VIM-1, NDM-1, CcrA and BcII, CphaA, L1 |
| C (cephalosporinas)    | 1                 | Cephalosporins      | −          | AmpC, CMY-2, ACT-1 |
| D (oxacillinas)        | 2                 | Penicillins, cloxacin | +/-       | OXA-1, OXA-10 |
|                        | 2de               | Extended-spectrum cephalosporins | +/-       | OXA-11, OXA-15 |
|                        | 2df               | Carbapenems         | +/-       | OXA-23, OXA-48 |

**IMPACT STATEMENT**

The World Health Organization (WHO) has published a global priority pathogens list of antibiotic-resistant bacteria, in order to increase the significance of and galvanize research into new treatments for particular antibiotic-resistant pathogens. Of critical importance on this list are carbapenem-resistant \textit{Acinetobacter baumanii}, \textit{Pseudomonas aeruginosa} and \textit{Enterobacteriaceae}. Pathogens of this nature cause high morbidity and mortality and increased healthcare costs. Carbapenem-resistant \textit{Enterobacteriaceae} encompasses a number of genera, many of which harbour acquired multidrug-resistance plasmids, which can carry and transmit antimicrobial-resistance genes on an intra- and interspecies level. This complicates surveillance, outbreak investigations and actions by infection control professionals. The spread of multidrug resistance is a globally important problem, with several countries currently reporting endemicity of highly resistant pathogens such as carbapenem-resistant \textit{Klebsiella pneumoniae}. We have reviewed the current literature on carbapenem and third-generation cephalosporin-resistant \textit{Enterobacteriaceae}. Our review highlights the continued increasing trend of resistance in \textit{Enterobacteriaceae} and discusses the mechanisms by which this occurs. We aim to provide valuable collated information as part of a series of reviews on the WHO priority pathogens and enhance the current understanding in this area.
antitoxin systems and stability mechanisms, all of which may have influenced plasmid and clade success [57, 59, 69]. Architecture of the ST131 accessory genome, including plasmids, further supports clade-specific adaptations that have likely contributed to the success of ST131 [70]. Multiple clusters of variable accessory genome content within clade C suggest that clonal expansions of stabilized accessory gene profiles occur frequently, allowing generalization of this highly structured clone [59, 70].

CPE

Rising ESBL-E prevalence correlates with increased carbapenem consumption [71, 72]; and appears to have driven the emergence and spread of carbapenem resistance, especially in Enterobacteriaceae [73]. Carbapenem resistance may be caused by different mechanisms, including inducible overexpression of chromosomal cephalosporinases, such as AmpC, combined with porin loss [74]. More problematic, however, is acquisition of carbapenemase genes via mobile genetic elements. The most frequently identified mechanism is the Ambler class A K. pneumoniae carbapenemase (KPC), followed by class B metallo-β-lactamases (MBLs) such as New Delhi MBL (NDM), and the class D OXA-type genes [75] (Table 2, Fig. 1).

Since its identification in the USA in 1996 [76], KPC has disseminated globally, has been reported to be present in more than 50 % of CPE in many countries, and in some cases 100 % of carbapenem-resistant K. pneumoniae [77–84]. The majority of KPC-encoding genes are seen in K. pneumoniae clonal group (CG)258, which includes the successful lineages ST258 and ST11 [85–87]. An example of this rapid dissemination can be seen in Greece. Following the first KPC isolation in 2007 [88], KPC had spread to most acute-care facilities within 2 years [89–92]. Most infections remain hospital-related, and associated with high mortality rates [6, 93–95]. Many early cases were epidemiologically linked to travel to high prevalence locations [96–101]; however, complex local transmission networks now signify endemicity [102, 103]. More than 20 KPC variants have been recognized, with blaKPC2 and blaKPC3 being the most abundant [79, 83, 85, 104–106]. The gene is located in isoforms of the 10 kb Tn4401 transposon [107], of the Tn3 transposon family [108, 109], and is associated with diverse plasmids including IncFIIK [87], IncI [110], IncN [111], IncL/M [112] and IncX [113].

Carbapenem-resistant lineages exhibit less diversity when compared to carbapenem-susceptible Enterobacteriaceae [114, 115] and lineages such as ST258 [112, 116, 117] and ST11 [84, 106] demonstrate clonal spread. However, in contrast to the clonality of ESBL lineages and predominance of a small number of globally disseminated epidemic lineages, carbapenemase genes and plasmids show increased transferability within and between species, lineages, STs and patients. This genetic mobility complicates the investigation of outbreaks [114, 118–120]. This has been observed more frequently in E. coli than other Enterobacteriaceae. The spread of carbapenem resistance displays increased diversity across STs, such as the large ST10 complex, rather than strong association with existing global epidemic lineages like ST131 [114, 121–123].

Non-clonal dissemination is also highly apparent in MBLs, especially NDM. These class B enzymes, which include NDM, GES, VIM and IMP, have also disseminated globally [124]. MBLs hydrolyse all β-lactams, are not inhibited by β-lactamase inhibitors, and their host bacteria often carry additional resistance mechanisms such as ESBLs [125–128]. First identified in a Swedish patient repatriated from a New Delhi hospital [129], most early cases had epidemiological links to the Indian subcontinent [130–133]. Epidemic spread and environmental contamination is evident in India, Pakistan and Bangladesh [144, 145], whilst sporadic cases or regional spread now occur on all continents [75, 84, 146, 147]. Clonal spread may occur during outbreaks [148, 149], but the high resolution of WGS enables tracking of varying blaNDM-positive plasmids including IncA/C, IncF, IncH, IncL/M, IncN and IncX types [113, 150–153], and fluctuating genomic contexts flanking the blaNDM gene among non-clonal isolates [128, 151, 154–156]. The blaNDM gene is chimeric following fusion with the aminoglycoside gene aphA6 and lies downstream of either entire, truncated or remnants of the ISAba125 element [157].

blaVIM genes were originally described in Italian Pseudomonas aeruginosa in the mid-1990s [158] and Enterobacteriaceae carrying blaVIM are predominantly reported in Europe as occurring sporadically or in single hospital outbreaks [147]. Sporadic cases are also seen in Africa, Taiwan, Mexico, Saudi Arabia and the USA [159]. Since 2015, Hungary, Italy and Spain have reported inter-regional spread; however, as with other CPE mechanisms, blaVIM is endemic in Greece [147]. More than 48 variants have been identified with blaVIM-1 and blaVIM-2 showing global dissemination [159]. blaVIM genes are carried on variable class 1 integrons within multiple plasmid Inc types [159–161].

blaIMP was the first described case of a transmissible carbapenemase gene [162]; however, large-scale epidemiological studies are lacking. The majority of blaIMP isolates originate in the South Pacific [163] and Asia [164]. blaIMP is found predominantly in K. pneumoniae, E. coli and Enterobacter spp. on class 1 integrons [165]. Integrons and their gene cassette combinations are variable and may show geographical correlations [164]. Despite being named due to imipenem resistance, certain variants of blaIMP, particularly blaIMP-6, actually exhibit low levels of imipenem resistance, which may lead to misidentification, and contribute to the lower detection rates of this mechanism [166, 167]. Genomic evidence is now emerging of this mechanism moving into epidemic Enterobacteriaceae such as E. coli ST131 [168, 169].

Finally, OXA-48 carbapenemases, first identified in 2001 in Turkey, are also a public-health threat [170–172]. Owing to their variable levels of carbapenem resistance, the spread of
Table 2. Carbapenem-resistance genes identified in Enterobacteriaceae

| Gene          | Species of origin† | Geographical origin† (year) | Active site | Ambler class | Location | Plasmid | No. of variants | Case                                                                 |
|---------------|--------------------|-----------------------------|-------------|--------------|----------|---------|----------------|----------------------------------------------------------------------|
| *bla* SME-1   | Serratia marcescens enzyme | London, UK (1982)          | Serine      | A            | Chromosomally encoded, SmarGI1 novel genomic island [250] | IncF types [251, 252] | 5       | Mataje et al. [250] – characterization of a novel genomic island     |
| *bla* IMI      | Enterobacter cloacae | California, USA (1984)     | Serine      | A            | Chromosomally encoded in Enterobacter cloacae, IncF plasmid in Klebsiella variicola [251] and Escherichia coli [252] | Multiple [107, 254] | 12      | Rasmussen et al. [253] – characterization of first clinical IMI isolate |
| *bla* KPC     | Klebsiella pneumoniae | North Carolina, USA (1996) | Serine      | A            | Tn401 [107] | Multiple [107, 254] | 24       | Munoz-price et al. [105] – description of an ongoing UK outbreak      |
| *bla* OXA-48   | Klebsiella pneumoniae | Istanbul, Turkey (2001)    | Serine      | D            | Tn999 [185] | IncI/M [185] | OXA-181, OXA-204, OXA-232, OXA-163 | Potron et al. [175] – description of a clonal multi-country outbreak   |
| *bla* IMP     | Serratia marcescens enzyme | Aichi Prefecture, Japan (1991) | Zinc        | B            | Variable – chromosomal, class I integron [255] | IncA/C, IncH, IncL/M [255] | >52      | Peleg et al. [256] – multi-genera dissemination of *bla* IMP in Australia |
| *bla* NDM     | Klebsiella pneumoniae | New Delhi, India (2008)    | Zinc        | B            | Tn125 [151] | Multiple [126, 151, 153] | 16       | Walsh et al. [145] – environmental spread of *bla* NDM              |
| *bla* VIM     | Pseudomonas aeruginosa | Verona, Italy (1997)       | Zinc        | B            | Class I integrons, In2-Tn402 [257] | IncHI2, IncHl [257], IncN [238] | >46      | Luzzaro et al. [259] – *bla* VIM in multiple genera from one patient |
| *bla* GM     | Pseudomonas aeruginosa | North Rhine-Westphalia, Germany (2004) | Zinc        | B            | Not determined | Not determined | Not determined | Rieber et al. [260] – emergence of *bla* GM in clinical samples       |
| *bla* KHIM   | Citrobacter freundii | Tokyo, Japan (1997)        | Zinc        | B            | Not determined | Not determined | Not determined | Sekiguchi et al. [261] – first identification of *bla* KHIM            |

*First species known to be reported in.
†First location reported in the literature.
*OXA-48* has been initially underestimated [173–175]. In parallel to *blaNDM* and its Indian origins, *blaOXA-48* was initially geographically linked to Turkey [171, 176]. However, since 2015, multiple countries have inter-regional spread and *blaOXA-48* is endemic in Malta and Turkey [147]. Further afield, extensively drug resistant (XDR) strains co-harbouring *blaNDM* and *blaOXA-48* have been identified in the Middle East [177, 178], and *blaOXA-48* strains have emerged in Canada [173], Algeria [179] and Korea [180]. *Shewanella* spp. may be the natural progenitors of *blaOXA-48* genes [181], which now predominantly appear in *K. pneumoniae*, *E. coli* and *Enterobacter* spp. [173, 182, 183]. *blaOXA-48* is associated with the Tn1999 transposon, which is composed of two copies of IS1999 bracketing the gene [184, 185]. The majority of *blaOXA-48* genes are associated with Tn1999 or the variants Tn1999.2 [171], Tn1999.3 [186] and Tn1999.4 [187]. Tn1999.4 is a mosaic of Tn1999 and a second transposon, Tn2015, which additionally carries *blaCTX-M-15* [187]. In contrast to other CPE genes, dissemination of *blaOXA-48* is associated with a single, successful IncL/M plasmid into which the Tn1999 transposon has inserted [173, 174, 178, 185, 187–193].

A variant of *blaOXA-48*, *blaOXA-181*, has also begun to disseminate among *Enterobacteriaceae* and appears to be establishing in the Indian subcontinent, South Africa and Singapore, or in patients epidemiologically linked to these areas [194–199]. Recently, the first cases of likely patient-to-patient transmission have also been reported [200, 201]. *blaOXA-181* has been identified on a non-self-conjugative ColE2 plasmid in association with IS*Ecp1* and the Tn2013 transposon [198]. Additionally, *blaOXA-181* has been identified in the same strains as *blaNDM* genes, reflecting its prevalence in India [201, 202], and now in a conjugative plasmid [202], suggesting widespread dissemination may occur in the future.

**THE CONTINUED THREAT OF AMR**

The impact of antibiotic consumption is reflected in geographical variations of CPE and ESBL-E prevalence. Countries with high antibiotic consumption rates, such as
Turkey, Tunisia, Algeria, Greece and Romania [71], have particularly high rates of multidrug-resistant (MDR) bacteria [11, 147]. Overuse of particular antibiotic classes also affects MDR organisms, such as in Greece where high cephalosporin use [203] is paralleled by high levels of ESBL-E [11]. Travel to endemic regions also may be having a global impact following acquisition of MDR pathogens by travellers [204–208].

A particularly concerning issue, especially in Asia, is transferrable colistin resistance [209]. Increased carbapenem resistance has resulted in an increase in the use of polymyxins (e.g. colistin) to treat XDR pathogens [71, 210]. We are now faced with the dissemination of genes conferring resistance to these drugs, which are frequently co-located with additional resistance genes, leaving some infections almost untreatable [211–214]. Following the first publication of the transferrable colistin-resistance gene, mcr-1 [209], screening has demonstrated global existence of mcr-1 in food, animal and human samples [215, 216]. Following the association of mcr-1 with ISApl-1 of the IS30 family and formation of the composite transposon Tn6330, mcr-1 and its genetic environment has stabilized [217–219]. It is now beginning to spread across multiple plasmid types [214, 220–224]. The ancestral mobilizable state of mcr-1 is more frequently identified in agricultural isolates than human isolates, particularly those in China, supporting the theory of an animal origin [209, 225–227]. Colistin is ubiquitous in food-animal production [228], but its use as a growth promoter has been banned in the European Union since 2006 and in China since 2016 [229, 230]. This may begin to ease the antibiotic selection pressure; however, it is difficult to speculate how this may affect the human situation as stabilization and dissemination of the gene into conjugative plasmids has already occurred.

**CONCLUSION**

Antimicrobial stewardship as a strategy to reduce AMR is high on policy agendas in many countries [231–235] and a positive impact on the prevalence of MDR pathogens is beginning to show [236, 237]. Continued strategy development is still required; accepted international definitions and guidelines are yet to be adopted, particularly those suitable for low-to-middle income countries [238]. With the inception of the ‘One Health’ initiative [233, 239, 240], consideration should also be given to antimicrobial prescription in primary care [30, 210, 241, 242], poorly regulated community antimicrobial use [243–246] and agricultural antimicrobial use [239, 247–249].

The ability of CPE and ESBL-E to evolve and adapt rapidly due to antibiotic selective pressures is one of the biggest threats to medical care. An international, multi-disciplinary approach is urgently required to tackle this global threat. Pressing issues include improving surveillance to recognize the importance of mobile AMR elements and increasing the drive to move rapid, high-resolution diagnostics, such as WGS, from the research environment into routine clinical practice. A proactive approach involving all users of antimicrobials is imperative to prevent a return to the pre-antibiotic era.

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**Conflicts of interest**

The authors declare that there are no conflicts of interest.

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