



Review Article

Laboratory Detection of Carbapenemase-Producing Enterobacterales: Phenotypic and Molecular Approaches - A Narrative Review

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Abstract

Background: Carbapenem-resistant Enterobacterales (CRE) are a critical-priority pathogen group on the World Health Organization's 2024 list. Most clinically significant carbapenem resistance in Enterobacterales is mediated by acquired carbapenemases, chiefly KPC, NDM, VIM, IMP and OXA-48-like enzymes. Accurate and timely laboratory detection of these enzymes directly shapes antimicrobial therapy, infection prevention and surveillance.

Aim: To review the phenotypic, immunochromatographic, molecular and mass-spectrometric methods available to clinical laboratories for detecting carbapenemase-producing Enterobacterales (CPE), and to propose a practical, tiered testing algorithm.

Review Results: The CLSI-endorsed modified carbapenem inactivation method (mCIM) offers sensitivity of about 97–99% and specificity of 99–100% at a reagent cost near one US dollar, but needs an overnight incubation. When paired with the EDTA-modified method (eCIM), it also separates metallo- β -lactamases from serine carbapenemases. Colorimetric tests such as Carba NP give results within about 2 hours but miss a proportion of OXA-48-like producers. Multiplex lateral flow immunoassays identify the five major enzyme families in about 15 minutes with reported sensitivity and specificity above 95%. Real-time PCR platforms such as Xpert Carba-R deliver gene-level results within about an hour but detect only targeted genes.

Conclusion: No single method is sufficient for every laboratory. A tiered approach that screens with a low-cost phenotypic test, classifies the enzyme with an immunochromatographic or molecular assay, and refers discordant isolates for sequencing gives the best balance of accuracy, speed and cost.

Keywords: Carbapenemase; Carbapenem-resistant Enterobacterales; Modified carbapenem inactivation method; Lateral flow immunoassay; Molecular diagnostics; Antimicrobial resistance.

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Introduction

Antimicrobial resistance (AMR) is one of the defining public health threats of this century. The Global Research on Antimicrobial Resistance

project estimated that bacterial AMR was directly responsible for 1.14 million deaths and associated with 4.71 million deaths in 2021. Among Gram-negative bacteria, resistance to carbapenems rose

faster than resistance to any other antibiotic class between 1990 and 2021. Without further intervention, the same analysis forecasts 39.1 million deaths attributable to AMR between 2025 and 2050^[1].

Carbapenems have long served as agents of last resort for serious infections caused by multidrug-resistant Enterobacterales. Their loss of activity therefore leaves clinicians with few, often more toxic or more expensive, alternatives. Reflecting this, the World Health Organization's Bacterial Priority Pathogens List 2024 retained carbapenem-resistant Enterobacterales in its critical-priority category, alongside carbapenem-resistant *Acinetobacter baumannii* and third-generation cephalosporin-resistant Enterobacterales^[2].

Carbapenem resistance in Enterobacterales arises through two broad routes. The first is production of a carbapenemase, a β -lactamase able to hydrolyse carbapenems. The second is the combination of an extended-spectrum β -lactamase (ESBL) or AmpC enzyme with reduced outer-membrane permeability caused by porin loss^[3]. The distinction matters clinically and epidemiologically. Carbapenemase genes are usually carried on mobile plasmids that spread readily between strains and species, driving hospital outbreaks and international dissemination^[4]. The choice of newer agents also depends on enzyme class: ceftazidime-avibactam, meropenem-vaborbactam and imipenem-relebactam are active against many serine carbapenemases, whereas metallo- β -lactamase (MBL) producers generally need other options, such as ceftazidime-avibactam combined with aztreonam, or cefiderocol^[5].

The clinical microbiology laboratory is therefore asked not only whether an isolate is carbapenem-resistant, but whether it produces a carbapenemase and, ideally, which one. Susceptibility results alone cannot answer these questions, because carbapenemase producers can show minimum inhibitory concentrations (MICs) within the susceptible range, particularly OXA-48-like producers^[6]. This review summarises the main

methods available for detecting carbapenemase-producing Enterobacterales (CPE), compares their performance, cost and turnaround, and proposes a practical testing algorithm for laboratories of differing resources.

Methodology

This narrative review was based on a literature search of PubMed/MEDLINE, Scopus and Google Scholar for articles published in English between January 2007 and [month year of final search]. Search terms combined "carbapenemase", "carbapenem-resistant Enterobacterales" and "carbapenemase-producing Enterobacteriaceae" with "detection", "mCIM", "eCIM", "Carba NP", "lateral flow", "immunochromatographic", "PCR", "Xpert Carba-R", "MALDI-TOF" and "whole-genome sequencing".

Priority was given to multicentre diagnostic evaluations, studies using molecular or sequencing results as the reference standard, systematic reviews, and guidance documents from the Clinical and Laboratory Standards Institute (CLSI), the World Health Organization (WHO) and the Infectious Diseases Society of America (IDSA). Reference lists of key articles were screened for further relevant studies. Because this is a narrative rather than a systematic review, no formal quality scoring or meta-analysis was performed; performance figures are reported as given in the cited studies.

Carbapenemase Classes and Epidemiology

Carbapenemases belong to three of the four Ambler molecular classes (Table 1) [3]. Classes A and D are serine enzymes, whereas class B enzymes are metallo- β -lactamases that need zinc at the active site and are therefore inhibited by chelators such as ethylenediaminetetraacetic acid (EDTA). This biochemical difference is the basis of several phenotypic differentiation tests.

Table 1. Main acquired carbapenemases in Enterobacterales

Ambler class	Active site	Main enzymes	Inhibited by	Typical hydrolytic profile	Treatment relevance
A	Serine	KPC, GES (some variants), IMI, SME	Avibactam, vaborbactam, relebactam; boronic acid	Penicillins, cephalosporins, aztreonam, carbapenems	Usually susceptible to ceftazidime-avibactam and meropenem-vaborbactam
B (MBL)	Zinc	NDM, VIM, IMP	EDTA, dipicolinic acid; not by avibactam	All β -lactams except aztreonam	Ceftazidime-avibactam plus aztreonam, or cefiderocol
D	Serine	OXA-48, OXA-181, OXA-232, OXA-244	Avibactam; poorly by clavulanate	Penicillins and carbapenems (weakly); spares extended-spectrum cephalosporins	Usually susceptible to ceftazidime-avibactam

MBL, metallo- β -lactamase; EDTA, ethylenediaminetetraacetic acid. Adapted from references [3,5,8].

KPC-producing *Klebsiella pneumoniae*, especially clonal group 258, became endemic in the United States, Greece, Italy and Israel, while NDM producers spread widely across South Asia and the Balkans^[4,7]. OXA-48-like enzymes, first described in Turkey, are now prominent in the Middle East, North Africa and much of Europe^[8]. OXA-48 is a particular diagnostic challenge because it hydrolyses carbapenems only weakly and does not attack extended-spectrum cephalosporins. Producers can therefore appear only marginally resistant, or even susceptible, to carbapenems unless an ESBL or permeability defect is also present^[8].

Regional epidemiology should guide test selection. In a multicountry study of hospitals in the six Gulf Cooperation Council states, 45 of 62 screened isolates produced a carbapenemase. OXA-48-type enzymes were found in 35 isolates and NDM-type enzymes in 16, with 6 co-producing both; no KPC, VIM or IMP producers were detected^[9]. In such settings, a method's performance against OXA-48-like and NDM enzymes, and its ability to detect co-production, matters more than its performance against KPC.

Phenotypic Detection Methods

Screening by susceptibility testing

Detection begins with routine antimicrobial susceptibility testing. CLSI recommends carbapenemase testing for Enterobacterales that are

non-susceptible to one or more carbapenems, when needed for infection prevention, epidemiology or therapy^[10]. Because OXA-48-like producers may have low carbapenem MICs, many laboratories also use reduced meropenem susceptibility combined with high-level temocillin resistance as a screening flag. The modified Hodge test, once widely used, was removed from CLSI recommendations because of poor specificity and failure to detect many NDM producers^[6,11].

Carbapenem inactivation methods (CIM, mCIM, eCIM)

The carbapenem inactivation method was introduced in 2015 as a simple, low-cost test of carbapenem hydrolysis^[12]. In the CLSI-modified version (mCIM), a 1- μ L loopful of the test isolate is suspended in 2 mL of tryptic soy broth with a 10- μ g meropenem disk and incubated for 4 hours at 35 °C. The disk is then placed on Mueller–Hinton agar freshly inoculated with a carbapenem-susceptible *Escherichia coli* indicator strain (ATCC 25922) and incubated for 18–24 hours^[10,13]. If the isolate produces a carbapenemase, the meropenem is hydrolysed and the indicator grows up to the disk. A zone of 6–15 mm, or pinpoint colonies within a 16–18 mm zone, is read as positive; a zone of 19 mm or more is negative; and 16–18 mm is indeterminate^[10].

In its multicentre validation, the mCIM showed 99% sensitivity and 100% specificity, and was simple to perform and reproducible across

laboratories^[13]. Its main limitations are an overall turnaround of about 24 hours, possible false negatives with weakly hydrolysing enzymes, and sensitivity to broth and disk quality. A three-site study in India found accuracy ranging from 84% with the standard CLSI method to 99% with a modified broth method, underlining the need for local validation^[14].

The EDTA-modified carbapenem inactivation method (eCIM) is run in parallel by adding EDTA to a second broth tube. EDTA chelates zinc and inhibits MBLs, so an increase in zone diameter of 5 mm or more relative to the mCIM indicates a metallo- β -lactamase [10,15]. In the original evaluation, eCIM had 100% sensitivity and specificity, and it was subsequently adopted by CLSI for use with the mCIM^[15]. The eCIM is interpreted only when the mCIM is positive, and isolates co-producing a serine carbapenemase and an MBL may be misclassified.

The mCIM also performs well for *Pseudomonas aeruginosa*, with a mean sensitivity of 98.0% and specificity of 95% across ten sites, but its performance in *Acinetobacter baumannii* was poor (79.8% sensitivity and 52.9% specificity), so it is not recommended for that organism^[16].

Colorimetric hydrolysis tests (Carba NP and variants)

The Carba NP test detects imipenem hydrolysis through acidification of the medium, shown by a phenol red indicator turning from red to yellow or orange. Results are available within about 2 hours^[17]. Commercial versions such as RAPIDEC CARBA NP and related tests (for example, Blue-Carba and β -CARBA) follow the same principle. Their major weakness is reduced sensitivity for enzymes with weak carbapenemase activity. In one evaluation of 244 isolates, false negatives were concentrated among OXA-48-like producers, GES-5 producers and mucoid strains^[18]. These tests also need fresh reagents and careful reading of intermediate colour changes^[11].

Inhibitor-based combination disk tests

Combination disk tests compare zones around a carbapenem disk with and without specific

inhibitors: boronic acid for class A enzymes, EDTA or dipicolinic acid for MBLs, and temocillin resistance as a marker of OXA-48. They are inexpensive and give a provisional class, but they are less standardised, take 18–24 hours and can be confounded by AmpC hyperproduction or enzyme co-production^[11,19].

Immunochromatographic, Molecular and Mass-Spectrometric Methods

Lateral flow immunoassays

Lateral flow immunoassays (LFIA) detect carbapenemase proteins with labelled monoclonal antibodies on a nitrocellulose strip. A few colonies are lysed in buffer, applied to the cassette, and read visually after about 15 minutes. The multiplex NG-Test CARBA 5 identifies and distinguishes the KPC, OXA-48-like, NDM, VIM and IMP families in one test^[20]. Unlike hydrolysis-based tests, LFIA identify the enzyme family, which supports immediate choice of a β -lactam/ β -lactamase inhibitor combination.

Performance has been consistently high. In a multicentre US evaluation of 309 Enterobacterales and *P. aeruginosa* isolates compared with a composite reference that included Xpert Carba-R, mCIM and eCIM, the positive and negative percent agreements were both 100% for colonies grown on blood and MacConkey agars^[21]. A European evaluation reported similar accuracy across all five targets^[22]. Growth medium can matter, however. In one study, sensitivity fell from 98.3% on sheep blood agar to 83.6–88.3% on chromogenic and MacConkey media, while specificity remained 100%^[23]. LFIA detect only the enzymes on the strip, so rarer carbapenemases such as IMI, GES and SME are missed, and novel variants with altered epitopes may also go undetected.

Nucleic acid amplification tests

Polymerase chain reaction (PCR) remains the reference for identifying carbapenemase genes. In-house multiplex PCR is inexpensive per test but needs skilled staff, validated primers and separate pre- and post-amplification areas. Commercial cartridge-based real-time PCR assays have made

molecular testing practical in routine laboratories. The Xpert Carba-R assay detects *bla*KPC, *bla*NDM, *bla*VIM, *bla*IMP and *bla*OXA-48-like genes in about 50 minutes with minimal hands-on time. A multicentre evaluation against bidirectional sequencing confirmed its accuracy on isolates grown on blood or MacConkey agar [24]. Syndromic panels on blood-culture and respiratory platforms now include the same gene targets, allowing detection directly from positive cultures or clinical specimens.

Molecular tests have three important limitations. They detect genes, not enzyme activity, so a positive result does not prove expression. They miss carbapenemases outside their target list and may miss divergent variants of targeted genes. And their reagent and instrument costs are substantially higher than those of phenotypic tests^[6,11].

MALDI-TOF mass spectrometry

Matrix-assisted laser desorption/ionisation time-of-flight mass spectrometry (MALDI-TOF MS), already used for bacterial identification in many laboratories, can detect carbapenemase activity by measuring the disappearance of the intact carbapenem mass peak and the appearance of its

hydrolysis products after incubation with the isolate^[25]. Results can be obtained within about 1–2 hours. The approach makes good use of existing equipment, but it needs standardised protocols and software interpretation, and sensitivity is lower for weak hydrolysers such as OXA-48-like enzymes unless incubation is extended^[19].

Whole-genome sequencing

Whole-genome sequencing (WGS) characterises the full resistome, including rare or novel carbapenemases, co-production, plasmid context and clonal relatedness. It is the method of choice for outbreak investigation and national surveillance. However, cost, turnaround, bioinformatic expertise and the need for curated resistance databases currently limit its use as a routine first-line test^[26].

Comparative Evaluation and Proposed Laboratory Algorithm

The methods differ less in accuracy for common enzymes than in speed, cost, the information they return and the enzymes they miss (Table 2). Choice should therefore be driven by local epidemiology, laboratory resources and the clinical question.

Table 2. Comparison of methods for detecting carbapenemase-producing Enterobacterales

Method	Principle	Time to result	Identifies class or family	Reported performance	Relative cost	Main limitations
mCIM	Meropenem inactivation, disk diffusion	~24 h	No	Sensitivity 99%, specificity 100% [13]	Very low	Slow; broth and disk quality affect results
mCIM + eCIM	EDTA inhibition of MBLs	~24 h	Serine vs MBL	eCIM sensitivity and specificity 100% [15]	Very low	Co-producers may be misclassified
Carba NP and variants	Imipenem hydrolysis, pH indicator	~2 h	No (variants: partly)	Lower for OXA-48-like and mucoid strains [18]	Low	Reagent stability; subjective reading
Combination disk tests	Inhibitor-enhanced zones	18–24 h	Provisional class	Variable [19]	Low	Not standardised; AmpC interference
Lateral flow immunoassay	Antibody detection of enzyme protein	~15 min	Five main families	Agreement 100% on blood and MacConkey agar [21]	Moderate	Medium-dependent; misses non-target enzymes
Real-time PCR (e.g.,	Gene amplification	~1 h	Five main gene families	High agreement with	High	Genes not expression;

Method	Principle	Time to result	Identifies class or family	Reported performance	Relative cost	Main limitations
Xpert Carba-R)				sequencing [24]		misses non-targets
MALDI-TOF MS hydrolysis	Mass shift of hydrolysed carbapenem	1–2 h	No	Lower for weak hydrolysers [19,25]	Low if instrument available	Needs standardised protocol
Whole-genome sequencing	Full resistome	2–5 days	All genes and variants	Reference for novel enzymes [26]	Very high	Cost, expertise, turnaround

mCIM, modified carbapenem inactivation method; *eCIM*, EDTA-modified carbapenem inactivation method; *MBL*, metallo- β -lactamase. Time to result is from a pure overnight culture.

We propose a three-tier algorithm (Figure 1). Tier 1 screens Enterobacterales flagged by carbapenem non-susceptibility, or by a low-level meropenem MIC with temocillin resistance, using mCIM with eCIM. Laboratories that need faster results can substitute a lateral flow immunoassay or a rapid colorimetric test. Tier 2 identifies the enzyme family in positive isolates with a lateral flow

immunoassay or PCR, so that results reach clinicians the same day. Tier 3 refers isolates with discordant results, such as a positive mCIM with negative lateral flow and PCR, to a reference laboratory for WGS. A positive result at any tier should trigger immediate notification of the clinical team and infection prevention staff.

Figure 1. Screen cheaply, identify the enzyme, sequence only discordant isolates

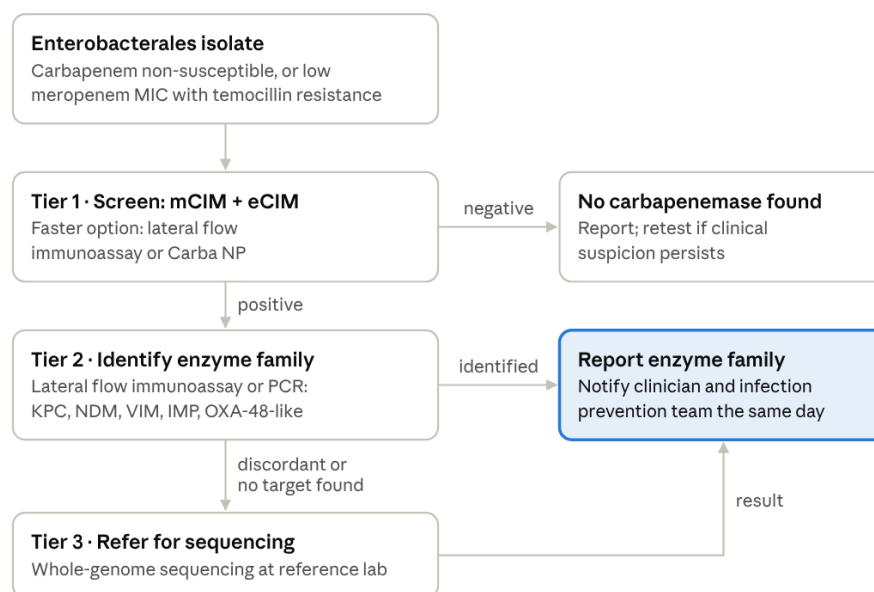


Figure 1 · proposed three-tier testing algorithm for carbapenemase-producing Enterobacterales

Figure 1 Proposed three-tier laboratory algorithm. Most isolates are resolved at Tier 1 or Tier 2; only discordant or untyped isolates need sequencing.

Challenges and Future Directions

Co-production and enzyme diversity. Isolates producing two carbapenemases, most often NDM

with OXA-48-like enzymes, are increasingly reported^[9]. Single-result phenotypic tests cannot reveal co-production, and eCIM may classify such isolates as serine producers. Multiplex LFIA or PCR is needed to detect both enzymes, which has direct treatment consequences because an MBL

partner removes the activity of avibactam-based combinations^[5,27].

Weak hydrolysers and low MICs. OXA-48-like producers with low carbapenem MICs may escape screening altogether^[8]. Laboratories in regions where these enzymes are common should consider screening criteria that do not rely solely on clinical breakpoints, such as epidemiological cut-off values and temocillin testing.

Speed from specimen to result. Most methods described here begin with an overnight culture. Testing directly from positive blood-culture broths, rectal screening swabs and other specimens can save 18–24 hours, and several molecular panels already do this. Wider validation of rapid phenotypic and immunochromatographic methods on direct specimens is a priority.

Resource-limited settings. The burden of CRE is greatest where laboratory capacity is weakest^[1]. The mCIM/eCIM pair is a realistic standard for such settings because it needs no special equipment, but it depends on quality-controlled media and meropenem disks^[14]. External quality assessment schemes and regional reference laboratories are essential to sustain accuracy.

Beyond detection. Identifying a carbapenemase does not replace susceptibility testing to newer agents such as ceftazidime-avibactam, meropenem-vaborbactam, imipenem-relebactam, aztreonam-avibactam and cefiderocol. Laboratories should be able to report these results, or refer isolates promptly, so that enzyme detection translates into effective therapy^[5,27]. Routine genomic surveillance, falling sequencing costs and improved resistance databases are likely to make WGS a more practical tool for reference laboratories in the coming years^[26].

Conclusion

Detecting carbapenemase-producing Enterobacterales is now a core task of the clinical microbiology laboratory, with direct consequences for treatment, infection prevention and public health. The mCIM/eCIM combination provides an accurate, inexpensive and widely accessible

foundation. Lateral flow immunoassays and real-time PCR add speed and enzyme-level identification, and whole-genome sequencing resolves discordant and novel cases. No single test is ideal. Laboratories should adopt a tiered strategy matched to their local enzyme epidemiology and resources, validate methods locally, participate in external quality assessment, and ensure that results reach clinicians and infection prevention teams without delay.

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