Effect of Colistin, Fosfomycin and Meropenem/Vaborbactam on Carbapenem-Resistant *Enterobacterales* in Egypt: A Cross-Sectional Study

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**Purpose:** The increasing multi-drug carbapenem resistance among *Enterobacterales* are a severe health problem limiting therapeutic options and worsen the prognosis. This study characterizes carbapenemase genes and integrons among uropathogenic carbapenem resistant *Enterobacterales* (CRE) isolates recovered from Mansoura University Hospitals and evaluates the effect of colistin, fosfomycin and meropenem-vaborbactam on these isolates.

**Patients and Methods:** A total of 200 *Enterobacterales* isolates were collected from patients with urinary tract infections. Antimicrobial susceptibility testing was performed by the disc diffusion method. Colistin susceptibility was tested using the broth microdilution method and fosfomycin and meropenem/vaborbactam susceptibility were tested by MIC Test Strips. Carbapenem resistant isolates were screened for carbapenemase activity phenotypically using the modified carbapenem inactivation method and EDTA-modified carbapenem inactivation method and genotypically by multiplex PCR. Integrons class 1 and 2 and *fosA* gene were assayed by PCR. Data were statistically analyzed using the Statistical Package for Social Sciences (SPSS) version 16. The Chi-square or Fisher’s exact test was used to compare groups, as appropriate.

**Results:** Ninety-two *Enterobacterales* isolates were resistant to meropenem (46%); 52 *E. coli* and 40 *K. pneumoniae* strains. All CRE isolates were multi-drug resistant (MDR). Sensitivity of CRE isolates to colistin, fosfomycin and meropenem-vaborbactam were 67.4%, 82.6% and 58.7%, respectively. Carbapenemase genes were detected by multiplex PCR in 69.6% of CRE isolates (*Carbapenemase producing Enterobacterales* (CPE) mainly *blaNDM* (37%)). CPE isolates were significantly more resistant to meropenem/vaborbactam than non-CPE isolates; 51.6% vs 17.8%, respectively (P = 0.003) especially *blaNDM* carrying isolates (70.6%). Class 1 integrons and *fosA* gene were detected in 91.3% and 11.9% of CRE isolates, respectively.

**Conclusion:** This study revealed that about half of the uropathogenic *Enterobacterales* isolates were MDR CRE. Carbapenemase gene *blaNDM* was the main gene among CRE isolates. Meropenem/vaborbactam sensitivity was significantly higher on non-CPE than CPE isolates and limited by the predominance of *blaNDM*.

**Keywords:** *Enterobacterales*, carbapenemases, carbapenem-resistant *Enterobacterales*, colistin, fosfomycin, meropenem-vaborbactam

**Introduction**

The increasing Carbapenem-resistant *Enterobacterales* (CRE) isolates are a severe threat worldwide due to the poor prognosis and limited therapeutic options.¹⁻³ The production of carbapenemases such as *Klebsiella pneumoniae* carbapenemase (KPC), Metallo- β-lactamases (MBLs) and oxacillinases (OXA) enzymes mainly cause carbapenem resistance. Moreover, the deficiency in the outer-membrane protein expression plays a minor role in carbapenem resistance.⁴

Integrons are mobile genetic elements that mediate the intracellular movement of antibiotic resistance genes. Class 1 integrons facilitate the spread of antibiotic resistance genes in *Enterobacterales*, reducing the spectrum of therapeutic options.⁵
CRE strains are usually resistant to many antibiotics, increasing the need for reusing old antibiotics such as colistin and fosfomycin and new drug combinations for treatment. These combinations use the old β-lactam drug with a new β-lactamase inhibitor effective on carbapenemases such as meropenem-vaborbactam (M/V) and ceftazidime-avibactam (C/A).

Colistin (polymyxin E) is an old antibiotic effective on most Enterobacterales species. It binds to the lipid A, disrupting the outer cell membrane and causing leakage of cytoplasmic contents and bacterial death. Colistin has been used as the last line of treatment for infections caused by CRE, yet the resistance limits its use. Loading doses colistin and colistin methanesulfonate, an inactive prodrug of colistin, are associated with favorable outcomes in infections caused by Gram-negative pathogens only when carbapenems cannot be used and with a close monitoring of the renal functions. The combining of the loading dose colistin and meropenem is associated with a better survival rate and can be a promising therapeutic strategy for treating carbapenems resistant infections.

Fosfomycin is a broad-spectrum bactericidal antibiotic that interferes with synthesizing Gram-negative and some Gram-positive bacterial cell walls. It is the first line of treatment for uncomplicated urinary tract infections (UTIs). Fosfomycin resistance is caused by many enzymes that inactivate fosfomycin, including metalloenzymes (fosA type); however, there is limited data about fosfomycin resistance in Africa, including Egypt.

A drug combination formed of meropenem paired with vaborbactam, a boronic acid β-lactamase inhibitor with a broad spectrum of carbapenemases inhibition, has been used to treat all types of CRE infections caused mainly by KPC-producing strains. Compared to the older drug combinations, this combination is a highly effective and safe therapy for severe infections in critically ill patients.

The objective of this study was to characterize the carbapenemase genes, and integrons among the uropathogenic CRE isolates recovered from Mansoura University Hospitals (MUHs) and to evaluate the effect of colistin, fosfomycin and meropenem-vaborbactam on CRE isolates. To our knowledge, this is the first study evaluating the effectiveness of meropenem-vaborbactam on uropathogenic CRE isolates in Egypt.

Materials and Methods
This cross-sectional study assessed the efficacy of colistin, fosfomycin and meropenem-vaborbactam on the uropathogenic CRE isolates recovered from MUHs.

Bacterial Isolates
Two hundred Enterobacterales strains were isolated from the urine of patients with UTIs attending MUHs from September 2021 to March 2022. Each patient underwent a clinical examination after taking a medical history to diagnose the UTI.

Isolation and Identification of the Enterobacterales Isolates
The urine samples were collected from adult patients with UTIs under complete aseptic conditions and cultured on cystine lactose electrolyte deficient agar (CLED) (Oxoid Ltd., England) to detect different Enterobacterales species.

Urinary tract infection was diagnosed if the patient suffered from symptoms and signs of UTI; fever (>38.0°C), suprapubic tenderness, costovertebral angle pain or tenderness, urinary urgency, urinary frequency or dysuria and confirmed when the bacterial colony count was ≥10^5 CFU/mL.

The isolates were identified by Gram staining and the standard biochemical tests; methyl red test, Voges-Proskauer test, citrate utilization test, oxidase test, Kligler iron agar, lysine iron agar and motility indole ornithine test. The isolates identification was confirmed by API 20E (BioMérieux, Marcy l’Étoile, France).

Detection of CRE
Carbapenem-resistant Enterobacterales (CRE) isolates are defined as any isolate that has imipenem/or meropenem MIC values of ≥ 4 μg/mL. All Enterobacterales isolates (No = 200) were tested for meropenem susceptibility by the disc diffusion and broth microdilution methods according to the Clinical Laboratory Standards Institute (CLSI) guidelines M100 and M07, respectively. Interpretative criteria for meropenem were susceptible ≤1 mg/l, intermediate 2 mg/l and resistant ≥4 mg/l.
Antimicrobial Susceptibility Testing

Antimicrobial susceptibility testing of CRE isolates was performed by the disc diffusion method for several antibiotics, including aztreonam (30 μg), amikacin (30 μg), cefuroxime (30 μg), cefazidime (30 μg), cefotixin (30 μg), piperacillin/tazobactam (100/10 μg), ciprofloxacin (5 μg), nitrofurantoin (300 μg) and trimethoprim/sulfamethoxazole (1.25/23.7 μg).

Colistin susceptibility testing was carried out using the broth microdilution method with cation-adjusted Mueller Hinton broth (Oxoid) as a culture medium and colistin sulfate powder (Acros Organics BVBA, Geel, Belgium). The test was interpreted using EUCAST cut-offs as MIC ≤ 2 μg/mL susceptible and >2 μg/mL resistant.

Fosfomycin susceptibility was tested using the disc diffusion method with fosfomycin 200 μg disc containing glucose-6-phosphate (G6P) (Liofilchem, Roseto Degli Abruzzi, Italy) on Mueller Hinton agar and interpreted using CLSI guidelines, where ≥16 mm was sensitive, 13–15 mm intermediate and ≤12 mm resistant. In addition, fosfomycin sensitivity was carried out using Fosfomycin MIC Test Strip (Liofilchem) containing fosfomycin and G6P and interpreted according to breakpoints set by the CLSI; ≤64 μg/mL as susceptible and ≥256 μg/mL as resistant for E. coli.

Meropenem/vaborbactam susceptibility was tested by the disc diffusion method using meropenem/vaborbactam disc (20μg-10μg) (MAST Laboratories Ltd., Bootle, Merseyside, UK) and the MIC Test Strip (MTS™ Meropenem-vaborbactam, Liofilchem). The susceptibility was interpreted using CLSI guidelines for Enterobacterales as susceptible ≥18 mm, intermediate 15–17 mm and resistant ≤14 mm using the disc diffusion method and susceptible ≤4/8 mg/L, intermediate 8/8 mg/l and resistant ≥16/8 mg/l for the MIC Test Strip method.

Quality control testing was performed using Escherichia coli ATCC 25922 and NCTC 13353 and Klebsiella pneumoniae ATCC 700603 and ATCC BAA-1705 as reference strains to ensure the proper test conditions.

Phenotypic and Genotypic Detection of Carbapenemase Producing Enterobacterales

Phenotypic detection of carbapenemase producers was performed by the modified carbapenem inactivation method (mCIM) and EDTA-modified carbapenem inactivation method (eCIM) according to CLSI guidelines to distinguish metallo-carbapenemase from serine-carbapenemase.

DNA was extracted from CRE isolates using the Gene JET genomic DNA purification kit (Thermo Fisher Scientific, Waltham, MA, USA) according to the manufacturer’s instructions. DNA was then stored at −20°C.

All CRE isolates were screened for carbapenemase genes; blaIMP, blavIM, blaOXA-48, blaNDM and blaKPC, as previously described. Carbenapenem genes were detected using two multiplex PCR reactions; one for blaIMP and blavIM and the second for detecting blaOXA-48, blaNDM and blaKPC. The thermal cycling steps involved initial denaturation of 10 min at 94°C and 36 cycles of 30s at 94°C, 40s at 52°C, and 50s at 72°C, with 5 min for the final extension. The gel electrophoresis using 2% agarose was used to detect blaIMP, blavIM, blaOXA-48, blaNDM and blaKPC amplicons; 232, 390, 438, 621 and 798 bp, respectively. Sequences of primers used to amplify the five carbapenemase genes are shown in Table 1.

Detection of Class 1 and 2 Integrons by Duplex PCR Among CRE Isolates

As previously reported, Integrons class 1 and 2 were detected using the genomic DNA by duplex PCR yielding 160 and 789 bp amplicons, respectively (Table 1).

Detection of fosA Gene by PCR Among CRE Isolates

The plasmid was extracted from fosfomycin-resistant CRE isolates using Gene JET Plasmid Miniprep Kit (Thermo Scientific). The purified plasmid was used to detect the fosA gene by PCR using the primers listed in Table 1.

Statistical Analysis

Data were statistically analyzed using the Statistical Package for Social Sciences (SPSS) version 16 (SPSS Inc, Chicago, IL, USA). Qualitative data were expressed as numbers and percentages. The Chi-square or Fisher’s exact test was used to compare groups, as appropriate. Results with p < 0.05 were considered statistically significant.
The present study was conducted on 200 Enterobacterales strains (121 E. coli, 78 Klebsiella pneumoniae, 1 Enterobacter cloacae) isolated from urine of adult patients over 7 months. The patients were 61.5% female (123/200) and 38.5% male (77/200).

Enterobacterales strains were recovered from patients with UTI and confirmed by traditional biochemical reactions and API 20E. Meropenem susceptibility testing using the broth microdilution method according to CLSI guidelines (susceptible ≤1 mg/l and resistant ≥4 mg/l) revealed 92 CRE isolates (46% of Enterobacterales isolates); 52 E. coli and 40 K. pneumoniae strains.

Using the disc diffusion method, all the isolates were resistant to cefuroxime and ceftazidime. About 24%, 15.2% and 8.7% of CRE isolates were sensitive to amikacin, nitrofurantoin and cefoxitin, respectively and only 6.5% of the isolates were sensitive to aztreonam, ciprofloxacin and trimethoprim/sulfamethoxazole (Table 2). Out of 200 Enterobacterales isolates, 105 isolates (52.5%) were MDR including all the CRE isolates.

Colistin susceptibility was tested using the broth microdilution method where sensitive CRE isolates had MIC ≤ 2 μg/mL. About 67.4% of CRE isolates were sensitive to colistin (Table 2) and the colistin MIC range was 0.25–64 μg/mL.

Testing the fosfomycin susceptibility of CRE isolates using the disc diffusion method and MIC Test Strip showed that 82.6% of the isolates were sensitive to fosfomycin (Table 2), where the fosfomycin MIC range was 0.125–256 μg/mL (Figure 1).

Meropenem/vaborbactam susceptibility was evaluated by the disc diffusion method according to CLSI guidelines; 58.7% of the CRE isolates were inhibited by meropenem/vaborbactam (Table 2). Using the MIC Test Strip, the range of meropenem/vaborbactam MIC was 0.032–256 μg/mL (Figure 1).

Screening of carbapenemase genes; bla<sub>IMP</sub>, bla<sub>VIM</sub>, bla<sub>OXA-48</sub>, bla<sub>NDM</sub> and bla<sub>KPC</sub> by two multiplex PCR revealed that 69.6% of the isolates had carbapenemase genes (Carbapenemase producing Enterobacterales (CPE)) mainly bla<sub>NDM</sub> (37%) followed by bla<sub>OXA-48</sub> and bla<sub>KPC</sub> (13% each). Four (4.4%) and two (2.2%) CRE isolates carried bla<sub>NDM</sub> plus bla<sub>OXA-48</sub> and bla<sub>KPC</sub> plus bla<sub>OXA-48</sub>, respectively. Carbapenemase genes bla<sub>IMP</sub> and bla<sub>VIM</sub> were not detected in any of the CRE isolates. Twenty-eight (30.4%) CRE isolates were non-CPE isolates (Table 3). The sensitivity and specificity of

### Table 1 Primers’ Sequences and Amplicons’ Size Used in PCR for Carbapenemase, Integrons and fosA Genes Detection

| Gene | Primer Sequence (5′-3′) | Amplicon (bp) | Reference |
|------|------------------------|--------------|-----------|
| bla<sub>IMP</sub> | GGAATAGAGTGGCTTAAYTCTC GGT'TAAAYAAAACACCCACC | 232 | 24 |
| bla<sub>VIM</sub> | GATGGTGTGGTGGCACA CATGAATGGCAGCATGAC | 390 | 24 |
| bla<sub>OXA-48</sub> | GGCAGTTAAGGATGAACAC CATCAAGTTCAACCAACCC | 438 | 24 |
| bla<sub>NDM</sub> | GGT'TGGCAGTGCTGGTTTC CGGAAATGGCTACATGAC | 621 | 24 |
| bla<sub>KPC</sub> | GTTTCTAGTTGCTTGTTGTTG CGGAATGGCATTGAGC | 798 | 24 |
| Integron class 1 | CAGTGACATAAGCCTGTTCC CCGAGGCGATAGCTGA | 160 | 25 |
| Integron class 2 | CACGGGATATGGCACAAGAAGGT GTAGCAAACGAGTGACGAAATG | 789 | 25 |
| fosA | ATCTGTGGCTGCTGCTGCTG ATGCGCCGATAGGCTTCT | 271 | 26 |

Note: Y = C or T.
Abbreviation: bp, base pair.

### Results

The present study was conducted on 200 Enterobacterales strains (121 E. coli, 78 Klebsiella pneumoniae, 1 Enterobacter cloacae) isolated from urine of adult patients over 7 months. The patients were 61.5% female (123/200) and 38.5% male (77/200).

Enterobacterales strains were recovered from patients with UTI and confirmed by traditional biochemical reactions and API 20E. Meropenem susceptibility testing using the broth microdilution method according to CLSI guidelines (susceptible ≤1 mg/l and resistant ≥4 mg/l) revealed 92 CRE isolates (46% of Enterobacterales isolates); 52 E. coli and 40 K. pneumoniae strains.

Using the disc diffusion method, all the isolates were resistant to cefuroxime and ceftazidime. About 24%, 15.2% and 8.7% of CRE isolates were sensitive to amikacin, nitrofurantoin and cefoxitin, respectively and only 6.5% of the isolates were sensitive to aztreonam, ciprofloxacin and trimethoprim/sulfamethoxazole (Table 2). Out of 200 Enterobacterales isolates, 105 isolates (52.5%) were MDR including all the CRE isolates.

Colistin susceptibility was tested using the broth microdilution method where sensitive CRE isolates had MIC ≤ 2 μg/mL. About 67.4% of CRE isolates were sensitive to colistin (Table 2) and the colistin MIC range was 0.25–64 μg/mL.

Testing the fosfomycin susceptibility of CRE isolates using the disc diffusion method and MIC Test Strip showed that 82.6% of the isolates were sensitive to fosfomycin (Table 2), where the fosfomycin MIC range was 0.125–256 μg/mL (Figure 1).

Meropenem/vaborbactam susceptibility was evaluated by the disc diffusion method according to CLSI guidelines; 58.7% of the CRE isolates were inhibited by meropenem/vaborbactam (Table 2). Using the MIC Test Strip, the range of meropenem/vaborbactam MIC was 0.032–256 μg/mL (Figure 1).

Screening of carbapenemase genes; bla<sub>IMP</sub>, bla<sub>VIM</sub>, bla<sub>OXA-48</sub>, bla<sub>NDM</sub> and bla<sub>KPC</sub> by two multiplex PCR revealed that 69.6% of the isolates had carbapenemase genes (Carbapenemase producing Enterobacterales (CPE)) mainly bla<sub>NDM</sub> (37%) followed by bla<sub>OXA-48</sub> and bla<sub>KPC</sub> (13% each). Four (4.4%) and two (2.2%) CRE isolates carried bla<sub>NDM</sub> plus bla<sub>OXA-48</sub> and bla<sub>KPC</sub> plus bla<sub>OXA-48</sub>, respectively. Carbapenemase genes bla<sub>IMP</sub> and bla<sub>VIM</sub> were not detected in any of the CRE isolates. Twenty-eight (30.4%) CRE isolates were non-CPE isolates (Table 3). The sensitivity and specificity of
the combined mCIM and eCIM for detection of carbapenemase activity among CPE isolates were 92% and 96.2%, respectively. The eCIM could not detect carbapenemase activity in 3 CPE isolates carrying both \textit{bla}_{NDM} plus \textit{bla}_{OXA-48} (Table 4).

Carbapenemase-producing \textit{Enterobacterales} (CPE) isolates were significantly more resistant to meropenem/vaborbactam compared to non-CPE isolates; 51.6% vs 17.8%, respectively (P = 0.003). This resistance was higher among the isolates carrying \textit{bla}_{NDM} (70.6%) than other carbapenemase genes. There was no significant difference in the resistance pattern of all other tested antibiotics between the CPE and non-CPE isolates (p ≥ 0.05, Tables 3 and 5).

Eleven out of the 16 fosfomycin-resistant CRE isolates (68.75%, 11.9% of CRE isolates) carried \textit{fosA} gene; 66.7% (4/6) and 70% (7/10) of fosfomycin-resistant \textit{E. coli} and \textit{K. pneumoniae} isolates, respectively. \textit{FosA} gene was more common among CPE than non-CPE isolates; 15.6% vs 3.6%, respectively (Table 5).

Integron class 1 was detected in 91.3% of the CRE isolates by duplex PCR, mostly among \textit{E. coli} isolates, while integron class 2 was not detected in any of the CRE isolates. Integron class 1 was more common among non-CPE than CPE isolates; 100% vs 87.5%, respectively (Table 5).

### Discussion

Carbapenem-resistant \textit{Enterobacterales} are a global health concern associated with patients’ morbidity and mortality. These strains have become an alarming issue due to limited therapeutic options that enforce the reuse of some old therapy and the development of new therapeutic alternatives.

The present study involved 200 \textit{Enterobacterales} isolates from adult patients with UTIs attending MUHs over seven months. According to meropenem susceptibility testing, ninety-two isolates (46%) were CRE strains; \textit{E. coli} (52, 56.5%) and \textit{K. pneumoniae} (40, 43.5%). Similar to these results, Kotb et al also stated that 47.9% of 2306 \textit{Enterobacterales} isolates were carbapenem-resistant, and the prevalence of CRE varied with different clinical samples.

The prevalence of CRE varies in Egypt from 34.1% to 66.08%.

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**Table 2 Antimicrobial Susceptibility Pattern of the Uropathogenic CRE Strains**

|                         | \textit{CR \textit{E. coli}} (No = 52) | \textit{CR \textit{K. pneumoniae}} (No = 40) | \textit{CRE Isolates} (No = 92) |
|-------------------------|---------------------------------------|--------------------------------------------|--------------------------------|
|                         | S          | R          | S          | R          | S          | R          |
| Aztreonam               | 4 (7.7)    | 48 (92.3)  | 2 (5)      | 38 (95)    | 6 (6.5)    | 86 (93.5)  |
| Piperacillin/tazobactam | 0 (0)      | 52 (100)   | 4 (10)     | 36 (90)    | 4 (4.3)    | 88 (95.7)  |
| Amikacin                | 14 (27)    | 38 (73)    | 8 (20)     | 32 (80)    | 22 (23.9)  | 70 (76.1)  |
| Ciprofloxacin           | 0 (0)      | 52 (100)   | 6 (15)     | 34 (85)    | 6 (6.5)    | 86 (93.5)  |
| Nitrofurantoin          | 12 (23)    | 40 (77)    | 2 (5)      | 38 (95)    | 14 (15.2)  | 78 (84.8)  |
| Cefuroxime              | 0 (0)      | 52 (100)   | 0 (0)      | 40 (100)   | 0 (0)      | 92 (100)   |
| Ceftazidime             | 0 (0)      | 52 (100)   | 0 (0)      | 40 (100)   | 0 (0)      | 92 (100)   |
| Cefoxitin               | 6 (11.5)   | 46 (77)    | 2 (5)      | 38 (95)    | 8 (8.7)    | 84 (91.3)  |
| Trimethoprim/           | 2 (3.8)    | 50 (96.2)  | 4 (10)     | 36 (90)    | 6 (6.5)    | 86 (93.5)  |
| sulfamethoxazole        |            |            |            |            |            |            |
| Colistin                | 30 (57.7)  | 22 (42.3)  | 32 (80)    | 8 (20)     | 62 (67.4)  | 30 (32.6)  |
| Fosfomycin              | 46 (88.5)  | 6 (11.5)   | 30 (75)    | 10 (25)    | 76 (82.6)  | 16 (17.4)  |
| Meropenem/vaborbactam   | 30 (57.7)  | 22 (42.3)  | 24 (60)    | 16 (40)    | 54 (58.7)  | 38 (41.3)  |

**Abbreviations:** CR, carbapenem resistant; CRE, carbapenem-resistant \textit{Enterobacterales}; S, sensitive, R, resistant.
Enterobacterales are a significant health issue as half of the Enterobacterales isolates were resistant to carbapenem in some hospitals. This resistance level is higher than other Arab, African, Asian, European and American countries.\(^{31,32}\)

Antimicrobial susceptibility testing of CRE isolates showed a high resistance pattern to most tested antibiotics with no sensitivity to cefuroxime and ceftazidime. These data are comparable to the data previously reported in India\(^{33}\) and the USA.\(^{34–36}\)

Of 200 Enterobacterales isolates, 105 isolates (52.5%) were MDR, including all CRE strains acquiring non-susceptibility to at least one agent in three or more antimicrobial categories.\(^{37}\) Similar results were also reported from Ethiopia,\(^{31}\) Egypt\(^{38}\) and Saudi Arabia,\(^{39}\) while, a higher percentage of MDR was reported in other studies\(^{30,40–42}\) and a lower percentage was documented in some Arab countries\(^{43}\) and USA.\(^{44}\) The high prevalence of MDR in Egypt emphasizes the importance of implementing effective infection control strategies and antibiotic stewardship programs, in addition to the education of healthcare workers for early surveillance and preventive measures of MDR isolates to control their spread.

Integron class 1 was detected in 91.3% of our CRE isolates. Multi-drug resistance is strongly associated with integrons, especially class 1, which is widely distributed among resistant Gram-negative bacteria. In this study, all

Figure 1. Meropenem/vaborbactam and fosfomycin susceptibility testing using the MIC Test Strip according to CLSI guidelines. (A) Meropenem/vaborbactam susceptible strain (MIC = 0.032 µg/mL), (B) meropenem/vaborbactam resistant strain (MIC > 256 µg/mL), (C) fosfomycin susceptible strain (MIC = 0.25 µg/mL) and (D) fosfomycin resistant strain (MIC > 256 µg/mL).
Table 4 Performance of the Modified Carbapenem Inactivation Method (mCIM) and EDTA-Modified Carbapenem Inactivation Method (eCIM) in Screening of Carbapenemase Activity of Carbapenem Resistant Isolates

| Bacterial Species (No) | Non-CPE | Genes | Integron Class 1 |
|------------------------|---------|-------|-----------------|
|                        | No of CRE strains | blaNDM | blaOXA-48 | blaKPC | blaNDM and blaOXA-48 | blaNDM and blaOXA-48 | Total |
| E. coli (52)           | 28 (30.4%) | 16 | 18 | 12 | 4 | 2 | 0 | 50 |
| K. pneumoniae (40)     | 12 | 16 | 0 | 8 | 2 | 2 | 34 |
| Total (92)             | 34 (37%) | 12 (13%) | 12 (13%) | 4 (4.4%) | 2 (2.2%) | 84 (91.3%) |
| Meropenem/vaborbactam sensitivity | 23 (82.1%) | 10 (29.4%) | 6 (50%) | 12 (100%) | 2 (50%) | 1 (50%) | 50 (59.5%) |

Abbreviation: Non-CPE, non-carbapenemase producing Enterobacterales.

Table 3 Detection of Carbapenemase and Integrons Genes by PCR and the Sensitivity of CRE Isolates to Meropenem/Vaborbactam

| Bacterial Species (No) | Non-CPE | Genes | Integron Class 1 |
|------------------------|---------|-------|-----------------|
|                        | No of CRE strains | blaNDM | blaOXA-48 | blaKPC | blaNDM and blaOXA-48 | blaNDM and blaOXA-48 | Total |
| E. coli (52)           | 28 | 34 | 12 | 12 | 4 | 2 | 92 |
| K. pneumoniae (40)     | 0 | 34 | 12 | 12 | 4 | 2 | 64 |
| Total (92)             | N/A | 34 | 1 | 0 | 1 | 0 | 36 |

Abbreviations: CRE, carbapenem-resistant Enterobacterales; Non-CPE, non-carbapenemase producing Enterobacterales; N/A, not applicable.

Table 5 Antibiotic Resistance Pattern and the Distribution of Integron and fosA Genes Among Carbapenemase Producing Enterobacterales (CPE) and Non-CPE Isolates

| Antibiotic                         | Non-CPE Isolates (No = 28) No/% | CPE Isolates (No = 64) No/% | P value |
|------------------------------------|---------------------------------|-----------------------------|---------|
| Aztreonam                          | 26 (92.8%)                      | 60 (93.7%)                  | 1       |
| Piperacillin/tazobactam            | 28 (100%)                       | 60 (93.7%)                  | 0.31    |
| Amikacin                           | 24 (85.7%)                      | 46 (71.9%)                  | 0.15    |
| Ciprofloxacin                      | 26 (92.8%)                      | 60 (93.7%)                  | 1       |
| Nitrofurantoin                     | 24 (85.7%)                      | 54 (84.4%)                  | 1       |
| Cefuroxime                         | 28 (100%)                       | 64 (100%)                   | NA      |
| Ceftazidime                        | 28 (100%)                       | 64 (100%)                   | NA      |
| Cefoxitin                          | 26 (92.8%)                      | 58 (90.6%)                  | 1       |
| Trimethoprim/sulfamethoxazole      | 28 (100%)                       | 58 (90.6%)                  | 0.17    |
| Colistin                           | 8 (28.6%)                       | 22 (34.4%)                  | 0.58    |
| Fosfomycin                         | 2 (7.1%)                        | 14 (21.9%)                  | 0.13    |
| Meropenem/vaborbactam              | 5 (17.8%)                       | 33 (51.6%)                  | 0.003*  |
| Integrons class I                  | 28 (100%)                       | 56 (87.5%)                  | 0.10    |
| fosA gene                          | 1 (3.6%)                        | 10 (15.6%)                  | 0.16    |

Note: *P value is significant; < 0.0.
Abbreviation: CPE, carbapenemase producing Enterobacterales.
CRE isolates were MDR, and integron class 1 was detected among most of them, which might play a role in the spread of MDR among these isolates.25

In this study, 62 CRE isolates (67.4%) were sensitive to colistin adopting EUCAST cut-offs in agreement with other studies.8,14,36 Castanheira et al,35 Qamar et al45 and Maraki et al50 have recorded a higher colistin sensitivity; 83.3%, 84.1% and 87.5% among the CRE isolates, respectively. In contrast, in Turkey, a high colistin resistance (76.19%) has been reported owing to the only testing multi- and extensive drug-resistant Enterobacteriales and the high level of antibiotic consumption.7

Both colistin and fosfomycin are considered a salvage treatment for multi- and extensive drug-resistant carbapenem-resistant Enterobacteriales infections as they are associated with better prognosis.45 In our study, fosfomycin inhibited 82.6% of the CRE isolates. The fosA gene was detected in 11 of 16 resistant isolates (68.75%), consistent with other studies from Egypt16 and Pakistan.45

Similarly, several studies have reported the sensitivity of CRE isolates from different clinical samples to fosfomycin.16,17,46–48 Moreover, 74% of carbapenem-resistant Enterobacter species were sensitive to fosfomycin, and the fosA gene was detected in only 42% of the resistant isolates.49 On the contrary, a high fosfomycin resistance was detected among carbapenem-resistant K. pneumoniae9,50 and extensive drug-resistant CRE isolates (67.35%).7

Several mechanisms are associated with fosfomycin resistance that differs with the geographic locality and the studied bacteria. Plasmid-mediated fosA enzymes are the most common mechanism of resistance in Enterobacteriales.39

In the USA, the fosA gene was detected in 80% of carbapenem-resistant K. pneumoniae isolates,51 whereas in China, the fosA gene has been identified in only uropathogenic K. pneumoniae (26.7%)52 and has not been recognized in any fosfomycin-resistant isolates in other studies.50,53 Lastly, Mosime et al have reported that fosA enzymes are not a common cause of resistance amongst community-acquired urinary pathogens.54

In the current study, 69.6% of CRE isolates were CPE, mostly blaNDM producers (37%), followed by blaOXA-48 and blaKPC producers (13% each). About 4.4% and 2.2% of the CRE isolates carried blaNDM plus blaOXA-48 and blaKPC plus blaOXA-48, respectively, while 30.4% of CRE were non-CPE isolates. The sensitivity of the mCIM combined with the eCIM in the screening of carbapenemase activity was 92%.

In accordance, 75.8% of CRE isolates carried carbapenemase genes, yet, 50.9%, 10.2% and 9.5% of the isolates had blaKPC, blaOXA-48 like genes and blaNDM-1, respectively34 consistent with other studies.5,35 On the other hand, a lower prevalence of carbapenemase encoding genes was documented in 53.4% of CRE isolates, where blaKPC was the most frequent gene (94.2%).36

In Egypt, carbapenem resistance genes have been recognized in 45.3% of MDR CRE isolates.38 Another Egyptian study reported that carbapenemase gene prevalence among CRE isolates was 89.62% and similar to the current study, the most prevalent gene detected was blaNDM (68.88%).42 Furthermore, a high prevalence of blaNDM has also been documented among CRE isolates in Alexandria, Egypt (67.5%)55 and Greece (85%),9 which might be due to its presence on conjugative plasmids that facilitate its spread between bacteria.42

However, some Egyptian studies have reported that blaOXA-48 was the most common carbapenemase gene among CRE isolates28,30 similar to the studies from Turkey7 and Ethiopia.40 On the other hand, Khalil et al29 have stated that the most prevalent carbapenemase genes among CRE were blaKPC in Gharbia, Egypt. This difference in the most prevalent carbapenemase gene type might be due to the different detection methods and geographic regions.40

In the current study, meropenem/vaborbactam inhibited 58.7% of CRE isolates, and its sensitivity was significantly higher on non-CPE than CPE isolates; 82.2% vs 48.4%, respectively, with a low sensitivity on the isolates carrying blaNDM (29.4%) and a complete sensitivity on the isolates carrying blaKPC (100%).

A study has stated that meropenem/vaborbactam inhibited 73.9% of CRE isolates with significant activity on blaKPC producing isolates (99.5%), limited activity on blaOXA-48 producing isolates and no activity on blaNDM-1 producing isolates. Meropenem/vaborbactam had a lower MIC50/90 with blaKPC than non blaKPC producing isolates due to the large number of MBLs and OXA-48 producing isolates.6 Meropenem-vaborbactam was 4-fold more active than meropenem alone and inhibited 84.2% of the CRE isolates.34
Similarly, several studies have documented meropenem-vaborbactam complete activity on bla<sub>KPC</sub> producing CRE isolates regardless of the bla<sub>KPC</sub> variant, limited activity on isolates producing bla<sub>OXA-48</sub> and no activity on MBLs producing ones.<sup>35,36</sup>

The low efficacy of meropenem/vaborbactam seen in our study compared to other studies might be due to the predominancy of bla<sub>NDM</sub> then bla<sub>OXA-48</sub> and bla<sub>KPC</sub> producing CRE isolates. Vaborbactam strongly inhibits bla<sub>KPC</sub> and has a good outcome when combined with different carbapenems. It does not inhibit MBLs producing isolates and has limited activity on isolates producing class D oxacillinases associated with resistance to carbapenems.<sup>34</sup> It has also been documented that meropenem-vaborbactam was active on non-bla<sub>KPC</sub> producers other than bla<sub>NDM</sub> and bla<sub>OXA-48</sub>.<sup>36</sup>

In the present study, meropenem/vaborbactam significantly inhibited non-CPE higher than CPE isolates. Other studies have similarly reported the whole activity of meropenem-vaborbactam on non-CPE isolates compared to other antibiotics.<sup>35,36,57</sup> The therapeutic options of non-carbapenem producing CRE are challenging, and further studies are still needed. The effect of meropenem/vaborbactam on the isolates varies with the bacterial species and the different resistance mechanisms.<sup>57</sup>

Clarifying the epidemiology of CRE isolates and their resistance mechanisms is mandatory to guide the clinicians on the appropriate therapeutic options for infections caused by these organisms to improve the clinical outcome. Surveillance of CRE, effective infection control measures and appropriate antibiotic stewardship are crucial approaches to reducing the spread of CRE. An antimicrobial restriction system could increase the appropriateness of prescribing antibiotics and decrease the expense for carbapenem.<sup>58</sup>

Our work emphasizes the importance of meropenem/vaborbactam therapy with the favorable clinical outcome for all physicians, pharmacists, and healthcare professionals worldwide. Meropenem/vaborbactam is a promising therapeutic option for bla<sub>KPC</sub>-producing uropathogenic isolates, yet its effect on non-bla<sub>KPC</sub> CRE producers (MBLs and OXA-48-like enzymes producers) is limited and needs more optimization. To the best of our knowledge, this is the first study in Egypt that highlights the effect of meropenem/vaborbactam on uropathogenic CRE isolates. However, this study had some limitations such as the short study duration and limited molecular techniques due to financial constraints. More studies are needed on different clinical samples, pathogenic bacteria and patients’ groups.

**Conclusions**

In conclusion, this study revealed that about half of uropathogenic Enterobacterales were MDR CRE isolates and colistin and fosfomycin had an excellent therapeutic effect on these CRE isolates. The carbapenemase gene bla<sub>NDM</sub> was the primary gene among CPE isolates, and meropenem/vaborbactam had an unsatisfactory therapeutic effect on CRE isolates due to the predominancy of bla<sub>NDM</sub>.

**Abbreviations**

KPC, Klebsiella pneumoniae carbapenemases; OXA, oxacillinases; MDR, multi-drug resistant; UTIs, urinary tract infections; MUHs, Mansoura University Hospitals; CLED, cystine lactose electrolyte deficient agar; CLSI, Clinical Laboratory Standards Institute; EUCAST, European Committee on Antimicrobial Susceptibility Testing; G6P, glucose-6-phosphate; MIC, minimum inhibitory concentration; CPE, carbapenemase producing Enterobacterales.

**Data Sharing Statement**

On request.

**Ethics Approval and Consent to Participate**

This study was approved by Mansoura Faculty of Medicine ethical committee (R22.09.1813) and a signed informed consent was obtained from each patient. This study complies with the Declaration of Helsinki.

**Author Contributions**

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically
The authors report no conflicts of interest in this work.

**Disclosure**

The authors report no conflicts of interest in this work.

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