REVIEW

Treatment of extended-spectrum β-lactamase-producing Enterobacteriaceae (ESBLs) infections: what have we learned until now? [version 1; referees: 2 approved]

Zoi Dorothea Pana¹, Theoklis Zaoutis²

¹Infectious Diseases Department, 3rd Department of Pediatrics, Hippokration General Hospital Aristotle University, Thessaloniki, Greece
²Infectious Diseases Department, The Children’s Hospital of Philadelphia, Perelman School of Medicine at the University of Pennsylvania, Philadelphia, PA, USA

Abstract
The spread of extended-spectrum β-lactamase (ESBL)-producing Enterobacteriaceae (ESBL-PE) has dramatically increased worldwide, and this “evolving crisis” is currently regarded as one of the most important public health threats. The growing problem of ESBL-PE antimicrobial resistance seems to have a dual face between “Scylla and Charybdis”: on one hand the potential for rapid spread and dissemination of resistance mechanisms and on the other hand the injudicious overuse of antimicrobial agents and the inadequate infection control measures, especially in the health-care setting. Given the World Health Organization’s warning against a “post antibiotic era”, health-care providers are at a critical standpoint to find a “balance” between safe and effective ESBL-PE treatment and avoidance of inducing further resistance mechanisms. The aim of the review is to summarize the updated published knowledge in an attempt to answer basic everyday clinical questions on how to proceed to effective and the best ESBL-PE treatment options based on the existing published data.

Keywords
lactamase producers, ESBL treatment, Enterobacteriaceae

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1 Jean-Ralph Zahar, Hôpital Avicenne (AP-HP), France

2 Patrice Nordmann, National Reference Center for Emerging Antibiotic Resistance and Foreign Reserach Unit (INSERM, France) University of Fribourg, Switzerland

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Introduction

Extended-spectrum β-lactamase (ESBL) enzymes are characterized by the ability to hydrolyze third-generation cephalosporins and aztreonam but are inhibited by clavulanic acid. The spread of ESBL-producing Enterobacteriaceae (ESBL-PE) has dramatically increased worldwide, and this “evolving crisis” is currently regarded as one of the most important public health threats. The growing problem of ESBL-PE antimicrobial resistance seems to have a dual face between “Scylla and Charybdis”: on one hand the potential for rapid spread and dissemination of resistance mechanisms and on the other hand the injudicious overuse of antimicrobial agents and the inadequate infection control measures, especially in the health-care setting. A multicenter study in the US reported that in 2012 the prevalence of ESBL-producing Klebsiella pneumoniae reached 16% and almost 12% for ESBL-producing Escherichia coli and that rates were much higher among intensive care unit (ICU) patients. Even in the pediatric population, a meta-analysis revealed that the worldwide prevalence of ESBL producers was estimated to be 9% (11% neonates and 5% children) with an annual increase of 3.2% and a wide variability among different geographic regions (15% in Africa, 12% in South America, 11% in India, 7% in the rest of Asia, and 4% in Europe).

ESBL-PE are associated with increased morbidity and mortality rates, prolonged hospital stays, and increased costs. In a matched cohort study, the nosocomial financial burden of non-urinary tract infections (non-UTIs) caused by ESBL producers was 1.7 times higher compared with the same type of infections caused by non-ESBL producers. A case control study in Canada showed that ESBL-PE infections were significantly associated with increased cost (C$10,507 versus C$7,882), hospitalization (8 versus 6 days), and mortality rates (17% versus 5%). In addition, data regarding the rates of ESBL-PE colonization (both health-care or community acquired) reveal an increasing trend over time with significant differences among several geographical regions and patient groups. For high-risk patients in the ICU, the ESBL-PE colonization rates might range from 2.3% for the US to 49% for India. According to a recently published systematic review, the most frequently reported risk factor for ESBL-PE colonization and infection remains prior exposure to antimicrobials as well as recent hospitalization and recent or repeated surgery. Although prior ESBL-PE colonization has been shown in a few studies to increase the risk of acquiring an ESBL-PE infection, further data are needed.

Decision making on ESBL-PE antimicrobial treatment

Before starting ESBL treatment

The first step before initiating ESBL-PE antimicrobial treatment is to carefully evaluate specific parameters that are directly associated with ESBL-PE therapeutic decision making. Of utmost importance is to clearly characterize (a) the isolate with the in vitro susceptibilities, (b) the location of the infection, (c) the degree of source control of the infection, and finally (d) the clinical condition of the patient (Table 1). In addition, recently published studies propose that all ESBL-PE do not belong in the same homogenous group as far as comorbidities, presentation, and outcome are concerned. In particular, data have shown that bloodstream infections (BSIs) associated with ESBL-producing E. coli were more frequently of a urinary source and community onset compared with BSIs with ESBL-producing Klebsiella spp.

### Table 1. Significant parameters for extended-spectrum β-lactamase-producing Enterobacteriaceae (ESBL-PE) antimicrobial treatment.

| Infection's location                                | High-versus low-inoculum infection                                                                 |
|-----------------------------------------------------|------------------------------------------------------------------------------------------------------|
| Infection source control                            | Adequate or no source control                                                                      |
| Patient's clinical condition                        | Critically ill patient; presence of immunosuppression                                              |
| Characterization of multidrug-resistant Gram-negative Enterobacteriaceae | Mechanisms associated with ESBL, AmpC, or carbapenem-resistant Enterobacteriaceae                  |
| Evaluation of minimum inhibitory concentration (MIC) susceptibilities | Especially for carbapenems, cephalime, and β-lactam/β-lactamase inhibitor (BLBLI) combinations       |
| Type of ESBL-PE                                      | Klebsiella pneumoniae versus Escherichia coli                                                      |

*Examples of high-inoculum infections could be large intra-abdominal collections and endocarditis vegetations.*
Among β-lactam/β-lactamase inhibitor (BLBLI) combinations, the combination of piperacillin–tazobactam (PTZ) has been extensively studied as an alternative carbapenem-sparing option against ESBL-PE infections. In 2012, a meta-analysis compared the mortality rates among carbapenems and alternative regimens, including BLBLIs, for the treatment of ESBL-PE BSIs. According to their results, differences were noticed in mortality rates when administered as either definitive or empirical therapy, although they mentioned one study’s significant heterogeneity. Since the question about the role of BLBLIs remained, six subsequent studies from 2012 to 2017 tried to elucidate the role of BLBLIs against ESBL-PE with rather conflicting results. These controversies were interpreted by substantial differences among the studies’ design. In particular, the Spanish groups included mainly E. coli as the attributed ESBL-PE, and their studies had lower inoculum infections, ICU admissions, and median PTZ minimum inhibitory concentration (MIC) and higher PTZ treatment dosages compared with the study by Tamma et al. A further analysis of cases of the Spanish group, conducted by Retamar et al., revealed that all patients who presented with ESBL-PE BSIs from a urinary source had a favorable outcome, irrespectively of the PTZ MIC. Furthermore, among patients with an ESBL-PE BSI with a source other than a urinary one, the outcome was dismal when the MIC of the isolate for PTZ was more than 2 mg/L. A recently published randomized controlled trial was conducted comparing PTZ, cefepime, and carbapenem for the treatment of ESBL-PE UTIs caused by E. coli. Based on the results, the clinical and microbiological response to PTZ treatment was estimated to be 94% and was similar to the response to etrapenem treatment. An ongoing retrospective observational study (BICAR) is trying to evaluate the efficacy of BLBLI combinations for the treatment of ESBL-PE BSIs in hematological patients with neutropenia. In addition, a recently published propensity score-weighted multicenter cohort study in Korea showed that, among 232 patients with ESBL-PE BSIs, non-carbenem regimen were not inferior to carbapenems (30-day mortality rates for non-carbenem 6.3% versus carbapenems 11.4%).

**Authors’ recommendations.** For invasive, high-inoculum ESBL-PE infections with a source of infection other than E. coli and in critically ill patients, carbapenems remain the “gold standard” of targeted treatment. Especially for ICU patients, according to a recent systematic review, the empirical use of PTZ when high risk of ESBL-PE is suspected should be avoided. Definitive therapy with BLBLIs should be selected under specific criteria such as stable condition, after microbial documentation with susceptibility results, in combination with dose and infusion modalities to the MIC in order to reach pharmacological targets.

Definite answers concerning the role of BLBLIs (and specifically PTZ) against ESBL-PE BSIs will be given by an ongoing multicenter clinical trial (MERINO trial) comparing PTZ versus carbapenems for the definitive treatment of BSIs caused by ceftriaxone-resistant E. coli and Klebsiella spp. Based on the preliminary MERINO results presented at European Congress of Clinical Microbiology & Infectious Diseases 2018, the most common ESBL-PE bacteremia source was the urinary tract (60.9%) with clear predominance of E. coli (86.5%). Although no difference between the two groups regarding subsequent infections of drug-resistant bacteria or C. difficile was reported, the 30-day mortality rate differed (12.3% for PTZ versus 3.7% for meropenem). In addition, it is of utmost importance to clearly define in future studies the specific subset of patients with ESBL-PE infections who could benefit from carbapenem-sparing treatments, especially regarding hematological patients with neutropenia.

**Clinical question 2: What is the role of cefepime in treating ESBL-PE infections?**

The results from published studies and reviews evaluating the efficacy of cefepime versus carbapenems for the treatment of ESBL-PE infections remain controversial. Few studies have shown comparable efficacy, whereas others reported significant inferiority of cefepime. Among these studies, Lee et al. and Wang et al. showed significantly lower mortality rates at 30 and 14 days, respectively (17% versus 59% and 41% versus 20%, respectively). In particular, in the study by Lee et al., a significant association was observed between the mortality rates of the patients receiving cefepime and the MIC of the drug. In particular, for cefepime MIC of not more than 1 μg/mL, the mortality rate was 16.7%; for MIC of 2–8 μg/mL, the rates reached 45.5%; while for MIC of at least 16 μg/mL, the rates were 100% (p = 0.035). Even after propensity score adjustment, cefepime remained inferior compared with carbapenem (adjusted odds ratio 6.8, 95% confidence interval (CI) 1.5–31.2, p = 0.01). A subsequent randomized controlled trial was conducted comparing PTZ, cefepime, and etrapenem for the treatment of ESBL-PE UTIs caused by E. coli showing inferiority of cefepime compared with the other treatment options. The efficacy of cefepime was 33.3% compared with 94% efficacy of PTZ treatment.

**Authors’ recommendations.** For serious invasive ESBL-PE infections with high inoculum and lack of source control, cefepime seems to be inferior compared with carbapenems because of two significant issues: increased MICs of the drug because of high inoculum effect and failure to achieve its pharmacodynamic targets in severe ESBL-PE infections. Cefepime could be administered only in non-severe ESBL-PE UTIs, where high drug concentrations could be achieved and when simultaneously low MIC of the drug is reported (MICs ≤2 μg/mL).

**Clinical question 3: What is the role for fosfomycin, aminoglycosides, or temocillin in ESBL-PE infections?**

Fosfomycin is an old bactericidal antibiotic agent (phosphonic compound) with a unique mode of action of inhibiting bacterial cell wall biosynthesis. A recently published literature review...
concerning the susceptibility of contemporary Gram-negative bacteria revealed that, for ESBL-producing E. coli, susceptibilities ranged from 81% to 100% and, for ESBL-producing K. pneumoniae, from 15% to 100%. Owing to its low molecular weight, its hydrophilicity, and its negligible serum protein binding, the drug achieves good tissue penetration and high concentrations in the serum, soft tissue, lungs, bone, cerebrospinal fluid, and heart valves. Especially for the urinary tract, the drug achieves high concentrations for a prolonged period of time. Finally, in critically ill patients, a significant increase of fosfomycin volume of distribution is observed; therefore, the current paucity of data on fosfomycin in critically ill patients prevents accurate dosing guidance. Clinical data concerning the efficacy of intravenous fosfomycin against ESBL-PE invasive infections are very limited and focus mainly on UTI treatment. A randomized clinical trial (“FOREST”) comparing the safety and efficacy of fosfomycin versus meropenem in bacteremic UTIs caused by ESBL-producing E. coli is ongoing. Fosfomycin as monotherapy for the treatment of multidrug-resistant organism (MDRO)-associated invasive infections is limited by the emergence of drug resistance to fosfomycin during treatment. A more recently published meta-analysis conducted by Grabein et al. tried to summarize the current clinical evidence of intravenous fosfomycin in 128 studies. According to their results, the drug showed comparable clinical or microbiological efficacy compared with other antibiotics when used for sepsis/bacteremia, urinary tract, respiratory tract, bone and joint, and central nervous system infections. The pooled estimate for resistance development during fosfomycin monotherapy was 3.4% (95% CI 1.8%–5.1%).

Up-to-date data concerning the role of aminoglycosides in combating MDRO infections showed that for ESBL infections they can be used as part of a combination regimen, especially for UTIs and intra-abdominal infections (IAIs), as a carbapenem-sparing option. An in vitro synergistic effect has been confirmed for the concomitant administration of aminoglycosides plus β-lactams, while the monotherapy is not generally recommended for ESBL-PE infections, except for ESBL-PE non-bacteremic UTIs, mainly owing to the high risk of resistance development. Among newer aminoglycosides, plazomicin (formerly ACHN-490), a next-generation aminoglycoside synthetically derived from sisomicin, is recently gaining more attention against MDRO infections. The unique characteristic of plazomicin is its resistance to inactivation by aminoglycoside-modifying enzymes compared with other agents of the same group. However, plazomicin is not active against bacterial isolates expressing ribosomal methyltransferases. In two studies, plazomicin has been shown to be more potent than other aminoglycosides in treating Enterobacteriaceae.

Temocillin is a β-lactamase-resistant carboxypenicillin active against both ESBL-PE and AmpC-producing Enterobacteriaceae and with limited activity against Pseudomonas, Acinetobacter spp., and anaerobic bacteria. Although this carbapenem-sparing drug option is licensed in only a few European countries (UK and Belgium), data from a multicenter study in the UK among 92 infection episodes (42 BSIs) treated with temocillin showed promising results. In particular, both clinical and microbiological cure rates were reported to be 86% and 84%. In addition, a prospective randomized controlled trial conducted in Belgium in 2014 showed that for critically ill patients the optimal dose regimen for temocillin in order to achieve its pharmacological targets with longer free-serum concentrations is 2 g three times a day administered by continuous infusion.

Authors’ recommendations. Fosfomycin is strongly suggested for ESBL-PE UTIs and as a step-down therapy in source-controlled ESBL-PE infections. A randomized clinical trial (“FOREST”) comparing the safety and efficacy of fosfomycin versus meropenem in bacteremic UTIs caused by ESBL-producing E. coli is ongoing. Other options of source-controlled ESBL-PE UTIs are aminoglycosides, especially for cystitis infections. In addition, they can be used as part of a combination regimen, especially for UTIs and IAIs, as a carbapenem-sparing option. For temocillin, larger clinical studies among different patient groups are needed in order to establish their role as a valuable carbapenem-sparing option against ESBL-PE BSIs.

Clinical question 4: What is the role of the newly approved drugs against ESBL-PE infections? In Table 2, some of the new drugs active against multidrug-resistant bacteria, including ESBL-producing ones, are reported. Among newer BLBLIs developed, two of them—ceftazidime–avibactam and ceftolozane–tazobactam—have already received US Food and Drug Administration (FDA) approval and therefore will be discussed further.

Ceftazidime–avibactam is a combination of cephalosporin with a new non-BLCLI that is generally active against Enterobacteriaceae and P. aeruginosa producing class A β-lactamases (ESBLs and KPCs) and class C β-lactamases (AmpCs) and some Enterobacteriaceae producing class D β-lactamases (OXAs) but lacks activity against class B carbapenemases and is less active against anaerobes compared with other BLBLIs. A phase 3 trial (RECLAIM 1 and RECLAIM 2) conducted by Mazuski et al. evaluated the efficacy of ceftazidime–avibactam in treating complicated IAI (cIAI), revealing non-inferiority of the tested combination drug and similar clinical cure rates of 81.6% versus 85.1%, respectively. A subsequent phase 3 (REPRIZE) study by Carmeli et al. recently published the results of the efficacy of ceftazidime–avibactam—2 to 0.5 g intravenously every 8 hours (q8h)—versus the best available therapy both for complicated UTI or cIAI due to ceftazidime-resistant Enterobacteriaceae or P. aeruginosa with similar clinical cure rates. Finally, in 2015, the drug was approved by the FDA for complicated UTIs and cIAI with a recommended dosage of 2 g/0.5 g) 8 hourly for 7 days for UTIs and 4 to 14 days for IAIs with dose adjustment in renal insufficiency. An ongoing clinical trial is evaluating the safety and efficacy profile of the drug for nosocomial pneumonia.

Ceftolozane–tazobactam is a co-formulation of a novel cephalosporin with an old β-lactamase inhibitor. Ceftolozane is a new cephalosporin based on the scaffold of ceftazidime—with only one modification of the side chain at the 3-position of the cephem
nucleus—with improved activity against multidrug-resistant 
*Pseudomonas* spp. Ceftolozane, like other oxyimino-cephalosporins 
such as ceftazidime and ceftriaxone, is not stable against class 
A, B, or D β-lactamases (mainly ESBLs or carbapenemases). 
The combination with tazobactam significantly broadens its 
spectrum against ESBL-PE and against few anaerobes. In 
2014, the FDA approved the administration of the combination 
drug for the treatment of complicated UTIs and cIAIs based on 
previously published clinical trials (ASPECT trials). In 
particular, the drug was evaluated in phase 3 non-inferiority 
clinical trials versus levofloxacin 750 mg daily in complicated 
UTI or meropenem 1 g q8h in cIAI. The UTI trial compared 
ceftolozane 1,000 mg q8h versus ceftazidime 1,000 mg q8h, 
including pyelonephritis, and demonstrated similar microbiologic 
and clinical outcomes, as well as a similar incidence of adverse 
effects after 7 to 10 days of treatment, respectively. The second cIAI 
trial has been conducted comparing ceftolozane–
tazobactam 1,000/500 mg and metronidazole 500 mg q8h 
versus meropenem 1,000 mg q8h in the treatment of cIAI. The 
recommended FDA dosage is 1 g/0.5 g 8 hourly for 7 days in 
complicated UTIs and 4 to 14 days in cIAIs, respectively.

### Table 2. New drugs with *in vitro* activity against extended-spectrum β-lactamase-producing Enterobacteriaceae (ESBL-PE).

| New drug              | *In vitro activity*                                                                 |
|-----------------------|--------------------------------------------------------------------------------------|
| Ceftazidime–avibactam | ESBL, AmpC, *Klebsiella pneumoniae* carbapenemase (KPC), OXA-48                       |
|                       | Not active against metallo-β-lactamase (MBL)                                        |
| Ceftaroline–avibactam | ESBL, Methicillin-resistant *Staphylococcus aureus* AmpC KPC OXA-48?                 |
| Ceftolozane–tazobactam| ESBL, Some AmpC, Multidrug-resistant *Pseudomonas aeruginosa*                        |
| Imipenem–relebactam   | ESBL, AmpC, KPC, OXA-48, Not active against MBL                                      |
| Plazomicin            | ESBL, AmpC, KPC, OXA, VIM, Not active against some NDM                                |

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References

1. Morrissey I, Hackel M, Badal R, et al.: A Review of Ten Years of the Study for 
Monitoring Antimicrobial Resistance Trends (SMART) from 2002 to 2011. 
*Pharmaceuticals (Basel)*. 2013; 6(11): 1335–46. 
PubMed Abstract | Publisher Full Text | Free Full Text

2. Fokas ME, Karamika S, Alevizakos M, et al.: Prevalence of ESBL-Producing 
Enterobacteriaceae in Pediatric Bloodstream Infections: A Systematic Review 
and Meta-Analysis. *PLoS One*. 2012; 7(1): e0171216. 
PubMed Abstract | Publisher Full Text | Free Full Text | F1000 Recommendation

3. Lee SY, Kotapati S, Kull JL, et al.: Impact of extended-spectrum 
β-lactamase-producing *Escherichia coli* and *Klebsiella* species on clinical 
outcomes and hospital costs: a matched cohort study. *Infect Control Hosp 
Epidemiol.* 2006; 27(11): 1226–32. 
PubMed Abstract | Publisher Full Text | F1000 Recommendation

4. Maślikowska JA, Walker SA, Elligsen M, et al.: Impact of infection with 
extended-spectrum β-lactamase-producing *Escherichia coli* or *Klebsiella* 
species on outcome and hospitalization costs. *J Hosp Infect*. 2016; 92(1): 
33–41. 
PubMed Abstract | Publisher Full Text | F1000 Recommendation

5. Biehl LM, Schmidt-Hieber M, Liss B, et al.: Colonization and infection with 
extended spectrum β-lactamase producing Enterobacteriaceae in high-risk
patients - Review of the literature from a clinical perspective. Crit Rev Microbiol. 2016; 42(1): 1–16. Published Abstract | Publisher Full Text | F1000 Recommendation

6. Escalier O, Schermer V, Carmeli Y, et al: Comparison of Predictors and Mortality Between Bloodstream Infections Caused by ESBL-Producing Enterobacteriaceae and ESBL-Producing Klebsiella pneumoniae. Infection Control Hosp Epidemiol. 2018; 39(6): 660–7. Published Abstract | Publisher Full Text | F1000 Recommendation

7. Papp-Walace KM, Endimiani A, Tanaka MA, et al: Carbapenems: past, present, and future. Antimicrob Agents Chemother. 2011; 55(11): 4943–60. Published Abstract | Publisher Full Text | Free Full Text

9. Tamma PD, Lin SY, Chang YT, et al: Carbapenem therapy is associated with improved survival compared with piperacillin-tazobactam for patients with extended-spectrum beta-lactamase bacteremia. Clin Infect Dis. 2015; 60(9): 1319–25. Published Abstract | Publisher Full Text | Free Full Text

10. Cannon JP, Lee TA, Clark NM, et al: The risk of seizures among the carbapenems: a meta-analysis. J Antimicrob Chemother. 2014; 69(9): 2043–55. Published Abstract | Publisher Full Text | Free Full Text

13. Gutiérrez-Gutiérrez B, Bonomo RA, Carmeli Y, et al: Ertapenem for the treatment of bloodstream infections due to ESBL-producing Enterobacteriaceae: a multinational pre-registered cohort study. J Antimicrob Chemother. 2012; 67(12): 2793–803. Published Abstract | Publisher Full Text | Free Full Text | F1000 Recommendation

14. Kang CI, Chung DR, Ko JH, et al: Risk factors for infection and treatment outcome of extended-spectrum beta-lactam-producing Klebsiella pneumoniae bacteremia in patients with hematologic malignancy. Ann Hematol. 2012; 91(1): 115–21. Published Abstract | Publisher Full Text | Free Full Text

15. Rodrigues-Baño J, Navarro MD, Retamar P, et al: Lactam–lactam inhibitor combinations for the treatment of bacteremia due to Enterobacteriaceae producing extended-spectrum beta-lactamasems: a systematic review and meta-analysis. J Antimicrob Chemother. 2012; 67(12): 2793–803. Published Abstract | Publisher Full Text | Free Full Text | F1000 Recommendation

23. Pilmis B, Jullien V, Tabah A, et al: Piperacillin-tazobactam as alternative to carbapenems for ICU patients. Ann Intern Med. 2017; 167(5): 113. Published Abstract | Publisher Full Text | Free Full Text | F1000 Recommendation

24. Harris PN, Peleg AY, Indelj J, et al: Meropenem versus piperacillin-tazobactam for definitive treatment of bloodstream infections due to ceftriaxone non-susceptible Klebsiella pneumoniae. J Antimicrob Chemother. 2015; 70(1): 106–12. Published Abstract | Publisher Full Text | Free Full Text | F1000 Recommendation

25. Tamma PD, Villegas MV: Use of β-Lactam/β-Lactamase Inhibitors for Extended-Spectrum β-Lactamase Infections: Defining the Right Patient Population. Antimicrob Agents Chemother. 2017; 61(8): pii: e01064-17. Published Abstract | Publisher Full Text | Free Full Text

26. Wang R, Cosgrove SE, Tsucllid-Sutter S, et al: Ceftolozane/Tazobactam for Ceftolozane/Tazobactam Susceptible Extended-Spectrum β-Lactamase-Producing Enterobacteriaceae. Open Forum Infect Dis. 2016; 3(3): ofw132. Published Abstract | Publisher Full Text | Free Full Text | F1000 Recommendation

27. Gnetto K, Van Looveren M, Lamadieu C, et al: High-dose cefepime as an alternative treatment for infections caused by TEM-44 ESBL-producing Enterobacter aerogenes in severely ill patients. Clin Microbiol Infect. 2006; 12(1): 56–62. Published Abstract | Publisher Full Text | Free Full Text

28. Chopra T, Marchaim D, Veltman J, et al: Impact of cefepime therapy on mortality among patients with bloodstream infections caused by extended-spectrum β-lactamase-producing Klebsiella pneumoniae and Escherichia coli. Antimicrob Agents Chemother. 2012; 56(7): 3936–42. Published Abstract | Publisher Full Text | Free Full Text | F1000 Recommendation

29. Zanetti G, Bally F, Greub G, et al: Ceftoliuzane and tazobactam for treatment of nosocomial pneumonia in intensive care unit patients: a multicenter, evaluator-blind, prospective, randomized study. Antimicrob Agents Chemother. 2003; 47(11): 3442–7. Published Abstract | Publisher Full Text | Free Full Text | F1000 Recommendation

30. Lee NY, Lee CC, Huang WH, et al: Ceftolozane therapy for monomicrobial bacteremia caused by ceftolozane-susceptible extended-spectrum beta-lactamase-producing Enterobacteriaceae: MIC matters. Clin Infeot Dis. 2013; 56(4): 486–95. Published Abstract | Publisher Full Text | Free Full Text

31. Tamma PD, Rodriguez-Baro J: The Use of Noncarbapenem β-Lactams for the Treatment of Extended-Spectrum β-Lactamase Infections. Clin Infeot Dis. 2017; 64(2): 972–90. Published Abstract | Publisher Full Text | Free Full Text | F1000 Recommendation

32. Falagas ME, Voulomianou EK, Samonis G, et al: Fosfomycin. Clin Microbiol Rev. 2016; 29(2): 312–47. Published Abstract | Publisher Full Text | Free Full Text | F1000 Recommendation

36. Rosso-Fernández C, Sojo-Dorado J, Barriga A, et al: Pharmacokinetic and pharmacodynamic characteristics of fosfomycin for the treatment of infections caused by multidrug-resistant non-fermenting Gram-negative bacilli: a systematic review of microbiological, animal and clinical studies. Int J Antimicrob Agents. 2009; 34(6): 506–15. Published Abstract | Publisher Full Text | Free Full Text

46. Eusebio HR, Dharnidharka VR, et al: Macrolides for the treatment of infections caused by multidrug-resistant non-fermenting Gram-negative bacilli: a systematic review of microbiological, animal and clinical studies. Antimicrob Agents Chemother. 2017; 62(2): 100–9. Published Abstract | Publisher Full Text | Free Full Text

50. Falagas ME, Kastoros AC, Kanaropogoules DE, et al: Fosfomycin for the Treatment of infections caused by multidrug-resistant non-fermenting Gram-negative bacilli: a systematic review of microbiological, animal and clinical studies. Int J Antimicrob Agents. 2009; 34(1): 111–20. Published Abstract | Publisher Full Text | Free Full Text

51. Bouxem H, Fournier D, Boullet K, et al: Which non-carbapenem antibiotics are
active against extended-spectrum β-lactamase-producing Enterobacteriaceae?

Int J Antimicrob Agents. 2018; 62(1): 100–3. PubMed Abstract | Publisher Full Text

42. Zhanel GG, Zhanel MA, Karlovsky JA: Oral Fosfomycin for the Treatment of Acute and Chronic Bacterial Prostatitis Caused by Multidrug-Resistant Escherichia coli. Can J Infect Dis Med Microbiol. 2018; 2018: 1604813. PubMed Abstract | Publisher Full Text | Free Full Text

43. Grabein B, Graninger W, Rodriguez Baño J, et al.: Intravenous fosfomycin-back to the future. Systematic review and meta-analysis of the clinical literature. Clin Microbiol Infect. 2017; 23(8): 563–72. PubMed Abstract | Publisher Full Text | F1000 Recommendation

44. Cha MK, Kang CI, Kim SH, et al.: In vitro activities of 21 antimicrobial agents alone and in combination with aminoglycosides or fluoroquinolones against extended-spectrum β-lactamase-producing Escherichia coli isolates causing bacteremia. Antimicrob Agents Chemother. 2015; 59(9): 5834–7. PubMed Abstract | Publisher Full Text | Free Full Text

45. Iopeci T, Seyman D, Berk H, et al.: Clinical and bacteriological efficacy of amikacin in the treatment of lower urinary tract infection caused by extended-spectrum beta-lactamase-producing Escherichia coli or Klebsiella pneumoniae. J Infect Chemother. 2014; 20(12): 762–7. PubMed Abstract | Publisher Full Text

46. Cho SY, Choi SM, Park SH, et al.: Amikacin therapy for urinary tract infections caused by extended-spectrum β-lactamase-producing Escherichia coli. Korean J Intern Med. 2016; 31(1): 156–61. PubMed Abstract | Publisher Full Text | Free Full Text | F1000 Recommendation

47. Zhanel GG, Lawson CD, Zelenitsky S, et al.: Comparison of the next-generation aminoglycoside plazomicin to gentamicin, tobramycin and amikacin. Expert Rev Anti Infect Ther. 2012; 10(4): 459–73. PubMed Abstract | Publisher Full Text | Free Full Text

48. Karaiskos I, Souli M, Giannarellou H: Plazomicin: an investigational therapy for the treatment of urinary tract infections. Expert Opin Investig Drugs. 2015; 24(11): 1601–11. PubMed Abstract | Publisher Full Text

49. Livermore DM, Mushafq S, Warner M, et al.: Activity of aminoglycosides, including ACHN-490, against carbapenem-resistant Enterobacteriaceae isolates. J Antimicrob Chemother. 2011; 66(1): 48–53. PubMed Abstract | Publisher Full Text | F1000 Recommendation

50. Walkty A, Adam H, Baxter M, et al.: In vitro activity of plazomicin against 5,015 gram-negative and gram-positive clinical isolates obtained from patients in Canadian hospitals as part of the CAnWARD study, 2011-2012. Antimicrob Agents Chemother. 2014; 58(5): 2554–63. PubMed Abstract | Publisher Full Text | Free Full Text

51. Balakrishnan I, Awad-El-Karim FM, Aali A, et al.: Temocillin use in England: clinical and microbiological efficacies in infections caused by extended-spectrum and/or derepressed AmpC β-lactamase-producing Enterobacteriaceae. J Antimicrob Chemother. 2011; 66(11): 2628–31. PubMed Abstract | Publisher Full Text

52. Laterrre PF, Witeboye X, Van de Velde S, et al.: Temocillin (6 g daily) in critically ill patients: continuous infusion versus three times daily administration. J Antimicrob Chemother. 2015; 70(3): 891–8. PubMed Abstract | Publisher Full Text

53. Mazuski JE, Gasink LB, Armstrong J, et al.: Efficacy and Safety of Ceftazidime-Avibactam Plus Metronidazole Versus Meropenem in the Treatment of Complicated Intra-abdominal Infection: Results From a Randomized, Controlled, Double-Blind, Phase 3 Program. Clin Infect Dis. 2016; 62(11): 1380–9. PubMed Abstract | Publisher Full Text | Free Full Text | F1000 Recommendation

54. Carmell Y, Armstrong J, Newell P, et al.: Ceftazidime-avibactam in ceftazidime-resistant infections. Lancet Infect Dis. 2016; 16(9): 997–8. PubMed Abstract | Publisher Full Text

55. [Internet]. AAssc-avmhawprliCg. Reference Source

56. Sucher AJ, Chahine EB, Cogan P, et al.: Ceftolozane/Tazobactam: A New Cephalosporin and β-Lactamase Inhibitor Combination. Ann Pharmacother. 2015; 49(9): 1046–56. PubMed Abstract | Publisher Full Text

57. Scott LJ: Ceftolozane/Tazobactam: A Review in Complicated Intramembranous and Urinary Tract Infections. Drugs. 2016; 76(2): 231–42. PubMed Abstract | Publisher Full Text | F1000 Recommendation

58. Merck Sharp & Dohme Corp: Ceftolozane/Tazobactam: A New Beta-Lactamase Inhibitor Combination. J Infect Chemother. 2014; 20(12): 1567–79. PubMed Abstract | Publisher Full Text

59. Solomon J, Hersherberger E, Miller B, et al.: Ceftolozane-Tazobactam Plus Metronidazole for Complicated Intra-abdominal Infections in an Era of Multidrug Resistance: Results From a Randomized, Double-Blind, Phase 3 Trial (ASPECT-clAI). Clin Infect Dis. 2015; 60(10): 1462–71. PubMed Abstract | Publisher Full Text | Free Full Text

60. LucaI C, Hersherberger E, Miller B, et al.: Multicenter, double-blind, randomized, phase II trial to assess the safety and efficacy of ceftolozane-tazobactam plus metronidazole compared with meropenem in adult patients with complicated intra-abdominal infections. Antimicrob Agents Chemother. 2014; 58(9): 5350–7. PubMed Abstract | Publisher Full Text | Free Full Text

61. Wagnerlehner FM, Umeh O, Daruich RC: Ceftolozane-tazobactam versus levofloxacin in urinary tract infection - Authors' reply. Lancet. 2015; 386(10000): 1242. PubMed Abstract | Publisher Full Text
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The referees who approved this article are:

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1. Patrice Nordmann Medical and Molecular Microbiology, Faculty of Science and Medicine, National Reference Center for Emerging Antibiotic Resistance and Foreign Researc Unit (INSERM, France) University of Fribourg, Fribourg, Switzerland
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2. Jean-Ralph Zahar Infection Control Unit, Hôpital Avicenne (AP-HP), Bobigny, France
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