



PRECISION THERAPY FOR MULTIDRUG-RESISTANT BACTERIAL INFECTIONS

¹*Mr. Manthan Bibhishan Mirkale, ²Dr. Kelgaonkar Prajakta N., ³Mr. Kamble Savidhan S.,
⁴Mr. Akshay Anand, ⁵Ms. Patil Vaishnavi

¹Student, Pharm. D 3rd Year Department of Pharmacy Practice Channabasweshwar College of Pharmacy Latur, Maharashtra, India.

^{2,3,4,5}Department of Pharmacy Practice, Channabasweshwar Pharmacy College Latur. 413512.

How to cite this Article: ¹*Mr. Manthan Bibhishan Mirkale, ²Dr. Kelgaonkar Prajakta N., ³Mr. Kamble Savidhan S., ⁴Mr. Akshay Anand, ⁵Ms. Patil Vaishnavi (2026). Precision Therapy For Multidrug-Resistant Bacterial Infections. World Journal of Advance Pharmaceutical Sciences, 3(10), 44-50.



Copyright © 2026 *Mr. Manthan Bibhishan Mirkale | World Journal of Advance Pharmaceutical Sciences

This is an open-access article distributed under creative Commons Attribution-Non Commercial 4.0 International license (CC BY-NC 4.0)

Article Info

Article Received: 18 August 2026,

Article Revised: 08 Sept. 2026,

Article Accepted: 28 Sept. 2026.

*Corresponding author:

Mr. Manthan Bibhishan Mirkale

Student, Pharm. D 3rd Year
Department of Pharmacy Practice
Channabasweshwar College of
Pharmacy Latur, Maharashtra,
India.

DOI: <https://doi.org/10.5281/zenodo.23245187>

ABSTRACT

Multidrug-resistant (MDR) bacterial infections are becoming increasingly difficult to manage because the organisms involved can withstand several commonly used antimicrobial classes. This problem is not caused by a single mechanism; antibiotic exposure, selection pressure, horizontal transfer of resistance genes, healthcare transmission and gaps in infection prevention all contribute to it. Precision therapy aims to replace prolonged guesswork with a more individualized process: identify the pathogen quickly, determine its resistance profile, consider patient-specific factors and then select the narrowest effective treatment. Rapid molecular tests, whole-genome sequencing, MALDI-TOF mass spectrometry, pharmacogenomics and artificial intelligence can support this process. Alongside conventional antibiotics, emerging approaches such as bacteriophage therapy, CRISPR-based antimicrobials, antimicrobial peptides, monoclonal antibodies and targeted nanomedicine are being investigated for difficult-to-treat infections. The field is promising, but most of these technologies still require stronger clinical validation, reliable delivery systems, standardized workflows and affordable access. Therefore, precision therapy should be viewed not as a replacement for antimicrobial stewardship, but as a way of making stewardship more informed, faster and more patient-centred.

KEYWORDS: precision therapy; multidrug-resistant bacteria; antimicrobial resistance; rapid diagnostics; pharmacogenomics; bacteriophage therapy; CRISPR; antimicrobial stewardship.

1. INTRODUCTION

Antibiotics changed the course of modern medicine, but their effectiveness is being steadily reduced by antimicrobial resistance (AMR). The global burden is substantial: the large 2019 AMR analysis estimated that bacterial AMR was directly responsible for at least 1.27 million deaths and was associated with nearly 5 million deaths worldwide.^[3] WHO continues to identify resistant bacterial pathogens as a major public-health priority, particularly carbapenem-resistant *Acinetobacter baumannii*, carbapenem-resistant *Enterobacterales* and drug-resistant *Mycobacterium tuberculosis*.^[1,2]

MDR infections are especially challenging because treatment decisions often have to be made before complete susceptibility information is available. Empirical therapy remains important in seriously ill patients, but unnecessarily broad treatment can expose the patient and the surrounding microbial community to avoidable antibiotic pressure. Once laboratory information becomes available, therapy should be refined whenever clinically appropriate. Current IDSA guidance similarly emphasizes pathogen identification, susceptibility results and pathogen-specific treatment strategies for resistant Gram-negative infections.^[24]

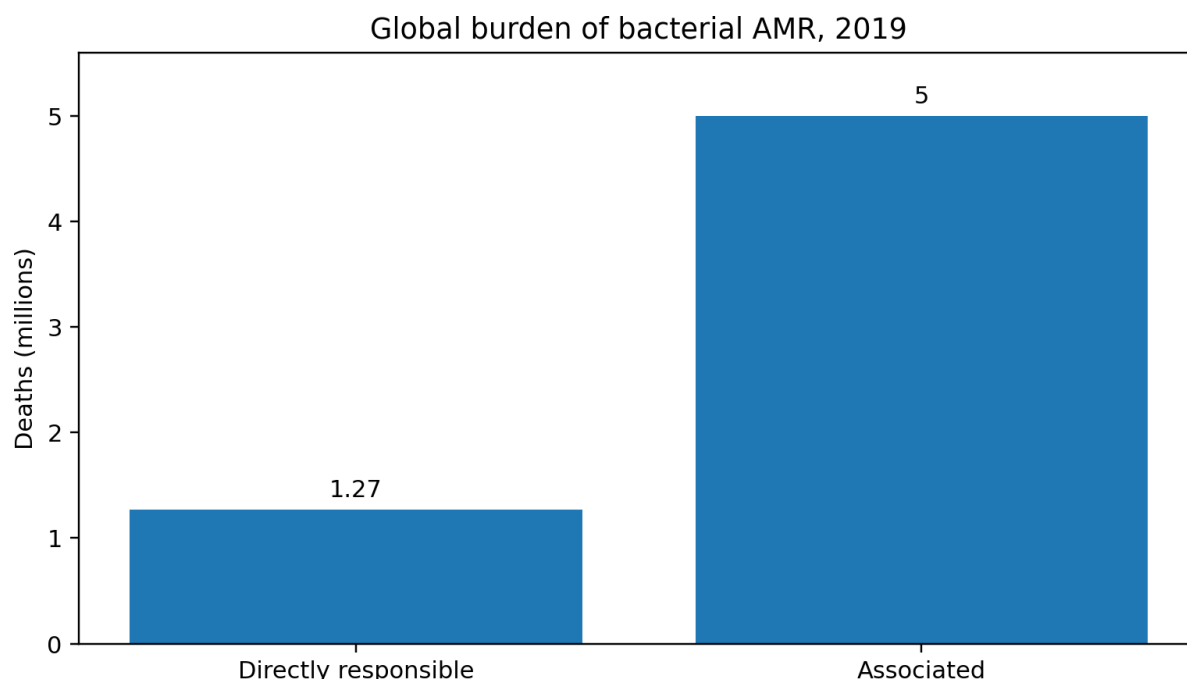


Figure 1: Global burden of bacterial antimicrobial resistance in 2019. Data reported in reference.^[3]

Precision therapy takes this idea one step further. Instead of asking only which antibiotic is usually recommended for a syndrome, it asks which treatment is most appropriate for this patient, this pathogen and this resistance pattern. Modern diagnostics can identify organisms and selected resistance determinants more quickly, while genomic and computational tools can help interpret complex data.^[9–14] The approach is therefore best understood as an integrated clinical workflow rather than as a single drug or technology.

2. Objectives of the Review

- To explain the clinical significance and major drivers of multidrug-resistant bacterial infections.
- To describe the concept and practical workflow of precision antimicrobial therapy.
- To review rapid diagnostics, genomics, pharmacogenomics and artificial intelligence as tools for individualized treatment.
- To discuss emerging targeted therapies, including phages, CRISPR-based approaches, antimicrobial peptides, antibodies and nanomedicine.
- To summarize current clinical applications, limitations and future directions.

3. Methodology

This narrative review was developed from peer-reviewed literature and authoritative guidance identified through PubMed-indexed publications, WHO reports, CDC resources and infectious-disease guidance. The search concepts included multidrug-resistant bacteria, antimicrobial resistance, precision medicine, rapid diagnostics, whole-genome sequencing, MALDI-TOF, pharmacogenomics, artificial intelligence, bacteriophage therapy, CRISPR antimicrobials, antimicrobial peptides and targeted nanomedicine. Priority was given to recent

evidence while retaining influential foundational publications needed to define MDR and explain the evolution of antimicrobial resistance. The final reference list contains 25 sources, and statements in the review are linked to the relevant references using Vancouver-style numerical citations.

4. Multidrug-Resistant Bacterial Infections

4.1 Definition

The widely used international definition describes MDR bacteria as organisms that are non-susceptible to at least one antimicrobial agent in three or more antimicrobial categories.^[4] This definition is useful for communication and surveillance, although the exact resistance pattern and its clinical meaning vary by organism, infection site and available treatment options.

4.2 How resistance develops and spreads

Resistance emerges through a combination of bacterial evolution and antimicrobial selection pressure. Mutations can alter drug targets, reduce drug entry, increase efflux or change metabolic pathways. Bacteria can also acquire resistance determinants through mobile genetic elements such as plasmids, transposons and integrons, allowing resistance traits to move between bacterial populations.^[5–7] The problem is amplified when antibiotics are used unnecessarily, at inappropriate doses or for longer than needed. Transmission in hospitals, inadequate infection control and antibiotic exposure in agriculture can further increase the reservoir and spread of resistant organisms.^[1,5–8]

4.3 Important MDR pathogens

Table 1: Important MDR bacterial pathogens highlighted in the review.

MDR pathogen group	Representative organism	Key resistance feature	Refs.
MRSA	Staphylococcus aureus	Methicillin resistance	[1,24,25]
VRE	Enterococcus faecium	Vancomycin resistance	[1,25]
ESBL-producing Enterobacterales	Enterobacterales	Extended-spectrum β -lactamase production	[1,24,25]
CRE	Enterobacterales	Carbapenem resistance	[1,24,25]
Difficult-to-treat / CRPA	Pseudomonas aeruginosa	Carbapenem or multidrug resistance	[1,24]
CRAB	Acinetobacter baumannii	Carbapenem resistance	[1,24,25]
Drug-resistant TB	Mycobacterium tuberculosis	Resistance to antitubercular agents	[1,24,25]

- Methicillin-resistant *Staphylococcus aureus* (MRSA)
 - Vancomycin-resistant *Enterococcus faecium* (VRE)
 - Extended-spectrum β -lactamase (ESBL)-producing Enterobacterales
 - Carbapenem-resistant Enterobacterales (CRE)
 - Difficult-to-treat or carbapenem-resistant *Pseudomonas aeruginosa*
 - Carbapenem-resistant *Acinetobacter baumannii* (CRAB)
 - Drug-resistant *Mycobacterium tuberculosis*
- These pathogens are not equally important in every setting, but several appear prominently in current global priority lists and clinical treatment guidance.^[1,24,25]

5. Precision Therapy: Concept and Clinical Logic

Table 2: Practical workflow for precision antimicrobial therapy.

Step	Main action	Key information
1. Clinical assessment	Assess syndrome, severity and infection site; collect an appropriate specimen.	Clinical context
2. Rapid identification	Identify the organism and, where feasible, resistance determinants.	Rapid molecular tests / MALDI-TOF
3. Susceptibility & patient factors	Combine susceptibility data with organ function, prior exposure and other patient factors.	Microbiology + clinical assessment
4. Individualized treatment	Select agent, dose, route and duration appropriate to the patient and pathogen.	Precision dosing / stewardship
5. Monitoring & refinement	Monitor response and toxicity; de-escalate or modify therapy as new information appears.	Follow-up + stewardship

Precision therapy can be viewed as a stepwise attempt to match treatment to the actual biology of an infection. The first step is accurate clinical assessment and specimen collection. The second is rapid identification of the organism and, where feasible, its resistance determinants. The third is interpretation of susceptibility data together with the infection site, disease severity, organ function, previous antimicrobial exposure and other patient factors. The final step is selection, dosing and monitoring of therapy, followed by de-escalation or modification when new information becomes available.^[9,24]

The main goals are to:

- identify the pathogen as early as possible;
- recognize clinically relevant resistance mechanisms;
- select an effective and appropriately narrow antimicrobial regimen;
- individualize dose and duration when patient factors require it;
- reduce avoidable toxicity and unnecessary antibiotic exposure; and
- support antimicrobial stewardship while improving clinical outcomes.

6. Major Components of Precision Therapy

6.1 Rapid Molecular Diagnostics

Table 3: Comparison of major diagnostic and genomic tools discussed in the review.

Tool	Main role	Potential advantage	Important limitation
PCR / multiplex molecular assays	Rapid detection of bacterial DNA and selected resistance genes	Faster than conventional culture	Interpretation must match clinical context. ^[10,11]
Rapid phenotypic	Early assessment of	Can shorten time to targeted	Availability and validation

susceptibility testing	antimicrobial susceptibility	therapy	vary. ^[10,11]
MALDI-TOF MS	Rapid organism identification; AMR applications developing	Rapid identification	Routine AMR detection remains under development. ^[11]
Whole-genome sequencing	Species, strain relationships and resistance-associated genes/mutations	Comprehensive genomic information	Genotype does not always equal phenotype. ^[12]
Metagenomic approaches	Detection and characterization of microbial DNA from clinical material	Potentially broad detection	Cost, interpretation and clinical validation remain important. ^[10-12]

Traditional culture and susceptibility testing remain essential, but they can take time. Rapid molecular methods can detect bacterial DNA or specific resistance genes earlier, which may help clinicians move from empirical treatment toward targeted therapy sooner.^[10,11] Their greatest value is achieved when the result is connected to an antimicrobial stewardship team that can interpret it in the clinical context. A rapid result by itself does not automatically improve prescribing; the result must lead to an appropriate action.^[10]

Commonly used or developing tools include PCR-based assays, multiplex panels, rapid phenotypic susceptibility testing and metagenomic approaches. These methods differ in the organisms and resistance determinants they can detect, their turnaround time, cost and need for confirmatory testing.

6.2 MALDI-TOF Mass Spectrometry

MALDI-TOF MS has become an important clinical microbiology tool because it can identify many organisms rapidly from characteristic protein spectra. Research has also explored its use for detecting antimicrobial resistance through growth-based approaches, resistance-associated spectral patterns and machine-learning interpretation.^[11] At present, its role in routine AMR detection is still developing, and laboratory validation and standardized interpretation remain important.

6.3 Whole-Genome Sequencing and Genomics

Whole-genome sequencing (WGS) can provide a detailed view of bacterial species, strain relationships and resistance-associated genes or mutations. This makes it valuable for outbreak investigation and increasingly relevant to antimicrobial susceptibility prediction.^[12] However, genomic prediction is not identical to a conventional phenotypic susceptibility result. Some resistance mechanisms are incompletely understood, gene expression may vary and the clinical meaning of a detected determinant can depend on the organism and drug. Consequently, WGS is most useful when genomic information is interpreted alongside microbiological and clinical evidence.

6.4 Pharmacogenomics and Therapeutic Individualization

Pharmacogenomics examines how inherited genetic differences influence drug response. In antimicrobial

treatment, the field is still less mature than in some other areas of medicine, but it may help identify patients at increased risk of specific adverse reactions or altered drug handling.^[13] In practice, precision dosing currently depends heavily on renal and hepatic function, age, body size, critical illness, drug interactions, therapeutic drug monitoring and infection characteristics. Pharmacogenomics may complement these established factors rather than replace them.

6.5 Artificial Intelligence and Machine Learning

AI and machine-learning systems can analyze large clinical, microbiological and genomic datasets. Potential applications include estimating the probability of resistance before final susceptibility results, identifying patterns in MALDI-TOF spectra, supporting antimicrobial selection and monitoring treatment response.^[11,14] Recent work highlights that the clinical usefulness of these models depends not only on predictive accuracy but also on data quality, external validation, calibration, interpretability and integration into real clinical workflows.^[14] AI should therefore support clinical judgment rather than function as an unsupervised prescribing system.

6.6 Bacteriophage Therapy

Bacteriophages are viruses that infect bacteria and can kill their bacterial hosts. Their specificity makes them attractive for difficult infections because a selected phage may attack the pathogen while causing less disruption to unrelated members of the microbiota.^[15,16] Modern phage therapy may involve naturally occurring phages, phage cocktails or engineered phages selected according to the patient's isolate. Clinical translation remains challenging because phages often have a narrow host range, bacteria can develop phage resistance, manufacturing and quality control are demanding, and regulatory pathways differ across countries.^[15-17]

6.7 CRISPR-Cas-Based Antimicrobials

CRISPR-Cas systems provide programmable nucleic-acid targeting and have been investigated as a way to selectively damage bacterial genomes or target resistance determinants. The theoretical advantage is precision: instead of broadly suppressing many bacteria, a CRISPR construct can be designed around a sequence found in a selected pathogen or resistance element.^[18] The main translational problem is delivery. Getting the CRISPR machinery into the correct bacterial population at the

infection site, while avoiding unintended effects and maintaining activity in vivo, remains a major challenge.^[18]

6.8 Antimicrobial Peptides

Antimicrobial peptides (AMPs) are a diverse group of molecules that can act through membrane disruption, intracellular effects and immune modulation. Their mechanisms differ from many conventional antibiotics, which makes them attractive against MDR organisms.^[19] However, toxicity, stability, pharmacokinetics, peptide degradation and the possibility of bacterial adaptation can limit clinical use. Research is increasingly focused

on peptide engineering and combinations with existing antibiotics to improve selectivity and efficacy.^[19,20]

6.9 Monoclonal Antibodies and Targeted Immunotherapy

Monoclonal antibodies can recognize defined bacterial surface structures or virulence-associated targets. This approach may provide highly specific prevention or adjunctive treatment while reducing reliance on broad-spectrum antibiotics.^[21] Evidence is still developing, and success depends on identifying clinically useful targets, achieving adequate tissue exposure and demonstrating meaningful patient benefit.

6.10 Nanotechnology-Based Delivery

Table 4: Emerging precision-oriented therapies for MDR bacterial infections.

Approach	Primary action	Potential value	Key challenge
Bacteriophages	Specific bacterial killing	Narrow host targeting; microbiota-sparing potential	Host range, phage resistance, manufacturing and regulation. ^[15-17]
CRISPR-Cas antimicrobials	Programmable targeting of bacterial genomes/resistance determinants	High sequence specificity	Delivery into the correct bacterial population. ^[18]
Antimicrobial peptides	Membrane disruption, intracellular effects and immune modulation	Mechanistically diverse activity	Toxicity, stability and pharmacokinetics. ^[19,20]
Monoclonal antibodies	Target bacterial surface structures or virulence factors	Highly specific adjunctive treatment/prevention	Target selection and adequate tissue exposure. ^[21]
Nanoparticle delivery	Improve antimicrobial stability, distribution or local concentration	Targeted delivery potential	Safety, biodistribution, scale-up and regulation. ^[22,23]

Nanoparticles and related delivery systems can be designed to improve the stability, solubility, distribution or local concentration of antimicrobial agents. Liposomes, polymeric nanoparticles and metallic nanomaterials have been investigated for targeted delivery and activity against resistant bacteria.^[22,23] The concept is promising, but safety, reproducibility, biodistribution, manufacturing scale-up and regulatory requirements must be resolved before widespread clinical use.

7. Clinical Applications

The practical value of precision therapy is most apparent in infections where treatment delays are dangerous or the probability of resistance is high. Potential and emerging applications include:

- bloodstream infections and sepsis, where rapid identification can shorten the period of uncertain therapy.^{[10];}
- hospital-acquired and ventilator-associated pneumonia caused by resistant Gram-negative bacteria;
- complicated urinary tract infections caused by ESBL-producing or other MDR organisms;
- chronic wound and device-associated infections where biofilms and repeated antimicrobial exposure complicate treatment;

- tuberculosis, where resistance patterns directly influence drug selection and treatment duration; and
- outbreak investigation, where genomic data can help identify transmission links and resistance patterns.^[12]

Precision approaches do not eliminate the need for empirical therapy in critically ill patients. Rather, they aim to shorten the period of uncertainty and make subsequent treatment more targeted. Current guidance for resistant Gram-negative infections illustrates this principle by linking treatment choices to the organism, resistance mechanism and susceptibility profile.^[24]

8. Advantages

- Earlier identification of the causative organism and selected resistance determinants.
- Faster movement from broad empirical treatment to pathogen-directed therapy.
- Potential reduction in unnecessary antibiotic exposure and collateral microbiome damage.
- More informed dose selection and monitoring for patients with unusual pharmacokinetic characteristics.
- Better outbreak detection and infection-control decision making through genomic surveillance.
- Potential access to highly specific non-traditional therapies for infections with few remaining options.

9. Limitations and Challenges

Precision therapy is not automatically precise simply because a test is technologically advanced. Several barriers can prevent a laboratory result from becoming a useful clinical decision.

- High cost of sequencing platforms, specialized diagnostics and some targeted therapies.
- Unequal access to advanced laboratories, especially in resource-limited settings.
- Need for trained microbiologists, pharmacists, clinicians, bioinformaticians and data-science support.
- Incomplete understanding of genotype–phenotype relationships for some resistance mechanisms.^[12]
- Potential false-positive or clinically irrelevant molecular findings when colonization is mistaken for infection.
- Data privacy, cybersecurity, interoperability and governance issues when genomic and clinical data are combined.
- Regulatory uncertainty for phages, CRISPR-based products, engineered biological agents and some nanomedicines.
- Limited high-quality clinical trial evidence for many emerging therapies compared with established antibiotics.^[15–23]
- Risk of overreliance on AI models when datasets are biased, poorly validated or not representative of the local population.^[14]

10. Future Perspectives

The future of precision antimicrobial therapy is likely to depend on combining several technologies rather than relying on one diagnostic or therapeutic platform. Routine WGS may become more practical as sequencing and interpretation become faster and less expensive.^[12] AI may help integrate laboratory, genomic and clinical data, provided models are transparent and independently validated.^[14] Phage engineering, CRISPR-based antimicrobials, antimicrobial peptides, antibody-based strategies and targeted drug-delivery systems may expand the therapeutic options for infections in which conventional antibiotics are failing.^[15–23]

Another important direction is precision antimicrobial stewardship. The goal is not simply to prescribe a 'stronger' drug, but to choose the right agent, dose, route and duration for the individual infection while preserving future antibiotic effectiveness. WHO's recent work on antibacterial development emphasizes the need for innovation that addresses high-priority resistant pathogens while also considering access and affordability.^[1,8,23]

11. CONCLUSION

Precision therapy offers a more individualized way to manage MDR bacterial infections. By bringing together rapid diagnostics, genomic information, clinical assessment, susceptibility testing, pharmacological

principles and targeted therapies, it can make antimicrobial decisions more timely and better matched to the pathogen and patient. The strongest current clinical foundation remains rapid diagnosis combined with expert antimicrobial stewardship, while technologies such as phages, CRISPR, antimicrobial peptides, antibodies and nanomedicine represent promising extensions of this approach.^[10,15–24] Most emerging technologies still need stronger clinical evidence, standardized manufacturing, regulatory clarity and wider access. The long-term objective should therefore be a practical, affordable precision workflow that improves patient care without creating new forms of avoidable antimicrobial pressure.

REFERENCES (Vancouver Style)

1. World Health Organization. WHO bacterial priority pathogens list, 2024: bacterial pathogens of public health importance to guide research, development and strategies to prevent and control antimicrobial resistance. Geneva: WHO, 2024.
2. World Health Organization. Antimicrobial resistance. Geneva: WHO, 2026.
3. Antimicrobial Resistance Collaborators. Global burden of bacterial antimicrobial resistance in 2019: a systematic analysis. *Lancet*, 2022; 399(10325): 629–655. doi:10.1016/S0140-6736(21)02724-0.
4. Magiorakos AP, Srinivasan A, Carey RB, Carmeli Y, Falagas ME, Giske CG, et al. Multidrug-resistant, extensively drug-resistant and pandrug-resistant bacteria: an international expert proposal for interim standard definitions for acquired resistance. *Clin Microbiol Infect*, 2012; 18(3): 268–281.
5. Ventola CL. The antibiotic resistance crisis: part 1: causes and threats. *P T.*, 2015; 40(4): 277–283.
6. Davies J, Davies D. Origins and evolution of antibiotic resistance. *Microbiol Mol Biol Rev.*, 2010; 74(3): 417–433.
7. Laxminarayan R, Duse A, Wattal C, Zaidi AKM, Wertheim HFL, Sumpradit N, et al. Antibiotic resistance—the need for global solutions. *Lancet Infect Dis.*, 2013; 13(12): 1057–1098.
8. O'Neill J. Tackling drug-resistant infections globally: final report and recommendations. London: Review on Antimicrobial Resistance, 2016.
9. Jung N, Schommers P, Leisse C. Precision medicine in infectious diseases. *Inn Med (Heidelberg)*, 2024; 65(3): 220–227. doi:10.1007/s00108-023-01620-z.
10. Peri AM, Chatfield MD, Ling W, Furuya-Kanamori L, Harris PNA, Paterson DL. Rapid diagnostic tests and antimicrobial stewardship programs for the management of bloodstream infection: what is their relative contribution to improving clinical outcomes? A systematic review and network meta-analysis. *Clin Infect Dis.*, 2024; 79(2): 502–515. doi:10.1093/cid/ciae234.
11. Singla S, Murk F, Singla B, Lama S, Fareed MU, Anika NN. Enhancing bloodstream infection management: a systematic review of rapid diagnostic tests and their integration into

- antimicrobial stewardship programs. *Cureus.*, 2025; 17(9): e92866. doi:10.7759/cureus.92866.
12. Samuelsen Ø, López-Causapé C, Aarestrup FM, et al. The role of whole genome sequencing in antimicrobial susceptibility prediction of bacteria: 2025 update from the European Committee on Antimicrobial Susceptibility Testing Subcommittee. *Clin Microbiol Infect.*, 2026; 32(7S): S1-S34. doi:10.1016/j.cmi.2026.05.012.
 13. Lim G, et al. Pharmacogenomic considerations in antibiotic therapy: a pathway to personalized medicines with antibiotic use. *Nurs Clin North Am.*, 2025. doi:10.1016/j.cnur.2024.12.009.
 14. Bonomo RA, Hujer AM. Enhancing clinical utility of AI-based antimicrobial resistance models: a perspective. *mBio.*, 2026; 17(7): e0077626. doi:10.1128/mbio.00776-26.
 15. Kim MK, Suh GA, Cullen GD, et al. Bacteriophage therapy for multidrug-resistant infections: current technologies and therapeutic approaches. *J Clin Invest.*, 2025; 135(5): e187996. doi:10.1172/JCI187996.
 16. Malik DJ, Nir-Paz R, Pirnay JP, et al. Phage therapy. *Nat Rev Methods Primers.*, 2025; 5: 9. doi:10.1038/s43586-024-00377-5.
 17. Bacterial phage therapy in women with chronic recurrent cystitis caused by multidrug-resistant bacteria: a prospective, observational, comparative study. *Urol-related clinical study.*, 2025. doi:10.1097/CU9.0000000000000268.
 18. Wizrah MSI. CRISPR-Cas systems as next-generation antimicrobials: a systematic review of mechanisms, delivery strategies, and translational challenges. *Front Microbiol.*, 2026; 17: 1747931. doi:10.3389/fmicb.2026.1747931.
 19. Fodor A, Abate BA, Deák P, et al. Multidrug resistance (MDR) and collateral sensitivity in bacteria, with special attention to genetic and evolutionary aspects and to the perspectives of antimicrobial peptides—a review. *Pathogens.*, 2020; 9(7): 522. doi:10.3390/pathogens9070522.
 20. Yang J, Zhang J, Feng Z, Ma Y. The role and mechanisms of antimicrobial peptides in overcoming multidrug-resistant bacteria. *Molecules.*, 2024; 30(1): 128. doi:10.3390/molecules30010128.
 21. Slarve MJ, Tkaczyk C, Doyle MP, et al. Monoclonal antibodies targeting bacterial infections: a broad review of the field. *BioDrugs.*, 2026; 40(4): 641-671. doi:10.1007/s40259-026-00787-9.
 22. Lei Z, Sun T, et al. Research progress of nanoparticle targeting delivery systems in bacterial infections. 2023. PMID:37453264.
 23. Nanomaterial -based drug delivery systems in overcoming bacterial resistance: current review. 2025. PMID:40057006.
 24. Tamma PD, Heil EL, Justo JA, Mathers AJ, Satlin MJ, Bonomo RA. Infectious Diseases Society of America 2024 guidance on the treatment of antimicrobial-resistant Gram-negative infections. *Clin Infect Dis.*, 2024; 79(5): 1109-1125. doi:10.1093/cid/ciae403.
 25. Centers for Disease Control and Prevention. Antibiotic Resistance Threats in the United States, 2019. Atlanta (GA): US Department of Health and Human Services, CDC, 2019.