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Mechanisms of Antibiotic Effectiveness against Pathogenic Bacteria: A Literature Review

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Abstract

Antibiotics have become one of the most influential discoveries in the history of medicine due to their ability in reducing mortality rates from bacterial infections. In general, the mechanism of antibiotics can be divided into two types: bacteriostatic, which inhibits bacterial growth, and bactericidal, which kills bacteria directly. This article reviews various literatures on the effectiveness of several antibiotics that are often prescribed in health services such as amoxicillin, ciprofloxacin, metronidazole, azithromycin, ceftriaxone, amikacin, and gentamicin, as well as their specific correlation with pathogenic bacteria that cause infection. We discovered that the effectiveness of antibiotics is greatly influenced by molecular targets, dosages, environmental conditions, and usage patterns. Inappropriate use, in terms of antibiotic selection and dosage, has been shown to contribute to the emergence of resistance through gene mutation mechanisms and metabolic changes in bacteria. This situation has made antibiotic resistance a serious challenge in clinical practice and global public health. Therefore, a more rational, selective, and evidence-based antibiotic usage strategy is needed to maintain the effectiveness of therapy and reduce the rate of pathogenic bacterial resistance.

Keywords: Antibiotic; Bacteria; Effectiveness; Mechanisms

Introduction

Antibiotics represent one of the most significant breakthroughs in modern medicine. The discovery of penicillin by Alexander Fleming in 1928 revolutionized the treatment of infectious diseases, providing a powerful tool to cure illnesses and reduce mortality. Between 1950 and 2017, the availability of antibiotics contributed to a decline in infant mortality rates from 216 to 39 per 1,000 live births and an increase in male life expectancy from 48 to 71 years [3]. Their widespread use also replaced many traditional remedies, such as herbal preparations and natural extracts, with faster and more reliable therapeutic alternatives [11].

Antibiotics act by targeting pathogenic microorganisms, with mechanisms generally classified as either bacteriostatic, which inhibit bacterial growth, or bactericidal, which directly kill bacteria [17]. However, prolonged and excessive use of antibiotics has accelerated the emergence of resistance through bacterial genetic mutations. The Global Burden of Diseases, Injuries, and Risk Factors Study [15] reported that 7.7 million deaths were attributable to infections caused by only 33 bacterial species, highlighting the urgent threat of antimicrobial resistance. Moreover, high-dose antibiotic administration not only fails to address resistance but

may also impose adverse effects on human health.

This review examines current literature on the effectiveness of antibiotics in inhibiting bacterial growth and eliminating pathogens. Particular emphasis is given to their specificity against different bacterial strains. By integrating existing evidence, this article aims to provide insights that support the optimization of antibiotic use and contribute to global efforts in reducing antimicrobial resistance.

Materials and Methods

This article will review several publications that discussing antibiotics that are frequently prescribed in hospitals. Some of these publications will discuss the specific mechanisms of action of antibiotics against pathogens. Data from these publications will be categorized and analyzed in terms of their effectiveness. The analysis will be conducted thoroughly to avoid bias and any questionable data will be resolved through further review or comparison between sources. Therefore, that the results of this review can provide a comprehensive picture of the effectiveness of antibiotics against pathogenic bacteria.

Results and Discussion

Antibiotics prescribed in hospitals

The need for antibiotics around the world will certainly vary depending on healthcare services and needs of each patient. This makes it difficult to standardize data collection. The literature from [27] uses WHO criterias to record frequently prescribed antibiotics. The literature explains that patients are often prescribed antibiotics from the penicillin class, followed by antibiotics from the macrolide, aminoglycoside, and fluoroquinolone classes. Antibiotics in these classes are known to have a large spectrum. The prevalence of prescribing the same antibiotics will lead to a rapid rate of antibiotic resistance. High prescription rates, without an even prevalence of antibiotics, will become a critical condition. This condition has apparently been occurring for the last two decades, emphasizing the need for a review of antibiotic use management [17].

Bacteriostatic or Bactericidal

The mechanism of action of antibiotics in fighting bacterial cells is generally divided into two categories. Bactericidal is the way antibiotics work by directly killing bacterial cells, while bacteriostatic tends to inhibit cell growth so that bacteria will die slowly [17]. Determining whether an antibacterial agent is bactericidal or bacteriostatic in in vitro microbiological testing can be influenced by growth conditions, bacterial inoculum density, testing duration, and the extent of bacterial reduction [27].

Research conducted by [6] states that fluoroquinolones and β-lactams are classified as bactericidal antibiotics because they be able to completely eliminate infectious agents. Fluoroquinolones work on bacterial DNA metabolism by inhibiting the DNA gyrase enzyme (topoisomerase II), which ultimately causes DNA fragmentation. Meanwhile, β-lactam antibiotics, including penicillin, work by

inhibiting the synthesis of bacterial cell walls. Conversely, clindamycin and chloramphenicol are examples of bacteriostatic antibiotics, which work by suppressing or stopping bacterial growth, mainly through the mechanism of inhibiting protein synthesis. As a result, infectious agents become easier to eliminate by the host's immune system.

How Antibiotics Work Effectively

One of the causes of the high number of cases of antibiotic resistance in bacteria is the ineffective administration of antibiotics, both in terms of treatment of pathogenic bacteria and dosage. As a result, common infections that were previously easy to treat have now become more serious challenges, leading to high mortality rates. One of the main challenges associated with antibiotic resistance is the slow pace of new antibiotic development. Therefore, this review will provide several effective ways antibiotics work and their specific pathogens, which can be seen in Table 1.

The antibiotics presented in Table 1 are those analyzed from the collected references. Several of these antibiotics are frequently prescribed in hospital settings due to their broad-spectrum activity. Amoxicillin is one of the large-spectrum antibiotics that could kill almost whole bacteria. These antibiotics work by directly killing bacterial cells. This mechanism occurs when the formation of bacterial cell wall is inhibited by penicillin-binding proteins (PBP), that causing the cell wall to weaken and ultimately leading to cell rupture and bacterial death [24]. This ability causes a large amount of amoxicillin waste to be discharged into water. A report by [14] shows that antibiotic contamination in water can be degraded with the help of oxidized activated carbon.

Ciprofloxacin is a fluoroquinolone antibiotic that is widely used in the treatment of various diseases. Ranging from chronic otitis media, endocarditis, lower respiratory tract infections, gastrointestinal disorders, skin infections, to urinary tract infections [23]. This class of antibiotics usually works by inhibiting the DNA topoisomerase enzyme, causing DNA damage. These antibiotics are important in clinical practice, but their detailed mechanism of action is not yet fully understood [19]. Research by [22] states that the difficult-to-detect mechanism of ciprofloxacin causes a lot of resistance by bacteria.

Metronidazole is commonly used with good results in treating infections caused by microorganisms that live without oxygen (anaerobic) or with low oxygen levels (microaerophilic) [13]. This drug is activated through a reduction process by redox enzymes under anaerobic conditions, producing toxic nitro free radicals. These radicals bind to DNA, causing structural damage and replication inhibition, resulting in bacterial cell death [8]. The action of this antibiotic can be inhibited in the presence of oxygen. Research by [7] states that oxygen attracts electrons more easily than metronidazole. As a result, the active radicals needed are not optimally formed, and oxygen can even regenerate metronidazole through a toxic cycle or inhibit its absorption. This condition explains why the effectiveness of metronidazole can be reduced and bacteria become more resistant to the drug. Therefore, health services have to identify the pathogenic bacteria infecting the patient first.

Table 1. Results of analysis of various literature regarding the mechanisms of antibiotics

Antibiotics	Pathogens	Mechanisms (Bacteriostatic or Bactericidal)	References
Amoxicillin	*Streptococcus pneumoniae, Haemophilus influenzae, Escherichia coli, Moraxella catarrhalis*	Bactericidal	[24] [14]
Ciprofloxacin	*Pseudomonas aeruginosa* (Gram positive and gram negative bacterias)	Bacteriostatic	[23] [19] [22] [16]
Metronidazole	*Trichomonas vaginalis, spirochaeta, Helicobacter pylori*, protozoa like *Entamoeba histolytica*, and *Giardia lamblia*	Bactericidal	[13] [7] [8]
Azithromycin	*Neisseria gonorrhoeae, Moraxella catarrhalis, Legionella* sp., *Chlamydia* sp.	Bacteriostatic	[12] [10] [26]
Ceftriaxone	*Escherichia coli, Klebsiella sp.,* Proteus *sp., Enterobacter sp., Serratia sp., Streptococcus agalactiae, Staphylococcus aureus*	Bactericidal	[1]
Amikacin	*Nontuberculous mycobacteria (whole mycobacteria except M. tuberculosis, M. leprae, and M. ulcerans)*	Bactericidal	[25] [4] [21] [9]
Gentamicin	*Escherichia coli, Klebsiella pneumoniae, Serratia sp., Enterobacter sp., Pseudomonas aeruginosa, Haemophilus genera,* and some *Neisseria sp., Moraxella sp* strains.	Bactericidal	[5] [18] [9]

Azithromycin (AZM) works by inhibiting protein synthesis in bacteria through binding to the 50S ribosomal subunit, thereby inhibiting bacterial growth. Additionally, AZM also has immunomodulatory effects, such as suppressing the production of proinflammatory cytokines, reducing neutrophil infiltration, and affecting macrophage polarization [12]. Its antimicrobial activity increases under alkaline pH conditions because the un-ionized form more easily penetrates cell membranes. This drug binds to the 23S rRNA portion of the peptide exit tunnel, thereby disrupting the protein translation process [26]. Research by [10] found that antibiotic resistance can occur due to, among other things, overexpression of efflux pumps (MtrCDE), mutations in the 23S rRNA gene, and methylation of ribosomal subunits by the erm gene, all of which reduce azithromycin's ability to bind to its target. Ceftriaxone is a bactericidal antibiotic that works by inhibiting bacterial cell wall synthesis. This drug has good penetration into cerebrospinal fluid, making it effective in the treatment of meningitis caused by sensitive bacteria [1]. This antibiotic is very effective when given to newborns, so it is widely prescribed in health services.

Amikacin and gentamicin are aminoglycoside antibiotics that work by inhibiting bacterial protein synthesis. These drugs attach to the 30S ribosomal subunit, specifically to the 16S rRNA at the A decoding site. Thereby disrupting the reading of the genetic code. This error in the translation of mRNA into protein prevents bacterial proteins from forming correctly [21] [9]. Research by [4] found that aminoglycoside antibiotics tend to accumulate in kidney tissue, but the exact relationship between drug exposure levels and the risk of kidney damage is not yet clearly defined. Resistance to amikacin is achieved through mutations in 16S RNA that prevent amikacin binding. Low-level resistance is achieved through molecular transformation into inactive compounds by aminoglycoside-transforming enzymes [25].

Conclusion

This literature review confirms that the effectiveness of antibiotics is greatly influenced by their mechanism of action, whether bacteriostatic or bactericidal, as well as their suitability for use against specific pathogenic bacteria. Each class of antibiotics has specific molecular targets, ranging from inhibition of cell wall synthesis, DNA damage, to protein translation disruption, which determine the success of infection therapy. However, inappropriate antibiotic use has led to the emergence of resistance in various pathogenic bacteria through gene mutation, biofilm formation, and other defense mechanisms. This shows that the effectiveness of antibiotics depends not only on the strength of the drug, but also on the strategy of administration and management in health services. Thus, optimizing the rational and selective use of antibiotics is key to maintaining the effectiveness of therapy while reducing the rate of pathogenic bacterial resistance.

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