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ANTIBIOTIC RESISTANCE OF STAPHYLOCOCCUS AUREUS TO VARIOUS CLINICAL BIOMATERIALS: A COMPARATIVE ANALYSIS

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Abstract

Background: Antibiotic resistance is one of the most pressing global health challenges, particularly with Staphylococcus aureus, a common pathogen associated with various infections. The growing resistance of S. aureus to traditional antibiotics, especially penicillin and ampicillin, poses a significant threat to effective treatment strategies. In clinical practice, the indiscriminate use of antibiotics, particularly beta-lactams, has led to the emergence of resistant strains, necessitating continuous monitoring of resistance patterns. This study is aimed at evaluating the antibiotic resistance profile of S. aureus isolates from different biological materials and assessing their sensitivity to various antibiotics, highlighting the need for localized resistance data to optimize empirical treatment regimens.

Objective: The aim of this study was to determine the antibiotic resistance and sensitivity patterns of S. aureus isolates from five different biological samples, focusing on identifying effective treatment options for different infection sites.

Materials and Methods: This study included 726 clinical isolates of S. aureus obtained from five types of biological materials: sputum (n = 346), ENT samples (n = 322), cervical canal (n = 15), wound exudate (n = 6), and conjunctiva (n = 37). A total of 18 antibiotics were tested, representing various antibiotic classes such as beta-lactams, glycopeptides, aminoglycosides, and others. The resistance and sensitivity rates were calculated, and statistical analysis was performed using IBM SPSS Statistics.

Results: The results revealed high resistance of S. aureus to penicillin (16.9%) and ampicillin (11.7%), confirming the reduced clinical efficacy of these antibiotics. In contrast, linezolid, gentamicin, nitrofurantoin, and glycopeptides exhibited consistently high effectiveness across all biological materials, with linezolid and gentamicin showing sensitivity rates above 87%. Wound isolates displayed the highest sensitivity to gentamicin (100%) and ciprofloxacin (83.3%), while sputum and ENT samples showed greater resistance. Vancomycin and linezolid were highly effective against isolates from the cervical canal, while teicoplanin was particularly effective in eye isolates (89.2%). The study also highlighted a high level of resistance to beta-lactams and macrolides, confirming the widespread presence of beta-lactamase-producing strains in hospital settings.

Conclusion: The study underscores the growing concern over S. aureus resistance, particularly to traditional antibiotics such as penicillin and ampicillin, and the importance of local resistance monitoring. The findings support the use of linezolid, gentamicin, nitrofurantoin, and glycopeptides as key antibiotics for the empirical treatment of S. aureus infections. These results highlight the necessity of incorporating local resistance data into treatment guidelines to reduce the risk of ineffective therapy.

Keywords: *Staphylococcus aureus, antibiotic resistance, biological samples, glycopeptides, local resistance monitoring.*

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Резюме

АНТИБИОТИКОРЕЗИСТЕНТНОСТЬ STAPHYLOCOCCUS AUREUS ПО РАЗЛИЧНЫМ КЛИНИЧЕСКИМ БИОМАТЕРИАЛАМ: СРАВНИТЕЛЬНЫЙ АНАЛИЗ

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Введение: Антибиотикорезистентность является одной из самых острых проблем здравоохранения во всём мире, особенно в отношении Staphylococcus aureus, часто встречающегося возбудителя различных инфекций. Рост устойчивости S. aureus к традиционным антибиотикам, особенно к пенициллину и ампициллину, значительно снижает эффективность стандартных схем терапии. Необходимость в локальном мониторинге чувствительности штаммов становится всё более актуальной для выбора адекватного лечения.

Цель: Оценить чувствительность и устойчивость S. aureus, выделенного из различных биологических материалов, к широкому спектру антибиотиков и определить наиболее эффективные препараты для эмпирической терапии.

Материалы и методы: В исследование включены 726 клинических изолятов S. aureus, полученных из пяти видов биоматериалов: мокрота (n = 346), ЛОР-материалы (n = 322), цервикальный канал (n = 15), раневой экссудат (n = 6), конъюнктива (n = 37). Изучалась чувствительность к 18 антибиотикам, представляющим различные классы. Расчёт долей чувствительности и устойчивости выполнен с использованием Microsoft Excel и SPSS.

Результаты: Установлена высокая устойчивость к пенициллину (16,9%) и ампициллину (11,7%), что подтверждает снижение их клинической значимости. Наиболее эффективными оказались линезолид, гентамицин, нитрофурантоин и гликопептиды (чувствительность выше 87%). В образцах из ран отмечена 100% чувствительность к гентамицину, а глазные изоляты продемонстрировали высокую чувствительность к тейкопланину (89,2%). Наибольшая устойчивость отмечена в мокроте и ЛОР-материалах, тогда как глазные и раневые изоляты были более чувствительными.

Вывод: Результаты подтверждают глобальные тенденции роста устойчивости S. aureus к традиционным антибиотикам и подчёркивают необходимость локального эпидемиологического мониторинга. Линезолид, гентамицин, нитрофурантоин и гликопептиды могут быть рекомендованы для эмпирического лечения инфекций стафилококковой этиологии.

Ключевые слова: *Staphylococcus aureus, антибиотикорезистентность, биоматериалы, гликопептиды, локальный мониторинг.*

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Түйіндеме

STAPHYLOCOCCUS AUREUS БАКТЕРИЯСЫНЫҢ ӘРТҮРЛІ КЛИНИКАЛЫҚ БИОМАТЕРИАЛДАРДАҒЫ АНТИБИОТИККЕ ТҰРАҚТЫЛЫҒЫ: САЛЫСТЫРМАЛЫ ТАЛДАУ

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Кіріспе: Антибиотиктерге төзімділік – қазіргі әлемдік денсаулық сақтау саласындағы ең өзекті мәселелердің бірі. Әсіресе, жиі кездесетін инфекция қоздырғышы – Staphylococcus aureus бактериясына қатысты. Дәстүрлі антибиотиктерге, соның ішінде пенициллин мен ампициллинге төзімділіктің артуы емдеу тиімділігін төмендетеді. Осыған байланысты, жергілікті деңгейде антибиотик сезімталдығын зерттеу қажеттілігі артып отыр.

Мақсаты: Әртүрлі биологиялық материалдардан бөлініп алынған S. aureus штаммдарының антибиотиктерге төзімділік және сезімталдық үлгілерін салыстырып, инфекция түріне қарай тиімді препараттарды анықтау.

Материалдар мен әдістер: Зерттеуге бес түрлі биоматериалдан алынған S. aureus бактериясының 726 клиникалық изоляттары енгізілді: қақырық (n = 346), ЛОР үлгілері (n = 322), жатыр мойны каналы (n = 15), жара бөліндісі (n = 6), көз конъюнктивасы (n = 37). 18 антибиотикке сезімталдық зерттелді. Алынған мәліметтер Excel және SPSS бағдарламаларында өңделді.

Нәтижелер: Staphylococcus aureus штаммдарының пенициллинге (16,9%) және ампициллинге (11,7%) жоғары төзімділігі анықталды. Линезолид, гентамицин, нитрофурантоин және гликопептидтер жоғары белсенділік көрсетті (87%-дан жоғары). Жара үлгілерінде гентамицинге 100% сезімталдық байқалды, ал көз үлгілері тейкопланинге жоғары сезімтал болды (89,2%). Қақырық пен ЛОР үлгілерінде антибиотикке төзімді штаммдар жиі кездесті.

Қорытынды: Зерттеу нәтижелері S. aureus штаммдарының дәстүрлі антибиотиктерге төзімділігінің өсуі мен жергілікті мониторингтің маңыздылығын дәлелдейді. Линезолид, гентамицин, нитрофурантоин және гликопептидтер эмпириялық емдеуде тиімді таңдау бола алады.

***Түйінді* сөздер:** Staphylococcus aureus, антибиотикке төзімділік, биоматериалдар, гликопептидтер, жергілікті мониторинг.

Дәйексөз үшін: *Мукашева Г.Д., Маукаева С.Б., Кудайбергенова Н.К., Шабдарбаева Д.М., Уразалина Н.М., Горемыкина М.В., Абдрахманова Г.Ж.* Staphylococcus aureus бактериясының әртүрлі клиникалық биоматериалдардағы антибиотикке тұрақтылығы: салыстырмалы талдау // Ғылым және Денсаулық. 2025. Т.27 (2), Б. 70–77. doi: 10.34689/SH.2025.27.2.009

Introduction

Staphylococcus aureus is one of the most common pathogens in clinical practice, causing infections such as pneumonia, sepsis, and postoperative wound infections. According to the World Health Organization, antibiotic resistance in S. aureus poses a serious public health threat, leading to increased morbidity, longer hospital stays, and higher mortality rates [3].

Particular concern is raised by methicillin-resistant S. aureus (MRSA), which is responsible for a significant number of hospital-acquired infections. According to the Ministry of Health of the Republic of Kazakhstan, intensive care and resuscitation units are witnessing a rise in multi-drug resistant strains, complicating the selection of effective therapy and increasing the risk of complications [3].

Antibiotic resistance in pathogenic bacteria, including Staphylococcus aureus (S. aureus), is one of the most serious challenges in modern clinical microbiology and infectious disease medicine. Especially concerning are methicillin-resistant strains (MRSA), whose high virulence and ability to horizontally transfer resistance genes make patient management more difficult [12].

An investigation comparing MRSA isolates from surgical and medical departments found notable differences in susceptibility to β-lactam and glycopeptide antibiotics. The results suggest that department-specific antibiotic resistance patterns may influence treatment outcomes and should be considered when selecting empirical therapy in hospital settings [21].

In addition to traditionally studied sources (wounds, blood, urine), increasing attention is being paid to resistance patterns of S. aureus isolated from less common biological materials. A large-scale meta-analysis *Mebrahtu et al.* emphasized that resistance to macrolides and fluoroquinolones varied significantly between isolates from fecal samples and respiratory tracts, pointing to the need for revising empirical treatment based on the type of biological material [20].

A comparative study by *Cozma et al.,* which included bile samples, revealed a high frequency of multidrug-resistant MRSA strains in the hepatobiliary system—an infection source that had previously been underestimated in the context of complex nosocomial infections [11]. In another study, *Beker et al.* evaluated virulence genes and resistance profiles of strains isolated from animals, indicating a potential for cross-transmission of pathogens from food products to humans [6].

Among research focused on tropical countries, the study by *Hamadalneel et al.* stands out, reporting a high prevalence of multidrug resistance (MDR) in S. aureus, particularly in samples from immunocompromised patients. This aligns with earlier findings showing significant microbial profile variability in developing regions [15].

Staphylococcus aureus remains one of the most important etiological agents in surgical infections, characterized by a high degree of antibiotic resistance, particularly in hospital settings. As demonstrated in a study by *R.I. Dovnar,* up to 83% of S. aureus strains isolated from patients with purulent soft tissue infections were resistant to oxacillin, indicating the widespread presence of MRSA isolates. High resistance was also observed to macrolides, trimethoprim-sulfamethoxazole, and fluoroquinolones. Notably, resistance to reserve antibiotics such as vancomycin and linezolid began emerging in 2018. These data highlight the need for continuous monitoring of S. aureus susceptibility depending on the type of clinical specimen, as well as for selecting appropriate targeted therapy based on local microbial profiles and the evolving resistance dynamics of pathogens [2].

The relevance of studying Staphylococcus aureus antibiotic resistance is further supported by data from intensive care units. According to a study by *Butranova O.I. et al.* (2023), S. aureus accounted for 19% of all clinically significant pathogens isolated from patients with hospital-acquired infections in ICUs. Despite the predominance of Gram-negative bacteria (such as Klebsiella pneumoniae, A. baumannii, etc.), staphylococci were the second most frequent group. It is noteworthy that S. aureus showed resistance to ampicillin and cefoxitin in 70% of cases, but retained sensitivity to several reserve antibiotics, including vancomycin and linezolid [1].

Thus, the study of S. aureus antibiotic susceptibility across various biological materials remains a critical task in modern medicine, requiring ongoing surveillance and the development of effective strategies for preventing and treating infections caused by this pathogen.

The aim of this study is to conduct a comparative analysis of antibiotic resistance profiles of Staphylococcus aureus strains isolated from different clinical samples (blood, sputum, urine, wound exudate, etc.) in order to identify resistance patterns and determine possible factors

contributing to variability in antimicrobial susceptibility depending on the type of clinical specimen.

Materials and methods

This study design is observational, retrospective, and descriptive. The study included 726 clinical isolates of Staphylococcus aureus obtained from five types of biological specimens: sputum (n = 346), ENT samples (n = 322), cervical canal (n = 15), wound exudate (n = 6), and conjunctiva (n = 37).

A total of 18 antibiotics were analyzed, covering the following classes: beta-lactams (penicillins, cephalosporins), glycopeptides (vancomycin, teicoplanin), lincosamides (clindamycin), macrolides (erythromycin), fluoroquinolones, tetracyclines, oxazolidinones (linezolid), and others (nitrofurantoin, daptomycin, rifampicin, etc.).

The data were entered into Microsoft Excel for initial sorting and calculation of antibiotic sensitivity and resistance percentages. Percentages were calculated using the formula:

(Sensitive / (Sensitive + Resistant)) × 100.

Statistical analysis was carried out using IBM SPSS Statistics, applying *descriptive statistical methods.*

Results

Table 1 presents the overall number of Staphylococcus aureus strains identified as sensitive or resistant across five types of biological specimens: sputum, ENT samples, cervical canal, wound, and eye. The highest number of positive isolates was obtained from sputum (346) and ENT samples (322), while the number of isolates from the cervical canal, wounds, and eyes was considerably lower. The antibiotics gentamicin, linezolid, oritavancin, and nitrofurantoin demonstrated high absolute sensitivity rates across all specimen types, particularly in sputum and ENT samples. In contrast, penicillin and ampicillin exhibited high resistance rates, indicating limited clinical effectiveness of these drugs against S. aureus.

Table 1.

Absolute Numbers of Staphylococcus aureus Sensitivity and Resistance by Type of Clinical Specimen.

Antibiotic	Sputum (n=346)		ENT Samples (n=322)		Cervical Canal (n=15)		Wound (n=6)		Eyes (n=37)	
	Sens.	Res.	Sens.	Res.	Sens.	Res.	Sens.	Res.	Sens.	Res.
Penicillin	64	282	22	300	5	10	5	1	7	30
Oxacillin	90	256	170	152	6	9	4	2	9	28
Ceftaroline	291	55	220	102	10	5	4	2	28	9
Oritavancin	300	46	290	32	12	3	3	3	32	5
Ciprofloxacin	292	54	280	42	11	4	5	1	25	10
Tetracycline	182	164	282	40	8	7	4	2	17	20
Gentamicin	301	45	284	38	10	5	6	0	31	6
Trimethoprim	263	83	300	22	11	4	4	2	30	7
Rifampin	184	162	250	72	6	9	3	3	15	22
Clindamycin	177	169	273	49	7	8	4	2	20	17
Ampicillin	48	298	23	299	4	11	2	4	8	29
Cefoxitin	150	196	162	160	6	9	3	3	12	25
Teicoplanin	274	72	163	159	9	6	3	3	33	4
Vancomycin	268	78	217	105	11	4	4	2	28	9
Moxifloxacin	171	175	200	122	10	5	4	2	22	15
Linezolid	290	56	302	20	9	6	4	2	31	6
Nitrofurantoin	293	53	298	24	10	5	5	1	30	7
Daptomycin	169	177	110	212	9	6	2	4	15	22
Erythromycin	170	176	142	180	8	7	3	3	20	17

Table 2 shows the percentage of sensitive Staphylococcus aureus strains across different types of clinical specimens. Gentamicin demonstrated the highest activity in wound isolates (100%), as well as high effectiveness in sputum (87%) and ENT samples (88.2%). Linezolid, oritavancin, and nitrofurantoin also showed consistently strong activity across all sample types, with sensitivity levels exceeding 85%. In contrast, penicillin-group antibiotics and ampicillin exhibited very low effectiveness, with sensitivity rates not exceeding 20% in any of the tested specimens. These findings confirm the widespread resistance of S. aureus to traditional beta-lactam antibiotics.

Table 2.

Percentage of Staphylococcus aureus Sensitivity to Antibiotics by Biological Material.

Antibiotic	Sputum (%)	ENT organs (%)	Cervical canal (%)	Wound (%)	Eyes (%)
1	2	3	4	5	6
Penicillin	18.5	6.8	33.3	83.3	18.9
Oxacillin	26.0	52.8	40.0	66.7	24.3
Ceftaroline	84.1	68.3	66.7	66.7	75.7
Ortavancin	86.7	90.1	80.0	50.0	86.5
Ciprofloxacin	84.4	87.0	73.3	83.3	67.6
Tetracycline	52.6	87.6	53.3	66.7	45.9
Gentamicin	87.0	88.2	66.7	100	83.8

Continuation of Table No. 2.

1	2	3	4	5	6
Trimethoprim	76.0	93.2	73.3	66.7	81.1
Rifampin	53.2	77.6	40.0	50.0	40.5
Clindamycin	51.2	84.8	46.7	66.7	54.1
Ampicillin	13.9	7.1	26.7	33.3	21.6
Cefoxitin	43.4	50.3	40.0	50.0	32.4
Teicoplanin	79.2	50.6	60.0	50.0	89.2
Vancomycin	77.5	67.4	73.3	66.7	75.7
Moxifloxacin	49.4	62.1	66.7	66.7	59.5
Linezolid	83.8	93.8	60.0	66.7	83.8
Nitrofurantoin	84.7	92.5	66.7	83.3	81.1
Daptomycin	48.8	34.2	60.0	33.3	40.5
Erythromycin	49.1	44.1	53.3	50.0	54.1

Table 3 shows a comparative effectiveness of antibiotics by each source of Staphylococcus aureus isolation. For all biological materials, gentamicin ranked among the top five most active antibiotics, confirming its broad-spectrum activity. In isolates from ENT organs and eyes, linezolid, ortavancin, and nitrofurantoin were also highly effective. In wound samples, 100% sensitivity to gentamicin and ciprofloxacin was observed. Cervical isolates demonstrated high sensitivity to vancomycin, confirming its effectiveness in gynecological infections. The results suggest that these antibiotics can be recommended as the primary agents in empirical therapy for staphylococcal infections of various localizations.

Table 3.

The most effective antibiotics for each biomaterial.

Rank	Sputum	ENT Organs	Cervical Canal	Wound	Eyes
1	Gentamicin (87.0%)	Linezolid (93.8%)	Gentamicin (66.7%)	Gentamicin (100.0%)	Teicoplanin (89.2%)
2	Ortavancin (86.7%)	Ortavancin (90.1%)	Ortavancin (80.0%)	Ciprofloxacin (83.3%)	Gentamicin (83.8%)
3	Nitrofurantoin (84.7%)	Nitrofurantoin (92.5%)	Vancomycin (73.3%)	Nitrofurantoin (83.3%)	Linezolid (83.8%)
4	Ceftaroline (84.1%)	Trimethoprim (93.2%)	Ciprofloxacin (73.3%)	Ortavancin (50.0%)	Nitrofurantoin (81.1%)
5	Ciprofloxacin (84.4%)	Gentamicin (88.2%)	Teicoplanin (60.0%)	Teicoplanin (50.0%)	Vancomycin (75.7%)

Table 4 illustrates the average sensitivity level of S. aureus to the main classes of antibiotics. Aminoglycosides, oxazolidinones, and nitrofurans demonstrated the highest average sensitivity levels, exceeding 83% across all materials. Glycopeptides, including vancomycin and ortavancin, also showed high activity, particularly in eye and respiratory isolates. In contrast, beta-lactams and macrolides exhibited the lowest average sensitivity values. This indicates the continued spread of beta-lactam resistance mechanisms in hospital strains of S. aureus.

Table 4.

Average Sensitivity of Staphylococcus aureus by Antibiotic Classes (%).

Antibiotic Class	Sputum	ENT Organs	Cervical Canal	Wound	Eyes
Beta-lactams (penicillin, ampicillin, oxacillin, ceftaroline, cefoxitin)	45.2	37.1	41.3	60.0	34.2
Glycopeptides (vancomycin, teicoplanin, ortavancin)	81.1	69.4	71.1	55.6	83.8
Aminoglycosides (gentamicin)	87.0	88.2	66.7	100.0	83.8
Fluoroquinolones (ciprofloxacin, moxifloxacin)	66.9	74.6	70.0	75.0	63.6
Oxazolidinones (linezolid)	83.8	93.8	60.0	66.7	83.8
Sulfonamides (trimethoprim)	76.0	93.2	73.3	66.7	81.1
Macrolides (erythromycin)	49.1	44.1	53.3	50.0	54.1
Lincosamides (clindamycin)	51.2	84.8	46.7	66.7	54.1
Tetracyclines (tetracycline)	52.6	87.6	53.3	66.7	45.9
Nitrofurans (nitrofurantoin)	84.7	92.5	66.7	83.3	81.1
Lipopeptides (daptomycin)	48.8	34.2	60.0	33.3	40.5
Rifamycins (rifampicin)	53.2	77.6	40.0	50.0	40.5

Table 5 presents a summarized assessment of antibiotic effectiveness based on the cumulative data from all biological materials. The most effective antibiotics were linezolid, nitrofurantoin, gentamicin, and ortavancin, with sensitivity levels exceeding 86%. This makes them the most preferable options for empirical therapy. Penicillin and ampicillin demonstrated the lowest activity (17% and 12%, respectively), indicating the complete exclusion of these drugs from treatment regimens for infections caused by S. aureus in the context of high resistance.

Table 5.

General sensitivity of Staphylococcus aureus to antibiotics (total number of isolates = 726).

Antibiotic	Sensitive (n)	Sensitivity (%)
Penicillin	123	16.9%
Oxacillin	439	60.5%
Ceftaroline	553	76.2%
Ortavancin	627	86.4%
Ciprofloxacin	613	84.4%
Tetracycline	493	67.9%
Gentamicin	632	87.1%
Trimethoprim	608	83.7%
Rifampin	508	70.0%
Clindamycin	501	69.0%
Ampicillin	85	11.7%
Cefoxitin	393	54.1%
Teicoplanin	542	74.6%
Vancomycin	528	72.7%
Moxifloxacin	407	56.1%
Linezolid	636	87.6%
Nitrofurantoin	636	87.6%
Daptomycin	406	55.9%
Erythromycin	443	61.0%

Discussion

The results obtained confirm the relevance of the issue of antibiotic resistance in Staphylococcus aureus, especially in clinical settings with a high frequency of beta-lactam antibiotic use. In our study, resistance to traditional penicillins (penicillin, ampicillin) remained consistently high regardless of the biological material. This is consistent with data from other studies reporting the widespread prevalence of β-lactamase-producing S. aureus strains [8].

The findings of this study highlight the severity of the antibiotic resistance problem in clinical practice. Our data demonstrate resistance to penicillin and ampicillin in most of the biological materials studied, which aligns with global trends. As noted in the review by *Liu et al.* (2024), resistance to beta-lactams, particularly penicillins, remains consistently high in most S. aureus strains, especially in hospital settings and with prolonged antimicrobial therapy [19].

Particular attention should be given to the high sensitivity to gentamicin and linezolid, making them key drugs for the empirical treatment of staphylococcal infections. According to Alghamdi et al., linezolid and gentamicin retain effectiveness against both methicillin-sensitive (MSSA) and methicillin-resistant (MRSA) strains, particularly in localized respiratory and skin infections [5].

The observed effectiveness of nitrofurantoin, especially in urine and ocular samples, is supported by the findings of the systematic review by *Belete et al.*, which emphasizes that this drug remains clinically significant for treating infections caused by sensitive strains when limited alternative options are available [7].

The results of this analysis emphasize the significant differences in antibiotic resistance of Staphylococcus aureus depending on the type of clinical sample from which the strains were isolated. This is consistent with the data from Liao et al., which demonstrated that in postoperative infections, S. aureus isolated from wound exudates more frequently exhibits resistance to linezolid and fluoroquinolones than isolates from blood [18].

The analysis conducted by Soleimani further underscores that S. aureus strains isolated from pediatric samples are more likely to exhibit high resistance to mupirocin (MupB-associated), indicating age-specific resistance patterns [23].

In turn, the study by *Furlan et al.* focuses on the global spread of epidemic multidrug-resistant S. aureus strains. The authors highlight that biological materials obtained from the respiratory tract show the highest levels of resistance to macrolides and glycopeptides [13].

As emphasized by *Heaton et al.*, Staphylococcus aureus strains isolated from various species of wildlife exhibit high molecular diversity, including both human pandemic clones (ST5, ST8, ST1) and strains associated with animals and interspecies transmission (ST398, ST130, ST133, ST425). Of particular interest are ST398 and ST130, as they show pronounced antibiotic resistance and the ability to circulate between animals and humans [16].

According to *Gherardi*, a key factor in the pathogenicity of Staphylococcus aureus is its ability to rapidly adapt and acquire antibiotic resistance, particularly to beta-lactams. The main resistance mechanism of MRSA lies in the presence of the mecA gene, which encodes the penicillin-binding protein PBP2a with reduced affinity for antibiotics. Increasingly, the alternative gene mecC is also being reported. MRSA causes infections both in hospital settings (HA-MRSA) and in the community (CA-MRSA), with the latter showing a trend toward infiltrating healthcare facilities [14].

As noted by Peacock and Paterson, methicillin resistance in Staphylococcus aureus is driven by the acquisition of the mecA gene encoding PBP2a – a penicillin-binding protein with low affinity for beta-lactams. This protein allows continued cell wall synthesis even in the presence of antibiotics. Integration of mecA occurs via the mobile genetic element SCCmec, whose diversity reflects the complex evolution of MRSA. The authors emphasize that, aside from mecA, resistance levels are regulated by numerous chromosomal genes and are strain-dependent, which may explain variability in resistance among isolates from different clinical samples. This genetic variability underscores the need for molecular typing and comprehensive analysis when studying S. aureus antibiotic resistance [22].

Cheung et al. highlight that the pathogenicity of Staphylococcus aureus is driven by a synergy of virulence factors, including toxins, immune evasion mechanisms, biofilm formation, and intracellular persistence. A major concern remains the high level of resistance in both MRSA and MSSA, including vancomycin resistance (VISA and VRSA). The authors note that S. aureus strains, especially the USA300 lineage, combine high virulence with resistance, posing serious threats during infections of various clinical specimens. Moreover, S. aureus is capable of forming abscesses and hiding within neutrophils, providing protection from the immune system and antibiotics [10].

Ahmad-Mansour et al. emphasize that the pathogenicity of Staphylococcus aureus heavily depends on the production of a broad spectrum of toxins, including alpha-hemolysin, Panton-Valentine leukocidin (PVL), phenol-soluble modulins (PSMs), exfoliative toxins, and

superantigens. Notably, most S. aureus strains, both MRSA and methicillin-sensitive, carry the hla gene encoding alpha-hemolysin, a key virulence factor involved in severe conditions such as pneumonia, osteomyelitis, and sepsis. PVL is more frequently associated with MRSA and is linked to skin and soft tissue infections. Some toxins, like PSMα, exhibit potent cytolytic activity, exacerbating tissue destruction [4].

Larkin et al. underline that Staphylococcus aureus remains one of the most pathogenic microorganisms, with marked resistance to antibiotics including methicillin and vancomycin. This resistance, combined with the production of potent superantigens - staphylococcal enterotoxins (SEs) and toxic shock syndrome toxin (TSST-1) - creates a dual threat. These toxins activate T cells independently of standard antigen presentation, triggering massive pro-inflammatory cytokine release and toxic shock. Importantly, different S. aureus strains may produce a range of such toxins, with their impact varying depending on the infection site and the clinical material from which the pathogen was isolated [17].

Chen et al. provided a detailed description of the diverse virulence factors of Staphylococcus aureus, including pore-forming toxins, modulins, exfoliative toxins, and superantigens. These factors play crucial roles in the pathogenesis of inflammatory diseases by activating a wide range of immune cells from keratinocytes to T-helper cells and neutrophils. Infections caused by S. aureus are associated with various forms of cell death, including pyroptosis, apoptosis, necroptosis, and autophagy, which directly affect clinical manifestations and disease severity. Particularly concerning is that MRSA strains combine high resistance with significant toxicity, making them dangerous in both superficial and invasive infections, depending on the clinical material involved [9].

Thus, the data of our study are consistent with modern global trends. Linezolid, gentamicin, nitrofurantoin and glycopeptides remain the leaders in effectiveness. This emphasizes the importance of their inclusion in empirical therapy regimens and the need to limit the use of highly resistant drugs, such as penicillin, ampicillin and macrolides

Conclusion

The results of the study showed high resistance of Staphylococcus aureus to penicillin and ampicillin, confirming their decreasing clinical significance. In contrast, linezolid, gentamicin, nitrofurantoin, and glycopeptides demonstrated consistent effectiveness regardless of the biological material.

Differences in the sensitivity profile were noted depending on the infection site. Sensitive strains were more frequently found in eye and wound samples, while greater resistance was observed in sputum and ENT samples.

Therefore, our data confirm global trends of increasing resistance of S. aureus to traditional antibiotics and emphasize the importance of local resistance monitoring. The results may be useful in developing rational antibiotic therapy protocols and in reducing the risk of ineffective treatment.

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