Catheter-Associated Urinary Tract Infections: Epidemiology, Biofilm Pathogenesis, Antimicrobial Resistance, and Prevention Strategies—A Comprehensive Review

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Abstract

Catheter-associated urinary tract infection (CAUTI) remains one of the most common healthcare-associated infections worldwide and represents a significant burden on patient outcomes and healthcare systems. The widespread use of indwelling urinary catheters, particularly in critically ill and long-term hospitalized patients, contributes substantially to infection risk. This review summarizes current knowledge on the epidemiology, pathogenesis, antimicrobial resistance patterns, diagnostic approaches, treatment challenges, and prevention strategies related to CAUTI. Special emphasis is placed on the role of biofilm formation on catheter surfaces, which facilitates microbial persistence, reduces antibiotic efficacy, and promotes the emergence of multidrug-resistant organisms. Common pathogens include Gram-negative bacteria such as *Escherichia coli*, *Klebsiella pneumoniae*, *Pseudomonas aeruginosa*, and *Acinetobacter baumannii*, many of which exhibit extended-spectrum β-lactamase and carbapenem resistance. Accurate diagnosis requires correlation of clinical features with quantitative urine culture to distinguish true infection from asymptomatic bacteriuria and avoid unnecessary antimicrobial therapy. Preventive strategies—including appropriate catheter use, aseptic insertion techniques, early catheter removal, and antimicrobial stewardship—remain the most effective methods for reducing CAUTI incidence. Emerging therapeutic and preventive approaches such as antimicrobial-coated catheters, anti-biofilm strategies, bacteriophage therapy, and rapid molecular diagnostics are also discussed. Strengthening infection control practices and surveillance systems is essential to limit the growing impact of antimicrobial resistance. This review highlights current challenges and future directions for improved management and prevention of CAUTI in clinical settings.

Keywords: Catheter-associated urinary tract infection; CAUTI; Biofilm; Antimicrobial resistance; Multidrug-resistant organisms; Infection control; Urinary catheter.

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Introduction

Urinary tract infections (UTIs) are among the most common bacterial infections worldwide and represent a significant cause of morbidity in both community and healthcare settings. In hospitals, UTIs account for a substantial proportion of healthcare-associated infections (HAIs), particularly among patients undergoing invasive procedures or prolonged hospitalization (Foxman, 2010; Stamm & Norrby, 2001; Magill et al., 2014). HAIs affect millions of patients globally each year and are associated with increased mortality, extended hospital stay, and rising healthcare costs (Allegranzi et al., 2011). Device-associated infections contribute considerably to this burden, as indwelling medical devices facilitate microbial colonization and biofilm formation.

Catheter-associated urinary tract infection (CAUTI) is the most frequently reported device-associated infection worldwide and remains a major challenge for infection control programs (Magill et al., 2014). Approximately 75–80% of hospital-acquired UTIs are linked to urinary catheterization (Lo et al., 2014;

Nicolle, 2014). Although urinary catheters are essential for patient management, inappropriate insertion and prolonged use significantly increase infection risk. Despite established prevention guidelines from the WHO and the CDC, CAUTI remains common, indicating persistent gaps in infection prevention practices.

Biofilm formation on catheter surfaces plays a central role in CAUTI pathogenesis. Microorganisms ascend through intraluminal or extraluminal routes and form structured biofilms that protect pathogens from host immune responses and antimicrobial therapy, leading to persistent infection (Flores-Mireles et al., 2015). The risk of bacteriuria increases with the duration of catheterization, with an estimated daily increase of 3–10% (Tambyah & Oon, 2012).

The growing emergence of AMR, particularly among MDR Gram-negative organisms such as *Escherichia coli*, *Klebsiella pneumoniae*, *Pseudomonas aeruginosa*, and *Acinetobacter baumannii*, has further complicated CAUTI management (Levison & Kaye, 2013; Flores-Mireles et al., 2015). Inappropriate use of broad-spectrum antibiotics has accelerated resistance development, limiting therapeutic options and worsening clinical outcomes (Magiorakos et al., 2012).

Although CAUTI is considered largely preventable, its continued high prevalence reflects challenges related to prolonged catheter use, inadequate infection control adherence, and limited regional surveillance data. Moreover, important gaps remain in understanding the interaction between biofilm-mediated persistence, evolving resistance mechanisms, and effective prevention strategies across different healthcare settings. Therefore, this review aims to provide a comprehensive overview of the epidemiology, biofilm-associated pathogenesis, antimicrobial resistance patterns, diagnostic approaches, and prevention strategies of catheter-associated urinary tract infections, highlighting current challenges and emerging control measures.

Literature Search Methodology

An extensive literature search was performed to identify relevant studies on catheter-associated urinary tract infections (CAUTI), biofilm mechanisms, and antimicrobial resistance published between January 2010 and July 2025. Electronic databases including PubMed, Scopus, and Google Scholar were systematically searched using predefined keywords and Boolean combinations such as "catheter-associated urinary tract infection," "CAUTI," "biofilm," "antimicrobial resistance," "multidrug resistance," "device-associated infection," and "urogenital infections." Only articles published in the English language were included. Original research articles, review articles, and clinical or epidemiological studies focusing on CAUTI pathogenesis, biofilm formation, antimicrobial resistance mechanisms, and prevention strategies were considered eligible. Studies reporting antimicrobial susceptibility patterns or molecular resistance among CAUTI pathogens were also included. Case reports with limited microbiological relevance, studies not specifically related to CAUTI, and publications lacking clear methodological detail were excluded. Duplicate records were removed, and reference lists of selected articles were manually screened to identify additional relevant studies.

Catheter-Associated Urinary Tract Infection (CAUTI)

Definition

CAUTI is defined as a UTI occurring in a patient with an indwelling urinary catheter that has been in place for more than two consecutive calendar days, with the day of catheter insertion considered as Day 1, and the catheter remaining in situ on the date of infection or the preceding day. If the catheter has been removed after being in place for more than two days, the infection must occur on the day of removal or within the following 24 hours to be classified as catheter-associated. Standardized surveillance definitions are provided by the Centers for Disease Control and Prevention and the National Healthcare Safety Network to ensure uniform reporting across healthcare settings (CDC, 2021; Al-Qahtani et al., 2019).

Clinical Presentation and Diagnostic Criteria

CAUTI may present as symptomatic infection or asymptomatic bacteriuria. However, differentiation between colonization and true infection in catheterized patients remains challenging. Diagnosis generally requires significant bacteriuria along with compatible clinical features such as fever, suprapubic tenderness, costovertebral angle pain, or altered mental status (Hooton et al., 2010; Nicolle, 2014). Clinical correlation is essential because catheterized patients frequently demonstrate bacteriuria without overt symptoms.

Pathogenesis and Role of Catheterization

Urinary catheterization predisposes patients to infection by disrupting natural host defense mechanisms, including the mechanical flushing action of urine and the integrity of the urethral mucosal barrier. Microorganisms may enter the urinary tract through intraluminal contamination of the drainage system or by ascending extraluminally along the catheter–urethral interface. These processes facilitate microbial adherence and subsequent biofilm formation on catheter surfaces, increasing the risk of persistent infection (Saint, 2000).

Epidemiology of Catheter-Associated Urinary Tract Infection (CAUTI)

CAUTI is the most frequently reported HAI worldwide and remains a major challenge for hospital infection control programs. The extensive use of indwelling urinary catheters in hospitalized and critically ill patients significantly contributes to this burden, with approximately 15–25% of hospitalized patients requiring catheterization and nearly 75–80% of hospital-acquired UTIs linked to catheter use (Magill et al., 2014; Nicolle, 2014). Global data suggest that device-associated infections are more common in resource-limited settings due to higher device utilization and gaps in infection prevention practices (Allegranzi et al., 2011).

CAUTI incidence varies across healthcare settings depending on catheter practices, surveillance systems, and infection control compliance. In ICUs, reported rates generally range from 5 to 10 per 1000 catheter-days (Magill et al., 2014). Duration of catheterization is the most important risk factor, with the daily risk of bacteriuria increasing by approximately 3–7% for each catheter day (Saint, 2000; Tambyah & Maki, 2000). Although bacteriuria commonly occurs during prolonged catheterization, more than 90% of cases represent asymptomatic colonization rather than true infection (Nicolle, 2014). Long-term catheter use in chronic care settings further contributes to persistent colonization and recurrent infections (Meddings et al., 2019).

Epidemiology in Indian Healthcare Settings

Studies from India demonstrate wide variability in CAUTI prevalence, ranging from approximately 6% to 27% among catheterized patients in tertiary care hospitals. This variation likely reflects differences in catheter utilization, infection control adherence, antimicrobial stewardship practices, and patient risk factors. Most studies consistently report predominance of Gram-negative pathogens such as *E. coli*, *K. pneumoniae*, *P. aeruginosa*, and *Acinetobacter* species, many exhibiting MDR patterns (Sandhu et al., 2022; Parihar et al., 2023). Frequently reported risk factors include prolonged catheterization, ICU admission, diabetes mellitus, and prior antibiotic exposure.

Clinical Burden and Surveillance

CAUTI contributes substantially to increased morbidity, prolonged hospitalization, and higher antimicrobial consumption (Magill et al., 2014). Biofilm formation on catheter surfaces plays a central role in persistent infection and treatment failure (Donlan, 2001; Flores-Mireles et al., 2015). Standardized surveillance using catheter-days as a denominator, as recommended by the National Healthcare Safety Network under the Centers for Disease Control and Prevention framework, is essential for monitoring trends and evaluating prevention strategies (CDC/NHSN, 2021).

Urinary Catheters and Risk of Infection

Urinary catheterization is widely used in clinical practice for relief of urinary retention, accurate monitoring of urine output, and management of perioperative or neurological conditions. However, catheter use significantly increases the risk of UTI, and CAUTI remains one of the most common HAIs worldwide. CAUTI contributes to prolonged hospital stay, increased antimicrobial exposure, and higher healthcare costs (CDC, 2009; Hooton et al., 2010).The normal urinary tract is protected by continuous urine flow, mucosal immunity, and the intrinsic antimicrobial properties of urine. Catheter insertion disrupts these defenses by providing a direct pathway for microbial entry into the bladder. Microorganisms may ascend either intraluminally through the catheter or extraluminally along the catheter–urethral interface (Tambyah & Maki, 2000).

Types of Urinary Catheters

Urinary drainage devices are broadly classified into indwelling, intermittent, suprapubic, and external catheters, each associated with different infection risks.

- **Indwelling (Foley) Catheters:**
  Indwelling urethral catheters allow continuous bladder drainage and are strongly associated with CAUTI due to prolonged placement. The risk of bacteriuria increases by approximately

3–10% per day of catheterization, and long-term use commonly leads to polymicrobial colonization (Nicolle, 2014; Warren, 2001).

- **Intermittent Catheterization:**
  This method involves periodic catheter insertion followed by immediate removal. When performed using clean or sterile technique, intermittent catheterization is associated with lower infection rates and is commonly recommended for patients with neurogenic bladder dysfunction (Wyndaele & Maes, 1990).
- **Suprapubic Catheters:**
  Inserted surgically through the abdominal wall into the bladder, suprapubic catheters may reduce urethral trauma but demonstrate infection rates comparable to long-term indwelling urethral catheters (Kidd & Stewart, 2015).
- **External (Condom) Catheters:**
  External urinary devices, primarily used in male patients, do not enter the urinary tract and therefore carry a relatively lower risk of CAUTI, although complications such as leakage and skin irritation may occur (Saint et al., 2006).

Indications and Duration of Catheterization

Appropriate indications for urinary catheterization include acute urinary retention, accurate urine output monitoring in critically ill patients, selected perioperative conditions, and specific neurological disorders (CDC, 2009). Avoidance of unnecessary catheter use is essential because duration of catheterization is the most important modifiable risk factor for CAUTI.Bacteriuria develops in approximately 10–30% of patients undergoing short-term catheterization and in nearly all patients with long-term catheterization beyond 30 days (Nicolle, 2014; Warren, 2001). Evidence shows that strategies such as daily evaluation of catheter necessity and nurse-driven removal protocols significantly reduce CAUTI incidence (Meddings et al., 2013).

Pathogenesis of Catheter-Associated Urinary Tract Infection (CAUTI)

CAUTI results from a multifactorial interaction between microbial virulence factors, biofilm formation, catheter-induced mucosal injury, and impaired host defenses. Although the general mechanisms resemble those of uncomplicated urinary tract infection, the presence of an indwelling urinary catheter alters the urinary tract environment and facilitates persistent microbial colonization (Flores-Mireles et al., 2015).

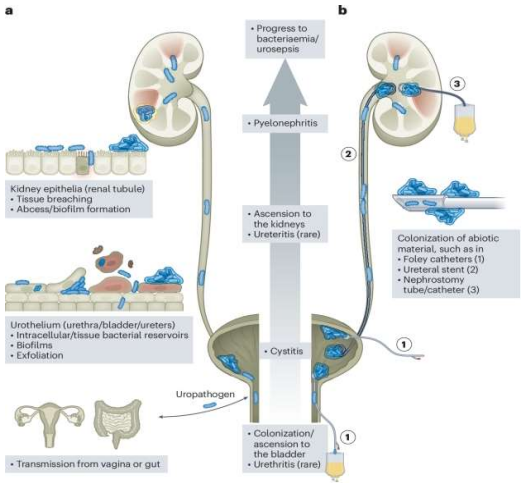

Figure 1: Pathogenesis of Uncomplicated and Device-Associated Urinary Tract Infection. [adapted from Flores, C., Rohn, J.L. 2025]

[a,] Uncomplicated UTI: in patients without comorbidities (uncomplicated UTI), infection typically starts with urethral colonization by bacteria often from the gut or vagina. This is followed by urinary tract ascension to the bladder, where infection establishes (cystitis), with the possibility of forming bacterial reservoirs. Some pathogens manage to ascend to the kidneys and establish pyelonephritis, which can progress to breaching of the epithelium. [b,] Device-associated UTI: in such cases, other sites can initiate infection depending on how and where the device (1–3) is introduced and the respective tissue damage. In both UTI scenarios, bacteria that breach the kidney epithelium have easier access to the bloodstream, potentially causing bacteraemia or urosepsis.

Routes of Microbial Entry

Microorganisms enter the bladder in catheterized patients through two principal pathways:

- **Extraluminal route:**
  This is the most common pathway, where organisms from the patient's gastrointestinal or periurethral flora migrate along the catheter–urethral interface into the bladder. Catheter insertion bypasses normal urethral defenses and reduces the flushing effect of urine, thereby promoting bacterial ascent (Flores-Mireles et al., 2015).

- **Intraluminal route:**
  Intraluminal infection occurs when breaks in the closed drainage system or contamination of the catheter lumen allow retrograde bacterial migration into the bladder (Trautner & Darouiche, 2004).

Unlike uncomplicated UTI, microbial attachment in CAUTI frequently begins on the catheter surface, which acts as an artificial substrate for bacterial adherence (Werneburg et al., 2020).

Biofilm Formation and Microbial Virulence

Biofilm formation is the central event in CAUTI pathogenesis. Biofilms are structured microbial communities embedded in an extracellular matrix composed of polysaccharides, proteins, and extracellular DNA, which enhance bacterial survival and antimicrobial tolerance (Kostakioti et al., 2013).Biofilm development begins soon after catheter insertion and increases with catheter duration (Werneburg et al., 2020). Catheter-induced inflammation promotes deposition of host proteins such as fibrinogen on catheter surfaces, which facilitates bacterial attachment through specific adhesins (Flores-Mireles et al., 2014).

Major uropathogens employ different virulence mechanisms:

- *Escherichia coli* utilizes fimbriae and adhesins to promote attachment and biofilm maturation (Danese et al., 2000; Flores-Mireles et al., 2015).
- *Proteus mirabilis* produces urease, increasing urinary pH and causing crystalline biofilm formation and catheter encrustation (Flores-Mireles et al., 2015).
- *Pseudomonas aeruginosa* forms biofilms through quorum sensing and alginate production, contributing to persistence and antimicrobial resistance (Mittal et al., 2009).

Biofilm-associated organisms exhibit reduced metabolic activity and altered gene expression, which significantly reduces antibiotic susceptibility (Kostakioti et al., 2013).

Host Response and Catheter-Induced Mucosal Injury

Insertion of a urinary catheter causes mechanical disruption of the uroepithelial mucosal barrier and damages the protective glycosaminoglycan layer, facilitating bacterial adherence (Parsons, 1986). The resulting inflammatory response leads to neutrophil recruitment and cytokine release; however, protein deposition on catheter surfaces paradoxically enhances microbial colonization (Flores-Mireles et al., 2014).The persistent presence of the catheter also interferes with normal bladder defense mechanisms, including complete voiding and mucosal turnover, thereby promoting chronic colonization and recurrent infection (Trautner & Darouiche, 2004).

Figure 2. Pathogenesis of Catheter-Associated Urinary Tract Infection and the Role of Biofilm in Antimicrobial Resistance.“developed from Flores-Mireles et al., 2015; Kostakioti et al., 2013; Trautner & Darouiche, 2004.”

Microbiological Profile Of CAUTI

UTIs, including CAUTI, are caused by Gram-negative bacilli, Gram-positive cocci, and fungi. Uropathogenic *E. coli* (UPEC) remains the predominant pathogen, accounting for approximately 75% of uncomplicated and 65% of complicated UTIs (Flores-Mireles et al., 2015). In complicated infections such as CAUTI, additional organisms frequently include *Enterococcus* species (11%), *K. pneumoniae* (8%), *Candida* species (7%), *S. aureus* (3%), *P. mirabilis* (2%), and *P. aeruginosa* (2%) (Flores-Mireles et al., 2015). Polymicrobial infections are common in prolonged catheterization. Biofilm-associated organisms such as *Proteus* and *Pseudomonas* species are particularly implicated in catheter encrustation and persistent infection (Donlan, 2001).

Antimicrobial Resistance in Catheter-Associated Urinary Tract Infection (CAUTI)

- **Prevalence of Multidrug-Resistant Organisms**

AMR has become a major challenge in the management of CAUTI, particularly in hospitalized and critically ill patients.MDR organisms are commonly defined as isolates resistant to at least three antimicrobial classes (Peng et al., 2018; Werneburg, 2022). The increasing prevalence of MDR pathogens is associated with prolonged catheterization, extended hospital stay, excessive use of broad-spectrum antibiotics, and biofilm formation on catheter surfaces (Flores-Mireles et al., 2015; Nicolle, 2014). Biofilm-associated bacteria exhibit reduced antibiotic penetration and enhanced horizontal gene transfer, facilitating persistence of resistant strains. Although uropathogenic *Escherichia coli* remains the predominant pathogen, non-*E. coli* organisms such as *Klebsiella pneumoniae*, *Pseudomonas aeruginosa*, *Proteus mirabilis*, and *Enterococcus* species increasingly demonstrate MDR phenotypes (Foxman, 2010; Peng et al., 2018). Global surveillance reports from the WHO and CDC identify carbapenem-resistant Enterobacteriaceae (CRE) and vancomycin-resistant enterococci (VRE) as critical threats (WHO, 2014).The increasing burden of multidrug-resistant organisms (MDROs) in intensive care settings has emerged as a major therapeutic challenge. A study from a tertiary care hospital in India reported a high prevalence of MDR pathogens among ICU isolates, particularly *Pseudomonas* spp., *Klebsiella* spp., and *Acinetobacter* spp., highlighting the impact of prolonged hospitalization, invasive devices, and antibiotic pressure on resistance development. The study further emphasized the importance of infection prevention measures and antimicrobial stewardship programs in limiting the emergence of MDR, XDR, and PDR organisms(Siddiqui et al., 2024).

- **Extended-Spectrum β-Lactamase (ESBL)-Producing Uropathogens**

ESBL production is one of the most significant resistance mechanisms among CAUTI pathogens. ESBL-producing *E. coli* and *K. pneumoniae* are widely reported in healthcare-associated infections and are strongly linked to prolonged catheter use (Levison & Kaye, 2013; Flores-Mireles et al., 2015). These enzymes hydrolyze penicillins, third-generation cephalosporins, and monobactams, thereby limiting therapeutic options (Foxman, 2010). Carbapenems are frequently used for severe ESBL infections; however, their widespread use has contributed to the emergence of carbapenem resistance (Werneburg, 2022).

- **Carbapenem and Metallo-β-Lactamase Producers**

The emergence of carbapenem-resistant Gram-negative bacteria, particularly *P. aeruginosa* and *Acinetobacter baumannii*, has further complicated CAUTI management. Metallo-β-lactamases (MBLs) can hydrolyze most β-lactam antibiotics, including carbapenems (Ventola, 2015; Werneburg, 2022). Therapeutic options are often limited to polymyxins or newer β-lactam/β-lactamase inhibitor combinations (Kaye et al., 2018; Bassetti et al., 2021). Plasmid-mediated dissemination of carbapenemase genes increases the risk of hospital outbreaks and emphasizes the need for strict infection control (Hover et al., 2018; Stokes et al., 2020).

- **Molecular Mechanisms of Resistance**

Resistance in CAUTI pathogens is largely driven by mobile genetic elements such as plasmids and transposons that facilitate horizontal gene transfer within catheter-associated biofilms. Common β-lactamase genes include **TEM**, **SHV**, and **CTX-M**, while carbapenem resistance is frequently associated with **NDM**, **VIM**, and **IMP** genes (Flores-Mireles et al., 2015; Werneburg, 2022). Molecular techniques such as polymerase chain reaction (PCR) and sequencing enable rapid detection of resistance determinants and are increasingly used for surveillance and targeted therapy (Bhattacharyya et al., 2019; Stokes et al., 2020).

Table:1 Major antimicrobial resistance mechanisms among common CAUTI pathogens and their clinical significance (developed from Flores-Mireles et al., 2015; Nicolle, 2014; Bassetti et al., 2021; Werneburg, 2022).

Pathogen	Major Resistance Mechanisms	Key Resistance Genes/Enzymes	Clinical Impact	Key References
***Escherichia coli* (UPEC)**	ESBL production, fluoroquinolone resistance, biofilm-mediated	**CTX-M**, **TEM**, **SHV**, *gyrA*, *parC* mutations	Reduced susceptibility to cephalosporins and fluoroquinolones; frequent MDR in	Flores-Mireles et al., 2015; Foxman, 2010

	tolerance		CAUTI	
Klebsiella pneumoniae	ESBL production, carbapenemase production, plasmid-mediated resistance	**KPC**, **NDM**, **OXA-48**, **CTX-M**	Limited treatment options; high mortality in severe infections	Levison & Kaye, 2013; Bassetti et al., 2021
Pseudomonas aeruginosa	Efflux pumps, porin loss, biofilm formation, carbapenemases	**VIM**, **IMP**, MexAB-OprM efflux system	Intrinsic resistance; persistent biofilm-associated infection	Mittal et al., 2009; Ventola, 2015
Acinetobacter baumannii	Carbapenem resistance, biofilm formation, target site mutations	**OXA-type carbapenemases**, **NDM**	Extensive drug resistance in ICU settings	Bassetti et al., 2021; Wernerburg, 2022
Proteus mirabilis	Urease production, crystalline biofilm formation, ESBL production	**TEM**, **CTX-M**	Catheter encrustation and recurrent infection	Flores-Mireles et al., 2015
Enterococcus spp.	Glycopeptide resistance, biofilm formation	**vanA**, **vanB**	Vancomycin-resistant enterococci (VRE) complicate	Nicolle, 2014; Peng et al., 2018
			therapy	

- **Phenotypic–Genotypic Correlation**

Phenotypic antimicrobial susceptibility testing remains the primary diagnostic approach in clinical laboratories. Methods such as the combination disk test and double-disk synergy test are commonly used to detect ESBL and carbapenemase production (Werneburg, 2022). However, phenotypic methods may miss emerging resistance mechanisms; therefore, integration with molecular detection improves diagnostic accuracy, particularly in polymicrobial biofilm-associated infections (Bhattacharyya et al., 2019).

Diagnosis of Catheter-Associated Urinary Tract Infection (CAUTI)

Accurate diagnosis of CAUTI requires integration of clinical features with microbiological evidence, as bacteriuria commonly develops after catheter insertion due to rapid microbial colonization and biofilm formation. Distinguishing asymptomatic bacteriuria from true infection is essential to avoid unnecessary antimicrobial therapy (Nicolle, 2014; Flores-Mireles et al., 2015).

Clinical Criteria

CAUTI is diagnosed in patients with an indwelling urinary catheter in place for more than 48 hours, or within 48 hours after catheter removal, in the presence of compatible clinical manifestations such as fever (≥38°C), suprapubic tenderness, costovertebral angle pain, or new-onset urinary symptoms after catheter removal. In elderly or critically ill patients, unexplained altered mental status may also be considered (Hooton et al., 2010).

According to surveillance definitions by the CDC and the NHSN, diagnosis requires clinical criteria along with microbiological confirmation, while findings such as cloudy urine, foul odor, or isolated pyuria are not diagnostic because they frequently occur in colonized catheterized patients (CDC, 2023; Crader et al., 2024).

Laboratory Diagnosis

Proper urine specimen collection is critical for accurate diagnosis. Urine should be collected aseptically from the catheter sampling port after

disinfection, and collection from the drainage bag should be avoided due to contamination risk (Parida & Mishra, 2013).

Quantitative urine culture remains the gold standard for confirmation. A bacterial count of $\geq 10^5$ CFU/mL (with no more than two organisms) is considered significant for surveillance purposes, although lower counts ($\geq 10^3$ CFU/mL) may be clinically relevant in symptomatic patients (Crader et al., 2024). Identified isolates should undergo antimicrobial susceptibility testing because MDR pathogens are common in healthcare settings (Michael & Gaido, 2004).

Adjunctive tests such as urine dipstick, microscopy, and Gram staining may support early assessment but lack sufficient specificity in catheterized patients. Therefore, definitive diagnosis should always rely on correlation between clinical findings and quantitative culture results (McNair et al., 2000; Nicolle, 2014).

Prevention and Control of Catheter-Associated Urinary Tract Infection (CAUTI)

CAUTI remains one of the most preventable healthcare-associated infections; however, it continues to occur due to prolonged catheterization, inadequate catheter care, and increasing antimicrobial resistance. Preventive strategies focus primarily on minimizing unnecessary catheter use, maintaining aseptic insertion techniques, ensuring proper catheter maintenance, and strengthening antimicrobial stewardship and surveillance systems (Nicolle, 2014; Saint et al., 2016). International recommendations from the CDC and WHO, along with national guidance from the Indian Council of Medical Research, emphasize standardized device-care bundles and rational antibiotic use for reducing CAUTI rates**.**

Appropriate catheter use is the most effective preventive strategy. Indwelling urinary catheters should be restricted to clear clinical indications such as acute urinary retention, accurate urine output monitoring in critically ill patients, selected surgical procedures, and palliative care. Daily reassessment and early catheter removal significantly reduce infection risk (Gould et al., 2017; Nicolle, 2014).

Aseptic insertion and maintenance care are essential components of CAUTI prevention. Recommended measures include strict hand hygiene, sterile insertion techniques, maintenance of a closed drainage system, unobstructed urine flow, and routine perineal care (Hooton et al., 2010; Gould et al., 2017). Biofilm formation can begin within 24–48 hours after catheter placement and contributes to persistent infection and antimicrobial resistance (Flores-Mireles et al., 2015).

Duration of catheterization remains the most important modifiable risk factor, with bacteriuria risk increasing by approximately 3–7% per catheter day (Nicolle, 2014). Nurse-driven removal protocols, electronic reminders, and use of intermittent or external devices have demonstrated significant reductions in CAUTI incidence (Meddings et al., 2010).

Antimicrobial stewardship and surveillance further support prevention by reducing unnecessary antibiotic exposure and monitoring resistance trends. Culture-guided therapy and avoidance of treatment for asymptomatic bacteriuria are key strategies (ICMR, 2017; Nicolle, 2014).

Treatment Challenges and Emerging Therapeutic Approaches in CAUTI

Management of CAUTI requires an integrated approach combining antimicrobial therapy, catheter management, and microbiological surveillance. Empirical antibiotic therapy should be initiated in symptomatic patients—particularly those with systemic infection—and guided by local antibiogram data and patient risk factors. Common empirical agents include third-generation cephalosporins, piperacillin–tazobactam, carbapenems in highMDR settings, and aminoglycosides. Therapy should be de-escalated once culture and susceptibility results become available (Flores-Mireles et al., 2015; Nicolle, 2014).

Catheter removal or replacement is critical because biofilm formation reduces antibiotic penetration and promotes persistent infection. Improved clinical outcomes have been reported when catheter exchange is performed before initiation of antimicrobial therapy in long-term catheterized patients (Raz et al., 2000; Werneburg, 2022).

The rising prevalence of MDR organisms—including ESBL-producing *E. coli* and *K. pneumoniae*, carbapenem-resistant *A. baumannii* and *P. aeruginosa*, and VRE species—has significantly complicated treatment. Contributing factors include prolonged catheterization, repeated antibiotic exposure, and hospital transmission.

Although antibiotics remain the cornerstone of CAUTI management, the antimicrobial pipeline remains limited. Recently introduced agents such as cefiderocol, meropenem–vaborbactam, plazomicin, and imipenem–relebactam have demonstrated enhanced activity against MDR Gram-negative pathogens; however, their use should be guided by antimicrobial stewardship principles because of their high cost and the potential for emerging resistance (Bassetti et al., 2021). In recent years, **fosfomycin** has re-emerged as a promising therapeutic option for the treatment of MDR Gram-negative urinary tract infections owing to its unique mechanism of action, excellent urinary concentrations, favorable safety profile, and activity against biofilm-associated pathogens. A recent review by **Dubey et al. (2024)** highlighted the retained efficacy of fosfomycin against ESBL-producing and other MDR uropathogens, supporting its role as an effective oral agent for complicated urinary tract infections. Furthermore, an in vitro study from a tertiary care hospital in Lucknow reported a low fosfomycin resistance rate of only **7%** among Gram-negative urinary isolates, with susceptibility rates of **96.6%** among non-ESBL *E. coli* and **92.1%** among ESBL-producing *E. coli*. These findings further reinforce the potential of fosfomycin as an effective therapeutic option for UTIs caused by MDR pathogens and suggest its utility in the management of CAUTIs, where similar resistant organisms are frequently encountered.

Because biofilm-associated infections are difficult to eradicate, current research focuses on alternative strategies including:

- Anti-biofilm therapies (enzyme-mediated disruption and quorum-sensing inhibition)
- Antimicrobial-coated and nanotechnology-based catheters
- Bacteriophage therapy targeting MDR pathogens
- Rapid molecular diagnostics (multiplex PCR, whole genome sequencing, and MALDI-TOF) for early pathogen detection

Advances in artificial intelligence–assisted antibiotic discovery and anti-virulence therapies targeting bacterial adhesion mechanisms also represent promising future approaches.

Conclusion and Future Perspectives

Catheter-associated urinary tract infection continues to be a major healthcare challenge due to widespread device use, biofilm formation, and increasing multidrug resistance. Despite established prevention guidelines, CAUTI remains common in critically ill and long-term hospitalized patients. The growing prevalence of ESBL-producing and carbapenem-resistant organisms has reduced the effectiveness of conventional antimicrobial therapy.

Global surveillance data, including reports from the Global Antimicrobial Resistance and Use Surveillance System, indicate increasing resistance trends worldwide, highlighting the urgent need for integrated infection prevention and antimicrobial stewardship programs. Biofilm formation plays a central role in microbial persistence and horizontal transfer of resistance genes, reinforcing the importance of prevention rather than treatment alone.

Future CAUTI control strategies are increasingly focused on interdisciplinary approaches combining clinical microbiology, biomaterials science, and biomedical engineering. Emerging technologies such as antimicrobial-coated catheters, nanotechnology-based surface modifications, bacteriophage therapy, and rapid molecular diagnostics offer promising solutions for reducing infection risk.

Innovations in catheter design—including biocompatible materials, smart sensor-integrated devices, and controlled antimicrobial-release systems—may significantly improve patient outcomes. Strengthened surveillance systems, rational antibiotic use, and translation of novel technologies into clinical practice will be essential to reduce the global burden of CAUTI.

Declarations

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