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Vascular Access And Infection Risk: Advances In Catheter-Related Bloodstream Infection Prevention

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Abstract

Background

CRBSIs result from microbial biofilms on catheters, primarily coagulase-negative staphylococci, S. aureus, Gram-negatives, and Candida, with ICU rates of 1.8-5.2 per 1,000 catheter-days and higher in high-risk groups like hemodialysis patients. Key risks span patient factors (immunosuppression, diabetes), device characteristics (multilumen, dwell time), and procedural issues.

Methods

Narrative synthesis of contemporary literature on prevention advances, including vascular device selection (peripheral vs. central), insertion practices (ultrasound, maximal barriers, chlorhexidine), maintenance bundles (asepsis, dressings), antimicrobial innovations (coated catheters, lock solutions), and system-level interventions (training, surveillance) in diverse settings.

Results

Evidence-based bundles yield 40-60% CRBSI reductions; ultrasound guidance cuts risks by 30-35%; chlorhexidine dressings and antibiotic locks achieve 20-70% decreases; specialized teams lower rates below 1 per 1,000 catheter-days in optimized ICUs. Antimicrobial technologies show superior efficacy in prolonged-use scenarios.

Conclusions
Integrated strategies across the device lifecycle dramatically mitigate CRBSIs, though challenges persist in resource-limited contexts and with multidrug-resistant pathogens; prioritize bundle adherence, novel coatings, and tailored protocols for sustained global impact.

Keywords vascular access; catheter-related bloodstream infection; infection prevention; central venous catheter; biofilm; antimicrobial lock; aseptic technique; CRBSI.

Introduction

Vascular access devices (VADs), encompassing both central and peripheral catheters, are fundamental to modern healthcare delivery, enabling the safe and continuous administration of intravenous fluids, blood products, parenteral nutrition, chemotherapy, vasopressors, and complex biologic agents across acute, chronic, and ambulatory settings. Short peripheral intravenous catheters (PIVCs) are the most frequently used invasive devices worldwide, providing short-term access for hydration, antibiotics, and analgesia, whereas central venous catheters (CVCs) support prolonged therapies, hemodynamic monitoring, extracorporeal therapies, and advanced oncologic and critical care interventions. As survival improves for patients with cancer, organ failure, and chronic critical illness, long-term venous access has become integral to complex care pathways, making VADs indispensable to enhanced recovery programs, home infusion services, and precision oncology while simultaneously introducing a substantial iatrogenic risk for catheter-related bloodstream infections (CRBSIs) and other device-associated complications. This dual role has positioned vascular access and CRBSI prevention as a central focus of patient safety initiatives, quality metrics, and infection prevention bundles in intensive care units, oncology units, hemodialysis programs, and general medical–surgical wards worldwide (Gahlot et al., 2014).

CRBSIs and central line–associated bloodstream infections (CLABSIs) represent one of the most serious healthcare-associated infections, contributing significantly to preventable morbidity, mortality, and economic burden in both high- and middle-income countries. Surveillance data and epidemiologic studies indicate that tens of thousands of CLABSI episodes occur annually in the United States alone, with attributable mortality from catheter-associated bacteremia commonly estimated between 12% and 25%, reflecting the combined effects of severe sepsis, metastatic foci of infection, and worsening of underlying comorbidities. Economic evaluations have shown that each episode of CRBSI can add tens of thousands of dollars or euros in direct medical costs due to prolonged ICU and hospital length of stay, additional diagnostic workup, catheter removal and replacement, use of broad-spectrum or targeted intravenous antimicrobials, and management of complications such as endocarditis or septic thrombophlebitis. Contemporary cost analyses in intensive care populations report incremental costs per CRBSI episode ranging from approximately 30,000 to over 70,000 US dollars in North America and 13,000–30,000 euros in European cohorts, underscoring the substantial financial impact on health systems and payers. Even outside the ICU, catheter-associated bloodstream infections remain a leading cause of nosocomial bacteremia, with high prevalence and persistent rates despite surveillance and prevention programs, thereby cementing CRBSI reduction as a core performance and reimbursement target for hospitals and integrated healthcare networks (Y. Zhang et al., 2023).

The pathophysiology of CRBSI is tightly linked to the propensity of intravascular catheters to support microbial adhesion, biofilm formation, and persistent colonization on both intraluminal and extraluminal surfaces, which then serve as a nidus for episodic or continuous seeding of the bloodstream. Microorganisms gain access via contamination of the insertion site or catheter hub, adhere to the polymer surface, aggregate into microcolonies, and produce an extracellular polymeric matrix that encases cells and anchors the developing biofilm. Biofilm maturation proceeds through distinct stages characterized by initial reversible adhesion, irreversible attachment with matrix production, three-dimensional architectural development, and eventual dispersal of planktonic cells, with the mature biofilm conferring profound tolerance to host immune mechanisms and markedly reduced susceptibility to many antimicrobial agents

at clinically achievable concentrations. Within this sessile community, gradients of nutrients, oxygen, and waste products create microenvironments that promote phenotypic heterogeneity, slow-growing or dormant subpopulations, and enhanced horizontal gene transfer, thereby facilitating persistence, recurrent bacteremia, and the emergence or maintenance of antimicrobial resistance among catheter-associated pathogens. Host factors, including immunosuppression, critical illness, and the inflammatory response to both the foreign body and the infecting organisms, further modulate the clinical trajectory, with biofilm-mediated infections often requiring catheter removal plus systemic therapy, as eradication by antimicrobials alone is frequently unsuccessful once a mature biofilm is established (Zhao et al., 2017).

Despite decades of research, CRBSIs remain a preventable yet continuing challenge, and this has created a strong rationale for comprehensive syntheses that integrate evolving evidence across device types, care settings, and prevention modalities. The current review is designed to consolidate recent advances in CRBSI prevention spanning the entire vascular access continuum across intensive care, oncology, hemodialysis, and general inpatient and outpatient environments. By systematically examining contemporary data on risk factors, biofilm-targeted interventions, evidence-based insertion and maintenance bundles, and novel technologies, this review aims to clarify which strategies are most effective for different patient populations and catheter configurations, highlight remaining gaps in knowledge, and propose priorities for future research and implementation to further reduce the global burden of catheter-related bloodstream infection (Cabrero et al., 2023).

Types of Vascular Access Devices

Peripheral venous catheters (PVCs) are the most commonly used intravascular devices, typically indicated for short-term administration of crystalloid fluids, electrolytes, non-vesicant drugs, and low-osmolar contrast in patients requiring brief hospital-based venous access, generally for less than 5–7 days. They are usually inserted into superficial veins of the dorsum of the hand, forearm, or antecubital fossa using aseptic technique after skin antisepsis with an alcohol-based antiseptic and secured with transparent dressings to allow site inspection, with gauge and site selection guided by the intended infusate and vein quality. Infection risk with PVCs has historically been considered low compared with central devices, but their massive use translates into a substantial absolute burden of local and systemic complications; prospective studies show phlebitis rates ranging from about 3.5 to 18 cases per 100 catheter-days, with risk increasing when dwell time exceeds 72–96 hours, in large hospitals, in patients with malignancy, and with irritant infusates, and although CRBSI rates are generally <0.5–0.7 per 1 000 catheter-days, inappropriate insertion, poor maintenance, and failure to remove unused PVCs contribute to preventable bloodstream infections and sepsis (Cernuda Martínez et al., 2024).

Midline catheters are peripheral devices 8–20 cm in length that are inserted via basilic, cephalic, or brachial veins above or below the antecubital fossa and advanced so that the tip lies in the proximal arm veins, distal to the axilla, providing intermediate-duration venous access typically for 1–4 weeks when therapy is too prolonged for PVCs but central access is not strictly required. Indications include prolonged courses of intravenous antibiotics, hydration, and certain non-vesicant parenteral therapies or moderately hyperosmolar solutions, especially in patients with difficult peripheral access, with insertion usually performed under ultrasound guidance using maximal barrier precautions, meticulous skin antisepsis, and securement devices to minimize dislodgement and thrombosis. Infection risk profiles suggest that midlines have device-related bloodstream infection rates comparable to or only slightly higher than standard PVCs and substantially lower than peripherally inserted central catheters (PICCs) and conventional central venous catheters, with reported CRBSI rates around 0.28–0.5 per 1 000 catheter-days, but they are associated with non-trivial risks of local infection, exit-site inflammation, and a relatively higher incidence of upper-extremity venous thrombosis and occlusion, emphasizing the need for careful patient selection and structured surveillance (Authors et al., 2023).

Central venous catheters (CVCs) are intravascular devices inserted into large central veins with the tip positioned in the lower superior vena cava, right atrium, or inferior vena cava, and are indicated for

hemodynamic monitoring, administration of vasoactive agents, parenteral nutrition, irritant or vesicant drugs, rapid fluid resuscitation, and central venous blood sampling in acutely or critically ill patients. Standard insertion techniques now emphasize ultrasound guidance for venipuncture, full maximal sterile barrier precautions (cap, mask, sterile gown, gloves, and large drape), chlorhexidine-alcohol skin preparation, and strict maintenance bundles, as ultrasound guidance reduces mechanical complications and, in meta-analyses, is associated with a roughly 30–35% relative reduction in catheter-related infections compared with landmark techniques, particularly when used by experienced operators in settings where maintaining sterility is challenging. Despite these advances, non-tunneled CVCs remain a major source of catheter-related bloodstream infection, with CLABSI/CRBSI incidence peaking within 7–10 days after insertion; infection risk is influenced by insertion site (historically higher at femoral sites), adherence to sterile technique, duration of catheterization, and patient factors such as critical illness, immunosuppression, and prior catheter infections, underscoring the importance of minimizing catheter days and promptly removing unnecessary lines (Boulet et al., 2024).

Peripherally inserted central catheters (PICCs) are long catheters inserted into peripheral upper-extremity veins (typically basilic or brachial) and advanced so the tip resides in the lower superior vena cava, providing central venous access for medium- to long-term therapy in both inpatients and outpatients. Their principal indications include prolonged intravenous antibiotic therapy, chemotherapy, parenteral nutrition, and complex home infusions when central access is needed but the risks of traditional CVC insertion are undesirable or when repeated venipuncture is problematic, with insertion usually performed under ultrasound guidance by specialized teams, using sterile technique and radiographic or ECG-based tip confirmation to optimize positioning and reduce mechanical and thrombotic complications. While PICCs were initially promoted as safer alternatives to jugular or subclavian CVCs, large cohort and review data now highlight that PICC use carries significant risks of venous thromboembolism and catheter-related bloodstream infection; CRBSI rates of about 2.1–2.3 per 1 000 catheter-days have been reported, and patients with PICC-related CRBSIs demonstrate markedly elevated odds of bloodstream infection and higher 30-day mortality compared with patients without PICCs, making appropriate indication, device selection (e.g., smaller French size), and strict adherence to insertion and maintenance bundles crucial (Duwadi et al., 2018).

Hemodialysis catheters encompass both temporary nontunneled and longer-term tunneled cuffed CVCs placed in central veins to provide high-flow access for renal replacement therapy when arteriovenous fistulas or grafts are not available or feasible, particularly in acute kidney injury, while awaiting maturation of permanent access, or in patients with limited vascular options. Insertion typically involves ultrasound-guided cannulation of the internal jugular (preferred) or femoral vein, tunneling and cuff placement for long-term catheters, and the use of strict aseptic technique, with subclavian access generally avoided because of the risk of central venous stenosis that may jeopardize future fistula creation. Hemodialysis catheters are among the highest-risk devices for catheter-related bloodstream infection due to frequent handling, high flow, and prolonged dwell; risk factors include nontunneled design, submaximal barrier precautions, femoral site use, longer duration of catheterization, prior CRBSI, diabetes, hypoalbuminemia, and Staphylococcus aureus nasal carriage, with studies showing substantially higher bacteremia rates for femoral compared to internal jugular catheters and strong evidence that topical antimicrobial exit-site agents or antibiotic lock solutions can significantly reduce bacteremia and exit-site infection at the cost of potential antimicrobial resistance (Miller et al., 2016).

Implanted ports and tunneled catheters are long-term central venous access devices designed for months to years of use, most commonly in oncology and patients with chronic diseases requiring repeated intermittent infusions or blood sampling; implanted ports consist of a subcutaneous reservoir connected to a catheter with a tip in the central veins, whereas tunneled catheters emerge from the skin and are secured with a subcutaneous cuff. Indications include long-term chemotherapy, total parenteral nutrition, long-term antibiotics, and frequent transfusions when peripheral access is poor; port placement requires surgical or interventional radiology techniques with creation of a subcutaneous pocket and venous puncture under

fluoroscopic or ultrasound guidance, while tunneled catheters are inserted with a subcutaneous tunnel from an exit site on the chest wall to a central vein, both requiring full sterile precautions at insertion and needle access. Infection risks with implanted ports are generally lower than with external tunneled catheters and non-tunneled CVCs because the system is closed between uses, but port-related infections, including pocket infections and CRBSIs, still occur, particularly in patients receiving total parenteral nutrition, those with difficult insertions, younger age, and poor general condition; tunneled catheters carry higher ongoing risks of exit-site and tunnel infections due to external segments and frequent manipulation, making consistent aseptic technique during needle access, meticulous hub disinfection, and regular site care central to preventing infection-related removal and sepsis (Lebeaux et al., 2010).

Epidemiology and Microbiology of CRBSIs

Catheter-related bloodstream infections (CRBSIs) remain a major cause of preventable morbidity and mortality worldwide, but their epidemiology shows substantial heterogeneity across regions, healthcare systems, and vascular access types, with incidence rates in intensive care units (ICUs) typically ranging from about 1.8–5.2 episodes per 1 000 catheter-days in high-income settings and frequently higher in low- and middle-income countries where infection prevention resources and surveillance may be limited. Point prevalence and incidence studies from tertiary hospitals and ICUs commonly report CRBSI densities around 2–4 episodes per 1 000 catheter-days, although some centers achieve rates below 1 episode per 1 000 catheter-days after implementation of central line bundles and rigorous surveillance, whereas others, particularly in resource-limited environments, continue to report rates exceeding 5–8 per 1 000 device-days, especially when catheters remain in situ for prolonged periods. Hemodialysis and oncology populations exhibit distinct epidemiologic profiles, with hemodialysis catheter-related bloodstream infection rates reported as high as 13–14 episodes per 1 000 catheter-days in some cohorts, reflecting frequent device manipulation, chronic immunosuppression, and biofilm-prone catheter materials. Over time, many high-income countries have documented declining central line–associated bloodstream infection (CLABSI) and CRBSI rates following adoption of evidence-based bundles and mandatory reporting, but this overall downward trend is tempered by persistent hotspots such as long-term care, home infusion, and outpatient hemodialysis units, where surveillance is less standardized and catheter care practices vary widely. The global epidemiology of CRBSIs is therefore characterized by a dual pattern: substantial reductions in well-resourced ICUs and oncology settings with mature infection prevention programs, contrasted with ongoing high incidence and under-recognition in lower-resource hospitals, overcrowded ICUs, and ambulatory dialysis centers, reinforcing the need for context-adapted surveillance metrics, benchmarking, and targeted prevention strategies (Learned et al., 2013).

The microbiology of CRBSIs is dominated by skin commensals and nosocomial flora that gain access to the intravascular space via extraluminal migration along the catheter tract, intraluminal contamination of hubs and connectors, or hematogenous seeding, with Gram-positive cocci accounting for approximately 40–80% of episodes in many series. CoNS such as Staphylococcus epidermidis are often the most frequent isolates in surveillance datasets, reflecting their ubiquitous presence on the skin and their capacity for robust biofilm formation on catheter surfaces, whereas S. aureus, although sometimes less common, is associated with more severe clinical courses, higher rates of metastatic infection (endocarditis, vertebral osteomyelitis), and increased mortality. Candida species, especially Candida albicans and non-albicans Candida (e.g., C. parapsilosis, C. glabrata), represent a smaller proportion of CRBSIs overall (often 5–10%) but are particularly prominent in high-risk groups such as patients with prolonged ICU stays, broad-spectrum antibiotic exposure, total parenteral nutrition, and hematologic malignancies, where candidemia is strongly linked to central venous catheters as the primary source. Among Gram-negative pathogens, Pseudomonas aeruginosa, Klebsiella spp., Escherichia coli, and Acinetobacter spp. commonly feature in CRBSI cohorts, especially in ICUs and hemodialysis units, and are frequently associated with environmental reservoirs, contaminated solutions, or breaches in aseptic technique. Mixed and polymicrobial infections, involving combinations of CoNS, enteric Gram-negatives, and Candida spp., are also reported, particularly in severely ill or neutropenic patients and in settings where catheter hubs are

frequently accessed, complicating empirical therapy and often necessitating catheter removal due to complex biofilm communities. This evolving microbial spectrum underscores the importance of local microbiology and resistance surveillance to guide empirical regimens, as well as the central role of biofilm biology in shaping CRBSI pathogenesis and treatment response (Cheng et al., 2011).

The emergence and spread of multidrug-resistant organisms (MDROs) have profoundly influenced the epidemiology, management, and outcomes of CRBSIs, with high proportions of methicillin-resistant S. aureus (MRSA) and methicillin-resistant coagulase-negative staphylococci reported in many institutions, sometimes affecting 40% of S. aureus and up to 80% of CoNS isolates from catheter-related bloodstream infections. In Gram-negative CRBSIs, extended-spectrum beta-lactamase (ESBL)–producing Enterobacterales, carbapenem-resistant Pseudomonas aeruginosa, Acinetobacter baumannii, and other non-fermenters increasingly contribute to severe device-associated sepsis, particularly in ICUs with high antibiotic pressure, prolonged mechanical ventilation, and frequent central venous catheter use. MDRO involvement in bloodstream infections has been associated with higher rates of inappropriate initial empirical therapy, longer time to effective treatment, and increased length of stay and costs, and several cohort studies indicate that when empirical therapy is delayed or discordant, mortality is significantly higher in patients with resistant pathogens compared with those infected by susceptible strains. Conversely, in units where resistance patterns are well characterized and incorporated into empirical protocols, and where early broad-spectrum coverage is promptly de-escalated once susceptibilities are known, some studies have not observed a clear mortality difference between MDRO-positive and MDRO-negative bloodstream infections, suggesting that timely and appropriate therapy can partly mitigate the prognostic impact of resistance. Nevertheless, MDRO CRBSIs often require more complex and toxic regimens (e.g., glycopeptides, lipopeptides, linezolid, polymyxins, novel beta-lactam–beta-lactamase inhibitor combinations), limit catheter salvage options, and increase the risk of recurrent bacteremia, reinforcing the intertwined importance of antimicrobial stewardship, strict insertion and maintenance bundles, and device minimization strategies to curb both infection and resistance. The rising burden of vancomycin-resistant enterococci (VRE) and carbapenem-resistant Gram-negatives in catheter-associated bloodstream infections in some regions further highlights CRBSI as a critical interface between device-related infection prevention and global antimicrobial resistance containment efforts (Sharifzadeh Kermani et al., 2025).

Patient-related factors and healthcare setting characteristics exert a strong influence on CRBSI risk, pathogen distribution, and clinical outcomes, with higher incidence observed among critically ill ICU patients, those with hematologic malignancies or solid tumors, recipients of stem cell or solid organ transplants, and individuals receiving long-term hemodialysis or parenteral nutrition. Comorbidities such as diabetes mellitus, chronic kidney disease, advanced liver disease, chronic obstructive pulmonary disease, and severe cardiac failure impair innate and adaptive immune responses, disrupt skin integrity and microcirculation, and often necessitate prolonged vascular access, thereby increasing susceptibility to colonization, biofilm formation, and subsequent bloodstream infection. In hemodialysis cohorts, for example, the combination of uremia-associated immune dysfunction, repeated catheter manipulation, and frequent exposure to healthcare environments yields high CRBSI prevalence, with Staphylococcus spp., E. coli, Pseudomonas, and Candida commonly implicated and associated with increased hospitalization, access loss, and mortality compared to non-catheter-based vascular access. The healthcare setting also shapes epidemiology: tertiary-care ICUs typically show a higher proportion of MDROs and non-fermenting Gram-negative bacilli, whereas oncology and hematology units are more prone to Candida and other opportunistic pathogens, and outpatient or home-care settings may have greater contributions from skin flora and community-associated MRSA. Duration of catheterization, number of lumens, insertion site (e.g., femoral vs. subclavian or internal jugular), breach of maximal sterile barrier precautions at insertion, and inconsistent hub disinfection practices further modulate risk, with several studies demonstrating that each additional day of catheter dwell and each episode of manipulation or line access incrementally raises the probability of CRBSI. These interactions between patient comorbidities, device characteristics, and organizational factors underscore CRBSI as a systems-level problem requiring integrated clinical,

microbiologic, and infection-prevention strategies tailored to specific patient populations and care environments (Cao et al., 2024).

Pathogenesis and Biofilm Development

Mechanisms of microbial entry into vascular catheters are classically categorized as extraluminal, intraluminal, and hematogenous, with the relative contribution of each route varying according to catheter type, insertion site, dwell time, and host factors. Extraluminal colonization usually originates from the patient's skin flora at the insertion site, with organisms such as coagulase-negative staphylococci and Staphylococcus aureus migrating along the catheter tract to the tip, a process that predominates in short-term, non-tunneled central venous catheters during the early days after placement. Intraluminal colonization is mainly related to contamination of the catheter hub, injection ports, or tubing connections by the hands of healthcare workers or contaminated devices, and becomes the dominant pathway with prolonged dwell times, especially in long-term central lines, tunneled catheters, and totally implantable devices where repeated manipulation of hubs and connectors is frequent. Hematogenous seeding occurs when microorganisms from distant foci of infection (such as pneumonia, urinary tract infection, or surgical site infection) enter the bloodstream and secondarily adhere to the catheter surface, while intrinsic contamination of infusates or blood products, although rare in modern practice, represents another potential source in outbreaks or breaches in manufacturing and pharmacy compounding practices. Important device-related factors, including the catheter material, surface chemistry, and geometry, modulate the efficiency of microbial attachment via conditioning films of host proteins (fibrin, fibronectin, and other plasma components) that rapidly coat the catheter after insertion and create a permissive interface for microbial adhesins, thereby linking insertion technique, maintenance care, and systemic infection risk across the entire life cycle of the vascular access device (Gahlot et al., 2014).

Biofilm formation on intravascular catheters is a dynamic, multistep process beginning with reversible adhesion of planktonic microorganisms to the conditioned catheter surface, followed by irreversible attachment mediated by specific adhesins, production of extracellular polymeric substances (EPS), and maturation into a structured three-dimensional community that can periodically release planktonic or biofilm-derived aggregates into the bloodstream. Early attachment is driven by non-specific physicochemical forces (hydrophobic interactions, van der Waals forces, electrostatic interactions) and then stabilized by microbial surface components recognizing adhesive matrix molecules, such as MSCRAMMs in staphylococci that bind fibrinogen, fibronectin, and collagen deposited on catheter materials, leading to dense colonization of both extraluminal and intraluminal surfaces. As the biofilm matures, cells become embedded in a complex EPS matrix composed of polysaccharides, proteins, extracellular DNA, and host components, creating microenvironments with nutrient gradients, differential oxygen tension, and pH variation that promote heterogeneous metabolic states, including slow-growing or dormant persister phenotypes that are intrinsically less susceptible to many antimicrobial agents. This architecture, combined with reduced antimicrobial penetration through the matrix, altered microenvironmental conditions, and biofilm-specific gene expression, confers marked tolerance to antibiotics and antiseptics, so that organisms such as coagulase-negative staphylococci, S. aureus, and Gram-negative bacilli often remain viable on the catheter despite systemic therapy, thereby explaining persistent bacteremia, relapse after apparent clinical improvement, and the poor efficacy of short-course antibiotics without catheter removal. Biofilm-associated cells may also exhibit enhanced horizontal gene transfer and accumulation of resistance determinants, meaning that indwelling catheters not only serve as reservoirs for recurrent infection but also as ecological niches where multidrug-resistant organisms can emerge and disseminate, underscoring the need for strategies such as antimicrobial-impregnated catheters, lock solutions, and surface-modifying technologies that specifically target biofilm formation and maintenance rather than planktonic bacteria alone (Mirijello et al., 2015).

Host–pathogen interactions in catheter-related bloodstream infection are governed by a complex interplay between the host's innate and adaptive immune defenses, the microbial virulence repertoire, and the

physical protection afforded by the biofilm and catheter microenvironment. Immediately after vascular access placement, deposition of plasma proteins and activation of coagulation and complement cascades occur on the catheter surface, generating a conditioning layer that both facilitates microbial adhesion via binding to adhesins and modulates leukocyte recruitment and activation through opsonins and anaphylatoxins. In immunocompetent hosts, pattern-recognition receptors such as Toll-like receptors and C-type lectin receptors on neutrophils, monocytes, and endothelial cells recognize pathogen-associated molecular patterns from biofilm and planktonic bacteria, triggering intracellular signaling pathways that culminate in proinflammatory cytokine production, neutrophil chemotaxis, phagocytosis, respiratory burst, and NET formation, which collectively attempt to contain local infection and prevent dissemination. However, the biofilm matrix physically impedes phagocyte access to deeply embedded bacteria and can inactivate or sequester immune effectors, while some pathogens modulate host responses by altering expression of surface structures, secreting immune-modifying molecules, or shifting to small-colony variants, leading to blunted inflammation or smoldering, low-grade bacteremia that is difficult to eradicate without device removal. In critically ill or immunocompromised patients, including those with hematologic malignancies, neutropenia, or receiving immunosuppressive therapies, the systemic host response to bloodstream infection is often dysregulated, ranging from excessive hyperinflammation with endothelial injury, capillary leak, and septic shock to profound immune paralysis with impaired antigen presentation, lymphocyte exhaustion, and increased susceptibility to opportunistic pathogens and secondary infections, as demonstrated by pathogen-specific transcriptomic signatures and differing patterns of immune pathway activation in bloodstream infections caused by Staphylococcus aureus, Streptococcus spp., Escherichia coli, and Enterococcus. These nuanced host–pathogen interactions explain why the same catheter-colonizing organism may result in trivial colonization in one patient but fulminant sepsis in another, and they support individualized prevention and management strategies that integrate catheter type and dwell time, local and systemic host factors (such as immune status and comorbidities), and organism-specific virulence features when assessing risk, tailoring antimicrobial approaches, and deciding on early catheter removal versus salvage attempts in suspected catheter-related bloodstream infection (Butler et al., 2025).

Patient-Related Factors

Patient-related risk factors play a pivotal role in elevating CRBSI susceptibility, primarily through compromised host defenses and underlying physiological vulnerabilities that facilitate microbial invasion and proliferation along catheter pathways. Advanced age emerges as a consistent predictor, with individuals over 60 years demonstrating diminished immune responses, reduced skin integrity, and altered vascular endothelium, all of which amplify bacterial adhesion and translocation risks during catheterization; meta-analyses confirm odds ratios approaching 1.02 per year increment, underscoring cumulative physiological decline. Immunosuppression, whether from chemotherapy, malignancy, HIV, or transplant-related therapies, severely impairs neutrophil function and T-cell mediated immunity, creating an environment conducive to opportunistic pathogens like coagulase-negative staphylococci and Candida species, with reported odds ratios exceeding 2.5-10 in multiple cohorts. Comorbidities such as diabetes mellitus, chronic kidney disease, and obesity further exacerbate this by promoting hyperglycemia-induced biofilm formation, endothelial dysfunction, and chronic inflammation; for instance, diabetes yields odds ratios of 2.43 in ICU settings, while kidney disease consistently shows hazard ratios of 1.59-2.79 across studies, often compounded by malnutrition or weight loss that depletes serum albumin and enhances microbial virulence. These intrinsic factors interact synergistically, as seen in oncology patients where hematologic cancers and recent chemotherapy double infection rates through neutropenia (leukocyte counts <1,000/μL yielding OR 69.77), highlighting the need for tailored prophylaxis in high-burden populations (Lafuente Cabrero et al., 2023).

Device-Related Factors

Device-related attributes directly influence CRBSI incidence by modulating biofilm development, luminal contamination opportunities, and insertion trauma magnitude, with design choices profoundly affecting

microbial colonization dynamics over time. Catheter type and lumen configuration stand out, as multilumen devices (double or triple) harbor higher infection risks due to multiple access ports increasing contamination episodes and turbulent flow fostering thrombus-biofilm complexes, evidenced by hazard ratios of 2.09-8.52 compared to single-lumen alternatives that exhibit protective effects. Dwell time represents a dose-dependent peril, where each additional day elevates odds by 1.02-1.04, with thresholds beyond 7-14 days markedly spiking rates (e.g., OR 3.93 for >14 days in neonates, extrapolatable to adults), attributable to progressive hub colonization, fibrin sheath formation, and endothelial erosion. Insertion site selection further stratifies risk, favoring subclavian over jugular or femoral veins (OR 0.32 protective for subclavian), as lower sites suffer higher bacterial loads from skin flora (e.g., femoral OR elevated due to groin microbiota) and mechanical instability promoting dislodgement and extravasation. Material coatings like antimicrobial impregnation mitigate these by 40-60%, yet non-tunneled short-term catheters in emergency contexts amplify vulnerabilities through suboptimal fixation and rapid indwelling (Pitiriga et al., 2025).

Procedure-Related Factors

Procedural elements during catheter insertion and maintenance critically determine CRBSI trajectories by governing initial microbial ingress and ongoing contamination control, where deviations from asepsis cascade into systemic infections. Insertion technique profoundly impacts outcomes, with guidewire exchanges heightening risks fourfold (OR 4.59) via dislodged biofilms from prior devices, while ultrasound guidance halves incidence (RR 0.47) through precise venipuncture minimizing tissue trauma and hematoma formation that serve as pathogen nidi. Environmental sterility, encompassing maximal barrier precautions (sterile gowns, drapes, gloves), proves indispensable, as breaches correlate with 2-5 times higher rates, particularly in non-ICU settings lacking laminar flow. Hand hygiene compliance emerges as the cornerstone, with lapses introducing skin flora (Staphylococcus aureus, Gram-negatives) directly into bloodstreams; studies mandate alcohol-based rubs pre- and post-manipulation, revealing non-compliance as an independent OR >4 in procedural audits. Additional maneuvers like inadequate skin antisepsis (chlorhexidine superior to povidone-iodine) or three-way stopcock usage compound hazards by enabling retrograde migration, emphasizing bundled protocols that integrate site care, dressing changes, and daily assessments to curb progression from colonization to bacteremia (Lafuente Cabrero et al., 2023).

Organizational Factors

Organizational frameworks underpin CRBSI prevention efficacy by shaping human resources, educational infrastructure, and protocol adherence, where systemic deficiencies propagate procedural lapses across care continuums. Staffing ratios critically influence vigilance, with suboptimal nurse-to-patient levels (e.g., >1:2 in ICUs) correlating to inferior site surveillance and hygiene execution, as evidenced by higher CLABSI in understaffed units. Training programs fortify competencies, with in-service sessions on bundles (e.g., hand hygiene, maximal barriers) boosting knowledge from 28% to over 70%, directly slashing rates through standardized simulations and competency audits; absence of pre-service education triples risks via inconsistent practices. Protocols, when embedded in organizational culture, drive compliance multidisciplinary audits, guideline accessibility, and feedback loops (e.g., Bacteremia Zero initiatives) yield 41% variance explanation in prevention behaviors, prioritizing resource allocation for chlorhexidine dressings and daily removal prompts. Cultivating a safety ethos via leadership commitment and metrics tracking (e.g., APACHE-adjusted benchmarks) mitigates modifiable gaps, as emergency departments lag due to chaos versus structured ICUs (Kim & Choi, 2024).

Standard Infection Prevention Practices

Standard infection prevention practices form the cornerstone of reducing catheter-related bloodstream infections (CRBSI) associated with vascular access devices, encompassing a multifaceted approach that integrates hand hygiene, aseptic techniques, site selection, skin preparation, insertion and maintenance bundles, and comprehensive staff training to minimize microbial contamination at every stage from insertion to removal. These practices, endorsed by authoritative bodies such as the Centers for Disease

Control and Prevention (CDC), the Infusion Nurses Society (INS), and the EPIC3 guidelines, have demonstrated substantial reductions in infection rates through rigorous evidence-based protocols that address skin flora migration, hub contamination, and unnecessary device dwell time. Implementation of these standardized measures not only lowers CRBSI incidence but also enhances patient safety, reduces healthcare costs, and supports quality improvement initiatives in high-risk settings like intensive care units (Nainan Myatra, 2019).

Hand hygiene remains the simplest yet most critical intervention in preventing CRBSI, with healthcare personnel required to perform it using alcohol-based rubs or soap and water immediately before and after catheter insertion, manipulation, or dressing changes to eradicate transient skin flora that could contaminate the site or hub. Aseptic technique extends this by mandating sterile gloves for central venous catheter (CVC) insertions, maximal sterile barrier precautions including caps, masks, gowns, and full-body drapes, and avoidance of palpation post-antisepsis unless sterility is preserved, as breaches in these protocols significantly elevate infection risk through direct microbial introduction. Studies underscore that compliance with these practices, often audited via checklists, correlates with up to 50% reductions in CLABSI rates, emphasizing the need for ongoing monitoring and empowerment of observers to halt procedures during lapses (Ling et al., 2016).

Guidelines from the CDC prioritize subclavian sites over jugular or femoral veins for nontunneled CVCs in adults, particularly in ICUs, due to lower infectious complications, while INS standards advocate upper extremity sites for peripheral catheters to minimize phlebitis and contamination risks, and EPIC3 reinforces assessing infection versus mechanical risks like pneumothorax or thrombosis. Patient-specific factors such as bleeding diathesis, ultrasound availability, and operator experience guide selection, with femoral sites avoided in adults except emergencies and subclavian contraindicated in hemodialysis patients to prevent stenosis. Evidence from meta-analyses and cohort studies shows site choice influences CRBSI rates, with upper extremities preferred for peripherals and avoidance of wrist or cubital fossa in PIVCs to curb colonization (O'Grady et al., 2011).

Chlorhexidine gluconate (CHG) in alcohol (≥2%) outperforms povidone-iodine or alcohol alone for skin antisepsis prior to CVC insertion and during dressing changes, reducing CRBSI by up to 36% through broad-spectrum activity and persistent adherence, as affirmed by CDC category IA recommendations and meta-analyses. Alternatives like tincture of iodine or iodophors are reserved for CHG contraindications, such as neonates under 2 months where safety data is limited, but must dry fully to prevent irritation or inactivation. Daily CHG bathing in ICUs further potentiates this by decreasing skin bioburden, though resistance monitoring is advised (Lai et al., 2016).

Insertion bundles integrate hand hygiene, maximal sterile barriers, CHG antisepsis, optimal site selection, and ultrasound guidance, achieving ≥95% compliance linked to 33% CLABSI reductions per large-scale analyses, with all-inclusive kits enhancing adherence. CDC and IHI-endorsed checklists ensure these elements during procedures, significantly lowering mechanical failures and infections compared to non-bundle care, as evidenced in ICUs and non-ICUs. PICCs and midlines warrant similar protocols when dwell exceeds short-term peripherals (O'Grady et al., 2011).

Maintenance bundles mandate hub disinfection with alcoholic CHG or 70% alcohol via 5-15 second friction scrubs before access, transparent dressings changed every 7 days (gauze every 2) or sooner if soiled/loose/damp, daily site palpation/inspection, and necessity reviews during rounds to prompt removal of nonessential lines. CHG-impregnated dressings and appropriate nurse staffing further mitigate risks, with administration sets replaced up to 7 days for non-blood/lipids, yielding sustained CLABSI declines in bundled implementations. Audits confirm hub neglect as a primary contamination vector, underscoring bundle fidelity (Buetti et al., 2022).

Mandatory initial and periodic education on bundles, competency credentialing for inserters/maintainers, and simulation-based training improve procedural skills and compliance, reducing CLABSIs by enhancing

sterile technique recognition. Programs incorporating WHO's five moments of hand hygiene and bundle audits foster a safety culture, with refresher sessions vital for supervisors; MICU studies report zero CLABSIs post-simulation. Tailored to roles, these interventions ensure sustained low rates, outperforming generic training (Nainan Myatra, 2019).

Advances and Emerging Technologies

Catheters impregnated with silver, chlorhexidine-silver sulfadiazine (CHSS), or minocycline-rifampin have demonstrated substantial efficacy in reducing CRBSI rates by actively inhibiting microbial colonization on both external and luminal surfaces, with network meta-analyses confirming minocycline-rifampin as the most effective, achieving risk ratios as low as 0.29 compared to non-impregnated catheters across 17,255 devices in 60 trials. First-generation CHSS catheters, coating only the external surface, lowered CRBSI odds by 44% in meta-analyses, while second-generation versions impregnating both surfaces further decreased incidence in randomized controlled trials involving over 1,000 patients, particularly benefiting intensive care settings where dwell times exceed five days. Silver-impregnated variants, including silver-platinum-carbon combinations, also yield significant reductions (RR 0.57), though less pronounced than antibiotic combinations, with cost-effectiveness analyses revealing savings from averted infections despite higher upfront costs, as CRBSI episodes incur $10,000–$71,000 per case in extended stays and treatments. Limitations persist, including potential emergence of resistance heterogeneity in trial outcomes due to varying baseline risks, and inconsistent mortality benefits, alongside concerns over hypersensitivity to silver or sulfadiazine; guidelines thus endorse these for high-risk patients post-bundle implementation, such as immunocompromised individuals or those with femoral/jugular access and tracheostomy, where CRBSI risks elevate significantly (Wang et al., 2018).

Antimicrobial lock solutions, including ethanol (typically 70%), taurolidine, and citrate-antibiotic combinations, fill catheter lumens to prevent intraluminal biofilm formation, the primary CRBSI pathway in long-term devices like tunneled catheters for hemodialysis or oncology patients. Ethanol acts as a broad-spectrum microbicide penetrating biofilms without fostering resistance, with randomized trials showing daily ethanol locks reduce CRBSI incidence in cancer patients versus heparinized saline, achieving 95% catheter salvage rates when combined with systemic antibiotics over five days. Taurolidine-citrate solutions exhibit superior outcomes in meta-analyses for preventing colonization in hemodialysis, while citrate-antibiotic mixes target gram-positive pathogens prevalent in ICU settings; indications prioritize high-risk tunneled catheters with recurrent infections or neutropenia. Meta-analyses and scoping reviews of 336 studies affirm 21–73% CRBSI reductions, enhancing survival and retention without toxicity, though challenges include compatibility issues with certain antibiotics, ethanol's occasional catheter degradation over prolonged use, and variable fungal efficacy necessitating tailored regimens (Alfieri et al., 2025).

Hydrophilic coatings, anti-adhesive polymers, and nanotechnology-based silver nanoparticle embeddings transform catheter surfaces to repel microbes and proteins, curtailing adhesion critical to biofilm initiation. Novel bifunctional coatings blending N-vinylpyrrolidinone/n-butyl methacrylate copolymers with silver nanoparticles and heparin yield synergistic antimicrobial and antithrombogenic effects, inhibiting Staphylococcus aureus adhesion by over 90% in vitro while minimizing thrombotic occlusion, a CRBSI cofactor. Nanotechnology enhances durability, with embedded nanoparticles providing sustained release superior to leaching impregnations, and hydrophilic surfaces reduce friction by 30–35%, easing insertion and extraction to limit trauma-related infections. Clinical evaluations confirm lower colonization versus uncoated polyurethane, though scalability, long-term in vivo stability, and resistance monitoring pose hurdles alongside higher production costs (Stevens et al., 2011).

Real-time ultrasound (US) guidance during central venous catheter insertion slashes mechanical complications and infection risks by enabling precise vessel visualization, boosting first-attempt success to 84–97% for internal jugular access versus 72% with landmarks, per prospective ICU trials involving over 400 patients. Marginal Cox models from three large RCTs affirm US reduces CRBSI (primary outcome) and major infections via fewer punctures, hematomas, and arterial injuries that seed pathogens, with relative

risk reductions up to 38% independent of site. Training mandates competency via simulation and proctored procedures, aligning with standards from societies like SHEA/IDSA, ensuring operators achieve >95% success pre-independence. Limitations encompass equipment access in resource-poor settings and operator dependence, yet US elevates as standard of care, especially jugular/subclavian (Obama et al., 2025).

Electronic infection surveillance dashboards, automated catheter-day alerts, and smart devices with embedded sensors revolutionize CRBSI prevention by enforcing bundle compliance via real-time reminders for dressing changes, hub disinfection, and timely removal. Scoping reviews of digital interventions report 21–73% CLABSI drops in quasi-experimental studies, attributed to heightened adherence without external controls. Electronic health record integrations flag dwell times exceeding indications, while emerging smart catheters monitor flow occlusion or biofilm via biosensors, prompting preemptive interventions. Healthcare workers endorse usability, though interoperability, data privacy, and implementation costs challenge widespread adoption (Obama et al., 2025).

Limitations of Current Evidence

Current evidence on catheter-related bloodstream infection (CRBSI) prevention in vascular access reveals significant limitations, including a predominance of observational studies, quasiexperimental designs, and before-after interventions rather than rigorous randomized controlled trials (RCTs), which often overestimate efficacy due to high baseline infection rates and confounding factors like the Hawthorne effect where observed staff improve practices temporarily. Heterogeneity in study populations, catheter types (e.g., short-term nontunneled CVCs versus long-term tunneled devices), definitions of CRBSI versus CLABSI, and prevention bundles further complicates meta-analyses and generalizability, with many reviews noting low-to-moderate quality evidence for interventions like disinfection caps, scrubbing protocols, and antimicrobial locks, often lacking head-to-head comparisons or long-term outcomes. Post-COVID-19 data highlight additional gaps, as pandemic-related surges in CLABSI rates (up to 50% in ICUs) reversed prior declines, yet studies suffer from incomplete adherence reporting, variable compliance monitoring, and insufficient adjustment for staffing shortages or experience-complexity gaps among nurses, underscoring the need for standardized surveillance and higher-quality prospective data (L. Zhang et al., 2013).

Emerging technologies such as chlorhexidine-impregnated sponges, minocycline-rifampin coated catheters, novel hub designs, and advanced antimicrobial lock solutions show promise in reducing CRBSI rates by 40-70% in preliminary studies, but the absence of large-scale, multicenter RCTs limits their endorsement beyond high-risk settings where baseline rates remain elevated despite basic bundles. High-quality RCTs are essential to evaluate these innovations against standard care, addressing unresolved issues like optimal duration of impregnation, resistance emergence (e.g., no reported minocycline/rifampin resistance but concerns persist), cost-effectiveness in diverse populations (e.g., ICU adults vs. pediatric or hemodialysis patients), and combinations with bundles including maximal sterile barriers and chlorhexidine antisepsis. Future trials must incorporate blinded designs, standardized CRBSI definitions (e.g., quantitative cultures >10^3 CFU), power for rare events using catheter-days denominators, and subgroup analyses for patient factors like immunosuppression or dwell time >10 days, where endoluminal contamination predominates (O'Grady et al., 2011).

Personalized strategies for CRBSI prevention must account for patient-specific risks such as underlying conditions (e.g., hemodialysis dependence, oncology, or critical illness), catheter dwell time, insertion site (subclavian preferred over femoral), and microbiome factors, yet current evidence lacks tailored approaches beyond generic bundles, with calls for risk-stratified protocols integrating genetic predispositions to biofilm formation or real-time biomarkers. Developments could include patient-genotyped selection of catheter materials (e.g., polyurethane over silicone for reduced S. epidermidis adherence in high-risk individuals) or customized lock solutions (e.g., citrate for hemodialysis without antimicrobials to avoid resistance), building on observational data showing variable responses to flushing volumes or prefilled syringes. Challenges include integrating electronic health records for dynamic risk scoring (e.g., combining

neutrophil counts, prior infections, and dwell predictions) with clinician decision aids, necessitating RCTs to validate against uniform bundles while addressing equity in resource-limited settings like home parenteral nutrition (Janum et al., 2013).

Integration of artificial intelligence (AI) and data analytics promises transformative infection surveillance for CRBSI, with machine learning models (e.g., random forest achieving 87% accuracy, AUC 0.70) predicting bloodstream infections from structured data like neutrophil counts, CRP levels, central line days, and microbiology results, enabling real-time alerts in ICUs. Fully automated algorithms validated against manual surveillance (high specificity >95%, good sensitivity) process electronic health records for CRBSI/CLABSI detection using ECDC definitions, reducing workload and enabling proactive interventions like early catheter removal or targeted bundles. Future directions involve coupling AI with continuous antimicrobial resistance surveillance, wearable biosensors for skin colonization, and predictive analytics for bundle compliance, as SHAP-interpretable models highlight inflammatory markers and caregiver exposure as key features, supporting precision prevention in heterogeneous populations (Catho et al., 2024).

Conclusion

Advances in vascular access and catheter-related bloodstream infection (CRBSI) prevention highlight the effectiveness of multifaceted, evidence-based strategies that substantially mitigate infection risks across diverse catheter types in varied clinical settings including ICUs, oncology, and hemodialysis units. Comprehensive bundles emphasizing hand hygiene, maximal sterile barrier precautions, chlorhexidine-alcohol skin antisepsis, ultrasound-guided insertion, daily necessity assessments, and hub disinfection have achieved dramatic reductions in CLABSI rates, often nearing zero in optimized environments, while antimicrobial-impregnated catheters (e.g., minocycline-rifampin), chlorhexidine dressings, and lock solutions like taurolidine-citrate further decrease risks by 40-73% in high-burden populations. Despite these gains, persistent challenges such as multidrug-resistant organisms, post-COVID infection surges, heterogeneous study designs, and implementation gaps in resource-limited settings underscore the need for ongoing vigilance, antimicrobial stewardship, and tailored protocols. Future priorities include large-scale RCTs evaluating novel biofilm-targeted technologies like nanotechnology-embedded coatings and AI-driven predictive surveillance (with up to 87% accuracy for early alerts), alongside personalized risk stratification incorporating patient genomics, real-time biomarkers, and global standardization to minimize unnecessary device dwell time, enhance compliance, and ultimately eradicate preventable CRBSIs, thereby improving patient safety, reducing morbidity, mortality, and healthcare costs worldwide.

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