



PATTERNS OF HEALTHCARE-ASSOCIATED INFECTIONS ACROSS ACUTE CARE HOSPITALS.

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Abstract

Healthcare-associated infections (HAIs) remain a major patient-safety challenge in acute care hospitals, where invasive procedures, vulnerable patient populations, antimicrobial exposure, and complex care pathways create sustained opportunities for transmission. This review synthesizes current evidence on the epidemiology, major infection types, etiological profiles, determinants, surveillance approaches, diagnostic advances, and prevention strategies associated with HAIs. The burden varies widely across regions, hospital units, and patient groups, with intensive care, surgery, prolonged hospitalization, and device use consistently associated with higher risk. Central line-associated bloodstream infections, catheter-associated urinary tract infections, ventilator-associated pneumonia, surgical site infections, and *Clostridioides difficile* infection remain prominent, while multidrug-resistant bacteria, opportunistic fungi, and biofilm-forming organisms increasingly complicate management. HAI patterns arise from interacting patient, microbial, environmental, workforce, and institutional factors. Electronic surveillance, molecular diagnostics, whole-genome sequencing, and artificial intelligence offer important gains in detection and outbreak investigation, although their implementation depends on data quality, infrastructure, and technical capacity. Effective control continues to rely on hand hygiene, device stewardship, environmental cleaning, antimicrobial stewardship, staff education, audit and feedback, and accountable leadership. Future progress will require integrated, context-sensitive prevention programs that link surveillance directly to action and ensure equitable access to both established and emerging technologies.

Keywords: healthcare-associated infections, acute care hospitals, antimicrobial resistance, infection surveillance, infection prevention

1. Introduction

Despite ongoing improvements in medical technology, infection prevention and control practices, and healthcare delivery, the burden of healthcare-associated infections (HAIs) is one of the most prevalent risks to the safety of patients in acute care hospitals, impacting millions of patients annually. These infections occur during the course of treatment and are linked to high levels of morbidity and mortality, high levels of antimicrobial use and high financial costs to health care systems. This trend towards more complex acute care, involving invasive procedures, immunocompromised patients and

high device use, has further increased the risk of HAIs and made the prevention and control of HAIs a priority for global healthcare (Allegranzi et al., 2017). Comprehensive infection prevention strategies, such as hand hygiene, environmental sanitation, antimicrobial stewardship, surveillance and the use of standardized clinical protocols, have proved to have great potential to reduce the incidence of infections, but consistent implementation in different healthcare settings has proven difficult (Fernando et al., 2017).

The impact of HAIs goes beyond the patient level, as these infections affect the quality and safety of healthcare services as a whole. The evidence suggests that many HAIs are preventable with active implementation of evidence-based infection control measures, highlighting the importance of the role of organizational commitment, multidisciplinary teamwork, and constant surveillance of infection control measures in prevention (Schreiber et al., 2018). With the ongoing evolution of healthcare systems, HAIs have become a more complicated clinical and public health problem, driven by the shifting demographics of patients, increasing antimicrobial resistance and the use of more highly advanced medical interventions. Therefore, knowing the epidemiology of HAIs is now critical to understanding the epidemiology of HAIs and designing targeted preventive measures, as well as improving the quality of health care (Percival et al., 2015).

The epidemiology of HAIs is very different between acute care hospitals, depending on the patient populations, clinical specialties, health care infrastructure and prevention capabilities, among other factors. Hospital-wide epidemiological evaluation has shown that the incidence of infection varies between intensive care units, surgical services, medical wards, and other specialized services, making it important to consider distribution patterns rather than individual infection events. These can be helpful for making decisions on prioritizing infection prevention resources and augmenting institutional surveillance programs (Kořpa et al., 2018). National surveillance programmes have also highlighted the need for national uniform structures for IPC in health care facilities, especially in health care systems with significant differences in infrastructure and resources. Consistent surveillance and effective implementation of infection control are essential, and strengthening of institutional preparedness is key (Zingg et al., 2015). The implementation of new diagnostic microbiology, molecular and epidemiological surveillance practices has also enhanced detection and characterisation of HAIs, facilitating a better understanding of the distribution of healthcare-associated pathogens, antimicrobial resistance and transmission patterns in acute care settings (Mirande et al., 2018). Moreover, continuing reports from developing healthcare systems have shown that the burden of HAIs is still disproportionately high where resources and surveillance systems for the prevention and control of infection are still to be strengthened, thus reinforcing the need for context-specific evaluations of HAI patterns (Swaminathan et al., 2017).

Although much research has been conducted on infection prevention, the literature tends to address specific types of infections, specific pathogens and/or a single healthcare setting, but rarely an integrated assessment of the patterns of HAIs in acute care hospitals. A detailed review of the epidemiology of distribution, risk factors and implications for surveillance and prevention in a variety of acute healthcare environments is limited.

In light of this, the aim of this review is to systematically review the most recent investigations and evidence on the epidemiology, distribution, risk factors, microbiological profile, surveillance methods, and prevention strategies for the most important types of HAIs, synthesizing the findings and offering an overall view of the situation, in order to support clinical practice, infection control policies, and further research.

2. Epidemiology and Distribution Patterns of HAIs in Acute Care Hospitals

The incidence of healthcare-associated infections (HAIs), an important epidemiological problem in acute care hospitals worldwide, varies widely by region, the type and size of health facility, patient characteristics and infection prevention measures. Acute care settings have patient populations with more invasive procedures, a need for intensive monitoring and longer stays, which provides the environment for the transmission of pathogens and risk of infection. However, recent global evidence shows that nosocomial infections are still very common, despite the efforts to improve the prevention

of infection, and that the reduction in nosocomial infections in different healthcare systems is still a major challenge (Khan et al., 2017). The epidemiological burden of HAIs is very different in low- and middle-income countries compared to high-income countries. Overcrowding, lack of infection prevention infrastructure, limited surveillance capacity, limited trained personnel and restricted access to diagnostic technologies are just a few factors that lead to higher infection rates in resource-limited healthcare systems. These structural and operational challenges are found to be significant reasons for hospital-acquired infections, with systematic evidence showing that these challenges exist at a global scale and are detrimental to healthcare quality and patient safety, particularly in low- and middle-income countries (Shahida et al., 2016).

Although high-income healthcare systems generally have stronger prevention infrastructure, HAIs continue to be clinically meaningful. A national multicentre point prevalence survey of acute care hospitals in Australia revealed that HAIs are a significant problem within healthcare settings, with the most common types being bloodstream infection, surgical site infection, UTI and pneumonia. The findings also reflected that the infection rate is different based on patient age, comorbidities, device exposure, and hospital specialty, highlighting the diversity of HAIs across the spectrum of acute care settings (Russo et al., 2019). The epidemiology of HAIs is similar throughout European acute care hospitals, where HAIs still account for significant morbidity and mortality and healthcare costs. Large-scale surveillance programmes have revealed that the impact goes beyond just the number of infections, but also onto long hospital stays, the consumption of increasing amounts of antimicrobials and the rise in antimicrobial resistance. The results confirm the significance of ongoing surveillance to detect shifts in the patterns of infections and to guide evidence-based infection prevention decisions in healthcare facilities (Kärki et al., 2019).

At the national level, further investigations show that the distribution of HAI is affected by local healthcare characteristics, antimicrobial resistance profiles, etc. In a prevalence study conducted in Greece, the presence of health-care associated infections was found to be strongly related to intensive care admission, invasive medical devices and resistant pathogens, and is associated with greater adverse clinical outcomes and resource consumption. This highlights the need for epidemiological assessments to consider both the occurrence of infection and the occurrence of resistance to be able to truly assess the burden on health care (Kritsotakis et al., 2017). The distribution of HAIs among healthcare units within acute care hospitals also depends on the hospital's patient flow and the relationship between healthcare units. Recent computational modelling studies have shown that the structure of a hospital's network has a significant effect on the spread of pathogens, with a network where wards are interconnected and patients are moved between wards allowing the spread of healthcare-associated pathogens to occur beyond the ward of origin, and away from the clinical department where the patient was first diagnosed. It is therefore important to understand these transmission patterns to design a specific surveillance system and optimize interventions for infection control at the institutional level (Nekkab et al., 2017).

Epidemiology of infectious diseases remains dynamic as a result of demographic changes, environmental changes, globalization and new pathogens. Larger epidemiological studies have shown that surveillance systems that can combine the trends in incidence and predict future trends in the burden of infectious diseases are valuable tools for tracking future changes in disease burden. While not focused on hospital-acquired infections, these studies underpin the increasing role of predictive epidemiology and effective surveillance systems in enhancing a nation's preparedness for the changing threat of infectious diseases that could impact acute care settings (Wang et al., 2019).

Based on current evidence, the epidemiology of HAIs in acute care hospitals is influenced by a region's healthcare capacity, patient characteristics, institutional practices, and regional transmission dynamics, but not one factor alone. This detailed assessment is essential to enhance surveillance ability, target infection prevention activities and inform evidence-based policy decisions to enhance patient safety in various healthcare environments. The main epidemiological trends that affect the distribution of HAIs in acute care hospitals are summarized in Table 1.

Table 1. Epidemiological Patterns of HAIs in Acute Care Hospitals

Dimension	Typical Pattern	High-Risk Group/Setting	Clinical Implication
Geographic variation	Higher burden in LMICs	Resource-limited hospitals	Strengthen IPC infrastructure
Hospital location	Uneven distribution	ICU, surgical wards	Unit-specific surveillance
Patient profile	Increased susceptibility	Elderly, immunocompromised	Risk-based prevention
Device exposure	Infection risk increases	Central lines, catheters, ventilators	Minimize device use
Antimicrobial resistance	Rising prevalence	MDR pathogen infections	Stewardship and surveillance

3. Major Types of Healthcare-Associated Infections and Their Etiological Profiles

Healthcare-associated infections (HAIs) in acute care hospitals encompass a diverse group of infections that vary in their anatomical site, modes of transmission, medical treatments and microbial etiology. The incidence of HAIs is different in different healthcare settings, but the vast majority typically include central line-associated bloodstream infections (CLABSI), catheter-associated urinary tract infections (CAUTIs), ventilator-associated pneumonia (VAP), surgical site infections (SSIs), and *Clostridioides difficile* infections. A knowledge of the epidemiological features and etiology of these infections is a prerequisite for specific prevention measures and the best management of patients (Kolpa et al., 2018). CLABSI is one of the most serious HAIs as it is associated with high mortality, hospital length of stay and health care costs. These infections are mostly caused by intravascular catheterization and by the invasion of the bloodstream by microbes. Causative organisms include coagulase-negative *Staphylococcus* species, *Staphylococcus aureus*, *Enterococcus* species, and Gram-negative bacilli and are becoming a concern because of the emergence of multidrug-resistant organisms. There is evidence that following central line insertion and maintenance packages by the critical care team significantly lowers CLABSI incidence in critical care units (Bell & O'Grady, 2017). Long-term surveillance has also shown that the use of bundle-based interventions consistently does better in the outcomes of bloodstream infections of the critically ill patient and that compliance and surveillance should be constant (Lin et al., 2017). Catheter associated UTI (CAUTIs) are still the most common device-associated hospital-acquired infections (HAIs) in hospitalized patients. The more a catheter is used, the more there is a risk of infection, as well as an increased risk of using the catheter inappropriately, if aseptic technique is compromised, and if biofilms form on the surface of the catheter. Most pathogens are *Escherichia coli*, *Klebsiella*, *Proteus* species, *Pseudomonas aeruginosa*, *Enterococcus* species and *Candida* species and increasing antimicrobial resistance is becoming a problem. Prevention strategies include primarily reducing unnecessary catheterization, promoting sterile catheter insertion and removal when clinically indicated (Shuman & Chenoweth, 2018). These clinical reviews have been reinforced in the recent past, which highlights the need for a multidisciplinary catheter stewardship approach combined with ongoing surveillance and staff education for effective CAUTI prevention (Cortese et al., 2018).

Ventilator-associated pneumonia is one of the most complex types of pneumonia seen in the intensive care unit (ICU) and is difficult to diagnose. Mechanical ventilation leads to abnormal respiratory defence, which allows the lower respiratory tract to be colonized by microaspiration of contaminated respiratory tract secretions. Commonly isolated pathogens include *P. aeruginosa*, *A. baumannii*, *K. pneumoniae*, *S. aureus* and other multidrug-resistant Gram-negative organisms. Improved knowledge of the biological diversity of VAP has been driven by significant interpatient heterogeneity in host immune responses, microbial community and disease trajectory, making diagnosis and treatment challenging (Kallet, 2015). Surgical site infections are a common source of postoperative complications and are associated with readmission, delayed healing and higher healthcare costs. These are dependent on patient factors, complexity of surgery, duration of surgery, perioperative antimicrobial prophylaxis and compliance with sterile surgical technique. The microbiological profile

is different depending on the surgical procedure performed, but typically includes *Staphylococcus aureus*, coagulase-negative staphylococci, *Enterococcus* species and enteric Gram-negative bacteria. Perioperative optimization, appropriate antimicrobial prophylaxis, careful surgical technique and wound treatment following surgery are all important strategies for reducing the incidence of SSI, which are summarized in the comprehensive evidence-based surgical infection guidelines (Ban et al., 2017).

C. difficile infection (CDI) is becoming a significant healthcare-associated gastrointestinal infection with a particular association with the use of broad-spectrum antimicrobial therapy and with extended hospitalizations. Dysbiosis of the intestinal flora allows *C. difficile* toxin-producing bacteria to take over and cause anything from diarrhoea to fulminant colitis. Hypervirulent strains and repeat infections have made this pathogen more of a clinical threat. Modern management focuses on the correct diagnosis, rational use of antimicrobials, infection control measures and antimicrobial stewardship to minimize the spread of infection in healthcare environments (Guery et al., 2019). Etiologies of HAIs are becoming more complex as multidrug-resistant bacteria and opportunistic fungal pathogens become more important. This leads to high rates of secondary bacterial and fungal HAI in hospitalized patients due to the long duration of hospitalization, invasive devices/immunomodulatory treatments, and critical illness. The results support the dynamic nature of HAI microbiology and the importance of ongoing surveillance to inform infection control policies and treatment decisions with antimicrobial drugs (Magill et al., 2018).

The epidemiology and etiology of major HAIs in acute care hospitals are still shifting, with the majority associated with invasive medical devices, surgical procedures and exposure to antimicrobials, with many becoming increasingly resistant to antimicrobials. The epidemiology and knowledge of the pathogens that cause infections are still essential for informing surveillance, maximizing clinical management, and effective prevention strategies for specific infections. Table 2 summarizes the main HAI types, risk factors, main pathogens and preventive measures.

Table 2. Major Types of HAIs and Their Etiological Characteristics

HAI Type	Primary Risk Factor	Common Pathogens	Key Prevention
CLABSI	Central venous catheter	<i>S. aureus</i> , CoNS, <i>Enterococcus</i>	Central-line bundle
CAUTI	Urinary catheter	<i>E. coli</i> , <i>Klebsiella</i> , <i>Candida</i>	Early catheter removal
VAP	Mechanical ventilation	<i>P. aeruginosa</i> , <i>A. baumannii</i>	Ventilator bundle
SSI	Surgical procedure	<i>S. aureus</i> , Enterobacterales	Sterile surgery & prophylaxis
<i>C. difficile</i> infection	Antibiotic exposure	<i>C. difficile</i>	Stewardship & isolation

4. Determinants and Drivers of HAI Patterns

A variety of factors, including patient factors, health care practices, microbial evolution, environmental factors and institutional capacity, all contribute to the occurrence and distribution of HAIs in acute care hospitals. HAIs are not the direct result of a single clinical incident, but are a product of the interplay of many factors affecting both the ability of the pathogen to spread within the hospital setting and the susceptibility of the patient during their hospital stay. Successful infection prevention and control strategies can be developed based on this identification of these drivers and adapted for different health care environments (Branch-Elliman et al., 2015). Patient-related factors are important factors influencing the occurrence of HAIs. The use of invasive medical devices, intensive care unit admission, prolonged hospitalization, immunosuppression, chronic comorbidities and advanced age are major risk factors for infections because they cause a breakdown of the host resistance mechanisms and provide more opportunities for infection. Repeated use of antimicrobial agents disrupts the normal microbial flora and enhances the growth of resistant microbes. While the

patient-related risk factors are well documented in both developed and developing countries, they are likely to be exacerbated in a healthcare system with limited resources, poor infrastructure and less capacity for infection control (Danasekaran et al., 2014). Antimicrobial resistance has become one of the most important microbiological factors affecting HAI patterns and is growing in prevalence. Resistant pathogens make treatment and cure more difficult, contribute to extended hospital stays and the resultant extra healthcare expenses, and can help with the ongoing transmission of disease within healthcare settings. In the United States, surveillance data show that MDR *E. coli* infections are associated with a significant impact on patient outcomes, and thus antimicrobial resistance, in addition to infection prevention, is an important contributor to these outcomes (Cai et al., 2017).

Pathogen persistence and transmission are also heavily influenced by the environmental conditions of the hospital. Healthcare-associated pathogens can be present and act as a reservoir on frequently touched surfaces, on reusable medical devices, in water, in ventilation systems, and in poorly cleaned clinical areas. Effective environmental cleaning, disinfection, infrastructure maintenance and periodic environmental surveillance are crucial elements of infection prevention programs, as microorganisms can survive on environmental surfaces, allowing them to be spread indirectly between patients and health care workers (Facciola et al., 2019). HAI rates in acute care hospitals are significantly affected by the practices of healthcare workers (HWs) with regard to infection prevention and control (IPC). Implementing hand hygiene, aseptic technique, correct PPE and standard precautions relies on good knowledge, ongoing education, institutional leadership, availability of resources and safety culture. Valuable systematic evidence reveals that each of these is a factor that can undermine compliance with IPC measures and create opportunities for transmission of healthcare-associated pathogens (Iliyasu et al., 2016).

The epidemiology of HAIs has also been changed by microbial adaptation and the changing ecology in hospitals. The development of various bacteria that could be multidrug-resistant, opportunistic fungal pathogens, and biofilm-forming microorganisms has made infection prevention more complicated, especially for patients in long-term care or who have undergone invasive procedures. The current evidence shows that microbes live closely with the environment in the healthcare environment, and integrated approaches to infection control need to be developed that take into account the ecology of the microbes, environmental contamination, and clinical practices (Facciola et al., 2019). The viral and bacterial respiratory tract infections added to predicted patterns of HAI, which are different around the world. High rates of intensive care admissions, more days in mechanical ventilation, high intensity of antimicrobial use, lower numbers of staff and overcrowding in the healthcare system offered conditions conducive to bacterial and fungal outbreaks in healthcare facilities. These experiences highlighted the potential for disruptions in routine health care delivery to quickly exacerbate the risks associated with infection and the need for resilient infection prevention programs to be able to adapt to future public health emergencies (Zumla et al., 2014).

Combined factors of patient vulnerability, antimicrobial resistance, the practices of healthcare workers, environmental contamination, microbial evolution, and preparedness of the healthcare system all influence the distribution of HAIs. Addressing these drivers, across multi-sectoral surveillance, strong IPC programs, antimicrobial stewardship and ongoing institutional engagement will help to lower the burden of HAIs and enhance patient safety. Figure 1 illustrates the major determinants and interactions shaping HAI patterns.

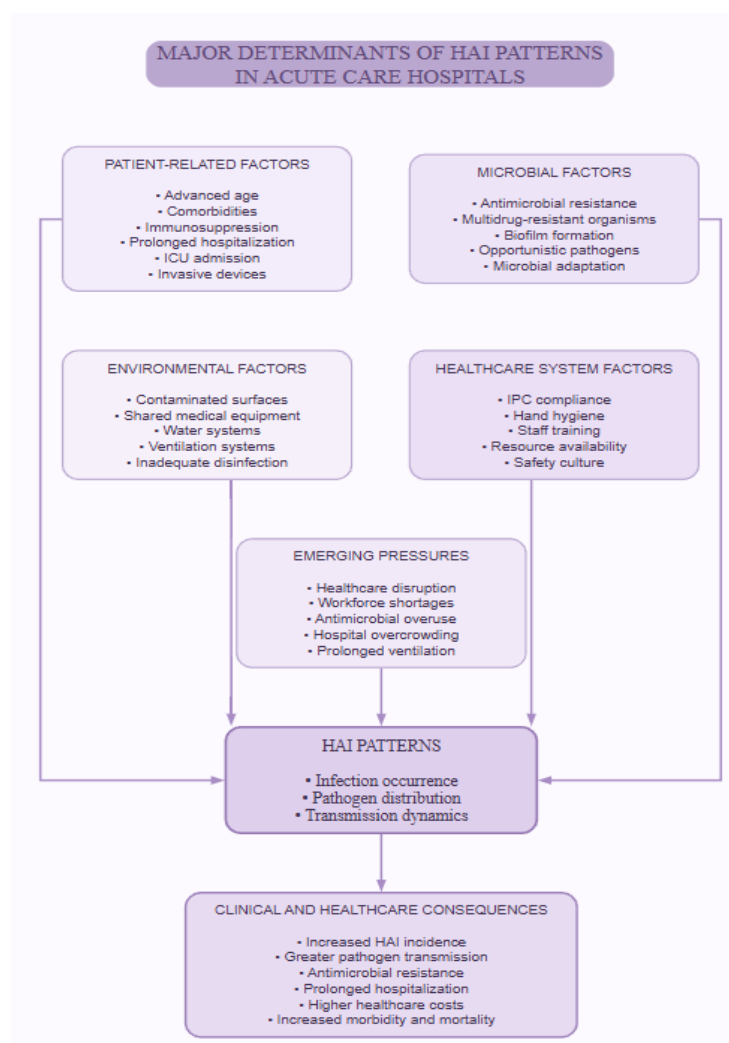


Figure 1. Major determinants driving healthcare-associated infection (HAI) patterns in acute care hospitals

5. Surveillance, Diagnosis, and Emerging Technologies

In an acute care hospital, effective surveillance and timely diagnosis play a key role in HAI prevention and control. Effective surveillance systems allow health care facilities to monitor trends of infection, detect outbreaks, assess the impact of infection prevention efforts, and inform policy. Healthcare systems are becoming more and more data-centric, and the shift from traditional, paper-based reporting to comprehensive, integrated electronic platforms is growing and expanding to provide support for real-time monitoring and evidence-based decision-making (Price et al., 2018). The traditional approach to HAI surveillance is based on the use of standard case definitions, microbiological confirmation, clinical evaluation and routine epidemiological investigations. While those methods are still needed, they can be time-consuming, delayed and require regular data collection by trained staff. Electronically-assisted surveillance (eSS) systems have been rigorously assessed in the presence of an electronic health record (EHR) system and have shown to be effective at improving surveillance efficiency, reducing manual workload, and increasing the accuracy and timeliness of detecting infections and supporting continuous monitoring between health care facilities (de Bruin et al., 2014).

A key role in managing HAIs is the accurate diagnosis in the laboratory. Pathogen identification and antimicrobial susceptibility testing are still performed using conventional culture-based microbiological methods, and molecular diagnostic tests have greatly enhanced the detection of pathogens with faster turnaround and increased sensitivity. Advancements in diagnostic testing, such as polymerase chain reaction testing, mass spectrometry, and biosensor assays, have improved the

identification of bacterial pathogens associated with HAIs, which can help to identify the pathogen earlier in the clinical course and provide targeted antimicrobial therapy (Akova, 2016). Genomic technologies have been evolving and have allowed new opportunities for investigations of outbreaks and surveillance of infections. Whole genome sequencing (WGS) can be used to accurately classify bacterial strains, to identify the routes of transmission, to detect antimicrobial resistance genes and to distinguish between unrelated and epidemiologically associated infections. Economic modelling studies have also shown that WGS-guided surveillance strategies could provide enhanced efficiency in infection control by earlier recognition of outbreaks and healthcare resources optimization, which could lead to reduced clinical and economic burden of HAIs (Gajdacs & Urbán, 2019). However, HAI surveillance is being rapidly redefined by the use of automation and artificial intelligence (AI), which provides continuous analysis of large amounts of clinical data that are too voluminous to be handled by traditional surveillance practices. By analyzing patterns of infections and outbreaks, automated surveillance systems can be linked to AI algorithms to detect abnormal infection patterns, forecast outbreak risks, assist with early warning systems and enhance the detection of healthcare-associated transmission by advanced data analytics. These technologies also allow for standardized surveillance across institutions and reduce the variation in reporting and improve the overall performance of surveillance (Sips et al., 2017).

AI is not just for surveillance; it's for clinical decision support as well. AI algorithms have shown great promise in forecasting the likelihood of infection, optimizing antibiotic treatment, aiding in the interpretation of diagnostics and identifying patients who might benefit from proactive prevention measures. There is a growing body of systematic evidence showing that AI-powered infection prevention interventions can enhance patient safety, as their effectiveness relies heavily on the accuracy of clinical data, the validation of algorithms, and the seamless integration into the clinical workflow (Rawson et al., 2019). Even with these advances in technology, there are still significant gaps in the ability to implement effective HAI surveillance systems in the various types of health care settings. The quality of surveillance remains limited in the laboratory, due to low capacity; in the digital infrastructure, due to underdeveloped support; in the workforce, due to limited resources; in reporting standards, due to disparities; and in resource availability, due to limited resources, especially in low-resource hospitals. Adequate surveillance systems are key in the detection of infections, responding to outbreaks, and assessing the effectiveness of infection prevention measures, which is why there is still a need to invest in building up surveillance systems, training surveillance staff and establishing consistent reporting systems as demonstrated in experiences from the South African intensive care unit setting (Mahomed et al., 2017).

Currently, HAI surveillance is undergoing a significant transformation with the use of electronic health records, new diagnostics, genomic epidemiology, automation, and artificial intelligence. Increased resilience and action to resolve implementation issues of these systems will be critical to meeting the goals of timely infection detection, better outbreak control, and effective infection prevention based on data in acute care hospitals. Current and emerging approaches to HAI surveillance, diagnosis, data analysis, and prevention are summarized in Table 3.

Table 3. Current and Emerging Approaches to HAI Surveillance, Diagnosis, and Prevention

Component	Current Practice	Emerging Approach	Expected Benefit
Surveillance	Manual reporting	Automated surveillance	Faster detection
Diagnosis	Culture-based testing	PCR, WGS	Rapid identification
Data analysis	Routine monitoring	Artificial intelligence	Early outbreak prediction
Prevention	IPC bundles	Integrated multimodal programs	Reduced HAI incidence
Future direction	Periodic evaluation	Continuous digital surveillance	Improved patient safety

6. Prevention Strategies, Current Challenges, and Future Directions

To prevent HAIs in the acute care hospital, coordinated interventions at patient, healthcare worker, institutional and health system levels are needed. In national and subnational programs, evidence suggests that the greatest likelihood of sustained reductions occurs when these activities are approached as a coordinated package, rather than as separate interventions. However, their effectiveness is dependent on implementation fidelity, organization culture, availability of resources, and the capacity to customize policies, all of which is dependent on local epidemiological conditions (Price et al., 2018). Multimodal prevention strategies continue to be a key part of minimizing the spread of infection and the emergence and spread of antimicrobial resistance. More often than not, bundles that include hand hygiene, aseptic device insertion and maintenance, antimicrobial stewardship, environmental decontamination, screening, and staff education are more likely to produce more benefits than single-component bundles. More recently, evidence has indicated that it is important to have continuous performance assessment, strong leadership, and a link between infection prevention goals and activities to control antimicrobial resistance (Harbarth et al., 2015).

Hand hygiene is the most broadly used intervention to break the cycle of infection transmission, but it requires ongoing compliance and proper use at critical moments of infection transmission. Current practice recommendations focus on hand-hygiene infrastructure that is easily accessible, alcohol-based hand rubs, institutional safety culture, direct observation, feedback, education and leadership accountability. Locally developed implementation strategies are needed to support these measures as knowledge is often not enough to create lasting behavioral change (Yokoe et al., 2014). Workload, understaffing, skin irritation, time pressure and inconsistent monitoring are also still affecting compliance among healthcare workers as there are persistent differences between reported knowledge and practice (Musu et al., 2017). Environmental cleaning is also a critical step as many surfaces and shared equipment are used by many people and can continue to spread infection from patient to patient, staff to patient or patient to patient and employee to employee. Other evidence gathered in non-intensive care units indicates that the effectiveness of cleaning is influenced by not only the cleaning product, but also by the frequency, technique, surface coverage, staff training and verification of the performance of the cleaning activity. Environmental programs should thus include using appropriate cleaning agents, as well as using standardized protocols and objective monitoring, and not just relying on routine visual assessment (Kuppelwieser et al., 2018). Surveillance systems should enable the ability to prevent an outbreak by providing timely, comparable and clinically actionable data. While automated surveillance can ease the burden of manual work and enhance case detection, it can also lead to collecting data without any prevention effort if the reporting requirements are not well-designed to do so. The next generation of surveillance should focus on standardization of definitions, interoperability, transparent validation, risk adjustment and quick feedback to the clinical team to enable surveillance to act as a tool for intervention and not be a mere requirement of administration (Van Mourik et al., 2018).

New technologies that prevent infection can be used in conjunction with existing practices to control infections. Vaccines and monoclonal antibodies (mAbs) against the most prevalent bacterial pathogens have the potential to decrease the likelihood of infection in susceptible individuals, decrease the use of antimicrobial agents, and provide protection when traditional methods are ineffective. The specific contribution they can make to the future of the IPC will be subject to pathogen selection, identification of high-risk groups, the durability of the protection, cost-effectiveness, and the integration of these elements with existing prevention programs, not an alternative to key IPC measures (Knisely et al., 2016).

There are significant issues that still need to be addressed, such as multidrug resistance, the ability to form biofilm, environmental persistence, diagnostic delays, staff shortages, non-compliance, and unequal access to prevention resources. More flexible and ecologically informed approaches are needed for microbial adaptation and complex interactions of pathogens, patients, devices and the hospital environment. Future studies should thus focus on analyzing transmission among interconnected reservoirs, reviewing context-specific interventions, and incorporating microbiological, environmental, behavioral, and genomic information in the context of intervention

planning (Facciola et al., 2019). A comprehensive overview of the key prevention strategies, new interventions, challenges and likely outcomes is included in Figure 2.

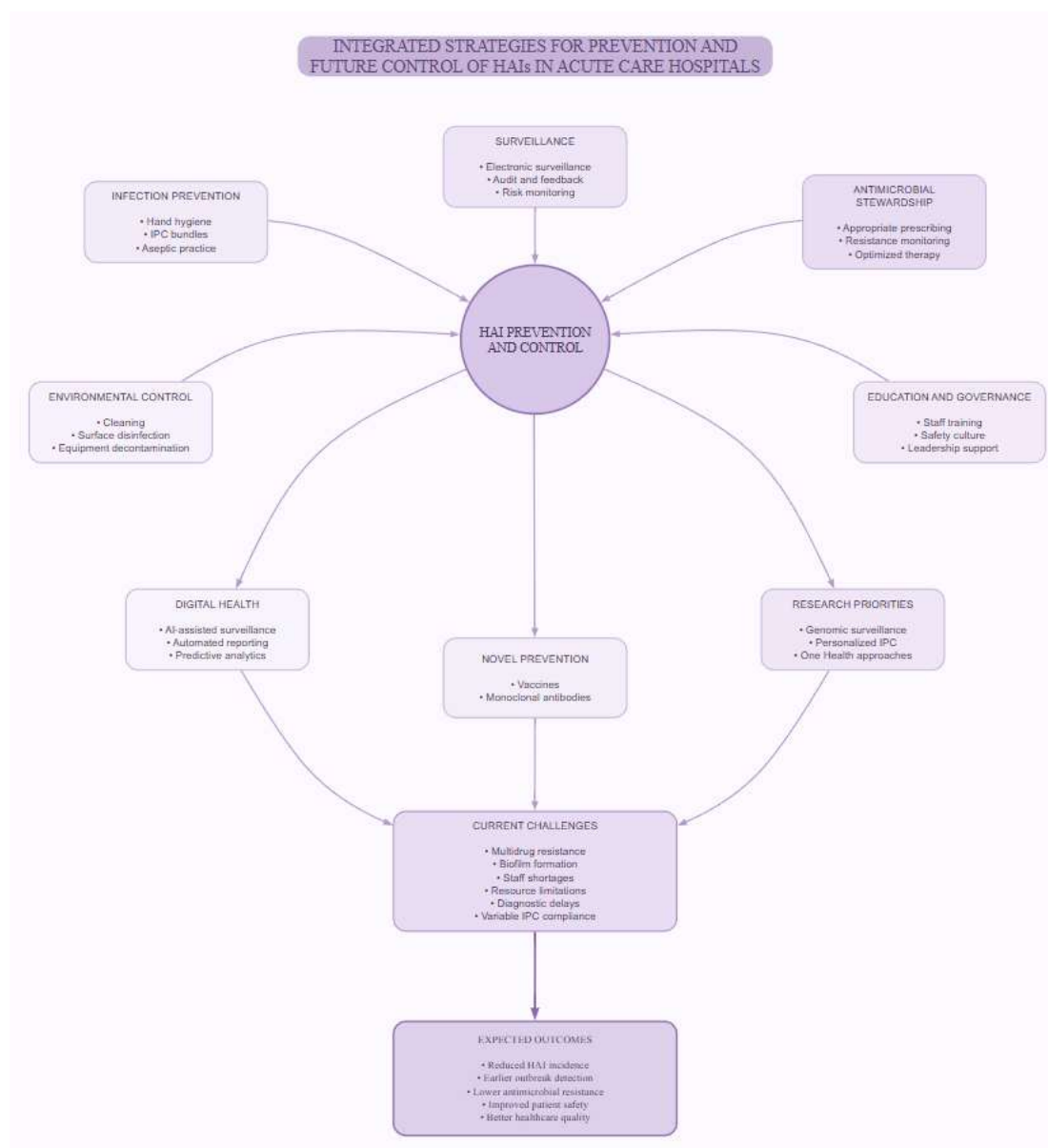


Figure 2. Integrated strategies for prevention and future control of healthcare-associated infections in acute care hospitals

The future of HAI prevention is on a foundation of effective practices supported by adaptive surveillance, antimicrobial stewardship, environmental control and specific preventive technologies. Advancing progress will be less dependent on the introduction of single innovations and more dependent on the continuous implementation, accessibility and adaptation of innovations to local contexts, as well as sustained evaluation within acute care hospitals.

7. Conclusion

HAIs are an ongoing and non-uniformly distributed problem in acute care hospitals, influenced by the vulnerability of patients, the presence of invasive devices, microorganisms, environment and hospital capacity, and the presence of antimicrobial resistance. So, their epidemiology is best viewed as a result of all the different factors which affect the infection, including the clinical environment, the microbes involved, and the systems involved. While device-associated infections, surgical site infections, pneumonia, bloodstream infections, urinary tract infections and *Clostridioides difficile* remain

predominant infections, antimicrobial resistance and evolving hospital ecology add to their complexity. Linkage of surveillance directly to prevention is the one critical pathway to progress. Data quality, data validation, data infrastructure, and data equitable rollout are key to the value of automated monitoring, molecular diagnostics, whole genome sequencing, and AI to enhance detection and outbreak response. Hand hygiene, device stewardship, environmental cleaning, antimicrobial stewardship, staff education and accountable leadership are core measures that are still essential. Next steps include the addition of these proven methods to adaptive digital surveillance, context-specific risk assessment and immunological strategies. It will take collective leadership, effective implementation and ongoing monitoring and assessment in a variety of acute care settings to achieve lasting decreases in HAI burden.

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