Advances in Infection Control Strategies: Emerging Technologies, Antimicrobial Stewardship, and Evidence-Based Approaches for Healthcare-Associated Infection Prevention

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ABSTRACT

Healthcare-associated infections (HAIs) continue to cause significant morbidity, mortality, longer hospital stays, antimicrobial resistance, healthcare costs and are a major healthcare problem around the world. An effective infection prevention program involves a broader approach to infection control that integrates current infection control methods with new technologies, and responsible use of antimicrobials. This narrative review focuses on the most important infection control measures such as hand hygiene, PPE, sterilisation, disinfection, environmental cleaning, isolation precautions, safe injection practices and the education of healthcare workers. It also emphasises the importance of antimicrobial stewardship in minimising inappropriate use of antimicrobials and the development and transmission of resistant organisms. There are potential opportunities for enhancing the detection, monitoring and prevention of infection through recent technological advances such as rapid molecular diagnostics, artificial intelligence, digital surveillance systems, genomic sequencing, antimicrobial nanomaterials and automated disinfection technologies. In addition, strategies for the successful implementation of a programme of infection control, ongoing surveillance, investigation of outbreaks, institutional education, and monitoring of adherence are necessary for the sustainability of these programmes. In resource-limited health care settings, where infrastructure is not always as robust and there are fewer staff and diagnostic facilities, special care must be taken to ensure preventive interventions are put into practice. Complementing traditional infection control with antimicrobial stewardship and proven technological solutions can enhance patient care and quality of care. The need for sustainable implementation of infection prevention programmes, continuous education

to support decision-making, multidisciplinary collaboration, and data-driven decision-making should be highlighted in future HAIs programmes to limit the burden of HAIs and fight antimicrobial resistance.

Keywords: Healthcare-associated infections; Infection prevention and control; Antimicrobial stewardship; Antimicrobial resistance; Hand hygiene; Artificial intelligence; Molecular diagnostics; Infection surveillance; Nanotechnology; Patient safety

1.INTRODUCTION

Infection prevention and control (IPC) is a crucial aspect of safe and effective health care provision. It includes a wide variety of evidence-based practices to prevent infectious agents from being acquired or spread to patients, healthcare workers, caregivers and visitors. More than just preventing specific infections, IPC is also a key component of patient safety, patient care, occupational protection, and resistance containment. IPC is 'a practical and evidence-based approach' that should be implemented at every level of the health system, including healthcare facilities, health and social care providers, policy makers and patients (World Health Organization [WHO], 2024). Hand washing, the use of personal protective equipment, standard precautions, transmission-based precautions, safe injection practices, routine and environmental cleaning, sterilisation and disinfection, the proper management of healthcare waste, and monitoring of HAI. HAPIs continue to be a huge problem for healthcare systems around the globe. HAIs can occur while obtaining care in a healthcare facility or soon after, and can include infections like surgical-site infections, catheter-associated urinary tract infections, central-line-associated bloodstream infections, and healthcare-associated pneumonia. These infections can result in extended hospital stays, higher health care costs, morbidity and mortality and a lower quality of life for patients. WHO estimates that about 7 of 100 patients in acute-care hospitals in high income countries and 15 of 100 patients in low- and middle-income countries develop at least 1 HAI during their hospital stay (WHO, 2024). The ongoing impact of HAIs illustrates that prevention of HAIs does not need to be limited to outbreaks, but should become part of the everyday practice of healthcare. Importantly, in many of these infections, prevention is possible with the use of suitable IPC measures, good infrastructure, water, sanitation and hygiene services, surveillance systems and trained health care personnel (WHO, 2024).

Healthcare-associated transmission of infectious microorganisms takes place via the complex pathways of infectious source, reservoir, mode of transmission and susceptible person. The hands of healthcare workers are especially significant as microorganisms can be spread from person to person, to healthcare workers' hands, to patients, and from patients to the surfaces of the healthcare environment or medical equipment when hand hygiene is not properly performed. Other environmental reservoirs, such as contaminated surfaces, re-useable equipment, medical devices, water systems, etc. can also facilitate transmission. Microorganisms can enter susceptible patients through direct contact, indirect contact, respiratory droplets and aerosols, contaminated instruments and invasive procedures. Other medical devices like urinary catheters, central venous catheters, and mechanical ventilators can increase the risk of infection by providing entry points for microorganisms to invade normally protected areas of the body (Centers for Disease Control and Prevention [CDC], 2025). Therefore, the control of infections must break

transmission at more than one point, and cannot rely upon a single intervention.

One of the very simplest and most effective steps to help prevent HAT is hand hygiene. However, the use of recommended hand-hygiene is not standardised in health care facilities. Compliance with hand-hygiene recommendations in the world has been suboptimal over the years, with specific difficulties in resource-limited healthcare settings (WHO, 2024). It is further important to take care of environmental hygiene as microorganisms can survive on surfaces of frequently touched surfaces and equipment and then spread to patients or health workers. Therefore, cleaning and disinfection, along with hand hygiene and other measures will help to help stop important transmission routes (CDC, 2024). The observations highlight the need to implement a multimodal approach to infection-control programmes involving infrastructure, education, surveillance, behavioural interventions, environmental measures and continuous monitoring, instead of relying on individual preventive activities.

Infection control is a major concern these days with the increasing prevalence and spread of antimicrobial resistant microbes. AMR makes infection control more problematic as organisms that used to be susceptible to antimicrobials that are used commonly might become resistant to multiple antimicrobials. Resistant organisms can be selected and transmitted in healthcare facilities due to high exposure to antimicrobial use, close patient and healthcare worker contact, close person-to-person contact, invasive procedures and vulnerable populations. Patients can be infected by resistant microorganisms spread by contaminated hands, surfaces, medical equipment, patient-to-patient contact and by patient transfers between healthcare facilities (CDC, 2026). So, infection prevention and antimicrobial stewardship are not one-off activities. Avoiding an infection prevents the need to treat with antimicrobial agents in the first place; and, effective use of antimicrobial agents can minimise the pressure for resistance. Strong IPC is thus an important part of the comprehensive response to AMR (WHO, 2024).

Effective and sustainable IPC programmes are a worldwide priority in healthcare because of the link between HAIs, AMR and IPC failures. Inadequacies in infection control systems, lack of the implementation of evidence-based practices, limited training, weak surveillance systems, and inadequate WASH capability can put patients at risk for HAI spread globally (WHO, 2022, 2024). On the other hand, a properly-designed IPC programme can yield significant gains in the form of less preventable infections, safer working conditions for healthcare workers, lower use of antimicrobials, and overall more efficient and safer healthcare provisioning. New technologies and innovations in diagnosis, surveillance, artificial intelligence, antimicrobial materials, environmental decontamination and data monitoring are also delivering additional opportunities to enhance traditional infection control measures.

In this context, the current review of the literature about infections and infection-control efforts focuses on the current state of infection-control strategies, especially in the context of preventing infections for individuals in health care environments, antibiotic use, new technologies, and things that have proven effective. The review will seek to combine existing infection-control concepts and practices with newer ones that could enhance detection, prevention, monitoring and management of infectious threats within health-care facilities. It also addresses the ongoing issue of antimicrobial resistance and the need for multi-disciplinary, multi modal solutions to creating safer health care settings.

2. CURRENT INFECTION CONTROL STRATEGIES

2.1 Standard Precautions and Transmission Based Precautions.

Modern infection prevention and control (IPC) starts with routine use of standard precautions for every patient, whether or not they are suspected or diagnosed with an infection. This approach is founded on the understanding that infectious microorganisms can be found in the absence of obvious clinical signs of infection. Standard precautions are therefore the minimum level of protection to be taken when providing routine health care, and they include hand hygiene, using appropriate personal protective equipment (PPE), respiratory hygiene, safe injection practices, environmental cleaning, safe handling of contaminated equipment and appropriate patient-care practices (Centers for Disease Control and Prevention [CDC], 2024a). The effectiveness of their interventions is dependent on supplies as well as appropriate risk assessment prior to each procedure.

Transmission based precautions are instituted beyond basic precautions when such precautions are not enough to stop the spread of the infection based on the suspected means of transmission. These precautions typically fall into three types: contact, droplet and airborne precautions. Contact precautions are important for microorganisms that can be spread directly from a patient by direct contact or indirectly from contaminated surfaces or items of equipment; droplet precautions are important if the infectious respiratory

particles can be spread during close interactions. Additional precautions for airborne pathogens that can survive in the air for extended periods should be used (CDC, 2024b). It is important to note that transmission-based precautions are not meant to replace standard precautions, but are used in addition to standard precautions (also referred to as universal precautions). Opportunities for transmission within healthcare facilities (CDC, 2024b) can be minimized by early recognition of the illness at the time of triage and prompt action to take necessary precautions.

2.2 Hand hygiene and personal protective equipment

Washing hands is among the most basic interventions that can be implemented for infection control. Healthcare workers often cross the patient, equipment, environmental surfaces, and clinical activities and offer opportunities for the transmission of microorganisms from one place to another. Hand hygiene should thus be conducted before touching the patient, before carrying out an aseptic procedure, after exposure to a body fluid, after touching the patient and after contact with the patient's environment. The use of hand rubs containing alcohol is generally recommended when hands are not visibly soiled, as they can be used easily at the point of care and are easy to use/implement (World Health Organization [WHO], 2022). Hand hygiene shall also be used after gloves are removed as there is a risk of contamination with gloves during patient care.

PPE will provide an extra physical barrier where there may be a risk of contact with blood, body fluids, respiratory secretions, contaminated materials and infectious microorganisms by the healthcare worker. Gloves, gowns, masks, eye protection or face shields should be selected based on the type of exposure expected, not by a blanket selection. The procedure for donning and doffing is also crucial since if it is not done properly, it can lead to contamination of the clothing, the skin, hands or surrounding surfaces. WHO also stresses on the practical training of healthcare workers on why they should use PPE, what PPE equipment to use, how and under what circumstances to use PPE, and how to access the appropriate PPE in a reliable way (WHO, 2022). Therefore, PPE should be viewed as part of a larger IPC system to complement hand hygiene and other preventive measures, not as a replacement for them.

2.3 Sterilization, Disinfection, and Environmental Cleaning

If reusable medical equipment is to be used again, it must be reprocessed to ensure that microorganisms are not spread from one patient to another. Disinfection is used for equipment and appropriate levels of disinfection are used depending on the risk of infection associated with its use while sterilization is used for critical instruments that come into contact with sterile tissue or vascular system. Good reprocessing starts with good cleaning since organic and inorganic material may interfere with the next step in reprocessing, which is disinfection or sterilization. The preferred method for sterilizing critical instruments that can withstand heat, moisture and pressure is steam. Low temperature methods such as ethylene oxide and hydrogen peroxide based systems may be used for heat and moisture sensitive instruments (Rutala & Weber, 2024).

Another area of infection control that plays a significant role in environmental cleaning is that microorganisms can survive on surfaces and equipment that are frequently touched. Appropriate cleaning and disinfecting of surfaces that are frequently touched, such as bed rails, door handles, examination areas, medical equipment etc. are needed at the correct time. It is important to have consistent procedures, appropriate disinfectants, staff training, performance monitoring and feedback to environmental services staff (CDC, 2024c). Environmental services staff should therefore be part of the overall patient safety culture and not viewed as a support function. Special attention should be given to areas where there is blood or other potentially infectious materials present on surfaces, as they are most likely to be capable of causing occupational and patient exposure and require immediate containment and decontamination efforts.

2.4 Safe injection practices and health care waste management

Unsafe injection practices can directly bring about blood-borne pathogens transmission as well as risk for patients and healthcare workers. Appropriate aseptic technique, new sterile needle and syringe for each injection, medication preparation and prevention of contamination of medication vials and preparation areas are required for a safe injection. Needles or syringes can be reused, even if the needle is changed, and may lead to the spread of microorganisms into containers of medications or directly to one person from another. Injection safety is a key component of IPC, and WHO stresses the importance of injecting without unnecessary risk to the person being vaccinated, to health workers and to the community (WHO, 2024a).

The safe disposal of used needles and other contaminated materials is closely related to injection

safety. Sharps should not be left on work surfaces or be needlessly touched, but should be disposed of in suitable puncture-proof containers. From a broader perspective, the healthcare waste needs to be segregated, collected, transported, treated and disposed of based on its hazard classification. While the majority of health care waste is similar to household garbage, a fraction is considered hazardous and may contain infectious, toxic, chemical or other harmful substances. Poor waste management poses risks to healthcare workers, waste collectors, patients and the public and can lead to the release of biological and environmental risks (WHO, 2024b). Thus, effective waste management simultaneously involves in infection prevention, occupational safety and environmental protection.

2.5 Isolation and Cohorting of Infected Patients

When a person is thought to be carrying a transmissible pathogen, patient placement becomes an important element of the operational aspect of infection control. The isolation of a patient typically means that they are in a separate room or a special area to limit the chance of them infecting others, including other patients and healthcare workers. This should take into account the nature of the infectious agent, the mode of transmission, clinical status, patient risk factors, infrastructure available, and current epidemiological situation. Early screening and triage can help identify patients that need extra precautions before entering into nooks where patients are packed together (WHO, 2024c).

In some situations, cohorting may be another strategy that can be considered if individual rooms are not available. Patients that have the same pathogen may be clustered and appropriate precautions and dedicated equipment used where possible. However, cohorting cannot be considered as a universal solution as patients can be infected with different microorganisms, resist the same antibiotics, and have different clinical statuses. Therefore, hand hygiene, PPE, environmental cleaning and the use of dedicated equipment where available, with communication of the precaution requirements for the patient during patient transfer should be used when appropriate patient placement is being used. They are especially significant during outbreaks, when patients might be moving around rapidly, and separation is not optimal that could aid in the spread of the illness within health care facilities (CDC, 2024b).

2.6 Healthcare-Worker Education and Compliance

Effectiveness of even well-designed IPC policies finally relies on the knowledge, conduct and constant adherence of healthcare workers. Therefore, it is important that training in infection control should be integral to the initial orientation of the professional and continuing training. Practical skills to be covered include hand hygiene, choice and use of PPE, safe injection, environmental hygiene, reprocessing of equipment, isolation, respiratory hygiene and recognition of risks of occupational exposure. WHO's 2024 IPC Education and Training curriculum focuses on competency-based learning for a wide spectrum of health care personnel, ranging from clinical, administrative, and support staff that engage in health care delivery (WHO, 2024d).

But education is not enough for attaining a lasting behavioural change. Healthcare organizations should put in place systems to ensure compliance, assess the problem areas, give them constructive feedback, and measure infection outcomes. Compliance to written policies and actual clinical practice can be identified by regular observation and performance measurement. CDC recommends to keep checking compliance with infection-prevention practices and giving immediate feedback to health care workers and facility leadership (CDC, 2024e). Therefore a positive safety culture is critical – staff need to be appropriately resourced, hand hygiene facilities be readily available, PPE be suitable, procedures be clear and understood, managers to be supportive and able to report problems without fear of blame. Providing continuous education and audit, feedback, leadership commitment and sufficient resources to increase IPC compliance is more sustainable than doing it in discrete training sessions. As a whole, standard precautions, transmission-based precautions, hand hygiene, PPE, reprocessing of equipment, environmental cleaning, injection safety, waste management, patient isolation, and competency of healthcare workers are complementary aspects of a multimodal infection control system. Successful implementation of this system requires regular and ongoing quality improvement, standardized processes at the point of care, policies at the institutional level, the infrastructure and surveillance.

3. ANTIMICROBIAL STEWARDSHIP IN INFECTION CONTROL

3.1 Concept and Objectives of Antimicrobial Stewardship

Antimicrobial stewardship (AMS) is a coordinated health-care effort that ensures antimicrobial

medicines are used in the most effective way, and that infectious diseases are treated effectively. The core focus of its use is not just to decrease antibiotic use, but also to enhance antimicrobial use by selecting the right antibiotic for the right patient, in the right dose, via the right route, and with the right duration. Good stewardship thus aims to reconcile the needs of individual patients with the overall goal of reducing antimicrobial resistance (AMR), adverse drug events, inappropriate health care spending and disturbances of the patient's normal flora (microbiota) (Sharland et al., 2022). AMS is a new issue in hospitals, due to a high level of exposure to antimicrobial drugs and the presence of several risk factors for resistant infections in patients.

The Hospital-based stewardship is closely linked to Infection Prevention and Control (IPC), and inappropriate use of antimicrobials can facilitate the selection of resistant organisms, and resistant, Hospital Associated Infections (HAI) can then lead to a need for broader-spectrum antimicrobial therapy. Stewardship and infection control programmes therefore need to be complementary to an overall approach to minimising the emergence and spread of resistant microorganisms (Timsit et al, 2024). Reducing prescriptions is not the only objective of AMS. Key objectives include better clinical results, reduced antimicrobial related toxicity, avoiding unnecessary or redundant antimicrobial therapy, improved microbiologically guided antimicrobial therapy, shortened periods of unnecessary antimicrobial therapy and antimicrobial stewardship and maintenance of the value of existing antimicrobials. The modern stewardship model thus focuses on quality of prescribing and patient outcomes measured, not just on reducing antibiotic use.

3.2 Appropriate Antibiotic Selection, Dosing, and Duration

Selection of the appropriate antimicrobials starts with an accurate determination of whether an infection is present and whether antimicrobials are needed. These include clinical presentation, level of illness, suspected site of infection, prior antimicrobial use, comorbidities, allergy history, local antimicrobial resistance and microbiological data. Ideally, microbiological testing should be performed on specimens prior to initiation of antimicrobial therapy (where clinically indicated) especially when patient has severe infection and/or suspected resistant pathogens. If laboratory data are available, then empirical therapy should be re-evaluated and adjusted as needed. WHO AWaRe is a useful framework to support responsible antibiotic selection, which classifies antibiotics into groups: Access, Watch, and Reserve antibiotics. The framework aims to ensure that the use of Access antibiotics is appropriate and that Watch antibiotics are used with prudence, and Reserve antibiotics used only when necessary. The WHO AWaRe antibiotic book also offers advice on the antibiotic line, dosage, route, and duration of antibiotic treatment for many common infections in adults and children (World Health Organization [WHO], 2022).

Optimizing doses is also crucial as over-exposure may cause unnecessary toxicity and under-exposure may mean failure to treat and may allow for resistant organisms to be selected for; and optimization and therapeutic benefit. Dosage adjustments may, therefore, be warranted based on renal and hepatic function, body weight, age, level of infection, pharmacokinetic properties, and, in certain cases, therapeutic drug monitoring. Route of administration should also be re-considered during treatment. Patients with good clinical stability and who can tolerate oral treatment may benefit from conversion to oral treatment, which minimizes complications of long-term intravenous treatment. Another stewardship target is the duration of treatment. Treatment is not always more effective with longer treatments, and may unnecessarily place patients at risk of adverse effects or selective pressures. Treatment should thus be related to the infection being treated, clinical response, source control, microbiological findings, and current treatment guidelines. Opportunities to discontinue antimicrobial therapy include review of the therapy course to stop therapy if it is determined that there is no probability of infection, to narrow therapy based on susceptibility if the clinical course does not change, and to change the therapy if the clinical course changes. The “Four S’s” of antimicrobial prescribing are to be used in conjunction with each other, not separately, and apply evidence-based guidance (Sharland et al., 2022).

3.3 Prevention of Unnecessary Antimicrobial Use

One major part of AMS is recognizing when it is appropriate to not use antimicrobial treatment, or to stop it. Do not routinely use antibiotics for viral diseases or for other diseases where there is no evidence of a bacterial infection that needs treatment. Unnecessary prescription can lead to allergic reactions, gastrointestinal disturbances/dysfunction, drug interactions, antimicrobial associated complications, and further selection pressure on resistant organisms. Stewardship interventions thus focus on more conscious, evidence-based prescribing rather than just limiting access to antibiotics. There are a number of practical measures that can help decrease inappropriate use. These include the creation of local treatment guidelines,

automated order sets, clinical decision support systems, limiting or pre-authorizing certain broad-spectrum agents, prescriptive restriction/review, audit with feedback, antimicrobial time-outs, dose optimization, de-escalation following microbiological results and/or IV to oral conversion.

The type of intervention should be tailored to the clinical context, resources, local prescribing habits and resistance profile. WHO has recognized several stewardship interventions that can be tailored based on the needs of the institution and combined in different ways to achieve the desired results (WHO Regional Office for Europe, 2021). Finally, diagnostic stewardship can be used to further aid antimicrobial optimization. Faster and more accurate microbiological testing could facilitate a more prompt change in empirical treatment, as well as earlier detection of pathogens and a differentiation between likely infectious and non-infectious conditions. The results of the diagnosis, however, should be evaluated in the appropriate clinical setting and the fact that a microorganism is detected should not be interpreted as proof of causation. Effective stewardship, then, requires working together with the diagnostic services and the prescribing teams, but is not solely about being able to perform laboratory testing.

3.4 Antimicrobial Resistance and its links to Infection Control

There is a close relationship between AMR and infection control. Exposure to antimicrobial agents again and again, or at inappropriate times, places a selective pressure on the organisms which may favor those that have developed resistance mechanisms. These organisms are resistant and can then be transmitted between patients by direct contact, contaminated equipment, health care workers, environmental reservoirs, or by invasive devices in health care settings. If resistant organisms do become established in a healthcare facility, treatment may be more difficult and more broad or last line of defense antimicrobial agents may be needed. This establishes an antimicrobial stewardship–infection prevention cycle. The differences lie in that infection prevention decreases the need for antimicrobial treatment of infections and antimicrobial stewardship decreases unnecessary antimicrobial pressure that could favor resistant organisms. A recent review highlighted the importance of the prevention and control of HAI as an integral part of hospital stewardship and that HAI is often associated with multidrug-resistant organisms, and can require wider antimicrobial treatment (Timsit et al., 2024).

3.5 Antimicrobial Stewardship Programs in Hospitals

An antimicrobial stewardship program (ASP) in a hospital can be used to coordinate these activities. A functional ASP typically must be led by institutional staff, with a clear accountability structure, staff with ASP expertise, adequate interventions, monitoring of antimicrobial usage, monitoring of outcomes, and reporting of results. Leaders' commitment to the program, accountability, expertise of the hospital pharmacist, action, monitoring, reporting, and education are key elements of effective stewardship, as outlined in the CDC's current Core Elements framework (Centers for Disease Control and Prevention [CDC], 2025).

The structure of an ASP is somewhat variable depending on the size of the hospital, the type of patient population, the knowledge of doctors and other experienced members, and the resistance patterns of local doctors. Interventions can range from prospective audit and feedback, formulary restriction, preauthorization, treatment guidelines, dose optimization, de-escalation, antimicrobial time-outs, education, to monitoring antimicrobial prescribing practices. More importantly, stewardship shouldn't be a standalone activity, but should be integrated into the normal course of clinical work. In addition, hospital programmes will also benefit from the ability to incorporate antimicrobial consumption data with microbiological surveillance and infection-control data to evaluate changes in antimicrobial prescribing alongside the trends in antimicrobial resistance and infections.

However, recent evidence suggests that hospital ASP can achieve improvements in antimicrobial prescribing and related outcomes, with the magnitude of benefit depending on the type of intervention, the quality of its implementation, the characteristics of the institutions and the outcome measures. A review of systematic reviews in 2024 has shown that success measures, such as indicators of implementation, process measures, antimicrobial-use outcomes, and clinical outcome measures should be included in ASP evaluation, not relying on a single measure of success (Ming et al., 2024). However, because of the lack of trained staff, diagnostic capability, surveillance systems, and financial resources, that may constrain traditional stewardship models, especially in low- and middle-income countries, the need for context-sensitive implementation is particularly acute. WHO suggests three steps for implementation: conducting the inventory assessment, building governance, and determining priorities, selecting interventions and tracking

progress over time, depending on available resources (WHO, 2019).

3.6 Role of Pharmacists, Microbiologists, and Clinicians

The main learning of AMS is a multi-disciplinary activity. Addressing the clinical, microbiological, pharmacological, epidemiological and behavioural aspects of antimicrobial use are a task for a single healthcare profession that simply cannot be covered by any single profession alone. The role of the prescribing clinician (physician, or other clinician) is still the same and remains primarily responsible for clinical diagnosis and therapeutic decisions that can be enhanced by the involvement of pharmacists, microbiologists, infection-control personnel, nurses and hospital epidemiologists. The role of clinical pharmacists in antimicrobial optimization is becoming more and more important. They can be involved in the process of reviewing antimicrobial prescriptions, checking dose and route, detecting drug interactions and adverse effects, recommending de-escalation, facilitating the transition from intravenous to oral therapy, tracking restricted antimicrobial use, developing treatment protocols, educating prescribers and in audit and feedback. A systematic review published in 2025 found that the scope of pharmacist participation in AMS has grown over time and interventions involving pharmacists or being based on their advice resulted in improved antimicrobial prescribing and consumption (Nampoothiri et al., 2025). Low- and middle-income countries also provide evidence that pharmacist-led interventions, especially education, audit and feedback, can also decrease antimicrobial use, duration and costs, and promote de-escalation (Abdallah et al., 2024).

Another crucial part of the stewardship team is clinical microbiologists. They contribute to the identification of infectious organisms, antimicrobial susceptibility testing, interpretation of resistance patterns, the production of cumulative antibiograms, and the communication of clinically relevant laboratory information to prescribing teams. Microbiological information can assist clinicians in shifting to targeted therapy from empirical therapy. Rapid diagnostic methods could complement clinical diagnostics to further enhance timeliness of these decisions. Clinicians are part of the team by making the initial diagnosis, deciding on antimicrobial therapy, taking appropriate cultures, deciding on empirical therapy, reassessing therapy as new information comes in, and communicating this to the multidisciplinary team. Their involvement is especially significant given that stewardship efforts are more likely to be effective when they are woven into the clinical discussion, and not seen as "restriction on prescriptions.

It is clear that the "multi-disciplinary" character of AMS is an important factor in the effectiveness of the programme. In a recent study of stewardship workforce needs, infectious-disease physicians and clinical pharmacists were often responsible for prescribing optimization; individuals responsible for monitoring stewardship were frequently from the infection-control field; individuals responsible for education were also frequently from the infection-control field; microbiologists were involved in stewardship in the diagnostic stewardship role; and epidemiologists were involved in stewardship in the surveillance and reporting role (2026). Therefore, it should be regarded as a coordinated clinical system in which various professionals provide complementary expertise, thus making effective stewardship.

To sum up, antimicrobial stewardship enhances antimicrobial safety, by decreasing overuse of antimicrobials, increasing the accuracy of antimicrobial therapy, aiding in early de-escalation, and minimizing the creation of selective pressure which can promote antimicrobial resistance. Its most beneficial use is in combination with antimicrobial prescription, microbiological surveillance, infection control measures, diagnostic processes, pharmacist knowledge and skills, and ongoing assessment of outcomes. It is an integrated model, which means that AMS becomes more than just an antibiotic-restriction programme – it becomes part of a patient-safety and infection-prevention strategy.

4. EMERGING TECHNOLOGIES FOR INFECTION PREVENTION

4.1 Rapid Molecular and Microbiological Diagnostic Technologies

Historically, micro-biological culture has been a time-consuming process that can take several days before a clinically meaningful result is available; therefore, the ability to diagnose a patient's infectious disease quickly, and often without resorting to a test, is becoming an important part of infection prevention in modern medicine. If the infectious agent is only identified after the initial period of time, then empirical treatment may be prolonged, isolation may be delayed, and potentially transmissible organisms may not be detected. Nucleic-acid amplification, multiplex polymerase chain reaction, isothermal amplification, biosensors, microfluidic systems, and CRISPR-associated detection technologies are newer molecular platforms that are engineered to decrease this diagnostic time. These can deliver information directly from clinical specimens and, in specific use cases, can deliver clinically relevant resistance determinants without the need for laborious conventional culture based workflows (Kardjadj, 2025).

A major allure of the molecular diagnostics at the point of care is the ability to bring the test closer to the patient, and to shorten the turnaround time for the patient and for clinical decision-making. Integrating molecular amplification, microfluidic areo manipulator, biosensing, and automated signals interpretation into compact systems has led to the development of detection systems that can be deployed outside of traditional centralized lab environments to detect infectious agents. CRISPR based assays are also being explored due to their programmable nucleic-acid recognition capabilities, and their ability to quickly detect pathogens. However, speed of the diagnostics must be taken into account in conjunction with the analytical sensitivity and specificity, and with the quality of the specimen, the quality assurance procedures, and the interpretation of the results in a clinical context. A fast and inaccurate test could lead to false reassurance, or inappropriate isolation and treatment (Xu et al., 2025).

Another significant advance is the implementation of whole genome sequencing (WGS) for infection surveillance and investigation of outbreaks. Whereas traditional methods of bacterial identification only give rough estimates of relationship between isolates, genomic sequencing can give much higher resolution information about relationships between isolates, and can assist investigators in determining if two apparently distinct infections are genetically related. WGS can then help to reinforce transmission mapping and help infection prevention teams make novel epidemiologic connections. It has expanded from retrospective outbreak investigation to prospective surveillance for key healthcare-associated pathogens (Hayden et al., 2026).

4.2 Artificial Intelligence and Machine-Learning Applications

Artificial intelligence (AI) and machine learning (ML) can be used as analytical tools to handle vast amounts of clinical, lab, microbiological and operational data. Infection prevention, these systems can be applied to predicting infections, early detection of HAI, outbreak detection, predicting antimicrobial resistance, monitoring hand-hygiene, and clinical decision support. Infection-control teams can potentially discover high-risk patients or patterns earlier using machine-learning algorithms that can recognise relationships within complex datasets that may be challenging to identify through manual analysis. (Gastaldi et al., 2025). AI can also serve to analyze EHRs, lab results, medication, microbiological, patient movement and more to facilitate automated case identification. In a recent review of the use of AI in hospital infection prevention, it has been observed that despite the range of different types of infections that have been studied, the performance of the predictive models has been promising, but there are differences regarding the type of data used, the development of the models and external validation (El Arab et al., 2025).

However, the application of AI needs to be done with the proper precautions. Retrospective testing is not a proven method to assess clinical utility of the model. After implementation, AI systems may be less reliable due to issues with incomplete datasets, algorithmic bias, shifting patient populations, poor interoperability, limited interpretability and cybersecurity, as well as inadequate prospective validation. An evaluation of AI-based models for surveillance of HAI by a 2025 systematic review and meta-analysis indicates that these systems have good performance, however, few were evaluated in actual clinical use, which restricts conclusions regarding the impact on workload, cost, and patient outcomes (Cozzolino et al., 2025).

4.3 Digital Surveillance and Infection-Monitoring Systems

Digital surveillance is slowly shifting the focus of infection monitoring from mainly a retrospective, manual process in identifying infections, to more constant and automated monitoring. EDWs can be used to share information from a variety of sources, including electronic health records (EHRs), laboratory information systems, pharmacy databases, patient-location information, electronic microbiology results, and others, to detect potential infections and provide alerts. Automated surveillance could minimize the workload associated with manual case finding and free up time for infection-prevention staff for investigation and intervention (Møller et al., 2025).

There are multiple tiers to monitor infections with digital platforms. Algorithms at the patient level can identify patterns of clinical observations, microbiological and/or treatment data that indicate a potential for a HAIN. Dashboards can even be created at the institutional level to show the number of infections, antimicrobial-resistance trends, device-associated infections, and infection clusters in specific wards. Integrated data can be used at the outbreak level to help identify unusual surges in case numbers and help with epidemiological investigations. Genomic surveillance could be further enhanced by the incorporation of genomic information to connect microbiological similarity to patient-location and clinical information

(Hayden et al., 2026).

Despite these benefits, automated surveillance systems are not necessarily effective, unless they are designed and configured properly. Recent evidence shows that there is significant design variation in the systems and data sources, interoperability, validation processes and implementation. There are numerous internal systems developed, and a few have proven to be integrated into daily routine clinical care or to bring clear benefits to patients, but overall, not many have shown sustained uptake in clinical practice and/or in daily use (Møller et al., 2026). For digital surveillance to be successful, data must be reliable, case definitions need to be standardized, cases must be validated, it must be interoperable, staff need to be trained, and signals for action need to be connected with digital surveillance cases.

4.4 Technology Antimicrobial materials and coatings using nanotechnology.

There's another new tactic in the fight against microbes in healthcare settings – the use of nanotechnology. Nanomaterials may have properties that vary significantly from the bulk materials with which they interact, to disrupt microbial membranes, to produce reactive oxygen species to release antimicrobial ions or to disrupt essential cellular processes. These properties have made the metallic and metal-oxide nanoparticles a choice of material for surface coatings, polymers, textiles, medical device surfaces, and more, where they may be exposed to patients or healthcare workers. Materials that contain silver, copper, zinc and titanium oxides are of special interest due to their wide antimicrobial activity. The nanostructured coatings can be designed to impart a long-lasting antimicrobial effect, and not just to be applied repeatedly with traditional disinfectants. This is particularly applicable to surfaces that are touched often, and where contaminants can reappear after regular cleaning. Antimicrobial surfaces, using materials like titanium oxide, that respond to exposure to a light source are being studied (2025).

But durability, toxicity, environmental release, manufacturing consistency, and the potential for microbial adaptation need to be taken into account when considering the potential of nanotechnology. Laboratory-measured antimicrobial activity may not be as effective in repeated mechanical abrasion, under varying humidity, organic contamination and extended clinical usage. The application of copper nanomaterial coatings is a good example of the ongoing efforts to design an antimicrobial coating while maintaining surface durability and desired material properties (2026). At present, antimicrobial nanocoatings need to be considered as an additional tool for infection control and prevention and not as an alternative to the standard cleaning and disinfection procedures. How useful they will be for clinical care depends on carefully conducted studies to prove that they will work under realistic healthcare conditions for long enough and that minimizing surface contamination will result in actual reductions in healthcare-associated infections.

4.5 Antimicrobial Surfaces and Advanced Disinfection Technologies

The emergence of antimicrobial surfaces is closely connected with the understanding that many of the surfaces in the environment come into contact with the body often and can become reservoirs for microorganisms. Engineered surfaces such as copper containing surfaces, antimicrobial polymers, self-disinfecting surfaces, photocatalytic coatings and more are being investigated to help decrease the persistence of microorganisms between routine surfaces. These technologies could be especially beneficial in high contact surfaces, but this will vary because of the type of microbes, environmental factors, surface wear, and frequency of use of the material. Advanced disinfection technologies also being integrated into healthcare facilities. In addition to regular cleaning, ultraviolet-C (UV-C) systems, pulsed-xenon ultraviolet systems, hydrogen-peroxide-based room decontamination systems and other automated methods can be used for additional environmental decontamination. Whole-room disinfection technologies have been found to be effective at reducing the environmental microbial bioburden though implementation may require preparation of the room, positioning of the device, exposure time, and environmental geometry and safety considerations (Madsen et al., 2023).

One of the most prominent advances in this area are UV-C disinfection robots. These systems can be programmed to maneuver or be programmed into rooms without people, and they can be used to irradiate the surfaces that are exposed. They have the main benefit of being treated in a standardized, automated fashion with a decreased amount of direct contact with disinfecting agents by workers. However, the shadowed areas could get insufficient irradiation and human exposure to UV-C should be avoided. Systematic evaluation of UV-C disinfection robots has recently revealed the need to map the environment, deliver the correct dose, navigate, and have safety controls for good performance (2025). Most importantly, advanced disinfection should be used in conjunction with, and not in place of, the normal cleaning practice.

Organic material and inaccessible surfaces, equipment positioning, and physical shadows can restrict the use of automated technologies. Therefore, technological decontamination is best included in a multimodal programme for environmental hygiene, where the regular cleaning will be the basis.

4.6 Robotics and Automated Environmental Decontamination

Robotics is now taking the automation of environmental disinfection a step further to other infection control uses. Automated systems may be able to help clean rooms, monitor the environment, perform ultraviolet irradiations, provide materials and more repetitive tasks. Their most useful applications could be when a repeated, invariable activity is desired, or where exposure to disinfectants or contaminated environments is an issue of concern in the workplace. Robotic disinfection systems can be equipped with the sensors, navigation algorithms, mapping technologies, and programmable exposure protocols. For instance, a UV-C robot may be designed to recognize the shape of the room, and to move to the optimum location for exposing the surfaces of the room that are accessible to the robot. Whole room systems, like automated hydrogen-peroxide systems, can also be used to clean an environment after the patient has left the room. However, the clinical efficacy of these systems cannot only be concluded from the ability to decrease microbial numbers on surfaces and requires correct implementation (Madsen et al., 2023).

It is also moving towards smaller systems such as robotic systems and micro/nanorobotic systems for infection-related applications. The potential application of micro- and nanobots, as extremely mobile platforms, for biosensing and imaging, anti-biofilm activity and targeted delivery of anti-infective agents, are being investigated. These systems are still in their developmental stages, but they show how robotics could help in the future with infection management in different scales, including the hospital and individual tissues (Ahmady et al., 2025). Though they are promising, the use of robotic technologies demands new requirements for maintenance, validation, cyber security, training of staff, safety evaluation and integration into the operational process. A technically proficient bot could be of little clinical benefit if it has trouble navigating a complex room, accessing dirty surfaces, recording exposure, or working alongside other cleaning tasks. Future development ought to focus on human–technology partnership, whereby automation systems would work alongside trained infection-control staff and not try to replace their role.

Infection prevention is becoming more of a proactive discipline with the emergence and advancement of technologies that are more predictive, connected and data-driven, and are moving at a faster pace. Molecular diagnostics can reduce the time needed to detect a pathogen; Genomic sequencing can help to determine the route of transmission; AI can help to process complex clinical and epidemiological data; Digital surveillance can help to streamline the process of detecting an infection; Nanotechnology can help to develop materials that are antimicrobial; Robotics can help to standardize environmental decontamination. But that doesn't mean that the more technologically sophisticated the equipment, the better the infection-control results. Existing data and evidence repeatedly point to the need for validation, interoperability, training of healthcare staff, cost-effectiveness evaluation, data governance, and integration into existing clinical workflows (Gastaldi et al., 2025; WHO, 2026). So, instead of replacing the current IPC practices, the future of infection prevention probably will rely on the smart application of proven technological innovation with existing IPC methods. The more sustainable technologies that are reliable, easy to use, safe and clinically effective can be more likely to become part of a clinical-control programme.

5. EVIDENCE-BASED APPROACHES AND FUTURE PERSPECTIVES

5.1 Evidence-based information about the main interventions for infection control.

A series of complementary interventions is most effective at infection prevention than is a single intervention, as evidenced by the experiences gained over the past several years. There is evidence to suggest that hand hygiene improvement, environmental cleaning, patient screening, isolation or decolonisation if appropriate, device associated infection bundles and multimodal IPC programmes are potential interventions that reduce HAIs. A recent systematic review established that multimodal programmes and prevention packages specific to a particular prevention category were consistently linked to a reduction in some outcomes of HAIs, but the results cannot be directly compared due to the differences between the study designs and the quality of their implementation (2026). Economically, there is evidence that many interventions used in IPC can be cost-effective if they are targeted and directed appropriately, such as through screening, environmental cleaning, surveillance, diagnostics, antimicrobial stewardship, and isolation/decolonization (2025).

5.2 Infection Surveillance and Outbreak Investigation

Effective surveillance is critical for detecting unusual outbreaks of infection, for understanding transmission, for assessing the effectiveness of preventative measures, and for starting investigation of outbreaks. Today, clinical data, microbiological data, laboratory data, information about patient location, and standardised case definitions are combined in a multitude of ways for modern surveillance. WHO recently released a surveillance handbook that highlights the importance of standard and simplified HAI definitions that can facilitate implementation in lower resource health care settings (World Health Organization [WHO], 2024). To prevent or interrupt transmission, the rapid identification of cases, epidemiological assessment, laboratory diagnostic testing, placement of patients, and ongoing surveillance of patients must be carried out during suspected outbreaks. Improving outbreak readiness prior to outbreak is especially relevant, as IPC capacity and capabilities can be undermined in healthcare settings, leading to the potential for amplification of transmission (WHO, 2025).

5.3 Implementation Strategies and Healthcare-Worker Adherence

Good IPC outcomes are dependent on putting recommendations into practice as normal behavior. The implementation of multimodal has grown in evidence – that is, addressing multiple aspects of the system, education and training, reminders, monitoring, feedback, and institutional culture change. An updated 2025 systematic review identified general improvements in hand hygiene or decreases in selected HAIs with most of the evaluated multimodal strategies, although the certainty of evidence varied from low to moderate (Sonpar et al., 2025). So it is best to have continuous assessment rather than reach just a single point in training. Practical education, sufficient supplies, periodic performance reviews and organizational support are to be provided to healthcare workers (Møller et al., 2025). The National IPC guidance in India also highlights the key components of infrastructure, training of staff, monitoring, feedback, workplace communication and strong safety culture as key implementation aspects (National Centre for Disease Control [NCDC], 2024).

5.4 Barriers to healthcare in resource-limited settings

In many low and middle-income countries, implementation is difficult due to the fact that infection-control programmes may be poorly resourced; have poor diagnostic capacity; lack funding; have interrupted supplies; lack information systems; and lack access to specialized training. The restrictions may apply to IPC and antimicrobial stewardship. A new review revealed a lack of key resources, such as trained personnel, funding, information technology, diagnostics, and institutional support as the main obstacles to effective implementation in resource-poor settings (2024). Thus, future IPC programmes must focus on interventions that can be adapted and implemented in a contextually appropriate way instead of just replicating resource-heavy programmes in settings that have higher income levels. Increasing the basic infrastructure, surveillance, lab capacity, and training of workers and securing reliable supplies could have more benefit than the introduction of costly technologies without the base (Campisi et al., 2026).

5.5 Linking Infection Control and Antimicrobial Stewardship

IPC and antimicrobial stewardship should be integrated and part of a healthcare quality and patient safety continuum. Prevention cuts down the need for antimicrobial therapy and it is important to use antimicrobials in the right way to minimise selection pressure on resistant microorganisms. There is current evidence which suggests that the combination of multimodal IPC interventions and antimicrobial stewardship is more likely to be effective than the two programmes alone. Integrated programmes may incorporate HAI surveillance data, antimicrobial prescription and consumption, microbiological results and clinical outcome data, to give a more comprehensive picture of infection risk. This integrated approach is also aligned with existing IPC guidance that specifically calls for linkages between HAI surveillance, microbiology services, AUP and stewardship programmes (NCDC, 2024).

5.6 Future Directions, Emerging Technologies, and Precision Infection Prevention

Data-driven and precision methods are likely to be more widely applied in the future in IPC. Digital surveillance, quick diagnostics, genomic epidemiology, AI, automated environmental monitoring, and advanced antimicrobial materials could enable infection control staff to capture risk earlier and adapt interventions on a pathogen, patient, ward, or transmission network level (Laufer Halpin et al., 2025). Technology should, however, be added on top of robust foundational IPC systems and not be a replacement for them. WHO's 2024 global report highlights the need for sustained programmes, proper infrastructure,

WASH services, trained staff, surveillance and constant improvement in the effective implementation of IPC. Further studies are thus needed to not only demonstrate the technological performance but also proven clinical effectiveness, cost-effectiveness, usability, equity, and sustainability in the real world. Especially more good studies in resource-limited settings are required as the current evidence is skewed towards HICs (Sonpar et al., 2025 & Campisi et al., 2026).

6. CONCLUSION

HAPIs continue to be a significant threat to patient safety, especially in HA settings where there is high level of antimicrobial resistance, invasive procedures, and clinical complexity. A comprehensive, multimodal approach that includes hand hygiene, standard and transmission-based precautions, proper sterilization and disinfection, environmental cleaning, safe injection practices, patient isolation, surveillance and ongoing education for healthcare workers is required for effective prevention. New evidence suggests that multimodal infection-prevention programmes and specific care bundles consistently reduce a number of HAIs, but study design and the quality of implementation of these programmes are important limitations. Infection control should not be the same, but should include these proven new technologies while continuing existing practices. The speed and precision of infection detection and intervention could be enhanced by the use of rapid molecular diagnostics, genomic sequencing, artificial intelligence, automated surveillance, antimicrobial materials and robotic decontamination. In particular, genomic sequencing could help in the investigation of antimicrobial-resistant and health care-associated pathogens, offering more detailed information on the transmission networks.

Antimicrobial stewardship should continue to be closely aligned with infection prevention. Prevention will reduce the need for antimicrobials; when antimicrobials are used, limits will be placed on the selective pressure in favour of resistant organisms. More recently, studies indicate that interventions that promote both infection prevention and antimicrobial-stewardship could help decrease inappropriate antimicrobial use and antimicrobial-resistant infections. The on-going surveillance, education, audit, feedback and workforce engagement will continue to be vital to maintaining gains in infection control. In addition to traditional surveillance, automated surveillance with EHRs and AI systems has the potential to further improve patient risk assessment and case detection efforts, potentially easing the burden of manual surveillance. Programmes should, however, give special consideration to building robust IPC infrastructure, staffing, diagnostics and access to resources before implementing complex technology in the future. This is especially true in LMICs as improving basic IPC and WASH systems could potentially save a significant number of AMR deaths (Naghavi et al., 2024).

In conclusion, the prospects for infection control in healthcare settings rely on the transition towards integrated, continually monitored, data-driven, and patient-centred infection-control systems. They will integrate evidence based conventional practices, antimicrobial stewardship, advanced surveillance, precision diagnostics, and appropriately validated technologies, in successful programmes. To make these advances contribute to continued patient and health worker safety (SHEA/APIC/IDSA/PIDS, 2025), strong institutional leadership and well-resourced IPC programmes will be necessary.

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Author contributions

The first draft of the manuscript was prepared by the original author and the corresponding author's supervisor. Both authors participated in data collection and editing, table design, and final approval for journal submission.

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