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Emerging Technologies and Evidence-Based Practice for Infection Prevention and Control in Surgical Sites

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Abstract: *This study conducted a systematic review of literature on surgical site infection (SSI) prevention and control technologies from PubMed, Web of Science, MEDLINE, EMBASE, EBSCO, Cochrane Library, CNKI, Chinese Medical Journal, Wanfang, VIP, and other databases between May 2015 and May 2025, ultimately including 49 eligible studies. The occurrence of SSI is closely associated with multiple factors including environmental elements (e.g., airborne bacterial counts), instrument contamination, staff hand hygiene, surgical duration, and patients' underlying conditions. The research highlights evidence-based practices for emerging infection control technologies such as Far-UVC ultraviolet disinfection, plasma technology, thermodynamic sterilization, electric field capture technology, and intelligent surgical environment control systems. It also examines optimized applications of vaporized hydrogen peroxide (VHP) and chemical disinfectants in instrument and surface sterilization, as well as the effectiveness of novel biomaterials like silver-coated nanosheets, biomimetic structures, and responsive antimicrobial coatings in inhibiting bacterial colonization. Additionally, the study explores AI applications in infection prediction and behavioral management, along with the positive impact of management models like PDCA and lean management on reducing SSI incidence. The research also notes discrepancies in international guidelines regarding certain preventive measures, highlighting gaps between evidence-based research and clinical practice. While these emerging technologies demonstrate promising prevention potential, their cost-effectiveness and long-term safety still require further validation. In the future, technology integration and multidisciplinary collaboration should be promoted to develop personalized prevention and control strategies based on risk stratification to achieve more efficient and accurate surgical infection prevention and control.*

Keywords: *Surgical Site Infection, Nosocomial Infection Prevention and Control, Clinical Practice, Evidence-based Research*

1. Introduction

Surgical Site Infection (SSI), prevalent complication in surgical practice, refers to infections at incisions, organs, or throughout the body caused by microbial invasion during hospital procedures. These infections significantly compromise patient outcomes and medical safety. With advancements in complex surgeries like minimally invasive procedures and organ transplantation technologies, coupled with the emergence of superbugs such as methicillin-resistant Staphylococcus aureus (MRSA) and carbapenem-resistant Enterobacteriaceae (CRE), the traditional empirical approach to SSI prevention has become inadequate for modern healthcare demands [1]. Evidence-Based Medicine (EBM) integrates the best research evidence, clinical expertise, and patient-specific needs to develop dynamic, precision prevention strategies, providing a scientific methodology for managing surgical site infections [2].

This study systematically analyzed relevant domestic and foreign studies, focusing on the application of new technologies and evidence-based practices in the prevention and control of surgical related hospital infections, aiming to provide theoretical basis for clinical practice and scientific research innovation.

2. Data and methods

This study conducted a systematic literature review of databases including PubMed, Web of Science, MEDLINE, EMBASE, EBSCO, Cochrane Library, CNKI, Chinese Medical Journal, Wanfang, and VIP,

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covering the period from May 2015 to May 2025. Inclusion criteria were: Research conducted in operating rooms; Content related to hospital infection control technologies; Reports with objective indicators such as SSI incidence rates or bacterial colony counts. Exclusion criteria included: Incomplete data; Design flaws; Unavailability of full texts (e.g., conference abstracts); Non-innovative traditional control techniques. The literature selection process was conducted through a structured procedure by three researchers: the first stage involved preliminary title screening based on inclusion/exclusion criteria, the second stage involved abstract review and determination, and the third stage involved full-text reading to confirm final inclusion. Disputed articles were resolved through mutual consultation among all three authors.

3. Results

3.1 Basic information of literature

A total of 13,104 articles were retrieved from the database, and 49 articles were finally included (Figure 1).

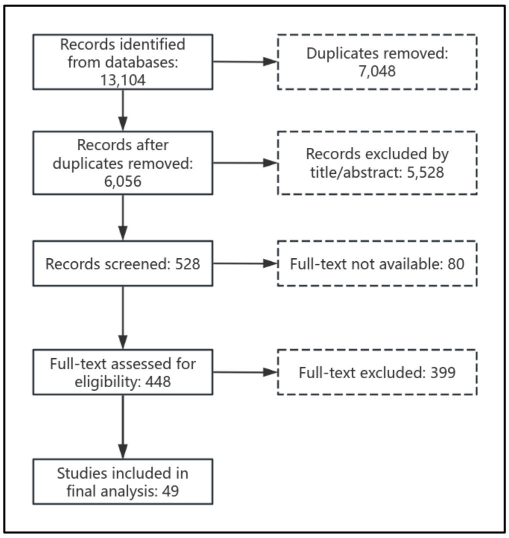

Figure 1. Flow chart of literature inclusion

3.2 Main problems of surgical site infection

3.2.1 Environmental Factors

Airborne transmission is the primary route of surgical site infections. Studies indicate that airborne bacterial counts in operating rooms correlate positively with incision infection rates. When airborne bacteria exceed 700 per m^2, the infection rate increases significantly. However, when airborne bacteria drop below 180 per m^3 , the infection rate decreases markedly [3]. Research by Zhu Zifu et al. revealed that airborne bacterial overgrowth rates in operating rooms vary across different cleanliness levels, ranging from 13.04% to 66.67% [4]. Aerosols generated during oral surgery contain components such as saliva, blood, nasopharyngeal secretions, and organic particles, which may carry various bacteria and serve as sources of surgical site infections [5].

3.2.2 Instrumental Factors

The cleanliness of surgical instruments is another critical concern for preventing postoperative infections. Prolonged storage of medical devices, particularly extended periods, can lead to bacterial growth. Monitoring studies by Tao Yajie et al. on orthopedic surgical instruments revealed a preoperative detection positivity rate of 2.47%, which increased to 6.73% within 2.5 hours after surgery [6]. Once contaminated, these instruments tend to accumulate and form biofilms with strong drug resistance and immune evasion properties [7-8].

3.2.3 Human Factors

Medical staff's hands serve as a critical transmission vector for surgical site infections. A study indicates that hand hygiene compliance rates among medical personnel stand at 65.38% in tertiary hospitals, 77.33% in secondary hospitals, and 45.28% in primary hospitals. Furthermore, unshielded body parts such as hair and beards of surgical personnel may also harbor bacteria [9].

3.2.4 Surgical Factors

Intraoperative blood loss, prolonged operation duration, and extended incision length may increase postoperative infection risks [10]. Research by Wang Xiumei et al. indicates that surgical procedures exceeding 4 hours, improper antibiotic administration, and invasive techniques are recognized risk factors for infections in orthopedic implant surgeries [11].

3.2.5 Patient Factors

Patient age and underlying medical conditions are significant risk factors for increased postoperative infection risks [10]. Wu Xing' an et al. conducted a single-center retrospective analysis revealing that diabetes history (OR=6.927, 95% CI=4.194-12.935), smoking history (OR=3.079,95% CI=2.261-4.913), and preoperative albumin levels <35 g/L (OR=0.572,95% CI=0.302-1.578) were independent risk factors for developing infectious complications in gastric cancer patients after surgery [12].

3.3 Evidence-based practice of new technology in operating room infection control

In recent years, the innovation of operating room infection control technology is mainly reflected in three aspects: high efficiency, safety and convenience of operation.

3.3.1 Evidence-based practice of air disinfection technology

(1) Ultraviolet Disinfection Technology. In recent years, the safety and effectiveness of new physical or chemical disinfection technologies have been validated. Unlike traditional UV-C (254nm) disinfection that requires unoccupied environments, Far-UVC (222nm) disinfection can be continuously used in occupied spaces while maintaining safety and achieving desired disinfection results. When applied in public areas with human activity, Far-UVC demonstrates virus inactivation rates of approximately 90%, 95%,99%, and 99.9% after continuous exposure for 8 minutes, 11 minutes, 16 minutes, and 25 minutes respectively [13]. Integrated applications, such as combining UV-C with air handling units or ventilation ducts, can further enhance air disinfection efficiency [14].

(2) Plasma Technology. Low-temperature plasma technology utilizes the synergistic effects of high-energy particles, reactive oxygen species, and ultraviolet radiation to effectively eliminate bacteria, fungi, and viruses. The plasma system developed by Tsinghua University for central air conditioning applications demonstrates significant efficacy in reducing airborne microbial concentrations while producing no harmful byproducts such as ozone [15].

(3) Thermodynamic Sterilization Technology. The Advanced Rapid Heating-Cooling System (ARHRCS) is an innovative sterilization method that disinfects ambient air through high-temperature heating followed by rapid cooling. Maintaining a temperature of 150℃ for 2 seconds can completely inactivate Mycobacterium tuberculosis, viruses, and other pathogens. This technology is applicable to hospital heating, ventilation, and air conditioning systems, producing safe, pathogen-free air. Studies demonstrate that simulated experiments achieve near-100% sterilization rates [16].

(4) Electric field capture technology. ZeBox equipment adsorbs electric field and extinguishes microorganisms. Multiple clinical center studies have shown that this technology can reduce 90% of air microorganisms and 75% of surface microorganisms [17].

(5) Intelligent Operating Environment Control Technology. The fully autonomous navigation UV-C robot (wavelength 254nm) is equipped with a LiDAR and visual obstacle avoidance system. It should be installed in the operating room for terminal disinfection, which can effectively reduce the disinfection time, effectively reduce the environmental bacterial burden, and demonstrate good disinfection effect [18].

3.3.2 Evidence-based practice of mechanical/surface disinfection techniques

(1) Optimization of Chemical Disinfectants. Studies indicate that quaternary ammonium disinfectant wipes outperform chlorine-based disinfectants by maintaining antibacterial activity for up to 4 hours, causing less corrosion to medical devices and delivering superior surface disinfection efficacy [19]. Meanwhile, hydrogen peroxide low-temperature plasma demonstrates distinct advantages over ethylene oxide sterilization and high-temperature/pressure sterilization, including shorter

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sterilization duration, zero residual toxicity, and higher equipment qualification rates [20].

(2) Innovations in Physical Disinfection Technologies. Vaporized Hydrogen Peroxide (VHP) terminal sterilization stands as one of the most promising technologies for disinfecting temperature-sensitive medical devices such as endoscopes. This method completes the sterilization process within under one hour while posing no safety risks to personnel or the environment [21-22].

3.3.3 Evidence-based practice for novel biomaterials

(1) Nano-material Coatings. The graphene-curcumin-copper coating exhibited antibacterial activity against Escherichia coli and Pseudomonas aeruginosa [23]. Nano-silver particles (AgNPs), a novel and highly effective antimicrobial agent, demonstrate efficacy against various bacteria including drug-resistant strains [24-25]. However, the long-term biosafety and cost-effectiveness of nano-silver remain critical factors for its widespread application [26].

(2) Biomimetic Structural Materials. The application of shark-patterned physical microstructures on catheter surfaces can effectively inhibit bacterial colonization and reduce catheter-associated urinary tract infections [27]. Flexible nanocolumn films exert antimicrobial effects by physically disrupting microbial cell membranes [28].

(3) Reactive antibacterial coating. The pH-sensitive coating releases antibacterial peptides in the microenvironment to resist microorganisms. When used in orthopedic implants, this material can effectively reduce the postoperative infection rate [29].

3.3.4 Evidence-based practice of artificial intelligence technology

(1) Intelligent monitoring and early warning. The real-time monitoring system uses AI model to monitor and warn surgical site infection and outbreak of multiple drug resistance in real time, and predict surgical site infection and urinary tract infection with AUC of 0.80, which is highly reliable [30].

(2) Behavioral Management and Intervention. The use of AI to manage healthcare workers' infection control behaviors can help reduce occupational exposure risks [31]. AI technology has been applied in monitoring hand hygiene, wearing of personal protective equipment, and infection prevention during hemodialysis procedures, with notable effectiveness observed [32].

In practical clinical applications, the promotion and application of intelligent equipment faces challenges such as cost-benefit, sensitive data leakage, and deterioration of basic skills of medical staff [33-35].

3.3.5 Evidence-based practice in management techniques

Zhong Ping'er and colleagues implemented a risk management model in breast surgery infection control, achieving a 76.25% reduction in surgical site infection rates after four years [36]. Liu Chunhong's team demonstrated that lean management process reengineering effectively decreased incision infections (0.18% vs 1.45% in the control group, $P<0.05$) while improving operating room air quality (99.72% vs 97.81%, $P<0.05$) [37]. Zhang Xiaoyu' s research revealed that the PDCA cycle management model effectively reduced non-compliant medical practices, enhanced nursing quality, and minimized surgical site infections [38].

3.4 Updating and disputes of international guidelines

In recent years, the core controversies in surgical infection prevention and control have mainly focused on balancing evidence levels, clinical effectiveness, and cost-effectiveness. For instance, in preoperative preventive measures, multiple domestic and international studies in recent years have shown that preoperative hair removal does not effectively reduce the risk of SSI [39-41], but there is no consensus yet regarding indications, tools, scope, timing, or settings for preoperative hair removal. Both WHO (2021 Revision) and CDC (2017 Edition) recommend preoperative full-body bathing, but WHO explicitly states that regular soap suffices (strong evidence), while CDC permits the use of antibacterial/non-antibacterial soaps. Regarding prophylactic antibiotic use, CDC mandates that antibiotics be administered before incision during cesarean delivery (reversing the previous practice of administering them after umbilical cord cutting). WHO recommends combining mechanical bowel preparation for colorectal surgery with oral antibiotics (e.g., neomycin + metronidazole). Intraoperative controversies center on the timing of adding antimicrobial agents, cost-effectiveness of laminar ventilation systems (WHO opposes its use in total joint replacement procedures while Japan still considers it standard), and the lack of standardized glove and instrument management protocols,

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particularly the absence of mandatory double-layer gloves and uniform instrument replacement frequency standards. Postoperative management conflicts primarily revolve around the scope of negative pressure wound therapy and the timing for drainage tube removal. WHO restricts its application to high-risk wounds, whereas American guidelines extend it to general incisions. Although China' s guidelines recommend early tube removal, they do not specify a time window. The guidelines and specifications in different fields are also controversial, mainly reflected in the disconnection between the guidelines and the implementation of clinical practice, such as the low compliance with intraoperative staff mobility measures, and the necessity of the completeness of the bundle measures [42-45].

4. Discussion

Surgical site infections (SSI), caused by bacteria entering through surgical incisions, have become a major public health concern in healthcare. The WHO Global Guidelines for the Prevention of Surgical Site Infections (2018) highlight that SSI threatens millions of lives annually and contributes to antibiotic resistance spread [42]. A Meta-analysis reveals a global SSI prevalence of 2.5%, with low-and middle-income countries facing particularly severe challenges due to inadequate medical resources and outdated technologies. Africa leads the world with a 7.2% incidence rate [43]. In China, SSI affects 2.91% of patients [44]. Studies show SSI imposes substantial additional economic burdens across low-, middle-, and high-income nations [45]. Compared to other surgical cases, SSI patients experience significantly longer hospital stays and face 2-11 times higher mortality risks [46].

Infection control in surgical settings faces multidimensional challenges involving environmental factors, instrument contamination, personnel competence, surgical procedures, and patient characteristics. Notably, excessive airborne bacteria remain a major contributor to surgical site infections (SSI), particularly in complex surgeries. Instrument contamination is especially prevalent among reusable devices, with biofilm formation significantly complicating prevention efforts. Furthermore, low compliance with hand hygiene practices among medical staff, extended surgical durations, and patients' pre-existing conditions collectively heighten infection risks.

In recent years, emerging technologies such as Far-UVC air disinfection, hydrogen peroxide plasma sterilization, nano-antimicrobial coatings, and AI-powered tools have gained prominence in SSI prevention and control. However, challenges persist including high costs, unproven long-term safety, and difficulties in grassroots implementation. Discrepancies in international guidelines further highlight the gap between evidence-based medical evidence and clinical practice, underscoring the need to develop localized prevention strategies tailored to specific healthcare conditions.

This review has certain limitations. First, the scope of databases used for retrieval is limited, which may have missed relevant literature outside the databases. In addition, due to incomplete search conditions or unintentional screening omissions, some applicable studies may not have been included in the study.

5. Conclusions and Prospects

This study systematically analyzes emerging technologies and evidence-based practices in surgical site infection (SSI) prevention, emphasizing the importance of multidimensional interventions. Emerging SSI prevention technologies have explored innovations in air disinfection, instrument/surface sterilization, novel biomaterials, artificial intelligence, and management systems, achieving notable progress in surgical site infection control. However, their cost-effectiveness and long-term safety still require further investigation. Future efforts should focus on integrating technologies such as smart operating room systems and advancing precision prevention strategies like personalized management based on patient risk stratification. Additionally, promoting multidisciplinary collaboration, enhancing global cooperation, and establishing international SSI databases will help optimize clinical guidelines and elevate surgical infection control standards, ultimately achieving more effective infection prevention goals.

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