DOI: 10.11910/j.issn.2791-2043.2025.4.07

Efficacy of Antimicrobial Materials on Environmental Surfaces: A 12-Week Prospective Controlled Trial

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ABSTRACT: Objective This study aims to evaluate the sustained antimicrobial efficacy of antimicrobial materials on high-touch surfaces in an intensive care unit (ICU). **Methods** A prospective, controlled study was employed. An experimental group (surfaces coated with antimicrobial material) and a control group (surfaces receiving routine disinfection) were established in an ICU. Environmental surface sampling was performed at weeks 1, 2, 4, 8, and 12, with microbial contamination measured as colony-forming units per square centimeter (CFU/cm^2). **Results** Surface contamination was significantly lower in the experimental group at all assessment time points versus the control (Week 1: 0.42 vs. 2.31 CFU/cm^2, P<0.01), with all experimental surfaces complying with the Class II specification (≤5 CFU/cm^2) specified in the national standard *Hygienic standard for disinfection in hospitals* (GB 15982—2012). The experimental group showed a trend of initial slight increase and subsequent decrease in CFU counts, with overall contamination remaining low. **Conclusion** Antimicrobial materials can maintain continuous microbial control on environmental surfaces independently of chemical disinfectants, and offer a valuable supplementary measure for integration into healthcare infection prevention strategies.

KEY WORDS: Intensive care unit; Healthcare-associated infection; Antimicrobial material; Environmental surface disinfection

Healthcare-associated infections (HAIs) represent a major global challenge for healthcare facilities, where the effectiveness of their prevention and control serves as a critical indicator of care quality[1]. The intensive care unit (ICU) is a particularly high-risk environment for HAIs, accounting for nearly one-third of all such infections[2]. This susceptibility is driven by the critical condition of patients, the high frequency of invasive procedures, and prolonged exposure to antimicrobial agents. In recent years, the role of environmental surfaces as a "second reservoir" in the chain of infection transmission has gained increasing attention, particularly due to the colonization and spread of multidrug-resistant organisms (MDROs) and resistance genes within healthcare settings[3-4]. Notably, pathogens such as carbapenem-resistant *Enterobacteriaceae* (CRE) and methicillin-resistant *Staphylococcus aureus* (MRSA) can persist on dry inanimate surfaces and be transferred via the hands of healthcare workers or contaminated equipment, facilitating cross-transmission[5-6]. Conventional strategies for environmental infection control rely heavily on chemical disinfectants, which present several inherent limitations. The effect of chemical disinfectants is transient and offer no protection against surface recontamination between ap-

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plications. Overuse may also promote microbial resistance, while their efficacy depends on multiple factors, including correct concentration, adequate contact time, organic load, and strict adherence to protocols by personnel[7-8]. Consequently, there is a growing need to develop environmental surface materials with inherent, sustained antimicrobial activity to address these gaps in current infection prevention practice[9].

Antimicrobial materials are engineered to provide long-term reduction of microbial adhesion, growth, and survival. This is achieved through the integration of active components such as antimicrobial metal ions (e.g., silver, copper, zinc), photocatalytic nanomaterials (e. g., TiO_2), quaternary ammonium polymers, or surfaces designed with micro- or nanostructured physical bactericidal features[10-11]. Promising clinical evidence from overseas studies suggests that copper-alloy surfaces in ICUs can sustainably reduce bacterial bioburden and may be associated with decreased incidence of certain HAIs[12-13]. However, applied research in this field in China remains at an early stage, with a lack of robust evidence regarding the effectiveness of such materials under real-world, complex ICU conditions. To address this evidence gap, we conducted a 12-week prospective controlled trial. This study aimed to evaluate the microbiological efficacy of antimicrobial materials deployed on high-touch surfaces within an ICU and to analyze their performance dynamics over time. The findings are expected to provide localized evidence to inform the development of more effective and sustainable strategies for environmental infection prevention and control in critical care settings.

1 Materials and Methods

1.1 Study design and setting

This single-center, prospective, parallel-controlled observational study was conducted between May and August 2025 in the general ICU of The First Affiliated Hospital of Nanjing Medical University. Two adjacent patient rooms with comparable bed layouts, patient illness severity (which is assessed by APACHE II Score), healthcare staff allocation, and frequency of daily medical procedures were selected. These rooms were then randomly assigned to either the experimental group or the control group.

1.2 Interventions

1.2.1 Experimental group (antimicrobial material group)

Key high-touch surfaces, including vertical storage cabinets, bedside tables, medication carts, and wall decorative panels, were locally coated with a nanosilver-loaded composite antimicrobial material (from Tongxi Group, Nanjing). All applied antimicrobial materials were accompanied by antimicrobial performance test reports conforming to relevant national standards.

1.2.2 Control group (routine disinfection group)

Surfaces in the control group remained the original non-antimicrobial materials. The types of items and areas monitored were kept identical to those in the experimental group.

1.3 Cleaning and disinfection protocol

1.3.1 Experimental group: Surfaces were wiped once daily at 8:00 AM with water-moistened wipes.

1.3.2 Control group: Surfaces were cleaned and disinfected once daily at 8:00 AM using double-chain quaternary ammonium salt disinfectant wipes.

All cleaning and disinfection procedures were performed by dedicated cleaning personnel with standardized training. Correctness of technique and compliance with the protocol were periodically verified through spot checks conducted by infection control nurses.

1.4 Microbiological monitoring

1.4.1 Sampling sites and timing

Identical sites on corresponding items in both groups were designated as sampling points, including the top surfaces of vertical storage cabinets, bedside tables, and medication carts. Sampling was performed during a fixed afternoon time window (15:00 to 16:00), selected to represent a period of relatively high clinical activity and environmental microbial load. Samples were collected on the same dates at weeks 1, 2, 4, 8, and 12 after the start of the intervention. Thirty-five sampling points were obtained from the experimental group on each occasion. The control group underwent a single baseline sampling

of 35 points at the corresponding time point during week 1.

1.4.2 Sampling method

Sampling was conducted in strict accordance with the industry standard *Regulation of disinfection technique in healthcare settings* (WS/T 367—2012). A standardized swab method was employed, in which a sterile template was used to define a 5 cm × 5 cm area. The surface within this area was sampled using sterile swabs moistened with a neutralizer-containing solution appropriate for quaternary ammonium compounds.

1.4.3 Microbiological culture

All samples were transported promptly to the microbiology laboratory. Each sample was inoculated onto Tryptic Soy Agar (TSA) plates and incubated at 36 ℃ ±1 ℃ for 48 h. Colonies were counted after incubation, and results were calculated and expressed as colony-forming units per square centimeter (CFU/cm^2).

1.5 Evaluation criteria

The primary outcome was the average bacterial colony count on surfaces, expressed as CFU/cm^2. Surface hygiene was assessed according to the *Hygienic standard for disinfection in hospitals* (GB 15982—2012), which defines a satisfactory level for Class II environments as a total bacterial colony count of ⩽5 CFU/cm^2.

1.6 Statistical analysis

Data were analyzed using SPSS software (version 26.0). Continuous variables are presented as mean ± standard deviation or median (interquartile range). Given the non-normal distribution of the data, CFU counts between the two groups at week 1 were compared using the Mann-Whitney U test. Changes in CFU counts across different time points within the experimental group were assessed with the Friedman test. A two-sided P value of <0.05 was considered statistically significant.

2 Results

2.1 Comparison of microbial contamination on environmental surfaces

At week 1 post-intervention, surface bacterial contamination differed significantly between the experimental and control groups. The experimental group exhibited a significantly lower median CFU count (0.42 [IQR: 0.12–0.50]) compared to the control group (2.31 [IQR: 0.36 – 2.6]) (Z=−2.987, P= 0.002 8; Figure 1). One outlier in the experimental group, likely attributable to a sampling artifact or a localized cleaning omission, did not affect overall group compliance. All sampled surfaces in the experimental group met the national hygiene threshold of ⩽5 CFU/cm^2 (qualification rate: 100%), whereas the control group showed a qualification rate of 85.71% (5/35 sample points exceeded the limit).

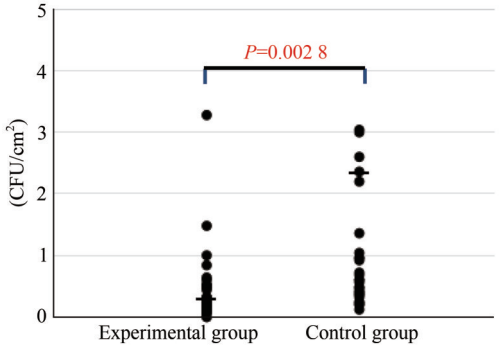

Figure 1 Comparison of object surface colony counts between the experimental and control groups at week 1

2.2 Temporal variation in surface contamination within the experimental group

Over the 12-week observation period, surface microbial loads in the experimental group remained consistently low (Figure 2). Mean CFU counts followed a non-linear temporal pattern: starting at 0.42 in week 1, increasing gradually to 0.48 (week 2) and 0.69 (week 4), peaking at 1.09 in week 8, and subsequently declining to 0.76 by week 12. The Friedman test confirmed statistically significant variation in CFU counts across the sampling time points (χ^2=15.82, P=0.003). All measured values throughout the study remained substantially below the regulatory threshold 5 CFU/cm^2.

3 Discussion

The findings of this study indicate that, under real-world ICU conditions, antimicrobial materials can provide sustained and effective control of microbial contamination on environmental surfaces without

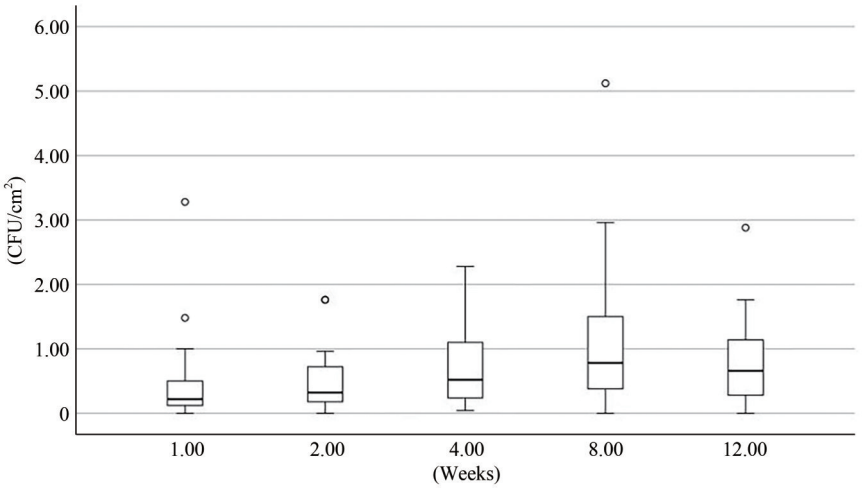

Figure 2 Temporal trend of surface colony counts in the experimental group

the need for routine chemical disinfection, with this effect maintaining relative stability over a 12-week period.

The underlying mechanisms can be explained as follows: antimicrobial materials incorporating metal ions (e. g., silver or copper) primarily act through the gradual release of ions. The released Ag^{+} or Cu^{2+} ions can impair microorganisms through multiple pathways, including the generation of reactive oxygen species (ROS), protein inactivation, disruption of membrane potential, and interference with DNA replication[10,14]. This multimodal action confers efficacy against a broad spectrum of bacteria, as well as some viruses and fungi. In addition, nanostructured surfaces engineered through surface science, such as biomimetic nanopillars, can mechanically rupture bacterial cell membranes by physical penetration, which is a mode of action associated with a lower risk of inducing microbial resistance[15]. Moreover, photocatalytic materials (e. g., nitrogen-doped TiO_2) catalyze the production of highly oxidative species under visible light, enabling broad-spectrum and non-selective degradation of both surface organic pollutants and microorganisms[16]. The composite material employed in this trial may integrate several of these mechanisms, thereby exerting a persistent "environmental pressure" on surface microbes without chemical disinfectants and effectively lowering the initial risk of pathogen colonization and transmission. This observation is consistent with recent reports on the use of composite antimicrobial coatings in ICU settings[17].

The slight increase in CFU counts observed in the experimental group at week 8 may be attributed to the interplay of several factors. First, material surfaces may undergo gradual "aging" or "passivation", whereby prolonged use and repeated cleaning could slowly deplete antimicrobial active ingredients or cause physical wear of surface microstructures. Furthermore, the accumulation of organic deposits (e.g., proteins, lipids) from patients and the environment may promote the formation of a surface "biofilm". This biofilm could then partially shield microorganisms from the material's active antimicrobial components[18]. Second, periodic variations in the environmental microbial burden probably contributed to changes in the total load and composition of surface contaminants. These variations could be influenced by factors such as patient turnover, antimicrobial prescribing patterns, and seasonal fluctuations in temperature and humidity during the study period. Third, unavoidable minor inconsistencies in the thoroughness and technique of daily water wiping, despite standardized protocols, represent a potential behavioral and compliance-related variable. Importantly, the subsequent decline in CFU counts by week 12 suggests that this fluctuation possibly reflects normal variability within a constrained range rather than a sustained loss of efficacy. This pattern underscores the dynamic balance among material

performance, environmental pressure, and operational intervention, and highlights the importance of long-term and dynamic monitoring of antimicrobial surfaces rather than assuming static, unchanging effectiveness.

The practical implications of these findings further indicate that antimicrobial materials can be incorporated as a foundational control measure within existing multimodal infection prevention and control (IPC) frameworks. Their integrative value manifests at three distinct levels. The first level is optimization of disinfection practices. Adopting a model that combines continuous material-mediated suppression with targeted disinfection only after known contamination events can reduce reliance on routine, broad-spectrum chemical disinfection. This approach may help mitigate the selective pressure driving antimicrobial resistance in environmental microbes, while also lowers potential chemical exposure for healthcare personnel and ecological impact[8,19]. The second level is bridging protection gaps. Conventional disinfection delivers "pulsed" antimicrobial activity, leaving intervals during which surfaces may become recontaminated. In contrast, antimicrobial materials provide "continuous background suppression". The inherent limitation of the intermittent approach is underscored by the afternoon's rise in CFU counts observed in the control group, a finding that persists despite the proven rapid efficacy of quaternary ammonium wipes. Conversely, the consistently low CFU levels in the experimental group during the same period demonstrate the ability of such materials to maintain "ongoing environmental protection". Together, these strategies achieve temporally uninterrupted coverage, reinforcing the resilience of the environmental barrier[20]. The third level is advancing the infection prevention checkpoint. Integrating antimicrobial surfaces facilitates a shift in emphasis from reactive measures, such as "terminal disinfection" and post-infection treatment toward proactive "prevention of pathogen colonization and accumulation" on high-touch surfaces. This aligns with the principle of "source control" in infection prevention[9]. Alongside these potential benefits, the safety of large-scale implementation, particularly regarding environmental risk, merits careful evaluation. The antimicrobial mechanism of materials such as those used in this study often depends on metal ions (e.g., silver). Although materials are engineered to minimize release, trace amounts could theoretically enter the environment through gradual material wear. Chronic low-level exposure may carry ecological toxicity risks, and the potential for such ions to exert selective pressure on environmental microbial communities, possibly facilitating the spread of resistance genes, warrants attention. In the present study, the composite antimicrobial agent was designed to stabilize silver ions within the substrate, and daily wiping with water further reduced surface residues; nevertheless, the long-term, cumulative ecological effects of sustained use in healthcare settings remain an important area for future full-cycle assessment.

However, several limitations exist in this study. First, its single-center design may restrict the generalizability of the findings. Second, the absence of repeated pre-intervention sampling meant that baseline microbiological data were unavailable to directly confirm the comparability of the two groups before the intervention. Third, the primary outcome was an intermediate microbiological endpoint. Its relationship with patient-centered clinical outcomes, such as MDRO acquisition or HAI incidence, involves a more complex causal pathway and would require larger studies with clinically relevant endpoints to establish. In addition, while the 12-week duration sufficed to demonstrate medium-term efficacy, it will require extended observation periods to assess the material's long-term durability, safety, and cost-effectiveness in real-world ICU settings.

4 Conclusion

This study demonstrates that the application of antimicrobial materials in an ICU setting can achieve sustained and effective control of microbial contamination on environmental surfaces without reliance on chemical disinfection. By leveraging their inherent and durable antimicrobial properties, these materials

offer a novel engineering-based approach to overcoming the limitations of traditional infection prevention models, which depend predominantly on intermittent disinfection. The systematic integration of such materials into multimodal infection prevention and control strategies enables the establishment of a dual environmental barrier combining continuous background protection with on-demand disinfection, and represents an advancing frontier in hospital infection control toward more proactive and sustainable practices. Future work should focus on conducting rigorous long-term effectiveness and cost-benefit studies, alongside incorporating Internet of Things and big data technologies, to advance the scientific basis, standardization, and intelligent integration of antimicrobial materials within healthcare environments.

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