The Review Of
DIABETIC
STUDIES OPEN ACCESS

# Next-Generation Disinfection: The Role Of UV-C, Hydrogen Peroxide Vapor, And Cold Plasma In Modern Hospitals

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## Abstract

**Background:** Healthcare-associated infections remain a leading cause of morbidity, mortality, and excess costs worldwide, driven by environmental reservoirs and the limitations of manual cleaning in achieving reliable high-level surface disinfection. Next-generation no-touch technologies have emerged to address persistent contamination by multidrug-resistant organisms and spores that withstand conventional methods.

**Methods:** This narrative review synthesizes evidence from experimental, quasi-experimental, and economic studies evaluating UV-C, HPV, and CAP in hospital settings. Key domains include mechanisms of action, device configurations, log reductions on pathogens, clinical impact on healthcare-associated infections, operational constraints, costs, and future AI- and IoT-enabled innovations.

**Results:** UV-C systems achieve rapid 3–6 log10 reductions in vegetative bacteria and some spores, with adjunct use associated with approximately 19–30% reductions in selected healthcare-associated infections and notable cost savings. HPV demonstrates superior sporicidal activity and up to 64–80% reductions in multidrug-resistant organism acquisition, albeit with longer cycle times and higher resource demands. CAP offers broad-spectrum, residue-free decontamination with 3–6 log10 reductions in biofilms and spores and promising early clinical and economic signals, but remains constrained by scalability and standardization gaps.

**Conclusions:** Collectively, these technologies provide complementary strengths that can substantially enhance terminal room decontamination, reduce infection risk, and deliver favorable long-term economic returns when integrated with manual cleaning. However, robust multicenter randomized trials, harmonized dosing and safety standards, and implementation frameworks are required before widespread adoption as core components of hospital infection prevention programs.

**Keywords** UV-C disinfection, Hydrogen peroxide vapor, Cold atmospheric plasma, Healthcare-associated infections, No-touch decontamination. Multidrug-resistant organisms.

## Introduction

Healthcare-associated infections (HAIs) impose a staggering global burden on healthcare systems, affecting hundreds of millions of patients annually and representing the most frequent adverse event in care delivery. In high-income countries, approximately 7% of acute-care hospital patients acquire at least one HAI, while rates in low- and middle-income countries reach 15%, with even higher incidences in intensive care units (up to 30% globally, and 2-20 times greater in resource-limited settings). The World Health Organization estimates that 136 million hospital-associated infections resistant to antibiotics occur worldwide each year, with the heaviest burdens in countries like China (52 million cases), Pakistan (10 million), and India (9 million), exacerbating antibiotic resistance and overwhelming healthcare infrastructure. Economically, HAIs drive substantial costs through prolonged hospital stays, additional treatments, and lost productivity; in the United States alone, they account for $8.3-11.5 billion annually, while in Central China, per capita economic losses reach $2,047 per case, primarily from pharmaceuticals and extended care. Clinically, these infections lead to increased mortality, disability, and sepsis with pathogen-specific impacts amplifying morbidity; for instance, Clostridioides difficile remains the leading cause in many settings, surging from 0.10% prevalence in 2017 to 0.80% in 2021 amid pandemics, while MRSA, VRE, and multidrug-resistant Gram-negatives like Acinetobacter baumannii and Klebsiella pneumoniae dominate, with MRSA comprising 5.6% of HAIs in large U.S. datasets and VRE showing 43% increases in bloodstream infections from 2017-2021. These pathogens persist due to environmental reservoirs, roommate exposures, and selective pressures from antimicrobials, underscoring the urgent need for enhanced prevention strategies beyond traditional methods (Iancu et al., 2023).

Traditional cleaning methods in hospitals, reliant on manual application of detergents and disinfectants, suffer from profound inconsistencies that undermine their effectiveness against HAIs. Studies reveal that up to 50% of surfaces remain contaminated post-cleaning due to operator errors in product selection, formulation, distribution, and contact time, with high-touch areas like bed rails and keyboards often neglected despite repeated efforts even four bleach rounds leave 25% of rooms harboring Acinetobacter baumannii. Chemical residues from agents like chlorine, quaternary ammonium compounds, phenols, and glutaraldehyde pose significant occupational hazards to cleaning staff, causing respiratory symptoms (26% of cases), skin issues (61%), and co-resistance to antibiotics, while physical risks include wet work, manual handling, slips, and poor ventilation in healthcare environments. Shadowed areas, biofilms in water systems, and porous surfaces further enable microbial persistence; UV-fluorescent markers and ATP testing highlight inadequate coverage in cluttered rooms, where recontamination occurs rapidly post-cleaning, and stringent protocols fail to fully disrupt resilient structures like C. difficile spores or MRSA/VRE reservoirs. These limitations are compounded by a lack of standardized monitoring thresholds and disconnects between clinical staff and cleaners, resulting in suboptimal decontamination and perpetuating transmission cycles despite EPA-registered products (H. Han et al., 2015).

No-touch disinfection technologies have emerged to address the inherent flaws of manual methods by automating delivery, ensuring uniform coverage, and minimizing human error in hospital terminal cleaning. The rationale stems from evidence that operator-dependent cleaning achieves only partial efficacy against spores and biofilms, prompting a shift toward systems like UV-C radiation, hydrogen peroxide vapor (HPV), and cold plasma, which penetrate shadowed areas and achieve log reductions in pathogens without physical contact. UV-C evolved from early mercury lamps to pulsed-xenon and LED systems, inactivating DNA/RNA via thymine dimers and reducing Gram-negative bloodstream infections by 19% in Veterans Health Administration hospitals when added to terminal cleaning. HPV, commercialized as Bioquell and Steris VHP since the early 2000s, saturates rooms to condense on surfaces, eradicating C. difficile, MRSA, VRE, and MDR Acinetobacter with superior sporicidal action compared to aerosolized alternatives, often breaking down to harmless water and oxygen post-cycle. Cold plasma, a newer ionized gas technology generating reactive species, offers dry, residue-free disinfection effective against biofilms and viruses, complementing UV-C/HPV in hybrid approaches for comprehensive room decontamination. These technologies have demonstrated meta-analytic reductions in HAIs through randomized trials and surveillance data, evolving from adjuncts to standard protocols

in high-risk wards, with implementation guided by cycle times, aeration, and validation via biological indicators (Edgeworth et al., 2020).

**Background on Technologies**

Next-generation disinfection technologies such as UV-C, hydrogen peroxide vapor (HPV), and cold plasma represent significant advancements in hospital infection control, offering automated, no-touch methods to combat multidrug-resistant organisms (MDROs) and persistent pathogens like Clostridium difficile spores that traditional cleaning often misses. These systems leverage physical and chemical principles to achieve high-level disinfection of surfaces, air, and equipment in clinical environments, reducing healthcare-associated infections (HAIs) where manual methods fall short due to human error and incomplete coverage. Extensive research demonstrates their complementary roles in terminal room decontamination, with UV-C providing rapid photon-based microbial inactivation, HPV delivering potent oxidative sporicidal action, and cold plasma generating multifaceted reactive species for broad-spectrum efficacy (Blau et al., 2024).

Ultraviolet-C (UV-C) light at 254 nm primarily inactivates microorganisms through photon absorption by DNA and RNA, leading to the formation of pyrimidine dimers that distort the helical structure, inhibit replication, and block transcription, ultimately causing cell death without viable repair in most pathogens. This mechanism is highly effective against a wide range of hospital-relevant microbes, including Clostridium difficile spores, methicillin-resistant Staphylococcus aureus (MRSA), vancomycin-resistant Enterococcus (VRE), and viruses like SARS-CoV-2, as the 254 nm wavelength from low-pressure mercury lamps delivers maximal germicidal energy by maximizing photon density at the peak absorption band of nucleic acids. UV-C devices are categorized into mobile robots, which autonomously navigate rooms to minimize shadowing and ensure 360-degree coverage; pulsed xenon systems that emit broad-spectrum UV (200-320 nm) in high-intensity millisecond pulses for faster cycles; and fixed upper-room or surface units that provide continuous or targeted irradiation in high-touch areas like operating theaters or ICUs. Mobile robots, such as those equipped with multiple UV lamps and sensors for obstacle avoidance, have shown superior performance in reducing bioburden across shadowed surfaces compared to stationary fixed units, while pulsed xenon devices like Xenex LightStrike achieve comparable log reductions to mercury lamps in about 10 minutes but with broader spectral output. Dose-response curves for UV-C follow a logarithmic inactivation profile, where microbial survival decreases exponentially with fluence (mJ/cm²), influenced by factors like organic load, surface reflectivity, and distance; for instance, 3-20 mJ/cm² often yields >3-log reduction in viruses on stainless steel, with energy efficiency higher in mercury lamps (radiant efficiency up to 40%) than emerging UV-LEDs due to better photon output at 254 nm, though robots optimize delivery by adjusting exposure times (e.g., 2-5 minutes per position) to achieve 4-6 log reductions hospital-wide (Ramos et al., 2020).

Hydrogen peroxide vapor (HPV) exerts its antimicrobial action through strong oxidation reactions, where $H_2O_2$ molecules penetrate microbial cells and react with essential components like proteins, lipids, and nucleic acids, denaturing enzymes, disrupting membranes, and oxidizing DNA/RNA thiol groups, with exceptional sporicidal performance due to spore coat perforation and core protein damage requiring concentrations of 240-600 ppm over 2-4 hours for >6-log inactivation of Clostridium difficile and Acinetobacter baumannii spores. This oxidative cascade generates highly reactive hydroxyl radicals (- OH) via Fenton-like reactions, amplifying damage to resistant structures like bacterial endospores and biofilms, outperforming liquid disinfectants in hospital trials where HPV cycles post-cleaning reduced MDRO contamination by 4-5 logs across porous and nonporous surfaces, including fabrics and electronics incompatible with wipes. Vaporized HPV systems differ fundamentally from aerosolized hydrogen peroxide (aHP) in particle size and distribution: HPV produces dry vapor (<5 μm droplets) at controlled humidity (30-50%) for uniform room penetration without wetting surfaces or residue, achieving consistent 6-log reductions in shorter cycles (50-120 minutes) and lower leakage (<1 ppm when sealed), whereas aHP generates larger droplets (10-20 μm) leading to uneven coverage, higher residual moisture, prolonged aeration (up to 3 hours), and inferior efficacy (<4 logs) with elevated hydrogen peroxide levels (2-8 ppm) posing safety risks. Head-to-head studies confirm HPV's superiority in speed, safety, and biological inactivation against nosocomial pathogens like VRE and

MRSA, with real-world hospital applications showing 64-80% reduced MDRO acquisition risk when integrated into terminal cleaning protocols (Goyal et al., 2014).
Cold atmospheric plasma (CAP) generates a cocktail of reactive oxygen and nitrogen species (RONS through ionization of ambient air at near-room temperature (<40°C), which collectively overwhelm microbial defenses by lipid peroxidation, protein oxidation, and DNA strand breaks, achieving rapid >4-log inactivation of bacteria, viruses, and spores without thermal damage to hospital surfaces. These short-lived RONS (lifespan seconds to minutes) diffuse into biofilms and shadowed areas, with energies of 15-72 eV enabling penetration beyond UV-C limits, as demonstrated in SARS-CoV-2 surface inactivation within 8-120 seconds via plasma plume exposure. CAP devices are classified primarily into dielectric barrier discharge (DBD) systems, which create stable plasma volumes between electrodes for large-area treatment like room surfaces or wounds, and atmospheric pressure plasma jets (APPJ), compact nozzles producing directed afterglow for targeted disinfection of equipment or ambulances, with DBD excelling in uniform coverage and APPJ in portability (e.g., >4-log spore reduction in 2 hours across 10 $m^3$ spaces). Currently at an advanced research-to-clinical transition stage, CAP demonstrates proof-of-concept maturity in pilot hospital studies for surface decontamination (e.g., MRSA/VRE on fabrics) and endoscope sterilization, with flexible DBD prototypes safe for chronic wounds (temporary erythema only) and multijet systems reducing pathogens by 2.9-4 logs in vivo, though commercialization lags behind UV-C/HPV due to standardization needs for RONS dosing and scalability. Ongoing trials highlight CAP's promise for decentralized use in high-risk areas like ICUs, with no resistance development observed (Braný et al., 2020).

**UV-C Disinfection in Modern Hospitals**
Ultraviolet-C (UV-C) light, typically at wavelengths of 200-280 nm with peak germicidal activity around 254-270 nm, demonstrates robust in vitro efficacy against a broad spectrum of hospital-relevant pathogens by inducing thymine dimers in microbial DNA, thereby inhibiting replication and leading to cell death. Studies consistently report log reductions exceeding 3-log10 (99.9%) for vegetative bacteria such as methicillin-resistant Staphylococcus aureus (MRSA), vancomycin-resistant Enterococcus (VRE), and multidrug-resistant Gram-negative rods like Klebsiella pneumoniae and Pseudomonas aeruginosa after exposures as short as 5 minutes at distances of 1-3 meters from the UV-C source, with even greater efficacy (>5-log10) against non-spore-forming pathogens under optimal conditions. Factors significantly influencing these achieved microbial reductions include distance from the emitter exposure time, which must deliver sufficient fluence (mJ/$cm^2$) often ranging from 10-100 mJ/$cm^2$ for high-level inactivation, and organic load from soil, blood, or biofilms that can shield microbes and necessitate precleaning to maintain efficacy, as demonstrated in controlled carrier tests on hospital surfaces like bed rails and keyboards. For instance, pulsed or continuous UV-C systems achieved near-complete eradication (up to 100% reduction) of Candida auris, VRE, and MRSA on contaminated objects after 24 seconds to 24 hours of exposure, though efficacy drops markedly with increasing distance or soiling, underscoring the need for standardized dosing protocols in laboratory validations that mirror real-world hospital contaminants (Yang et al., 2019).

In clinical hospital settings, UV-C disinfection as an adjunct to manual cleaning has been associated with healthcare-associated infection (HAI) reductions ranging from 19-30% facility-wide, particularly for multidrug-resistant organisms (MDROs), with one community hospital reporting a statistically significant drop from 4.87 to 3.94 HAIs per 1,000 patient-days over 12 months, yielding over $1.2 million in cost savings without operational disruptions. Comparative data across pathogens reveal stronger evidence for Gram-negative rod reductions (incidence rate ratio [IRR] 0.82, 95% CI 0.68-0.99), modest effects on VRE (IRR 0.72, 95% CI 0.38-1.37), and inconsistent impacts on Clostridioides difficile (CDI; IRR 0.90, 95% CI 0.62-1.32), as synthesized from nine U.S.-based studies including cluster-randomized trials and before-after designs, where UV-C excelled in high-burden units like hematology-oncology. Real-world implementations, such as in operating theaters and ICUs, showed 42-46% airborne bacterial reductions post-UVGI installation and significant surface CFU declines (e.g., from median 8 to 2 post-disinfection), though results vary by pathogen resilience and baseline contamination levels, with pediatric and transplant units often demonstrating the most pronounced HAI declines (up to 62% for CDI) (Baudart & Briot, 2025).

Effective UV-C implementation in modern hospitals requires meticulous room preparation, including manual precleaning with sporicidal agents like bleach or quaternary ammonium to remove organic debris that attenuates UV penetration, followed by evacuation of personnel, sealing doors, and disabling HVAC to prevent airflow disruption of fluence delivery. Operational protocols typically involve automated mobile robots or fixed emitters delivering multi-cycle exposures with cycle durations of 5-15 minutes per room based on size (e.g., 100-700 ft²), achieving targeted doses via motion sensors and reflectors to minimize shadowing. Safety interlocks, including motion detectors that halt emission if humans or animals enter, remote monitoring via UV dosimeters for cycle validation, and integration with hospital workflows ensure compliance; pilot programs in high-risk areas like ENT or oncology departments emphasize staff training on device positioning for 360° coverage and validation via biological indicators or ATP swabbing (Casini et al., 2023).

Despite its strengths, UV-C disinfection faces critical limitations including the shadowing effect, where direct line-of-sight obstruction by equipment, folds in linens, or complex geometries prevents irradiation of hidden surfaces, resulting in incomplete inactivation even after extended cycles as evidenced by persistent CFUs in shadowed rims or crevices. Material compatibility poses another constraint, with prolonged exposure risking degradation of polymers, plastics, and textiles necessitating scoping reviews of long-term impacts and selective use on robust surfaces. Performance variability arises from environmental factors like relative humidity (>60% reducing efficacy), temperature extremes, surface topography (rough textures increasing shadows), and inconsistent dosing across room layouts, compounded by the lack of penetration into biofilms or porous materials, leading to recommendations for hybrid protocols with vapor-phase methods and calls for standardized metrology in fluence measurement (Demeersseman et al., 2023).

**Hydrogen Peroxide Vapor Applications**

Hydrogen peroxide vapor (HPV) demonstrates exceptional sporicidal, bactericidal, and virucidal efficacy in controlled laboratory settings, consistently achieving log reductions of 5-7 across a broad spectrum of microorganisms, including bacterial spores like Geobacillus stearothermophilus, Bacillus atrophaeus, Bacillus thuringiensis, and Bacillus anthracis, as well as enveloped RNA viruses such as SARS-CoV-2, Venezuelan equine encephalitis virus, and Vaccinia virus. These reductions are validated through both qualitative and quantitative methods using biological indicators placed in challenging locations within biosafety level 3 (BSL-3) laboratories and material airlocks, where HPV cycles effectively penetrate shadowed areas and porous surfaces to inactivate viable pathogens, with spore viability dropping below detectable limits after standard exposure protocols. Studies confirm that HPV outperforms liquid disinfectants due to its gaseous phase allowing microcondensation on surfaces, enhancing oxidation of cellular components like proteins, lipids, and nucleic acids, while maintaining efficacy even in the presence of organic soil loads simulating real-world contamination. Validation with biological indicators, such as 6-log10 Geobacillus stearothermophilus strips, routinely shows complete inactivation (>6-log reduction) in enclosed environments, underscoring HPV's reliability for high-containment laboratory decontamination (Falaise et al., 2022).

In clinical environments, HPV significantly reduces multidrug-resistant organism (MDRO) transmission and healthcare-associated infection (HAI) incidence by eradicating environmental reservoirs of pathogens like Clostridium difficile, methicillin-resistant Staphylococcus aureus (MRSA), vancomycin-resistant Enterococcus (VRE), and Acinetobacter baumannii from high-touch surfaces in intensive care units (ICUs). ICU decontamination trials, such as those following patient discharge, demonstrate that HPV applied after terminal cleaning achieves near-complete elimination of MDROs, with post-treatment contamination rates dropping to levels far below those of standard cleaning alone, leading to hospital-wide reductions in C. difficile-associated diarrhea by up to 37% in large-scale implementations. Comparative studies in ICUs show no significant difference in efficacy between aerosolized and vaporized HPV systems, both outperforming routine protocols by reducing MDRO-positive rooms from 19% to negligible levels, particularly in high-risk areas occupied by infected patients for extended periods. These trials highlight HPV's role in breaking transmission cycles, with quasi-experimental designs reporting 64% lower acquisition risk for subsequent patients in HPV-treated rooms versus traditionally cleaned ones (Blazejewski et al., 2015).

Standard HPV cycles comprise four to five sequential stages ensuring comprehensive room or equipment decontamination without manual intervention. Safety protocols mandate remote operation,

pre-cycle humidity control below dew point to prevent excess condensation, and post-aeration monitoring to confirm vapor levels below 1 ppm (OSHA permissible exposure limit), with biological indicators verifying cycle success. Aeration requirements involve heated fresh air circulation through catalytic converters, typically lasting 1-2 hours depending on room volume, to eliminate residuals safely before re-entry, as demonstrated in BSL-3 and ICU applications where cycles complete in 2-4 hours total (Muino et al., 2023).

Despite its efficacy, HPV implementation faces challenges including extended cycle times (2-5 hours per room, disrupting workflow in high-turnover ICUs), high initial equipment costs (vapor generators and sensors exceeding standard cleaning budgets), and potential for surface corrosion or material degradation on sensitive metals, alloys, or plastics under repeated high-concentration exposures. Studies note time inefficiencies compared to faster methods like UV-C, with aeration phases alone prolonging room downtime, while cost analyses reveal elevated consumable and maintenance expenses, limiting scalability in resource-constrained hospitals. Corrosion risks, though minimal for most hospital surfaces (confined to superficial microstructural changes in alloys), necessitate compatibility testing for electronics and prolonged-use items, as higher concentrations or humidity can accelerate oxidation in vulnerable materials (Ayub et al., 2024a).

**Cold Plasma Disinfection in Healthcare**

Cold plasma produces a complex cocktail of RONS, including hydroxyl radicals (- OH), singlet oxygen ($^1O_2$), atomic oxygen (O), nitric oxide (NO), and peroxynitrite ($ONOO^-$), which collectively penetrate and disrupt microbial structures in biofilms and spores, key reservoirs of hospital-acquired infections. These species induce oxidative damage to cellular components, such as lipid peroxidation in membranes, protein oxidation, and DNA strand breaks, while the charged particles and UV photons enhance etchant effects that erode protective extracellular polymeric substances (EPS) in biofilms formed by pathogens like Pseudomonas aeruginosa and Staphylococcus aureus. Studies demonstrate up to 3-5 log reductions in biofilm viability within minutes, with polysaccharides and eDNA in the matrix scavenging RONS but ultimately succumbing to sustained exposure, as evidenced by enhanced inactivation when hydration synergizes plasma effects. Against spores, such as Clostridium difficile and Bacillus subtilis, RONS erode the spore coat and cortex through sequential oxidation, achieving 4-6 log inactivation in laboratory settings by targeting dipicolinic acid release and core dehydration, outperforming traditional chemical disinfectants in penetration depth (Gilmore et al., 2018).

The antiviral potential of cold plasma extends to enveloped viruses prevalent in healthcare settings, including SARS-CoV-2 surrogates, influenza, and herpes simplex virus type 1 (HSV-1), where lipid envelope disruption occurs via RONS-induced peroxidation and protein denaturation. Laboratory assays reveal rapid 2-4 log titer reductions in enveloped viruses within 30-120 seconds of exposure, attributed to the vulnerability of their lipid bilayers to oxidative attack, contrasting with more resilient non-enveloped viruses that require longer exposures targeting capsid proteins. For HSV-1, plasma treatment significantly lowers internalized viral genomes post-infection in cell lines like Vero and SH-SY5Y, with measurable effects at reduced viral loads, suggesting prophylactic surface decontamination efficacy. Synergistic UV radiation from plasma further damages viral nucleic acids, while non-thermal conditions preserve surrounding biomaterials (Bunz et al., 2020).

Clinical and pilot trials in operating rooms, surfaces, and medical devices highlight cold plasma's practical efficacy, with single-jet plumes achieving over 3 log reductions on nosocomial bacteria-contaminated hospital surfaces like stainless steel and plastics within 90 seconds, without exceeding safe temperatures below 45°C. In operating room simulations, flexible surface dielectric barrier discharge (sDBD) devices reduced Pseudomonas aeruginosa loads in ex vivo burn wound models and rat infection trials, demonstrating safety alongside temporary erythema and temperature rises manageable by power modulation. Surface trials on collagen membranes and titanium implants for dental and orthopedic applications showed enhanced decontamination without compromising material integrity, while device trials on endoscopes and ventilators confirmed biofilm disruption on complex geometries. Pilot studies in atopic dermatitis patients, analogous to chronic wound scenarios, reported reduced Staphylococcus aureus colonization and symptom relief, underscoring translational potential to hospital high-touch surfaces and surgical sites (Kim et al., 2021).

Cold plasma systems for hospital use typically employ dielectric barrier discharge (DBD), plasma jets, or surface microdischarge configurations powered at 10-50 kV and 1-20 kHz, with exposure parameters

optimized at 20-150 seconds per cycle, gas flows of 1-12 L/min (He/$O_2$/air mixtures), and nozzle-to-surface distances of 1-5 cm to balance efficacy and safety. Ozone management remains critical, as concentrations peak at 200-600 ppm during operation but dissipate rapidly post-treatment, kept below occupational limits (55 ppm/8h) via intermittent pulsing, ventilation, and catalysts; prototypes incorporate real-time sensors at multiple points (nose, throat) for upper respiratory or room-scale applications. Safety profiles from in vivo rat wounds and human volunteers confirm no cytotoxicity to fibroblasts at therapeutic doses, minimal genotoxicity, and reversible skin effects like 3-5°C warming, positioning cold plasma as viable for room-scale OR decontamination or portable device sterilization (Boekema et al., 2021).

Scalability challenges persist for cold plasma in modern hospitals, as current prototypes handle small areas ($cm^2$ scale) inefficiently for entire ORs or ICUs, requiring multi-nozzle arrays that amplify costs and power demands beyond 25-50 W portability. Standardization lags due to heterogeneous plasma chemistry influenced by electrode design, gas composition, humidity, and distance, complicating reproducible dosimetry; proposed metadata schemas aim to capture voltage, RONS flux, and treatment time, but lack universal adoption akin to PEF guidelines. Regulatory validation hurdles include sparse long-term clinical data, variable efficacy against mixed biofilms with organics, and needs for FDA/CE marking on ozone/UV emissions, delaying widespread implementation despite promising pilots (Pampoukis et al., 2025).

**Economic Perspectives**

Next-generation disinfection technologies like UV-C, hydrogen peroxide vapor (HPV), and cold plasma offer substantial economic advantages in hospital settings by reducing hospital-acquired infections (HAIs) and generating significant returns on investment through lower treatment costs and operational efficiencies. Economic models demonstrate that these interventions link HAI reductions directly to savings, with UV-C terminal disinfection achieving a 19.2% drop in multidrug-resistant organism HAIs, translating to over $1.2 million in direct cost savings in a single community hospital over 12 months without disrupting operations. Similarly, HPV has controlled outbreaks and reduced Clostridium difficile infections by up to 37% hospital-wide, while cold plasma's low manufacturing costs and antimicrobial efficacy position it as a cost-effective alternative for microbial load reduction, potentially easing financial burdens from antibiotic-resistant strains (Raggi et al., 2018).

Economic models consistently link HAI reductions from next-generation disinfection to substantial savings, with costs per prevented infection case often far outweighed by avoided treatment expenses. For UV-C, studies report attributable costs of multidrug-resistant HAIs ranging from $4,000 to $4,500 per patient, while interventions yield high internal rates of return, such as an 81% probability of at least 6% ROI over 10 years in large facilities through reduced repairs and HAI management. HPV decontamination of supply packaging prevented multidrug-resistant organism transmission, saving hospitals an estimated $387,055 annually in discarded items alone, excluding waste disposal costs, and demonstrated feasibility in high-occupancy settings with 94% bed utilization despite longer cycle times. Cold plasma offers promising ROI with lower production costs and no need for room evacuation, unlike UV-C or HPV, enabling prolonged sterilization without bed turnover delays; models project net present values up to $1.45 million over 10 years for related UV-C sanitizers, with similar potential for plasma in reducing HAIs like CLABSIs and VAPs that cost billions annually. Comprehensive analyses, including stepped-wedge trials, confirm these technologies dominate usual care by cutting HAI-related length-of-stay and medication costs, with UV-C showing 70% reductions versus HPV over five years including consumables (Sun et al., 2023).

High procurement costs, staff training requirements, and maintenance demands pose key barriers to adopting UV-C, HPV, and cold plasma, though these are often mitigated by long-term savings. UV-C systems face skepticism from leaders on efficacy claims, applicability to specific contexts, and local infection impacts, compounded by equipment costs, staffing shortages, and high patient turnover needs that prioritize speed over thoroughness. HPV requires 2-2.5 hours per room versus 32 minutes for manual cleaning, plus biocide consumables that inflate ongoing expenses by 67% compared to UV-C, alongside logistical challenges like room sealing and vapor residue management in busy hospitals. Cold plasma, while innovative, grapples with unproven residues, ozone emission risks necessitating

regulations, and the need for international standards on device design, integration with manual cleaning, and validation against biofilms, delaying widespread use despite no-vacancy advantages. Training for environmental services, monitoring fluorescence for thoroughness, and interprofessional collaboration between nursing, infection prevention, and engineering are essential but resource-intensive, with COVID-19 funding helping but competing priorities persisting (Dukes et al., 2025).

Integration of UV-C, HPV, and cold plasma into infection prevention budgets holds strong potential for large-scale adoption, bolstered by sustainability gains and environmental ROI that align with global healthcare pressures. UV-C reduces chemical use by 215,000 liters, water by one million liters, and energy by 200 million watts annually across NHS trusts, while shortening decontamination to 60 seconds and minimizing equipment repairs to prevent clinic cancellations. HPV's broad-spectrum efficacy against multidrug-resistant organisms supports scalable outbreak control, with systematic reviews confirming clinical benefits when combined with UV systems, though cost-effectiveness varies by setting. Cold plasma's economic edge facilitates adoption in resource-limited areas, with calls for trials confirming HAI impacts and plasma-activated liquids enhancing IPC programs. Overall, these technologies promise 765% ROI in national projects preventing thousands of HAIs, with sustained environmental cleaning over a decade correlating to dramatic infection declines, making them viable for budget integration amid rising antimicrobial resistance costs (Dancer & King, 2021).

**Future Directions in Next-Generation Disinfection Technologies**

The evolution of UV-C, hydrogen peroxide vapor (HPV), and cold plasma disinfection systems in modern hospitals hinges on transformative technological innovations that enhance precision, autonomy, and scalability, particularly through integration with artificial intelligence (AI)-driven autonomy and Internet of Things (IoT) monitoring. AI-enabled UV-C robots, such as those incorporating real-time UV intensity sensors and environmental monitoring, dynamically adjust disinfection paths to optimize dose delivery in complex hospital environments, reducing blind spots and energy consumption by up to 35% while ensuring operator safety via wearable exposure alerts. IoT platforms further enable remote oversight, predictive maintenance, and data analytics for infection trends, as demonstrated in systems like HygenX AI and UVCeed, which fuse multimodal sensors for 3D scene modeling and dosage accuracy improvements of 50% on high-touch surfaces. Hybrid systems combining UV-C with cold plasma and advanced sensors represent a paradigm shift, where plasma-generated reactive oxygen species (ROS) complement UV-C's DNA damage mechanisms, achieving synergistic log reductions against resistant pathogens like C. difficile spores, while integrated sensors validate fluence in real-time during terminal disinfection of wards or operating rooms. These innovations promise seamless deployment in high-traffic areas, minimizing human error and accelerating room turnover without chemical residues, as evidenced by trials showing 96.9% surface decontamination post-UV-C robot use compared to 50% with manual methods alone (Mehta et al., 2023).

Despite promising preclinical and observational data, significant research and knowledge gaps persist in validating the long-term clinical impact of these technologies through rigorous randomized controlled trials (RCTs) and comparative multi-center trials, which are essential to quantify reductions in healthcare-associated infections (HAIs) beyond surrogate markers like colony-forming units. Current evidence from prospective RCTs on continuous UV-C systems suggests infection reductions, but multi-center studies comparing UV-C, HPV, and cold plasma head-to-head remain scarce, with HPV outperforming UV-C in spore inactivation yet lacking standardization for shaded areas or hybrid applications. Pathogen-specific efficacy studies are urgently needed, particularly for emerging variants and resistance management, as cold plasma's ROS mechanisms show variable activity against biofilms and multidrug-resistant organisms like MRSA, while UV-C and HPV face challenges with shadowed surfaces and potential photoreactivation. Long-term RCTs must address durability over repeated cycles, material compatibility in diverse hospital settings, and cost-effectiveness analyses, as preliminary data indicate plasma-H2O2 hybrids achieve >6-log reductions rapidly but require validation against real-world HAIs in ICUs and operating theaters (Boyce, 2016a).

Seamless integration of these next-generation disinfectants into hospital protocols demands standardized guidelines for routine environmental disinfection, positioning UV-C robots and HPV systems as adjuncts to manual cleaning to achieve >90% HAI risk reduction in high-burden areas like patient rooms and ICUs. Protocols should mandate sensor-verified dosing for daily terminal disinfection, with cold plasma aerosols targeting thermolabile devices like ultrasound probes, ensuring

material integrity while inactivating viruses and bacteria without toxic residues. For pandemic preparedness and outbreak containment, hybrid UV-C-plasma-IoT networks enable rapid scaling, as seen in COVID-19 deployments where robots decontaminated wards in minutes, supporting reusable PPE and surge capacity without workforce strain. Multi-disciplinary protocols incorporating AI dashboards for compliance tracking and outbreak simulations will fortify resilience, bridging current gaps in operator training and regulatory harmonization to embed these technologies as core to infection prevention (Casini et al., 2019).

**The role of nurses**

Nurses play a pivotal role in implementing next-generation disinfection technologies like UV-C, hydrogen peroxide vapor (HPV), and cold plasma in modern hospitals, serving as frontline coordinators who ensure seamless integration into infection prevention workflows. They oversee room preparation by removing organic debris prior to automated cycles, validate efficacy through ATP swabbing or biological indicators, and monitor compliance with safety protocols such as personnel evacuation and post-aeration clearance to prevent occupational exposure. Beyond operations, nurses educate environmental services teams on hybrid protocols combining manual precleaning with no-touch methods, track healthcare-associated infection reductions attributable to these technologies (e.g., 19-30% via UV-C adjuncts), and advocate for resource allocation amid staffing constraints, leveraging their patient proximity to prioritize high-touch areas in ICUs and oncology wards. This multifaceted involvement enhances HAI control while minimizing disruptions, positioning nurses as essential bridges between technological innovation and evidence-based practice (Boyce, 2016b).

**The role of health informatic technician**

Health Informatic Technicians play a pivotal role in enhancing hospital disinfection programs by leveraging informatics tools for real-time surveillance, predictive analytics, and data-driven optimization of next-generation technologies like UV-C, hydrogen peroxide vapor, and cold plasma. These professionals manage electronic health records (EHRs) and health information systems to automate HAI monitoring, identifying contamination patterns and enabling early intervention through AI-integrated dashboards that track disinfection cycle compliance and environmental bioburden metrics. By facilitating antimicrobial stewardship alerts, interfacility MDRO communication, and automated outbreak detection, they reduce manual surveillance burdens, support hybrid no-touch protocols, and ensure resource allocation aligns with infection trends, ultimately amplifying the clinical and economic impact of advanced disinfection in high-risk wards (Lin & Trick, 2016).

**The role of emergency medical services**

Emergency medical services (EMS) represent a critical frontier for next-generation disinfection technologies, where ambulances serve as mobile high-risk environments contaminated by infectious patients during transport, necessitating rapid, residue-free decontamination to protect paramedics, subsequent patients, and hospital staff from multidrug-resistant organisms like MRSA and C. difficile spores. UV-C systems have demonstrated robust efficacy in ambulance compartments, achieving significant microbial reductions (e.g., 99.9% inactivation of spores at targeted doses) across varied surfaces and fixture positions, though validation for shadowing and reflectivity is essential. Hydrogen peroxide vapor (HPV) and nebulizers effectively penetrate equipment, glove boxes, and cabins, delivering 100% sporicidal activity against Bacillus atrophaeus in multi-cycle protocols without compromising ventilation-dependent devices. Cold atmospheric plasma (CAP) offers promising broad-spectrum inactivation (>4-log reductions in endospores, S. aureus, and phages within 30-120 minutes via compact DBD nozzles), enabling on-site treatment of complex interiors without thermal damage or residues, as validated in real-world ambulance trials. Integrating these no-touch methods into EMS protocols minimizes downtime, enhances biosafety amid pandemics, and complements manual cleaning for sustained infection control (Lindsley et al., 2018).

**The role of medical sterilization technician**

Medical Sterilization Technicians, often working within Central Sterile Supply Departments (CSSDs), play a pivotal role in integrating next-generation disinfection technologies like UV-C, hydrogen peroxide vapor (HPV), and cold plasma into hospital workflows by managing the reprocessing of

contaminated medical devices, ensuring high-level disinfection through standardized protocols for cleaning, packaging, and validation with biological and chemical indicators. These professionals oversee cycle monitoring for low-temperature HPV plasma sterilizers on heat-sensitive instruments such as endoscopes, conduct routine quality assessments to detect sterilization failures, and train clinical staff on sterile items handling to prevent recontamination, contributing to reduced healthcare-associated infections through closed-loop management that extends from device collection to delivery. Their expertise in responding to reprocessing breaches further enhances infection control, particularly for multidrug-resistant organisms targeted by no-touch methods, while quarterly audits and competency programs ensure sustained efficacy in high-volume settings (Rutala & Weber, 2016).

**The role of lab specialist**

Laboratory specialists play a pivotal role in validating and optimizing next-generation disinfection technologies like UV-C, hydrogen peroxide vapor (HPV), and cold plasma in modern hospitals by conducting microbiological surveillance, efficacy testing, and outbreak investigations to ensure reliable high-level decontamination against multidrug-resistant organisms (MDROs) and spores. Through collaboration with infection control teams, they perform timely sampling from environmental reservoirs, utilize biological indicators such as Geobacillus stearothermophilus for HPV cycle validation, and apply molecular techniques like PCR and genotyping to detect, characterize, and track nosocomial pathogens, confirming log reductions (e.g., 4-6 log10) and identifying transmission sources post-disinfection. Their expertise in antimicrobial susceptibility testing and real-time monitoring further supports data-driven protocol refinements, enhancing the integration of these no-touch systems into hospital workflows while minimizing healthcare-associated infection risks (Ayub et al., 2024b).

**Conclusion**

Next-generation no-touch disinfection technologies—UV-C, hydrogen peroxide vapor (HPV), and cold plasma—offer transformative solutions to combat healthcare-associated infections (HAIs) by overcoming the limitations of manual cleaning, such as human error, shadowing, and incomplete coverage of resilient pathogens like C. difficile spores, MRSA, and VRE. These systems demonstrate complementary strengths: UV-C provides rapid DNA-damaging photon inactivation with 19-30% HAI reductions in clinical trials, HPV excels in sporicidal oxidation achieving 5-7 log reductions across porous surfaces, and cold plasma delivers residue-free reactive species for biofilms and viruses, with hybrid approaches promising synergistic 6-log efficacy. Economic models confirm substantial ROI through HAI prevention, yielding millions in savings from reduced stays and treatments, while future AI-IoT integrations and standardized RCTs will drive scalable adoption in high-risk hospital areas amid rising antimicrobial resistance.

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