The role of environmental hygiene in preventing hospital-acquired infections (HAIs) has been a controversial topic.\textsuperscript{1,2} It was widely accepted that the bulk of HAIs were the result of transmission from one patient to another via the contaminated hands of caregivers or contaminated equipment that was sequentially used on patients.

However, the role of noncritical environmental surfaces as a reservoir for nosocomial pathogens to contaminate the hands of health care providers and subsequently infect patients remained undefined. Of note, a literature survey published less than 10 years ago concluded that there was no evidence to support environmental hygiene practices as a method for reducing HAIs.\textsuperscript{3}

The past 10 years have seen a progressive accumulation of evidence that clearly established environmental reservoirs of nosocomial pathogens as a cause of HAIs, and this information was used to shape what has become the foundation of currently recommended hospital-based environmental hygiene practices.

It had long been appreciated that shortly after being placed into a patient room, individuals shed bacterial organisms that contaminated environmental surfaces, including those thought to be involved in horizontal transmission and HAIs such as methicillin-resistant \textit{Staphylococcus aureus} (MRSA), vancomycin-resistant enterococci (VRE), \textit{Acinetobacter} and other gram-negative bacteria, and \textit{Clostridium difficile} spores.\textsuperscript{2,3} Additional research also documented that these organisms can persist on environmental surfaces for weeks or even months.\textsuperscript{4} Culture sampling demonstrated that certain surfaces carried a much higher bacterial bioburden than others, a consequence of more frequent contact with
patients. A conceptual model of “high-touch” surfaces evolved from these findings, which included the identification of key environmental surfaces in frequent contact with patients and health care workers such as bed rails, door knobs, etc.5-7 Subsequent studies have documented that routine cleaning and disinfection substantially reduces contamination and could be useful in controlling outbreaks.3,8-11 A landmark study published in 2013 reported that the risk for nosocomial infections could be substantially reduced by the use of environmental hygiene strategies that reduce the bacterial bio-burden on high-touch room surfaces.12

A number of recent studies have documented that patients who were placed in rooms previously occupied by individuals infected or colonized with VRE, MRSA, C. difficile, or Acinetobacter were 73% more likely to acquire the same pathogens than patients who did not occupy such rooms.3,13 Bacterial strain typing often confirmed this chain of transmission. These findings strongly supported terminal cleaning, the practice of cleaning and disinfecting all room surfaces following patient transfer or discharge before use by a new patient. Current guidelines now encourage hospitals to develop programs for cleaning and disinfecting high-touch surfaces as part of terminal room cleaning using a properly applied, Environmental Protection Agency (EPA)-approved germicide.14,15

### Monitoring Compliance

Establishing a monitoring program for periodic or ongoing assessments of environmental hygiene practices has been shown to significantly improve compliance with hospital policies and protocols. An environmental cleaning toolkit released in 2010 by the Centers for Disease Control and Prevention encouraged hospitals to create such programs as an adjunct to terminal room cleaning to ensure high-touch surfaces are thoroughly cleaned.14 The toolkit further advocates for an objective assessment of hygiene practices and outlines a variety of approaches and technologies to accomplish this task (Table 1).14

Covert direct observation can provide an objective assessment of compliance with cleaning protocols and is the most frequently used monitoring tool in US hospitals. The process is labor intensive, should employ a checklist, and in actuality is quite difficult to accomplish in a covert fashion. As a result, data generated from this method is not likely to reflect or measure true hygiene practices.

Serial swab cultures of environmental surfaces also can be used as a monitoring tool. Although samples are easy to acquire, processing costs and turnaround delays limit the practicality of this method as a monitoring tool. Furthermore, given the lack of established, concrete cutoffs to serve as a baseline for acceptable results, precleaning contamination levels must be determined for each surface to assess compliance with environmental cleaning policy.

Agar slide cultures have been adapted for environmental surface monitoring in hospitals and are capable of quantifying aerobic colony counts (ACCs) per cm². This technique is largely limited to culturing large flat surfaces and also requires measurements of precleaning contamination levels in order to assess the efficacy of environmental cleaning practices.

Fluorescent markers also have been developed to assess hygiene practices.14,16 This commercially available method involves the application of a fluorescent gel to target surfaces, which becomes transparent after drying. Following room cleaning, ultraviolet (UV) light will expose any areas that were not adequately cleaned. There is widespread hospital experience with the use of these markers, and a number of studies have demonstrated their accuracy for objectively evaluating environmental hygiene practices.16

A second commercially available solution is the adenosine triphosphate (ATP) bioluminescence assay, which measures ATP on surfaces using a luciferase assay and luminometer.14 A specialized swab is used to sample a targeted surface area, which is then analyzed using a portable handheld luminometer. The total amount of ATP, both microbial and nonmicrobial, is expressed as relative light units. Low readings have shown a reasonable correlation with low ACCs, but very high readings may indicate bacterial contamination, organic debris containing dead bacteria, or both. Moreover, high concentrations of liquid bleach disinfectant can interfere with the assay and may result in reduced signal strength. Again, the lack of a threshold cutoff value requires an assessment of precleaning ATP levels to properly interpret results. ATP systems have proven effective for documenting improvements in daily cleaning practices for high-touch surfaces.14

### Assessing Current Practice

Despite existing recommendations for hospitals to establish environmental hygiene programs and monitor
their effectiveness, suboptimal practices are common.\textsuperscript{13,17} Studies have established that terminal cleaning is about 49\% effective; however, success rates for high-touch surfaces show significant variation, ranging from 30\% to more than 75\%.\textsuperscript{13} A recent survey of infection preventionists documented that many continue to rely on direct observation to monitor environmental cleaning practices (employed by 70\% of respondents on a daily, weekly, or monthly basis) as well as poor uptake of fluorescent gel or ATP systems (used by 26\% to 28\% of respondents on a daily, weekly, or monthly basis).\textsuperscript{13}

Other recent studies have documented that even when aggressive interventions are employed, including intensive staff education and the use of newer, objective-based evaluation techniques with performance feedback, efficacy rates for high-touch surface cleaning remain in the range of 77\% to 82\%.\textsuperscript{13} Although these studies have documented that cleaning and disinfection need to be improved in US health care settings as part of efforts to prevent nosocomial infections, they also have resulted in the development and introduction of a variety of new technologies.

**Emerging Technologies**

The past 5 years have seen the rapid development of emerging technologies designed to enhance environmental hygiene practice. The proliferation of products is almost bewildering, and the pace at which new technologies are being introduced is accelerating rapidly. This section is not intended to provide an all-inclusive overview of every technology in development; instead, it will provide a broad overview of currently available technologies and the level of evidence supporting their use. Infection control practitioners should appreciate the need to revisit emerging technologies on an ongoing basis and should stay abreast of the burgeoning amount of literature that continues to surface regarding their performance and effectiveness. It also should be stressed that current recommendations and guidelines consider these products as adjuncts, rather than replacements, to existing environmental hygiene programs and practices. Products and strategies have been divided into 4 categories for discussion: disinfectants and cleaning tools; soft-surface disinfection; hard-surface disinfection; and whole-room disinfection.

**Disinfectants and Cleaning Tools**

Products in this category are summarized in Table 2. The development of new disinfectants is largely driven by a desire to decrease the long wet-contact time required with the use of iodine-based or quaternary disinfectants (ie, up to 10 minutes) and their apparent inability to optimally disinfect \textit{C. difficile} spores. \textsuperscript{18} Current recommendations for \textit{C. difficile} disinfection rely on the use of a 5\% to 6\% sodium hypochlorite solution (ie, household bleach), which is corrosive to environmental fixtures, bleaches fabrics, and carries occupational exposure risks. The advantage of slow-release chlorine products is that, although they are fast acting, they exert a prolonged bactericidal effect.\textsuperscript{15} Unfortunately, they still retain the potential to damage equipment and facilities. Another option is superoxidized water, which is created when saline is electrolyzed to produce a solution of hypochlorous acid and chlorine, with free chlorine the active microbicide.\textsuperscript{15} Point-of-use production systems are commercially available, but they are expensive and complicated to operate.\textsuperscript{15} The solutions appear to have a 48-hour shelf life.\textsuperscript{15} The product is FDA-approved for high-level disinfection, but further study of its application as an environmental disinfectant is required.

Microfiber mops and microfiber wipe cloths have a long history of use in hospitals. Both products are made of a blend of microscopic polyester and polyamide fibers, which are split to create microscopic hooks that collect and retain dust, dirt, and bacteria. Microfiber mops have been demonstrated to have superior efficacy in reducing microbial levels on floors compared with conventional, cotton string mops, and achieved 95\% efficacy.\textsuperscript{18} Furthermore, performance did not improve when they were used with a disinfectant. Microfiber mops are less work intensive than conventional mops, eliminate issues of cross contamination during environmental cleaning, and drastically reduce the use of water and chemicals due to more efficient cleaning and disinfection.

Similarly, microfiber cleaning cloths have consistently outperformed conventional cloths in their ability to decontaminate across all surfaces, even when bacteria were coated on to the surfaces with phosphate-buffered saline (PBS) or PBS-containing horse serum.\textsuperscript{19} Designed to be used without detergents or biocides, they have been shown to effectively decontaminate hard surfaces seeded with \textit{S. aureus}, \textit{Escherichia coli}, and \textit{C. difficile} spores under simulated conditions. An additional study compared the efficacy of 10 different microfiber cloths (9 reusable) under simulated conditions and found comparable performance among the products, even after 150 washes.\textsuperscript{20} Although the Joint Commission and the EPA have advocated for these products, continued research to evaluate their performance in real-world clinical settings is required, as well as to determine if their use can reduce HAI rates.

**SOFT-SURFACE DISINFECTION**

Soft-surface disinfection strategies include fabric impregnation with copper or silver to take advantage

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of their intrinsic antimicrobial properties, citric acid impregnation of cotton cloth, and organosilane-based quaternary ammonium impregnation of fabric materials (Table 3). These materials have been used to produce scrubs, uniforms, linens, and privacy curtains. A double-blind, randomized controlled trial (RCT) evaluating the use of antimicrobial-impregnated privacy curtains in the ICU setting showed a significant delay in time to colonization and an 8-fold reduction in the risk for VRE contamination compared with standard fabric curtains. Similarly, an ICU-based, blind, randomized crossover trial evaluating the efficacy of organosilane-based quaternary ammonium-impregnated scrub suits reported a significant reduction in MRSA contamination, with little effect on the burden of VRE or gram-negative rods. Further investigation is warranted to demonstrate the ability of these products to consistently perform under clinical conditions, followed by clinical trials to measure their effect on HAI rates.

**HARD-SURFACE DISINFECTION**

Hard-surface disinfection technologies are summarized in Table 4. Copper and copper alloy cladding of high-touch hard surfaces takes advantage of the natural antimicrobial properties of copper to significantly reduce high bacterial bioburden within 2 hours. Copper and copper alloy surfaces have demonstrated activity against a broad spectrum of bacteria, including nosocomial pathogens known to be transmissible from environmental reservoirs. Furthermore, copper technologies provide continuous bacterial disinfection on all surfaces where it is employed. More than 200 publications have documented its potent antimicrobial activity in both simulated and actual clinical conditions. Silver nanotechnology products are still in early development stages.

Disinfectant-based hard-surface technologies include the incorporation of triclosan into surfaces and the use of quaternary ammonium salt surfactants as a coating on hard surfaces. Triclosan-based products already have been proven to have limited application in the health care environment. Triclosan has a limited spectrum of antimicrobial activity and there is mounting evidence that bacteria can become triclosan-resistant in the setting of continued exposure. Triclosan-impregnated products are now primarily marketed for household use. Quaternary ammonium salt surfactants are in early development and, like all surface-coating technologies, they will need to demonstrate durability as well as efficacy.

The final category of hard-surface disinfectants includes a group of light-activated antimicrobial compounds. Titanium dioxide is the most developed product, with considerable prior use in food, toothpaste, and tooth-whitening preparations, and as a disinfectant in Japanese health care environments. Titanium dioxide is produced by crystallizing titanic iron ore into a nanoliquid form. When exposed to UV light in the sub-400 nm range, it becomes a photocatalyst oxidizer that produces hydroxyl radicals and superoxide ions with potent antimicrobial activity. Patented technologies now allow for the nanoliquid to penetrate and form permanent bonds with the surface that last for years. Titanium dioxide has required exposure to sunlight or UV light for maximum antimicrobial activity, and it has shown a broad spectrum of antibacterial activity, although this effect is slower in decontaminating spores. The addition of zinc to the preparation has now provided effective antimicrobial action after exposure to indoor lighting of any type, which provides continuous disinfection as long as room lighting is in use. A single application remains active on heavily used surfaces even after 1 year. Now marketed in the United States for disinfection in the health care setting, it will be interesting to see what efficacy information becomes available.
**WHOLE-ROOM DISINFECTION**

Table 5 summarizes approaches to environmental disinfection using whole-room technology. As a group, they (with the exception of titanium dioxide) employ devices placed in patient rooms and all use toxic technologies that prohibit patient or staff occupancy during the disinfection process. As a result, they all are limited to use as adjunct disinfection technologies during terminal room cleaning between patients. Disinfection cycle duration times will effect room turnover times, and this should be a consideration in addition to disinfection efficacy rates.

UV light room disinfection is probably the most studied of the whole-room technologies, and the products build on a long history of the use of UV light to disinfect well water, circulating dialysis fluid, and room air for tuberculosis control. Numerous products are commercially available and all employ the use of low-pressure mercury or xenon vapor lamps to generate UV light in the germicidally active wavelength range of 200 to 320 nm.\(^24^{,}25\) Shortwave UV-C radiation, primarily at 254 nm, kills by damaging DNA. Photon absorption leads to formation of pyrimidine dimers between adjacent thymine bases in DNA, rendering the microbe incapable of replication. These technologies offer broad-spectrum microbicidal activity, including C. difficile spores.\(^24\) A typically sized hospital patient room can be disinfected within 10 minutes, minimally affecting room turnaround times during terminal cleaning. The principal issue with UV light disinfection is that it provides for “line-of-sight” killing—meaning it does not work in shadowed areas and does not penetrate fabrics well—and there is no evidence that lack of a proper room cleaning before UV light disinfection can markedly reduce its efficacy.\(^24\) Line-of-sight killing has been addressed through the use of careful device placement in the room, rotating the light source, and UV-reflective shields and wall paint.\(^24,27\)

One manufacturer provides indicators that can be placed in potential problem areas in the room and are capable of monitoring for appropriate UV light exposure. UV light has proven effective as a hospital room disinfectant, reliably reducing the bacterial bioburden of a wide spectrum of pathogens under simulated and real-time clinical situations (provided the room is cleaned first). However, its ability to reduce HAI rates has yet to be studied.

Several systems have been developed that produce hydrogen peroxide vapor, aerosolized dry-mist hydrogen peroxide, or vaporized hydrogen peroxide for whole-room disinfection. Hydrogen peroxide is converted by catalysis after bacterial contact to generate free oxygen radicals with rapid bactericidal activity. Under simulated and real-time clinical conditions, hydrogen peroxide has demonstrated broad-spectrum activity as a disinfectant, including the rapid decontamination of spores. Whole-room treatment leaves no residue.\(^28\) When used as a follow-up to bleach disinfection, whole-room disinfection is extremely effective. In a retrospective study conducted in 334 patient rooms previously occupied with individuals infected with C. difficile, use of hydrogen peroxide vapor within the terminal cleaning program reduced nosocomial infection rates from 0.88 to 0.55 cases per 1,000 patient-days.\(^29\) Of note, the hydrogen peroxide intervention was only used in 54% of rooms.

Additional evidence suggests that hydrogen peroxide room disinfection can reduce VRE infection rates, but 2 studies have now identified that the process may not be as effective in reducing MRSA infection rates.\(^30,31\) It has been suggested that this may be related to the fact that MRSA are catalase-producing organisms. Similar to UV room disinfection technologies, hydrogen peroxide room disinfection carries a significant capital expenditure cost and requires the removal of surface debris before use.

Finally, titanium dioxide/zinc technologies have been developed and marketed as methods of whole-room disinfection. The technologies and means of action already have been discussed above. Beyond hard surfaces, the products also can be sprayed onto soft surfaces and brushed into fabrics to provide a long-lasting, broad-spectrum biocidal coating. A single room application would cost less than $650 and last for 1 year. The room only needs to be vacant during the application process, and these products offer continuous room disinfection whenever room lights are on, providing a biocidal disinfectant action far beyond a terminal cleaning technology. This product is in clinical testing and efficacy data should be available in the near future. A combined ozone/UV light/hepafiltration technology product also is commercially available and requires further evaluation.

**Conclusion**

Accumulating evidence has established that bacterial contamination of the physical hospital environment can serve as a reservoir for transmission to patients and can contribute to the acquisition of HAIs. Study findings have been used to shape current recommendations for environmental hygiene interventions, but achieving a high degree of compliance with guidelines has proven difficult. Emerging environmental hygiene technologies may provide important adjunct interventions in helping to achieve these goals.
References


Dr. Currie reported that he serves on the advisory board for Clorox and has received grant support from the Agency for Healthcare Research and Quality.