Aerosol Surface Disinfection in a Pandemic World: Gas/Vapor-Phase Biocides, Fogging, and Electrostatic Spraying

By Eugene C. Cole, DrPH

INTRODUCTION

In the midst of the current human coronavirus pandemic, many building cleaning and sanitation practices and protocols have been improved in quality and frequency; they have also been upgraded from the use of anti-bacterial sanitizer products to more broad-spectrum disinfectants, capable of inactivating a variety of bacterial, fungal, and viral human pathogens. That has raised the question of the effectiveness of those disinfectants as gas-phase, vapor-phase, or fogging biocides because disinfection via the aerosol route can readily reduce the time and cost of application. The question remains, however: Can aerosol disinfection achieve the same or higher level of infectious disease risk reduction as the manual application of those products? And can they overcome neutralizing substances that may reduce their effectiveness, and also maintain a critical dwell time for the exposure to effectively kill the microbes? In addition, the issue generates concern regarding the integrity of some surfaces and materials exposed to the aerosols, as there is no selective exclusion as to where the aerosols land. Those and related issues are the focus of this paper.

CLEANING AND MANUAL DISINFECTION

Whether conducting business of a routine nature or dealing with the challenges of a pandemic, management personnel have a responsibility for ensuring healthy indoor environmental quality across their properties, whether they are office buildings, schools, production facilities, aircraft, long-term care facilities, homes, and more. Accordingly, the current COVID-19 pandemic emphasizes the need for health-based cleaning, which,

About the Author

Dr. Cole *is Director of Research for LRC Indoor Testing & Research, Cary, NC, and formerly a Professor of Environmental Health Sciences at Brigham Young University, Provo, UT. His research focuses on the ecology of indoor environments, with special emphasis on identification and reduction of pollutant reservoirs and sources, bioaerosols, human exposure assessment and control, product evaluation, cleaning and restoration, mold and sewage remediation, and biocides. He has been a contributor to multiple editions of the IICRC S500 Water Damage Restoration Standard and the IICRC S520 Mold Remediation Standard. He holds both a Master of Science degree in Public Health Microbiology and a Doctor of Public Health degree in Biohazard Science & Occupational Health from the University of North Carolina at Chapel Hill. He is a member of the Scientific Advisory Council of the Cleaning Industry Research Institute (CIRI) and a Fellow of the American Industrial Hygiene Association (AIHA).*

SYNOPSIS

It is essential that cleaning and remediation management professionals take a science-based approach to the mitigation of human infectious disease transmission.

The application of an EPA-registered disinfectant as an aerosol generates three avenues of inquiry: 1) will it be effective in the absence of cleaning; 2) will it be as effective as manual application following cleaning; and 3) is there a rationale for its use pre- and/or post-cleaning?

To answer these questions, it's important to review the specifics of aerosol disinfection. In the context of this discussion, an aerosol is a collection of tiny particles or droplets, about 0.001 µm-100 µm. The size and/or density of those particles or droplets typically has a bearing on disinfection effectiveness. Commonly referenced terms include gas-phase, vapor-phase, fogging (mists), and sprays.

Gas-Phase. Gases are formless fluids that expand to occupy the confines of a space and are so small that they are not visible. Air is our most common gas. When ultra-fine particles or droplets are introduced into the air and also remain unseen, they are in gas-phase.

Vapor-Phase. A vapor is the volatile, gas-phase form of a substance that exists in the liquid state at room temperature and pressure. As temperature and pressure change, the substance is "vaporized."

Fogging (Mists). Mists are generated by breaking up a liquid into a dispersed state of very fine droplets, such as by atomizing. When the mist is dense enough to affect visibility, it is called a fog.

Spraying. Spraying involves chemicals typically dissolved in water and dispersed under pressure as tiny droplets greater than 10 µm. The size of the droplets and their distribution on surfaces depends largely on pressure and nozzle size.

A key question that arises in the use of all aerosol application methods: Will the product deposition be contiguous across all targeted surfaces and penetrate all cracks and crevices? One recently introduced methodology is designed to address those issues.

Electrostatic Spraying (ES). ES technology has been used in other industries for many years. Fine droplets (equal to or greater than 40 µm) discharged from electrostatic sprayers receive a positive charge as they leave the nozzle. They are then attracted to negative or neutral-charged surfaces, and can literally wrap around surfaces, providing an even and consistent distribution.

While many tout their disinfectant products and services as stand-alone approaches to eliminating microbial contamination, science continues to support cleaning as the basic and fundamental approach to reducing the risk of infectious agent transmission. With the exception of one-step cleaner-disinfectants, all EPA-registered disinfectants are required to be used on clean surfaces.

Because the cleaning of a non-porous surface may leave microbial contamination behind, if circumstances warrant, the application of a disinfectant following cleaning is needed. That application may be done manually or by an aerosol process.

EPA-registered disinfectants are primarily designated for use on hard, nonporous surfaces; thus, decontamination of porous and semi-porous surfaces may be problematic. In that situation, HEPA-vacuuming may be the primary cleaning method. Subsequent aerosol disinfection may result in some measure of microbial inactivation.

Long-lasting antimicrobial compounds, often referred to as bioactive coatings, bond to surfaces to prevent a build-up of microbial contamination. They are often applied using an aerosol method. These coatings can be effective at suppressing microbial growth, but they require unhindered contact between the microbes and the treated surface. Thus, a layer of dust or the deposition of microbes in a protective matrix will compromise the action of the compound. To maximize effectiveness, frequent cleaning is required.

in particular, targets high-contact touchpoints or "hot spots" that may serve as vehicles of infectious agent transmission to uninfected individuals. That targeted hygiene approach typically involves manual detergent cleaning of nonporous surfaces, followed by the application of an EPA-registered disinfectant. The cleaning process, through friction and emulsification, physically removes microbes and their associated matrices in which they may be embedded, such as saliva and/or nasal secretions from the nose or mouth, as generated by coughing or sneezing. The cleaning process is crucial. It removes soils, respiratory secretions, and other substances that may block or interfere with the antimicrobial action of the biocide to kill or otherwise inactivate any remaining microbial residues.

For specific use against the SARS-CoV-2 coronavirus, disinfectant products with public health claims may have: 1) demonstrated efficacy against SARS-CoV-2; 2) approval for use against specific viruses, to include a number of human respiratory viruses (e.g., Influenza A, Adenovirus, RSV), appropriate animal surrogate viruses similar to human viruses; or 3) an emerging pathogen claim that indicates the product is likely to be effective against SARS-CoV-2. The emerging pathogen claim confirms that the product has: 1) demonstrated efficacy against a harder-to-kill virus (non-enveloped ones such as Adenovirus, Hepatitis A, and Norovirus); or 2) demonstrated efficacy against another type of human coronavirus, similar to SARS-CoV-2. The EPA's *List N: Products with Emerging Viral Pathogens AND Human Coronavirus claims for use against SARS-CoV-2,* can be found on the agency's website. Fortunately, in regard to SARS-CoV-2, it is a virus with a lipid envelope that is very susceptible to dissolution by detergents, which contributes to the virus inactivation directly, or by making it very susceptible to the actions of all classes of disinfectants.

AEROSOL DISINFECTION

Consideration of the use of an EPA-registered disinfectant as an aerosol generates three potential avenues of inquiry: 1) will it be effective as a measure of targeted hygiene in the absence of cleaning; 2) will it be as effective as a manual disinfectant application at inactivating residual microbial contamination if used following cleaning; and 3) is there a rationale for its use pre- and/or post-cleaning, and as a matter of additional concern and precaution for building occupants, custodians, and perhaps contracted restoration professionals?

In an attempt to answer those questions, it's important to review the specifics of what is referred to as aerosol disinfection, and that begins with terms and definitions. In the context of this discussion, an aerosol is a collection of tiny particles or droplets, about 0.001 µm-100 µm, suspended in the air long enough to be observed and measured. And the size and/or density of those particles or droplets typically has a bearing on terms used in aerosol disinfection. Commonly referenced terms for treatment include gas-phase, vapor-phase, fogging (mists), and sprays.

Gas-Phase

Gases are formless fluids that expand to occupy the confines of a space or enclosure, and they are so small that they are not visible. Air is our most common gas. When ultra-fine particles or droplets are introduced into the air and also remain unseen, those particles or droplets can be said to be in gas-phase.

For decades, until it was declared a carcinogen, formaldehyde gas was used to primarily decontaminate laboratories that were used for work with highly infectious human pathogens, as well as some agricultural applications. Although it was effective, it involved a cumbersome and time-consuming process, and it was never proposed or used for office buildings or homes. Gas-phase ozone was proposed by some for buildings and home environments suffering water damage and mold growth more than two decades ago. Ozone (O_3) can be generated by corona discharge or UV light, to where high concentrations in the air can be achieved. Unfortunately, ozone can be extremely hazardous to human health, with concentrations above 0.07 ppm resulting in respiratory irritation and inflammation. Also, high concentrations of ozone can be damaging to rubber, plastics, fabric, paints, and metals. Moreover, it is ineffective in inactivating microbial growth on surfaces and materials. Although ozone is recognized as very effective in the aqueous phase (for water disinfection), and also as a deodorizer in smoke damage restoration, research has never shown a meaningful effect of gas-phase ozone on either airborne or surface microorganisms, relative to significant control of biological pollution in the indoor environment[1, 2].

Vapor-Phase

A vapor is the volatile, gas-phase form of a substance that exists in the liquid state at room temperature and pressure. As temperature and pressure change,

the substance can be "vaporized" and mix with air in various concentrations.

Presently, the most common vapor-phase biocide used today for microbial contamination control in the indoor environment is vaporized hydrogen peroxide (VHP). Hydrogen peroxide (H_2O_2) is an oxidizing agent that produces reactive hydroxyl radicals capable of inactivating a wide spectrum of potentially pathogenic bacteria and viruses[3]. Over 20 years ago it was shown to be a suitable replacement for the toxic formaldehyde and ethylene oxide gases formerly used to decontaminate laboratories and patient-care equipment, respectively. A 30-minute VHP exposure was shown effective at inactivation of a variety of exotic animal disease viruses, with no effects on exposed equipment[4]. A few years later, VHP was shown to be much more effective than manual terminal cleaning in surgical wards contaminated with Methicillin-Resistant *Staphylococcus aureus* (MRSA), as 66% of post-cleaning samples were positive for MRSA, compared to only 1% for post-VHP treatment[5].

A later study investigated the effects of VHP on resistant bacteriophage viruses suspended and dried in 10% and 50% horse blood to simulate the virus being present in blood or body fluids[6]. The VHP reduced virus concentration in the absence of blood by 6 $\log_{10}$ in 30 minutes at the lowest concentration of viruses (10^7 pfu), while 60 – 90 minutes was required for the inactivation of the virus at the highest concentration (10^9 pfu). However, the addition of blood to the viral suspensions "greatly reduced the effectiveness" of the VHP. The study demonstrated that the effectiveness of vapor-phase disinfection is a function not only of viral concentration but the degree of soiling. The authors noted that the results highlighted the importance of effective cleaning prior to disinfection to ensure adequate decontamination.

Presently, VHP is used primarily as a means of ensuring effective terminal decontamination of patient rooms in healthcare facilities, thus reducing or eliminating the risk of transmission to other areas. That is done utilizing any of a number of commercial VHP systems. Those systems typically use 30% – 35% H_2O_2 and the process may take anywhere from 1.5 to 8 hours[3].

The effects of soiling were readily noted in a study investigating area fumigation using VHP, as researchers used resistant bacterial spores on porous material in the presence of 50% whole blood[7]. Results showed that the efficacy of VHP was reduced in the presence of visible soil, but could be improved with longer exposure times. But they also emphasized that it was clear "that the cleaner the surface, the more reproducible a given decontamination method will be."

That has implications for those wishing to use VHP for the decontamination of HVAC ductwork. In a study examining the behavior of VHP for the decontamination of galvanized steel ducting, researchers used a computational fluid dynamics model to estimate surface VHP concentrations where biocontamination is likely to reside, and also where VHP decomposition was more likely to occur[8]. They concluded that the most efficacious strategy may be to decontaminate galvanized steel ducting separately from the rest of the building, as opposed to a single decontamination event in which the ventilation system is used to distribute VHP throughout the entire building. That is consistent with the current prudent practice of treating the decontamination of indoor areas separately from the HVAC systems supporting them. That allows for HVAC professionals to oversee the proper cleaning and decontamination of the air handling system, as well as verify cleaning effectiveness, according to industry standards.

Fogging (Mists)

Mists consist of very fine droplets dispersed in the air. They are generated by breaking up a liquid into a dispersed state, such as by atomizing. When the mist is dense enough to affect visibility, it is called a fog. ULV (ultra-low volume) fogging devices that are commonly used produce droplets in the 8 – 15 µm range.

Fogging has long been used in food processing to reduce microbial surface contamination[9, 12] and also in agriculture to improve air quality through reduction of airborne dust and microbes[10, 11]. Likewise, fogging has a history of use in varied infection-control scenarios employing a variety of disinfectants, including quaternary ammonium compounds[13], hypochlorous acid[14, 15], peracetic acid[16, 17, 18], guanidine[19], and hydrogen peroxide/silver nitrate[20], among others.

A recent study looked at the effectiveness of two fogged disinfectants, hydrogen peroxide (7.5%) and a chlorine dioxide (0.2%) surfactant-based product, against two strains of human norovirus and a norovirus surrogate, feline calicivirus[21]. Human norovirus is the leading cause of foodborne illness in the U.S. In the study, viruses were inoculated onto steel coupons, dried, and exposed to fogging from a machine capable of generating fogs at 30 ml/minute until the desired concentrations were achieved. The hydrogen peroxide

(HP) exposure was 5 minutes and the chlorine dioxide (ClO_2) exposure was 10 minutes. Results showed that while HP reductions of only 2.5 and 2.3 $\log_{10}$ against the human noroviruses were achieved, its 4.3 $\log_{10}$ reduction against the surrogate calicivirus met EPA criteria of acceptability. The ClO_2 product only showed reductions of 1.7 $\log_{10}$, 0.6 $\log_{10}$, and 2.4 $\log_{10}$ respectively. However, the exposure times used in the study were extremely short relative to the longer times needed to effectively decontaminate rooms or areas of large buildings. That was shown during a 22-month period in a 500-bed hospital where 1,565 rooms that had housed patients infected with multi-drug resistant pathogens over that time were decontaminated using VHP[22]. The decontamination required a mean time of two hours and 20 minutes, compared with 32 minutes for conventional cleaning. Despite the greater time required for decontamination, VHP use was deemed feasible based on its efficacy for infection control and its use in a hospital with a very high occupancy rate. Those studies emphasize the fact that successful disinfectant fogging or vapor-phase treatment is dependent upon multiple factors, including the targeted organism(s), chemical formulation and concentration, fogging rate and airborne density, exposure or dwell time, and temperature and relative humidity.

Any discussion of disinfectant fogging, whether in food, agriculture, healthcare, or office buildings, raises the question of its effectiveness compared to manual cleaning and disinfection. Fogging aims to kill microbial contamination where it lies. Concern focuses on whether all key surfaces receive an equal distribution of disinfectant as well as the question of interference from soils and the presence of biofilms. Manual cleaning and disinfection processes, however, focus on the physical removal of the bulk of microbial contamination from key surfaces prior to the application of a chemical disinfectant meant to inactivate any remaining residual.

The issue was addressed by the U.S. EPA, the agency that registers antimicrobial pesticides. In April 2013, the Director of the EPA's Office of Pesticide Programs sent a letter to all EPA registrants of antimicrobial pesticide products, which made claims to provide control of public health microorganisms when applied by fogging and/or misting[23]. The issue was efficacy. The letter explained why the EPA believed that fogging/misting methods of application may not be adequate, and afforded the following rationale:

> "Application by fogging/misting results in much smaller particle sizes, different surface coverage characteristics, and potentially reduced efficacy when compared to sanitization or disinfection product applications by spraying, sponging, wiping, or mopping.
>
> The absence of pre-cleaning in the presence of soil contamination, potential reaction with or absorption of the active ingredient for different surfaces, and humidity/temperature fluctuations can also impact distribution and efficacy of the product.
>
> A surface treated by fogging/misting does not receive the same amount of active ingredient per unit area as the standard methods of application and, as a result, the level of efficacy actually achieved may not be the same level claimed on the label."

In reality, disinfectant fogging and manual cleaning and disinfection are both subject to human error in a number of ways, and neither approach can be expected to eliminate all microbes on all targeted surfaces. In general, fogging tends to be quicker and more cost-effective, yet potentially less effective at inactivating the bulk of the microbial bioburden on non-porous surfaces. Manual cleaning tends to be more effective at decontamination, yet slower to achieve, and typically is more costly. Depending on the need for decontamination, it is also conceivable to use both approaches, that is, manual cleaning followed by disinfectant fogging. But first, the last approach to aerosol disinfection, spraying, needs to be addressed.

Spraying

Spraying involves chemicals typically dissolved in water and dispersed under pressure as tiny droplets greater than 10 µm. The size of the droplets and the extent of their distribution on surfaces depend largely on the pressure exerted to dispense them, along with the nozzle size. Thus, a pressurized can of aerosol spray disinfectant will deliver a very fine spray across surfaces, as opposed to the larger droplet sizes delivered by pump or hand trigger spray containers. And with all of those methods, the extent of distribution of the product across the targeted surfaces is also a factor of distance from the nozzle to those surfaces.

A key question that arises in the use of sprays — as well as the use of gas-phase, vapor-phase, and fogging methods — is will the product deposition be contiguous across all targeted surfaces to maximize microbial

contact and also penetrate all cracks and crevices that might harbor contamination? Such thorough coverage with any of those methods can't ever be assured. But one methodology is designed to address those issues: electrostatic spraying (ES).

ES technology has been used in the painting, agriculture[24, 25], and automotive industries for many years, although it has not been extensively researched in regard to the control of human pathogens. Using EPA List N-registered disinfectants with an approved efficacy claim for spray application, fine droplets (equal to or greater than 40 µm) from electrostatic sprayers receive a positive charge just before they leave the nozzle. As charged droplets, they are then attracted to negative or neutral-charged surfaces, and can literally wrap around surfaces and materials, providing what may be considered an even and consistent distribution. While ES maximizes disinfectant distribution across both horizontal and vertical surfaces, the question of efficacy remains regarding its effectiveness in the absence of a pre-cleaning step. That is emphasized by the EPA in its current efficacy requirements for List N disinfectant manufacturers seeking ES application[26]. Requirements include ensuring the targeted surfaces remain wet for the duration of the proposed dwell claim, the specifically required distance from the equipment to the surfaces is specified and followed, and data must demonstrate the droplet size of the aerosol. In addition, the use of personal protective equipment (PPE) must be described for the ES process. Efficacy has also been emphasized in recently presented health care environment studies that have recommended the use of ES application, but only after routine cleaning and disinfection.[27, 28]

DISCUSSION

Cleaning

Although many manufacturers and contractors tout their disinfectant products and services as stand-alone approaches to eliminating indoor microbial contamination, science continues to support the fact that the basic and fundamental approach to reducing the risk of infectious agent transmission is the process of cleaning. *Clean* is a condition free of unwanted matter, and *cleaning* is the process of achieving the clean condition so human activities can take place in a healthy environment[29]. For cleaning to be effective, unwanted matter must become separated from the environment[30]. Thus, the removal of soil (organic dusts, cells, oils, and proteinaceous substances) and its associated microbes from key high-contact surfaces and materials remains the primary approach to achieving a healthy environment[31]. If the process is carried out at an established frequency, then the clean condition becomes easier to achieve on a routine basis. And let's not forget that EPA-registered disinfectants (with the exception of one-step cleaner-disinfectants) are required to be used only on clean surfaces, in order to maximize their effectiveness in meeting label claims.

Disinfection

Any type of cleaning of a non-porous surface may leave a microbial contamination residual behind, even if a one-step detergent cleaner is used. Thus, if circumstances warrant, such as with a localized bacterial outbreak in an indoor facility, or a newly emerged virus in a global pandemic, the subsequent application of an effective disinfectant following the cleaning process becomes mandatory. The final disinfectant application may be done manually, or by a fogging or spraying process, either of which can be considered time-saving and cost-effective, whether done in-house or by a contractor. Currently, with the COVID-19 situation, reliable contract cleaners and restoration contractors have the equipment, trained personnel, and expertise to effectively respond to a potentially infectious agent situation, such as one where occupants of an office building have tested positive for the coronavirus. Disinfection protocols may differ among those professionals. Some may prefer an initial fogging to begin the disinfection process, then perform the manual cleaning. Others may initially perform the manual cleaning and then follow with disinfectant fogging or electrostatic spraying to address any remaining microbial contamination.

Porous/Semi-porous surfaces/materials. Additionally, it must be understood that EPA-registered disinfectants are primarily designated for use on hard, non-porous surfaces, which makes the decontamination of porous and semi-porous surfaces/materials, such as carpet, upholstered furniture, and unpainted wood, problematic. In that situation, HEPA-vacuuming becomes the primary method of cleaning by removing microbial contaminants, especially those associated with resident dust and particulates. Subsequent aerosol disinfection of those surfaces/materials may then result in some measure of microbial inactivation, especially if the product used has an approved soft surface claim. Although research studies in that area are scant, a

controlled laboratory study was conducted in the aftermath of the anthrax attacks in the U.S. in the fall of 2001. The study addressed the effectiveness of VHP to inactivate *Bacillus anthracis* (anthrax) spores on a variety of materials, including industrial carpet, bare pine wood, and painted wallboard paper[32]. Using 30% hydrogen peroxide vaporized to 1,000 ppm and held for 20 minutes, high spore challenges were reduced by 3.0 $\log_{10}$ on the carpet, 3.7 $\log_{10}$ on the bare wood, and 6.9 $\log_{10}$ on the painted wallboard paper. Although that is useful information, the effects of aerosol disinfection on porous and semi-porous surfaces and materials under actual field conditions in the less-controlled indoor environment are needed.

Bound Antimicrobials. There is a category of long-lasting antimicrobial compounds, often referred to as bioactive coatings, that bond covalently to inert surfaces to prevent a build-up of microbial contamination, primarily bacterial and fungal. They are often applied to precleaned surfaces using an aerosol method, such as electrostatic spraying. Although those coatings are effective at suppressing microbial growth through a biostatic effect (preventing microbial growth), they require direct and unhindered contact between the microbes and the treated surface. Thus, a layer of dust, or the deposition of microbes in a protective matrix, such as respiratory secretions, will eliminate the action of the compound. So, to maximize the effectiveness of the coating, frequent cleaning of the treated surfaces is required.

SUMMARY

It is essential that cleaning and remediation management professionals take a science-based approach to the mitigation of human infectious disease transmission. It all comes down to selecting the right disinfection application process for the targeted microbe in the target environment, in order to maximize effectiveness and minimize undesired effects. That requires an investigation of the critical factors that must be addressed, as the use of aerosol surface disinfection is considered part of a decontamination protocol. Such factors include the following:

- *Category of infectious agent.* (Viral, bacterial, fungal) and its key pathology (respiratory, intestinal, hemorrhagic), potential for surface contamination and contact transmission, and susceptibility to classes of disinfectants.
- *Presence and degree of surface soiling.* Its potential for disinfectant neutralization, and an approach to its effective removal via cleaning prior to aerosol application.
- *Disinfectant efficacy.* In terms of chemical formulation and concentration, whether surfaces are nonporous or porous, and disinfectant compatibility with the surface materials. Utilize an EPA List N product with approval for aerosol application and strive for targeted effectiveness along with economy — there's no reason to hunt down a mouse with an elephant gun! That will also reduce potential unintended collateral effects on non-target surfaces and materials, as well as persons who will reoccupy the environment.
- *Aerosol generation.* Distribution across targeted surfaces, dwell time, aerosol size, generation rate, and airborne density, along with temperature and relative humidity, should all be considered in order to maximize the effectiveness of the process.

CONCLUSION

This review of the science of aerosol surface disinfection has shown the effectiveness or ineffectiveness of various types of biocidal aerosols, along with associated limitations, especially in the absence of the physical process of cleaning. However, the value of aerosol surface disinfection as an adjunct to cleaning remains undisputed, especially in situations of disease outbreak or pandemic. In those situations, rapid response and economy of approach may prove critical in eliminating or significantly slowing the spread of human infectious disease agents. CSQ

References

1. Cole, E.C. (2003). "Gas-Phase Ozone: Assessment of Biocidal Properties for the Indoor Environment – A Critical Review." *Applied Biosafety* 8(3):112-117.
2. Foarde, K.K., Vanosdell, D.W., Steiber, R.S. (2011). "Investigation of Gas-Phase Ozone as a Potential Biocide." *Applied Occupational and Environmental Hygiene* 12(8):535-542.
3. Weber, D.J., Rutala, W.A., Anderson, D.J., Chen, L.F., Sickbert-Bennett, E.E., Boyce, J.M. (2016). "Effectiveness of ultraviolet devices and hydrogen peroxide systems for terminal room decontamination: Focus on clinical trials." *American journal of Infection Control* 40:e77-e84.
4. Heckert, R.A., Best, M., Jordan, L.T., Dulac, G.C., Eddington, D.L., Sterritt, W.G. (1997). "Efficacy of Vaporized Hydrogen Peroxide Against Exotic Animal Viruses." *Applied and Environmental Microbiology* 63:3916-3918.
5. French, G.L., Otter, J.A., Shannon, K.P., Adams, N.M.T., Watling, D., Parks, M.J. (2004). "Tackling Contamination of the Hospital Environment by Methicillin-Resistant Staphylococcus aureus (MRSA): a Comparison Between conventional Terminal Cleaning

and Hydrogen Peroxide Vapour Decontamination." *Journal of Hospital Infection* 57(1):31-37.

6. Pottage, T., Richardson, C., Parks, S., Walker, J.T., Bennett, A.M. (2010). "Evaluation of Hydrogen Peroxide Gaseous Disinfection Systems to Decontaminate Viruses." *Journal of Hospital Infection* 74(1):55-61.
7. Meszaros, J.E., Antloga, K., Justi, C., Plesnicher, C., McDonnell, G. (2005). "Area fumigation with hydrogen peroxide." *Applied Biosafety* 10(2):91-100.
8. Verce, M.F., Jayaraman, B., Ford, T.D., Fisher, S.E., Gadgil, A.J., Carlsen, T.M. (2008). "Minimizing decomposition of vaporized hydrogen peroxide for biological decontamination of galvanized steel ducting." *Environmental Science & Technology* 42(15):5765-5771.
9. Burfoot, D., Hall, K., Brown, K., Xu, Y. (1999). "Fogging for the disinfection of food processing factories and equipment." *Trends in Food Science* 10(6-7):205-210.
10. Ellen, H.H., Bottcher, R.W., von Wachenfelt, E., Takai, H. (2000). "Dust Levels and Control Methods in Poultry Houses." *Journal of Agricultural Safety and Health* 6:275-282.
11. Costa, A., Colosio, C., Gusmara, C., Sala, V., Guarino, M. (2014). "Effects of Disinfectant Fogging Procedure on Dust, Ammonia Concentration, Aerobic Bacteria and Fungal Spores in a Farrowing-Weaning Room." *Annals of Agricultural and Environmental Medicine* 21(3):494-499.
12. Dunowska, M., Morley, P.S., Hyatt, D.R. (2005). "The Effect of Virkon®S Fogging on Survival of *Salmonella enterica and Staphylococcus aureus* on Surfaces in a Veterinary Teaching Hospital." *Veterinary Microbiology* 105(3-4):281-289.
13. Friedman, H., Volin, E., Laumann, D. (1968). "Terminal Disinfection in Hospitals with Quaternary Ammonium Compounds by use of a Spray-Fog Technique." *Applied Microbiology* 16:223-227.
14. Clark, J., Barrett, S.P., Rogers, M., Stapleton, R. (2006). "Efficacy of Super-Oxidized Water Fogging in Environmental Decontamination." *Journal of Hospital Infection* 64(4):386-390.
15. Park, W.P., Boston, D.M., Kase, J.A., Sampson, M.N., Sobsey, M.D. (2007). "Evaluation of Liquid- and Fog-Based Application of Sterilox Hypochlorous Acid Solution for Surface Inactivation of Human Norovirus." *Applied and Environmental Microbiology* 73(14):4463-4468.
16. Wood, J.P., Calfee, M.W., Clayton, M., Griffin-Gatchalian, N., Touati, A., Egler, K. (2013). "Evaluation of Peracetic Acid Fog for the Inactivation of Bacillus anthracis spore Surrogates in a Large Decontamination Chamber." *Journal of Hazardous Materials* 250:61-67.
17. Gregersen, J-P., Roth, B. (2012). "Inactivation of Stable Viruses in Cell Culture Facilities by Percetic Acid Fogging." *Biologicals* 40(4);282-287.
18. Mana, T.S.C., Sitzlar, B., Cadnum, J.L., Jencson, A.L., Kognati, S., Donskey, C.J. (2017). "Evaluation of an Automated Room Decontamination Device Using Aerosolized Peracetic Acid." *American Journal of Infection Control* 45(3):327-329.
19. Nevzat, U., Yanik, K., Karadag, A., Odabasi, H., Saban, E., Murat, G. (2014). "Evaluation of the Efficacy of Akacid Plus® Fogging in Eradicating Causative Microorganism in Nosocomial Infections." *International Journal of Clinical and Experimental Medicine* 7(12)"5867-5871.
20. Taneja, N., Biswal, M., Kumar, A., Edwin, A., Sunita, T., Emmanuel, R., Gupta, A.K., Sharm, M. (2011). "Hydrogen Peroxide Vapour for Decontaminating Air-Conditioning Ducts and Rooms of an Emergency Complex in Northern India: Time to Move On." *Journal of Hospital Infection* 78:200-203.
21. Montazeri, N., Manuel, C., Moorman, E., Khatiwada, J.R., Williams, L.L., Jaykus, L.A. (2017). "Virucidal Activity of Fogged Chlorine Dioxide- and Hydrogen Peroxide-Based Disinfectants Against Human Norovirus and its Surrogate, Feline Calicivirus, on Hard-to-Reach Surfaces." *Frontiers in Microbiology* 8(1031):1-9.
22. Otter, J.A., Puchowicz, M., Ryan, D., Salkeld, J.A.G. (2009). "Feasibility of Routinely Using Hydrogen Peroxide Vapor to Decontaminate Rooms in a Busy United States Hospital." *Infection Control and Hospital Epidemiology* 30(6):574-577.
23. EPA (2013). Letter on antimicrobial pesticide products which make claims to provide control of public health microorganisms when applied by fogging and/or misting methods. EPA Office of Pesticide Programs, Washington, DC. www.epa.gov/sites/production/files/2015-09/documents/fogger-mister-final-signed-letter.pdf
24. Ganesh, V., Hettiarachchy, N.S., Griffis, C.L., Martin, E.M., Ricke, S.C. (2012). "Electrostatic Spraying of Food-Grade Organic and Inorganic Acids and Plant Extracts to Decontaminate Escherichia coli O157:H7 on Spinach and Iceberg Lettuce." *Journal of Food Science* 77(7):M391-396.
25. Russell, S.M. (2003). "The Effect of Electrolyzed Oxidative Water Applied Using Electrostatic Spraying on Pathogenic and Indicator Bacteria on the Surface of Eggs." *Poultry Science* 82(1):158-162.
26. EPA (2020). Expedited Review for Adding Electrostatic Spray Application Directions for Use to Antimicrobial Product Registrations. EPA Office of Pesticide Programs, Washington, DC. www.epa.gov/pesticide-registration/expedited-review-adding-electrostatic-spray-application-directions-use
27. Sutton, J. (2015). "Decontaminating the Operating Room Environment Utilizing Persistent Technology." Presented at the APIC Annual Educational Conference & International Meeting, Nashville, TN, June 27-29, 2015.
28. Stroman, D.W., Whitely, B.S., Robertson, S.M., Stoltz, M.L., Rohde, R.E. (2018). "Quick and Effective Disinfection of Hospital Rooms after Discharge of Patients." Presented at the APIC Meeting, June 2018.
29. Berry M.A. (2018). "Cleaning Professionalism and Competent Management." *Cleaning Science Quarterly* 1(1):8–12.
30. Berry M.A. (2019). "Matter Separation and Biological Destruction." *Cleaning Science Quarterly* 1(2):24–29.
31. Spivak S.M. (2019). "Matters, Means and Methods of Surface Hygiene and Disinfection." *Cleaning Science Quarterly* 1(2):8–16.
32. Rogers, J.V., Sabourin, C.L.K., Choi, Y.W., Richter, W.R., Rudnicki, D.C., Riggs, K.B. (2005). "Decontamination and assessment of Bacillus anthracis, Bacillus subtilis, and Geobacillus stearothermophilus spores on indoor surfaces using a hydrogen peroxide gas generator." *Journal of Applied Microbiology* 99:739-748.