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The Risks and Benefits of Chemical Fumigation in the Health Care Environment

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Fumigation of hospital rooms with high concentrations of toxic chemicals has been proposed to reduce microbial agents on hospital surfaces and to control infections. Chemical fumigation has been used effectively in other areas, such as building decontamination after bioterrorism events, in agriculture, and in residential structures. However, even in these situations, there have been incidents where fumigants have escaped, causing illness and death to exposed workers and the public. Before expanding the use of a potentially hazardous technology in areas where there are vulnerable individuals, it is important to fully weigh benefits and risks. This article reviews the effectiveness of fumigation as a method of inactivating microbes on environmental surfaces and in reducing patient infection rates against the potential risks. Peer-reviewed literature, consensus documents, and government reports were selected for review. Studies have demonstrated that fumigation can be effective in inactivating microbes on environmental surfaces. However, the current consensus of the infection control community is that the most important source of patient infection is direct contact with health care workers or when patients auto-infect themselves. Only one peer-reviewed, before-after study, at one hospital reported a significant reduction in infection rates following chemical fumigation. The limitations of this study were such that the authors acknowledged that they could not attribute the rate reduction to the fumigation intervention. A serious concern in the peer-reviewed literature is a lack of evidence of environmental monitoring of either occupational or non-occupational exposures during fumigation. Currently, there are neither consensus documents on safe fumigation exposure levels for vulnerable bedridden patients nor sampling methods with an acceptable limit of detection for this population. Until additional peer-reviewed studies are published, demonstrating significant reductions in patient infection rates following chemical fumigation and consensus guidance on the safe exposure levels and monitoring methods, chemical fumigation in health care should be conducted only in the most stringently controlled research settings.

Keywords chlorine dioxide, decontamination, fumigation, health care, hydrogen peroxide

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INTRODUCTION

There has been recent interest in the use of chemical fumigation in health care facilities because of concerns about the role of the environment as a cause of health care-associated infections (HAIs) and a perception that current surface cleaning and disinfection methods are ineffective. HAIs are a significant contributor to morbidity, mortality, and cost in U.S. hospitals.[1,2] Klevens et al.[1] estimated there were 1.7 million HAIs in 2002 and 98,987 deaths. Scott[2] estimated the cost of HAIs to range from $28.4 to $33.8 billion after adjusting to 2007 dollars. Cost has been of particular concern for the health care industry because in 2008, the Centers for Medicare and Medicaid Services began denying payments for HAIs.[3] Furthermore, methicillin-resistant *Staphylococcus aureus* (MRSA) and other gram-positive bacteria have become an increasingly common problem in health care environments.[4–7] A more recent concern is the upswing in incidence of infections caused by *Clostridium difficile*.[8] This organism is now considered to be the most important cause of diarrheal HAI.[9] *Acinetobacter baumannii* is yet another microorganism involved in HAIs that has been linked to environmental contamination.[10,11]

Of course, for each infectious agent there are a variety of potential pathways of exposure (how the agent survives and moves in the environment) and different routes of exposure (how the agent enters the host). It is commonly assumed that the most important risk factor for HAI is contact spread. A health care worker may directly or indirectly spread infection to patients, or patients may self-inoculate themselves with colonizing organisms.[12–14]

Other microbial sources in decreasing order of importance are high risk/high touch surfaces, such as bed rails, faucets, toilets, door knobs, and so on. Floors and other low touch surfaces present the lowest risk of infection. According to the Centers for Disease Control and Prevention (CDC), there have only been a few reports documenting "cause and effect" between environmental contamination and infection.[12] An infection control task force formed by the Society for Healthcare

Epidemiology of America and the Infectious Diseases Society of America Standards and Practice Guidelines Committee assessed the importance of cleaning the environment to control HAIs.[15] They concluded that there was moderate evidence for the role of the environment in the control of *C. difficile* and weak evidence in the control of MRSA.

Other authors suggest a more important role for the environment in HAI.[6,10,14,16–27] There are a variety of factors that contribute to the contamination of health care environments. Patients infected with MRSA and other communicable diseases can spread bacteria on furniture, curtains, and many other objects, and some pathogens such as *A. baumannii*, *C. difficile*, and MRSA can survive on dry surfaces for prolonged periods.[17,20,22,28–31] Since *C. difficile* is a spore former, it is highly resistant in the environment and would be expected to be viable for months.[32] Even gowns and gloves worn to protect the health care worker have been found to be contaminated and to serve as potential vehicles of transmission.[33]

There is also consistent evidence that the type of species or strain of microorganism affects survival in the environment. *A. baumannii* strains survive desiccation better than other *Acinetobacter* sp.[28,34] In the case of *C. difficile*, there is evidence of a "frameshift" mutation in this organism that results in greater toxin production, pathogenicity, and infectivity.[8,35] Akerlund et al.[35] refer to this mutated organism as "hypervirulent."

Also, there may be certain inherent weaknesses in standard infection control practices in U.S. hospitals. For example, the use of alcohol-based hand scrubs has been the standard of practice for hand hygiene for many years.[7,36] However, alcohol is ineffective in destroying *C. difficile*, and in the case of *A. baumannii*, Edwards et al.[37] found that alcohol enhances the growth and pathogenicity of the organism. Periodic outbreaks of *C. difficile* and *A. baumannii* suggest that there should be a return to basic handwashing as the primary approach to hand hygiene.[19] The other important reason for the increased incidence of these pathogens has been the inappropriate use of antibiotics in health care facilities.[11,19,38]

There are also concerns about health care building construction or mechanical systems in their abilities to protect patients from potentially dangerous microorganisms. Some of the issues included building water infiltration that contributes to mold growth, non-airtight patient rooms, and isolation rooms with substandard air exchange rates or inadequate pressurization.[29–43] In one study, the authors found 9% of negative pressure isolation rooms were actually under positive pressure relative to the corridor.[43] The problem with insufficient negative pressurization was most pronounced in isolation rooms with suspended ceilings.

In the 1960s, chemical fumigation was used in addition to standard environmental surface disinfection in hospital isolation rooms and other critical areas.[44] The belief was that surface disinfection was inadequate and that a chemical fog would destroy microorganisms in hard to reach locations. Over time, this approach lost favor due to questions of effectiveness. The CDC, in its *Guidelines for Environmental Infection Control in Health-Care Facilities*, recommends against the practice of using chemical fogging for general infection control in routine patient care areas.[12] Following the 2001 anthrax bioterrorism attack, there was renewed interest in using fumigants for microbial decontamination. To ensure that the anthrax was completely eradicated from the buildings, a fumigation technique was used to destroy bacteria and their spores.[45] Because of the success in destroying anthrax using fumigation, health care officials are considering adopting this technique in hospitals and similar institutional environments as an adjunct to routine cleaning methods.

Researchers have explored using chlorine dioxide, hydrogen peroxide vapor (HPV), super-oxidized water, or ozone for terminal disinfection of hospitals contaminated with mold and bacteria.[30,46–49] In the past, paraformaldehyde has been used to decontaminate biological safety cabinets and entire buildings.[50]

Fumigants such as chlorine dioxide and HPV are two agents most frequently examined to decontaminate hospitals, animal research facilities, or similar environments. Fumigants are being considered as an adjunct to conventional environmental disinfection due to their composition as a gas or vapor, allowing them to easily penetrate hard to reach areas.[30] Although many of these fumigants will kill microorganisms, there are still concerns for the safety of patients, workers, or research animals who may be inadvertently exposed to these toxicants. Health effects resulting from exposure to certain fumigants may include neurological signs and respiratory damage.[51] Other symptoms from exposure may include severe nausea, vomiting, dizziness, and even death. Limiting exposure to these toxic chemicals must be considered when using fumigants in health care facilities or other institutions, such as animal care environments.

It is important to note that although this study is looking at the efficacy and safety of fumigation in institutional environments, there are other areas that frequently use this practice. By observing consequences of fumigation in other environments, the findings may be analyzed for relevance in health care or research institutions. One of the most common uses of fumigation is for the control of pests and mold in homes and other buildings. The standard approach is to evacuate people and pets and then fill the space with a gaseous pesticide to kill the target organism. A similar method is also used in controlling pests in soil, grain, and produce.

This article reviews the safety, efficacy, and effectiveness, and cost-efficiency of fumigant use in health care and other related environments. The primary objective was to identify when the benefits associated with fumigation outweigh the risks of human injury or other adverse effects. It is hypothesized that fumigation is an effective method of killing microorganisms; however, it is uncertain whether the benefits in terms of reducing overall hospital patient infection rates outweigh the risks and costs associated with this infection control technique.

To assess risk, it is important to consider the severity of a potential hazard and the probability of exposure to that hazard. A primary concern in assessing severity is a chemical's toxicity. However, toxicants may have different effects depending on a

person's overall health. A patient with pre-existing illness may be seriously harmed by an exposure that will have no obvious effects on a healthy worker. The other important consideration is the probability of exposure. Occupational exposure limits are most typically based on an 8-hr exposure. Bedridden patients may be subject to 24-hr exposures. Therefore, a consideration of risk potential must factor in differences in toxic effect and exposure opportunities.

METHODS

Research methods included the selection, collection, and review of peer-reviewed, consensus, and government publications. Authors used a variety of standard Internet tools, including Medline, Science Direct, and Google Scholar. Reference lists were then used to expand the library of relevant papers. Papers selected for consideration covered the topics of health care infection control, specific types of pathogenic microorganisms, fumigation, and environmental health and safety. Many of the papers described the use of fumigants as an adjunct to conventional environmental disinfection.[23,26,30,42,46–49,52–55] Fumigation efficacy or effectiveness tests were performed under a variety of conditions. Some were conducted in laboratory facilities with controlled environmental conditions, and in other cases, fumigation was administered in the field under ambient conditions. The two studies of human exposures involved the use of fumigation in agriculture or residential settings.[56,57] While these are not institutional settings, they were included because they demonstrate the potential for accidents.

Fumigation is being marketed as an effective means of controlling undesirable microorganisms. The challenge faced by fumigation researchers is to develop an approach that is successful in killing harmful microorganisms, while preventing health effects and environmental harm from exposure. Each study was examined for information on safety and efficacy or effectiveness. Unfortunately, most studies that were reviewed addressed only the degree of microbial disinfection, not safety. Also, with the exception of reports by the Environmental Protection Agency (EPA), environmental damage from exposure to materials or equipment was mentioned only occasionally in the studies investigated.[30,50,58]

In the assessment of the potential severity of health effects from fumigation exposure, information on the type of chemical and its application concentration were compared with levels listed in threshold limit values (TLVs®) and the Occupational Safety and Health Administration's (OSHA's) permissible exposure limits (PELs).[51] Estimated exposure intervals were compared with TLVs or PELs when determining a chemical's severity potential. Exposure routes other than inhalation, such as dermal absorption, were also considered. Once information was gathered and interpreted, results were compiled and analyzed for significance. It was also important to distinguish between possible worker exposure and exposure to patients or visitors. The concern is that patients may be more susceptible to adverse health effects and bedridden patients may receive longer exposure. Therefore, using occupational exposure limits as a measure of safety may underestimate the risk in this sensitive group.

Primary sources included recent publications that reported the latest research and review consensus data on the most likely reservoirs and sources of infectious disease transmission in health care. Articles describing the most effective means to reduce or eliminate disease transmission were also collected and reviewed. The rationale for this search was fundamental to the question of whether fumigation is the most effective means to control infection rates in health care or whether other disinfection techniques are more effective. The terms used in the review of literature are listed in Table I.

RESULTS

Fumigation Benefits: Efficacy and Effectiveness

The efficacy and effectiveness of different types of fumigation approaches were examined. An early method of fumigation was to use a high-velocity fogger to spray quaternary ammonium compounds in hospital rooms.[44] The unit was operated with the room air-conditioners off and the doors and windows closed. The apparatus was placed in the middle of the hospital room and the fogging cycle was 10–15 min. Researchers believed that this approach was effective because they observed a reduction from the average of 351–470 culturable bacteria per cubic meter of air prior for fogging to less than 106 microorganisms per cubic meter after fogging. Similar reductions were seen on surface samples.

The EPA reviewed the results of four models of fumigation equipment for their ability to destroy three types of spore forming bacteria.[58] The bacteria were *Bacillus anthracis* Ames strain (*B. anthracis*), *Bacillus subtilis* (*B. subtilis*), and *Geobacillus stearothermophilus* (*G. stearothermophilus*). Test strips of seven types of porous (e.g., carpet) and nonporous (e.g., galvanized metal) materials were treated with a concentration of 10^8 viable biological spores. Two approaches used chlorine dioxide as a fumigant, one used formaldehyde, and one used HPV.

The Sabre Technical Services (Slingerlands, N.Y.) system achieved a concentration of 3000 ppm of chlorine dioxide in a 3-hr treatment. The CDG Research Corporation (Bethlehem, Pa.) system was designed to achieve a concentration of 2000 ppm of chlorine dioxide over a 6-hr period. The CERTEK, Inc. (Raleigh, N.C.) formaldehyde generator achieved an average concentration of 1100 ppm over an 11-hr period, and the Bioquell Inc. (Horsham, Pa.) HPV generator achieved a 1000 ppm concentration in a 1-hr hour cycle.

The EPA-published tests provided for "worst-case" scenarios for fumigation treatment because it is more difficult to destroy surface contamination than spores dispersed in the air.[47] The EPA tests of sporicidal efficacy found significant differences depending on the type of surface, the type of microbial spore, and the type of fumigant. As expected, all fumigants performed better on nonporous materials, and industrial grade carpet proved most difficult to decontaminate. In general,

TABLE I. Terms Used in Disinfection and Fumigation

Cleaning	The removal of visible soil and organic contamination from a surface or device using either physical action or chemical agents.[12]
Disinfection	The process of microbial inactivation that eliminates virtually all vegetative pathogenic microorganisms but not necessarily their spores.[12] (Disinfection is often subcategorized into low, intermediate, and high levels. High level disinfectants are expected to be sporicidal.)
Efficacy	Did the agent work under controlled conditions such as in the laboratory?
Effectiveness	Did the agent work as intended in field conditions?
Efficiency	If the agent was determined to be effective, does the benefit exceed the cost?
Enhanced environmental cleaning	This term is being used to describe additional control measures used in the presence of problem pathogens, such as *C. difficile*.[7] These additional measures include such steps as additional training and monitoring of housekeepers and the use of germicides with greater potency such as 10% bleach and water solution.[63]
Safety	Did the product harm humans, laboratory animals, environmental surfaces, or equipment.
Sterility	The use of physical or chemical means to destroy all microbial life, including large numbers of spores.[12]

chlorine dioxide and formaldehyde performed better than HPV in destroying spores. For example, the Sabre Technical Services chlorine dioxide generator achieved a greater than 7.0 log kill of spores in carpeting, whereas the Bioquell HPV generator had only a 0.81 log reduction. Table II shows a comparison of fumigation methods.

While HPV was found to be less effective in the inactivation of bacterial spores, French et al.[30] found it to be more effective than conventional cleaning in destroying MRSA in rooms previously occupied by patients carrying this organism. After treating these rooms for 40 min at a concentration of 500 ppm, they found that MRSA had been destroyed in 84 of 85 locations tested. They also reported the destruction of test samples containing 10^6 *G. stearothermophilus* spores that were applied to some stainless steel disks suspended in the room.

Krause et al.[53] had similar success with HPV in decontaminating animal research laboratory areas. They used the Steris VHP1000 system (Mentor, Ohio) for HPV fumigation of animal rooms. This unit was designed for direct connection to cages and rooms. Because of the design of the rooms, work could be continued in adjacent rooms or areas. The process included a 15-min conditioning phase where the hydrogen peroxide achieved a concentration of approximately 1500 ppm in the animal room and a 75-min decontamination phase at a concentration of approximately 10,000 ppm. The machine ran for a total cycle of 3 hr, and outside monitoring of concentration of HPV never exceeded 0.02 ppm. After fumigation, test strips of *G. stearothermophilus* spores placed inside the rooms were negative for growth. They also found that this fumigant did not appear to be corrosive or damaging to surface materials.

Boyce et al.[23] conducted a before-after intervention study of the effectiveness of HPV in the control of *C. difficile*. During the intervention period, rooms that had previously housed *C. difficile* patients were fumigated using the Bioquell system. Each room took approximately 3–4 hr to disinfect. The average incidence rates of *C. difficile* infection dropped from 2.28 per 1000 patient days during the pre-intervention phase to 1.28 ($p = 0.047$) during the intervention phase.

Andersen et al.[46] used the Sterinis system (Gloster Stante Europe, Toulouse, France) to generate a 30–60 ppm concentration of hydrogen peroxide as a "dry fume."[46] This process involved closing the room door but not sealing the room, and

TABLE II. Comparison of EPA Approved Disinfection Fumigation Methods/Chemicals

Vendor	Chemical	Concentration (ppm)	Time (hours)	PEL (ppm)	TLV (ppm)	STEL (ppm)	IDLH (ppm)
Sabre	Chlorine dioxide	3,000	3	0.1	0.1	0.3[A]	5.0
CDG	Chlorine dioxide	2,000	6	0.1	0.1	0.3	5.0
CERTEK	Formaldehyde	1,100	11	0.75[B]		[C]	20.0
BIOQUELL	Hydrogen peroxide	1,000	1	1.0	1.0		75.0

[A]Both ACGIH and OSHA include a STEL of 0.3 ppm for chlorine dioxide.
[B]The OSHA formaldehyde standard includes an action level of 0.5 ppm.
[C]The OSHA formaldehyde standard includes a 15 minute STEL of 2.0 ppm and ACGIH has formaldehyde ceiling level of 0.3 ppm.

the cycle time was reported to be 4–5 hr. They used spore strips containing 2.5×10^6 spores of *Bacillus atrophaeus* as the test agent, and the results were reported as pass-fail. There was a 100% spore inactivation in the 48 surgical suite tests and an 87% inactivation (127 of 148 spore strips) in the other rooms tested.

Barbut et al.[26] used the same system and compared it with a 0.5% liquid sodium hypochlorite solution for the eradication of *C. difficile* spores. The authors found the hydrogen peroxide was significantly ($p < 0.005$) more effective at inactivating spores than the bleach solution. They also performed a laboratory test using 2.0 cm^2 pieces of polyvinyl chloride plastic that were coated with approximately $10^{5.5}$ *C. difficile* spores. In this test, both hydrogen peroxide and a 0.5% liquid sodium hypochlorite solution achieved a 10^4 reduction in culturable spores. In a recent study, Otter and French[55] demonstrated 100% inactivation of *C. difficile* spores and vegetative organisms after a 90-min exposure to HPV. The authors did not report the airborne concentration of HPV used in this study. Burton et al.[47] explored the efficacy of chlorine dioxide in destroying bacteria and mold in a private home. Mold was present on the first, second and third floors of a residence. During the treatment process, concentrations were monitored outside and on each floor. The house was enclosed in a plastic tent, and the treatment process did not start until a minimum concentration inside the house reached 500 ppm. The highest concentration in the house was 902 ppm. A variety of microbial air sampling methods were used, including an Andersen N-6 single stage sample, spore traps, fungal PCR, and endotoxin samples. In addition, sticky tape was used to measure total surface fungi.

A laboratory evaluation was also conducted using a challenge liquid test sample of 10^6 fungal spores/mL. The liquid containing the spores was applied to surfaces and allowed to dry. The laboratory evaluation was conducted inside a plastic chamber, and the test was performed using three time periods (4, 8, and 12 hr) at 760 ppm. While the fumigant proved to be effective in destroying culturable microorganisms in the field tests (kill rates of vegetative organisms and spores ranging from 84.9% to 97.6%), researchers found an increase in endotoxins or (1–3)-β-D glucans levels. When they repeated their experiments in a laboratory setting, they obtained similar but slightly lower efficacies.

Clark et al.[49] used an entirely different approach. They used a Dyna-Fog model (Westfield, Ind.) to dispense superoxidized water fog to kill MRSA and *A. baumannii* organisms. The superoxide fog solution was marketed under the trade name of Sterilox. In this study, ceramic tiles were treated with 10^9 concentrations of the bacteria and allowed to dry. The Sterilox fumigant was released into a laboratory using a fogging machine containing a liquid volume of 3.8 L that created an airborne concentration of 180 ppm of free chlorine. The generator was operated for 10 min. An hour later, the samples were removed for testing. The MRSA strains showed approximately a 10^4 log reduction and the *A. baumannii* strain showed a greater reduction (approximately 10^6 log). No information was provided on the effects of this product on surfaces or equipment.

Other approaches were not as successful. For example, Berrington and Pedler[48] found that ozone killed microorganisms only in the immediate vicinity of the generator. At greater distances, ozone was deemed to be ineffective in its ability to kill MRSA.

Fumigation Risks: Health, Safety, and Costs

While efficacy and effectiveness are important, so is the safety of workers and other building occupants. As of this writing, there were no reports of injuries or illnesses to either fumigation operators or patients in health care settings. There was also little evidence presented in the peer-reviewed literature regarding routine monitoring of occupational and environmental exposures that result from fumigation activities in health care. The Krause study mentions that the HPV level never exceeded 0.02 ppm; however, the details of sample collection were not described.[53]

While there have been no incidents reported in health care, there have been serious incidents in non-institutional settings. Nine greenhouse workers were accidentally exposed to the fumigant methyl bromide in a greenhouse.[56] In this incident, one of the sections of the greenhouse was being fumigated at the same time workers were in an adjacent section. It was believed that the workers were safe from exposure because their section was separated with a glass partition wall. Unfortunately, the fumigant traveled up a sewage pipe into the occupied section of the greenhouse. It was noted that exposure lasted for up to 6 hr and reached a concentration that peaked at 200 ppm. This concentration of methyl bromide was 200 times the accepted exposure limit of 1 ppm.[51] All nine workers experienced nausea, repeated vomiting, and dizziness. Some had symptoms that included twitching of the limbs and generalized seizures, and two of the workers were placed in intensive care for several weeks.

Another study investigating the safety of fumigation involved methyl bromide exposure to a family of three.[57] The accident occurred when a neighboring house was being fumigated, and once again, the fumigant moved from the target structure through sewer lines to the occupied house. This incident resulted in the death of a newborn and severe illness to the parents. The family was exposed for an estimated 5–6 hr. The methyl bromide level inside the home of the victims was not measured, but the concentration at the source location was estimated to be 12,850 ppm. The infant experienced vomiting and severe diarrhea. The symptoms lasted 6 to 7 hr, and the infant was declared dead on arrival at the hospital. An autopsy revealed that the infant had received severe lung tissue damage. The cause of death was due to acute pneumonia due to aspiration from inhalation of methyl bromide. The two adults experienced dry cough, sore throat, nausea, vomiting, dizziness, and drowsiness. In both situations, the site of fumigation was unoccupied, but in each case, the fumigant breached containment, exposing the workers and the family.

As stated earlier, the effect of fumigants on environmental surfaces or equipment was not routinely evaluated in studies. In one study, formaldehyde did not appear to damage equipment, but there was some evidence of corrosion of brass electrical contacts in a laboratory autoclave.[59] Chlorine dioxide caused bleaching of surfaces, and HPV discolored dyes and had unfavorable interactions with nylon.[50,58] An EPA report also concluded that HPV may degrade porous materials.

DISCUSSION

Fumigants are used for pest and mold control in buildings and in post-harvest pest eradication in agriculture. Chemical fumigation is now being applied as a nosocomial infection control measure in the health care environment because of the difficulty in completely disinfecting rooms and equipment. Beds, railings, and other objects are subject to continual contamination from patients that use them. In the United Kingdom, HPV is being released into unoccupied hospital rooms in an attempt to better control MRSA, *Escherichia coli,* and other microbes.[30] The concern is that traditional surface disinfecting methods may not reach all patient contact surfaces and that fumigation will decrease the chance of infection spread.[49]

Many different types of chemicals have been used over the years to clean and disinfect critical environments. For example, formaldehyde will kill microorganisms, including their resistant spores, but as Krause[53] points out, it is slow, difficult to generate, and, more importantly, toxic and potentially carcinogenic to humans. It is also extremely irritating and both a dermal and respiratory sensitizer.[58] These undesirable properties have limited its use as a chemical fumigant.

Some other chemicals that have been considered were HPV, ozone, superoxidized water (Sterilox), and chlorine dioxide. Ozone was considered to be ineffective as a fumigant, and Sterilox was evaluated in only one study with modest success.[48,49] HPV and chlorine dioxide are the two products most commonly cited for use as a chemical fumigant. Both products have been shown in multiple studies to inactivate microbes, including spores in laboratory and field applications. A major advantage of HPV is that it breaks down into oxygen and water, leaving no toxic residues; however, it is listed as a confirmed animal carcinogen.[51,53] Chlorine dioxide achieved a higher kill rate on test samples of industrial carpeting than did HPV.[60] On the other hand, chlorine dioxide is more likely to bleach the color from exposed materials and is more acutely toxic than HPV.[51]

While these fumigants have demonstrated high kill rates, does this mean that they are an effective infection control technique? To be considered an effective technique, the methodology must be able to demonstrate a significant improvement in infection rates. As of this writing, there was only one peer-reviewed study that demonstrated a significant reduction in infection incidence following the application of HPV, and this study (sponsored by a vendor) had serious limitations.[23] It was a before-after study, and according to the authors, the reduction in *C. difficile* infection rates could not be attributed to a specific intervention. They noted that the infection rate was already below the hospital's action threshold of 1.1 infections per 1000 patient days the month before the intervention started. It was also observed that during the last 3 months of the HPV intervention, there was a steady increase in incidence. The last month's rate was above the hospital's action threshold. If fumigation was an effective infection control method, then one would expect consistently low incident rates throughout the 10-month intervention period.

One of the major difficulties in any infection control technique is that in occupied hospital rooms, environmental surfaces will be constantly recontaminated. The CDC does not recommend chemical fogging for general infection control in routine patient-care areas because of the issue of recontamination and the lack of evidence that chemical fogging will reduce nosocomial infection rates.[12]

Another important issue is that, while chemicals such as chlorine dioxide effectively kill viable microorganisms, they will not effect the toxicity associated with nonviable microorganisms and their endotoxins or mycotoxins.[47,61] This is an important limitation because the primary health effect from mold exposure is an allergic reaction, not an infection, and the effects of fumigation on the integrity of allergens is unknown.[62]

Fumigation is being considered because gases and vapors can permeate areas that are not easily reachable. This characteristic also means ventilation ducts, plumbing fixtures, doors, windows, and any other openings must be sealed with a material that will resist penetration. Blocking ventilation supply, return, and exhaust ducts, however, has the potential of seriously disrupting the air balance of the ventilation system in other rooms served by the same blowers. This could negatively affect air pressurization in other critical areas such as isolation rooms. Rice[40] and others[41,43] have demonstrated that there are problems in room leakage and pressurization in a significant number of health care facilities, and this room leakage could contribute to infection spread. In addition, these problems with non-airtight hospital rooms increase the potential for leakage of chemical fumigants into adjacent spaces.

The decision to use fumigation in occupied buildings must be carefully considered since a breach in containment could injure patients, visitors, or personnel and, in the case of chlorine dioxide and HPV, damage surfaces. To avoid operator errors, the safest approach would be to evacuate during fumigation. However, this would be costly, and relocating displaced patients should be carefully considered to ensure there is adequate bed capacity in other facilities.

In summary, chemical fumigation of a health care facility has merit under certain conditions, such as in response to a bioterrorism attack. If a building is heavily contaminated with dangerous pathogens, fumigation may allow the building to be safely reoccupied. In other situations where patients are shedding organisms, such as MRSA, this approach must be used with caution. It is unclear how fumigation can be effective when there is a likelihood of continuous recontamination, and

the consequences of an accidental breech could be devastating. While as of this writing, an accidental fumigant release has not been reported in health care, this does not mean that there is no potential for an incident. Also, it is possible that worker or patient exposures have occurred but were never reported.

There is also currently a lack of consensus and guidance on the safe application protocols for the use of fumigants in healthcare. Methods for the recognition and control of hazards must be developed, approved, and implemented to protect workers, patients, and the general public if fumigation is to be used. Non-occupational exposure limits for these agents currently do not exist, making it difficult to determine the safe concentration of chlorine dioxide or HPV for a sick patient on a ventilator. The current PEL for chlorine dioxide is 0.1 ppm, and OSHA's sampling method (ID-202) has a limit of detection for a 120-L sample of 0.004 ppm. If a 100-fold safety factor were applied to the PEL, the exposure limit of 0.001 ppm could not be detected using OSHA's validated sampling method. Neither OSHA nor the National Institute for Occupational Safety and Health has fully validated methods for measuring hydrogen peroxide. OSHA's partially validated method (VI-6) can detect as low as 0.043 ppm, and the other partially validated method (ID-126-SG) can detect only 0.1 ppm. Once again, with a PEL of 1.0, these methods would not be low enough to determine the safety of a non-occupational exposure. If, at some point in the future, fumigation is determined to be safe and effective, the cost efficiency should be determined. The assessment of cost must consider more than just the vendor fees. Fumigation techniques using hydrogen peroxide vapor typically reported a 2–4 hr per room cycle time. Other techniques had longer cycle times. A greater than 2-hr delay could affect room turnover rates and potentially create a significant burden on the short supply of beds in hospitals. While there are no valid methods of monitoring non-occupational exposures, rooms to be fumigated must be checked by a qualified person for potential leakage. The cost of environmental monitoring should be factored into the total price of a fumigation procedure.

A frequent problem cited in many studies was an inconsistent adherence to facility cleaning policies by housekeepers and other staff.[10,63,64] If ineffective housekeeping is the problem, then strategies that improve housekeeping effectiveness should be considered.[25,65,66] Dancer and colleagues[4] addressed the problem with MRSA contamination in a hospital in the U.K. by improving patient screening and isolation of patients infected with MRSA and by implementing an enhanced cleaning protocol. This enhanced protocol simply involved adding an additional housekeeper, more frequent cleaning, and careful monitoring of cleaning performance. The enhanced cleaning resulted in a 32.5% reduction in aerobic colony counts. There was also a reduction in new nosocomial MRSA cases. However, the authors noted that the study lacked sufficient power to determine if the reduction in infections was significant. According to the authors, the increased cost of an additional staff member and additional supplies was more than offset by the reduction in MRSA infections and the costs associated with patient care.

Goodman et al.[65] did a similar study in an intensive care unit targeting MRSA and vancomycin-resistant enterococci (VRE) contamination. Their approach was to study high-touch surfaces, train housekeepers to focus on these surfaces, and then monitor the effectiveness of cleaning using microbial cultures and a black light. Their enhanced cleaning procedures also resulted in significant reductions in culturable MRSA and VRE levels.

CONCLUSION

Fumigation in health care facilities and other related institutions should be limited to those instances where the benefits clearly exceed the risks of human exposure or environmental damage. Decontamination of an unoccupied building following a bioterrorism incident would meet this criterion. In situations where the building is occupied and the potential for recontamination is high, the benefits of fumigation do not appear to exceed the risks. Before potentially risky procedures such as fumigation are considered, simpler and safer approaches such as enhanced cleaning should be considered.

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