Applications of ultraviolet germicidal irradiation disinfection in health care facilities: Effective adjunct, but not stand-alone technology

Farhad Memarzadeh, PhD, PE,[a] Russell N. Olmsted, MPH, CIC,[b] and Judene M. Bartley, MS, MPH, CIC[c]
Bethesda, Maryland; Ann Arbor, Michigan; and Beverly Hills, Michigan

This review evaluates the applicability and relative contribution of ultraviolet germicidal irradiation (UVGI) to disinfection of air in health care facilities. A section addressing the use of UVGI for environmental surfaces is also included. The germicidal susceptibility of biologic agents is addressed, but with emphasis on application in health care facilities. The balance of scientific evidence indicates that UVGI should be considered as a disinfection application in a health care setting only in conjunction with other well-established elements, such as appropriate heating, ventilating, and air-conditioning (HVAC) systems; dynamic removal of contaminants from the air; and preventive maintenance in combination with through cleaning of the care environment. We conclude that although UVGI is microbiocidal, it is not ''ready for prime time'' as a primary intervention to kill or inactivate infectious microorganisms; rather, it should be considered an adjunct. Other factors, such as careful design of the built environment, installation and effective operation of the HVAC system, and a high level of attention to traditional cleaning and disinfection, must be assessed before a health care facility can decide to rely solely on UVGI to meet indoor air quality requirements for health care facilities. More targeted and multiparameter studies are needed to evaluate the efficacy, safety, and incremental benefit of UVGI for mitigating reservoirs of microorganisms and ultimately preventing cross-transmission of pathogens that lead to health care-associated infections.

Key Words: UVGI; ultraviolet germicidal irradiation; environment; HVAC; airborne infectious agents; air disinfection.

 (Am J Infect Control 2010;38:S13-24.)

INTRODUCTION

Ultraviolet germicidal irradiation (UVGI) has been used to ''scrub'' the air in health care facilities and laboratories for many decades. UVGI is known to be efficacious to varying degrees in controlling the circulation of airborne infectious particles. Approximately 60% of all UVGI air disinfection systems are installed in health care facilities. According to Kowalski and Bahnfleth,[1] this equates to 41% in hospitals and 19% in clinics. Until recently, most of the experimental data that led to the development of UVGI systems were decades old. Aside from anecdotal observations, little information about the actual performance of these systems in hospital rooms was available. Although UV light is known to inactivate microorganisms, limiting their ability to grow and multiply when inhaled or picked up on surfaces, there is insufficient evidence on which to base a decision to rely solely on UVGI as an engineering control for preventing health care-associated tuberculosis (TB) transmission.[2]

Numerous laboratory studies, dating back to the 1930s, have been conducted to analyze the efficacy of UVGI for various microorganisms in a range of temperature and humidity conditions; few studies have evaluated the practical application of UVGI in health care buildings, however.[3] Most of the existing evidence comes from laboratory investigations conducted under simulated conditions. Our search revealed only one study that has been conducted in a physically realistic setting under controlled conditions.[4] That study served as the basis for the 2009 National Institute for Occupational Safety and Health (NIOSH) technical guidance document on the use of UVGI systems to protect health care providers from occupational TB infection.[5] This

From Technical Resources, National Institutes of Health, Bethesda, MD[a]; Infection Prevention and Control Services, St Joseph Mercy Health System, Ann Arbor, MI[b]; and Epidemiology Consulting Services Inc, Beverly Hills, MI.[c]

Address correspondence to Judene M. Bartley, MS, MPH, CIC, Epidemiology Consulting Services, Inc, 17094 Dunblaine, Beverly Hills, MI 48025. E-mail: jbartley@ameritech.net.

STATEMENT OF CONFLICT OF INTEREST: The authors report no conflicts of interest.

Publication of this article was made possible by unrestricted educational grants from The Clorox Company, the American Society for Healthcare Engineering, and the Facility Guidelines Institute.

0196-6553/$36.00

doi:10.1016/j.ajic.2010.04.208

review examines the gaps in existing evidence and highlights design and operational factors that can significantly impact the efficacy of UVGI systems.

OVERVIEW OF AIRBORNE AND SHORT-RANGE DROPLET TRANSMISSIBLE AGENTS

Myocobacterium tuberculosis, an obligate inhalational airborne pathogen, is inactivated by UVGI systems, which are most often are installed in the upper portion of rooms to disinfect air. Today UVGI is receiving renewed interest, given the emergence of new infectious diseases such as pandemic strains of influenza, the ongoing threat of bioterrorism, and increased controls for aerosol-generating procedures.[6] In addition, highly drug-resistant strains of *M tuberculosis* have been reported in several countries.[7] Others have also highlighted problems from pathogens known to survive in the environment, such as multidrug-resistant *Acinobacter baumannii, Clostridium difficile,* and others, which are increasingly the cause of invasive infections and outbreaks in a various settings.[8-12]

Four technological methods can be used to reduce the risk of airborne transmission: pressurization, dilution, filtration, and purification.

Pressure. Differential pressurization refers to measurable differences in air pressure that creates a directional airflow between adjacent spaces. For example, airflow into airborne infection isolation rooms (AIIRs) ensures that the rooms are negative with respect to adjacent spaces, such as corridors. Positive pressure, or airflow out of a defined space, is also common in facilities, used to mitigate the entrance of contaminants from adjacent areas into spaces in which invasive procedures are performed, such as an operating and procedure rooms.

Dilution. High ventilation rates, in terms of high values of air changes/hour (ACH), control particles by removal through ventilation. Current guidelines suggest a value of 12 ACH for new facilities when designing an AIIR, with 6 ACH the absolute minimum value. The trade-off with this means of control is that increasing the ventilation rate results in diminishing returns in terms of removal; that is, there is increased removal of particulates with ACH >12, but at a cost of greater energy consumption. Thus, the incremental benefit to prevent cross-transmission is much more difficult to demonstrate beyond 12 ACH. For other spaces, such as operating rooms, national guidelines recommend 20 ACH.

Filtration. Filters are a key element of air-handling units (AHUs) that supply air to occupied spaces. There are two banks of filters: a prefilter of approximately 30% particle removal efficiency (defined in terms of a minimum efficiency reporting value [MERV] as MERV 7), followed by a final filter of 90%-95% efficiency (MERV 14). High-efficiency particulate air (HEPA) filtration can be used to supplement other recommended ventilation measures by providing a minimum removal efficiency of 99.97% of 0.3-μm particles. HEPA filters are typically used in ventilation systems that recirculate the air from an AIIR or from a portable device. HEPA filters also are used to filter special care areas for highly immunocompromised patients, such as a protective environment room as part of a bone marrow transplantation unit. Proper installation, maintenance, and monitoring of the HEPA filters is essential.

Purification. Purifying the air through UVGI destroys the infectious agents in the air through exposure to ultraviolet (UV) radiation, which damages the nucleic acid of bacteria and viruses, including *M tuberculosis*, preventing replication.[13] For spores, UV-C exposure is postulated to result in the formation of lethal photoactive products.

Airborne transmission

Airborne transmission of infectious agents involves droplets that are expelled by sneezing or coughing or are otherwise distributed into the air. Although the liquid/vapor around the infectious agent evaporates, the residue (or droplet nuclei) may remain in the air for long periods, depending on such factors as particle size, velocity, force of expulsion, particle density, infectivity (ie, viability of the microorganism when exposed to the environment and its ability to cause infection when a susceptible host is subsequently exposed), humidity, and rate of air flow.

Roy and Milton[14] suggested that transmission of infectious agents does not correlate solely with the size of the microbes in droplet nuclei or larger droplets. The size can range from obligate inhalational airborne pathogens, such as *M tuberculosis*, to preferential inhalational transmission, such as measles virus or varicella-zoster (VZV) (based on the ability to cause infection in distal airways), to opportunistic pathogens like SARS-CoV that take advantage of unique environmental and clinical circumstances that permit dissemination over several meters. For *M tuberculosis*, the prototype obligate inhalational pathogen, airborne droplet nuclei containing this agent can travel via air currents, aided by the ventilation system, and be spread over a wide area. The disease-causing organisms then are inhaled and cause infection.

Droplet transmission

Opportunistic dissemination can be accomplished from respiratory droplets generated during such procedures as suctioning, endotracheal intubation, and

induction of cough by chest physiotherapy. There is theoretical chance that pathogen-laden droplets expelled during these procedures might travel further distances and reach deeper into the respiratory tract of susceptible persons. Concerns over the protection of health care personnel performing these types of procedures on patients with H1N1 2009 infection led to recommendations for higher facepiece filtering devices, such as N95 respirators. The latter have traditionally been required only to protect health care personnel against occupational exposure to *M tuberculosis*.

Droplet transmission involves relatively short-range movement of the infectious agent, over a distance of 1-2 m. Some of these agents (eg, influenza virus) also can be transmitted by direct and indirect contact. With droplet transmission, respiratory droplets containing infectious pathogens travel directly from the respiratory tract of the infectious individual to another susceptible person through deposition on mucosal surfaces of the recipient. The distance that droplets travel depends on the velocity and mechanism by which respiratory droplets are propelled from the source, the density of respiratory secretions, environmental factors such as temperature and humidity, and the ability of the pathogen to maintain infectivity over that distance. Droplets in dry air evaporate quickly, shrink in size, and fall to the ground more slowly. The changing size of a droplet affects how it responds to airflow patterns and how quickly it settles.

DYNAMICS OF TRANSMISSIBLE AGENTS IN HEALTH CARE FACILITIES

Small pressure differences, induced by natural forces such as thermal buoyancy due to air temperature differences, the wind, or mechanical fans, can generate air flows that move air from one room to another. Air filtration aims to reduce airborne concentrations to well below infectious doses. In a hospital setting, patients lie in bed much of the time. The direction of an exhalation jet from a standing or seated person and that from a lying person can be different (eg, the latter may face up). The upward thermal plume generated by a standing or seated person is much stronger than that generated by a lying person. Thus, some differences between the behaviors of breathing flows in hospital and other indoor environments are expected. The exhalation jet from a lying patient can behave differently in different ventilation systems, and also can be affected by other factors, such as the mode of contaminant release and the thermal plume generated by the human body or other heat sources. Understanding breathing flows from a patient lying supine with different ventilation systems is useful for developing an effective ventilation method for minimizing the risk of cross-infection via airborne transmission. Droplet nuclei <5 μm in diameter exhibit a settling velocity of <1 m/h (88 feet per minute in still air, and can follow the exhalation flows as well as the ambient air flows in a hospital ward. Clinically applicable distinctions are made between short-range airborne infection routes (between individuals, generally <1 m apart) and long-range routes (within a room, between rooms, or between distant locations, generally distances >1 m). Fennelly et al[15] and Bjorn and Nielsen[16] set the following size definitions:

- Large droplet: diameter >60 μm
- Small droplet: diameter <60 μm
- Droplet nuclei: diameter <10 μm.

Small droplets also may participate in short-range transmission, but they are more likely than larger droplets to evaporate to become droplet nuclei and then be considered to have the potential for long-range airborne transmission.

True long-range aerosol transmission becomes possible when the droplets of infectious material are sufficiently small to remain airborne almost indefinitely and to be transmitted over long distances. Pathogens that are not transmitted routinely by the droplet route can be dispersed into the air over short distances. For example, as reported by Bassetti et al,[17] although *Staphylococcus aureus* is most commonly transmitted by the contact route, viral upper respiratory tract infection has been associated with increased dispersal of *S aureus* from the nose into the air over a distance of 4 feet under both outbreak and experimental conditions, known as the ''cloud baby'' and ''cloud adult'' phenomena.

EFFECT OF ENVIRONMENT ON TRANSMISSION OF INFECTIOUS AEROSOL

Once infectious droplets are released, the main factors that determine how they move are their size and the airflow patterns that carry them around. Droplet size changes with time, depending on the environmental conditions. Droplets in dry air evaporate quickly, shrink in size, and fall to the ground more slowly. The changing size of a droplet affects how it responds to airflow patterns and how quickly it settles. Movement of people in a room plays a significant part in disturbing airflow and also in transporting infected air from one place to another. Thus, room airflow is governed primarily, but not solely, by mechanical ventilation. Other influences include temperature, humidity, movement of personnel and patients, and equipment. The varying combinations of these factors make the route and suspension time of an infectious particle very difficult to predict in a dynamic, real-world environment of a health care facility.

Measles and chickenpox (VZV) are both lipid-enveloped and sensitive to changes in temperature, relative humidity (RH), and UV radiation. According to Cox,[18] Stephenson et al,[19] and Ijaz et al,[20] viruses without a lipid envelope (eg, poliovirus) generally survive longer at high RH (>50%), but lipid-enveloped viruses (eg, influenza, Lassa fever virus, human coronavirus [hCV] 229E) survive longer in low RH (<50%).[18-20] Data on hCV 229E indicate that when airborne, this virus has a survival half-life of about 3 hours at an RH of 80%, 67 hours at an RH of 50%, and 27 hours at an RH of 30% at 20 °C, suggesting that high RH (>80%) is most detrimental to the survival of this coronavirus. Bean et al[21] reported that influenza can survive for 24-48 hours on hard, nonporous surfaces such as stainless steel and plastic, but for less than 8-12 hours on cloth, paper, and tissues. In addition, influenza virus can survive for up to 5 minutes on hands, and can be transferred to hands from these nonporous surfaces for 24 hours and from tissues for 15 minutes.[21]

More recently, Lai et al[22] demonstrated that SARS CoV can survive in alkaline diarrhea stools for up to 4 days and can remain infectious in respiratory specimens for more than 7 days at room temperature. Similarities with other viruses of nosocomial importance (eg, other RNA lipid-enveloped respiratory viruses, such as influenza) suggest that such organisms can survive long enough in aerosols to cause disease, especially when associated with biological fluids such as mucus, feces, and blood. This sensitivity to environmental conditions also might help explain the seasonality of some viral infections.

Regarding influenza transmission, Brankston et al[23] concluded that natural influenza transmission in humans occurs via droplets and contact over short distances as opposed to long distances. Although none of the studies that they reviewed could specifically rule out airborne transmission, the authors believed that the airborne route is neither the predominant mode of transmission nor a frequent enough occurrence to be of significant concern when considering control measures for most clinical settings.[23] A recent epidemiologic investigation confirmed their conclusions.[24]

MICROBIOCIDAL ACTIVITY OF UVGI IN AIR AND ENVIRONMENTAL SURFACES: EFFICACY AND LIMITATIONS

A recent systematic review by Li et al[25] demonstrated that adequate or inadequate ventilation has an effect on the risk of infection via infectious aerosols. An inefficient ventilation system causes the spread of airborne disease, whereas an efficient ventilation system can help mitigate the spread of infectious particles and thereby reduce transmission of disease.[25] Even

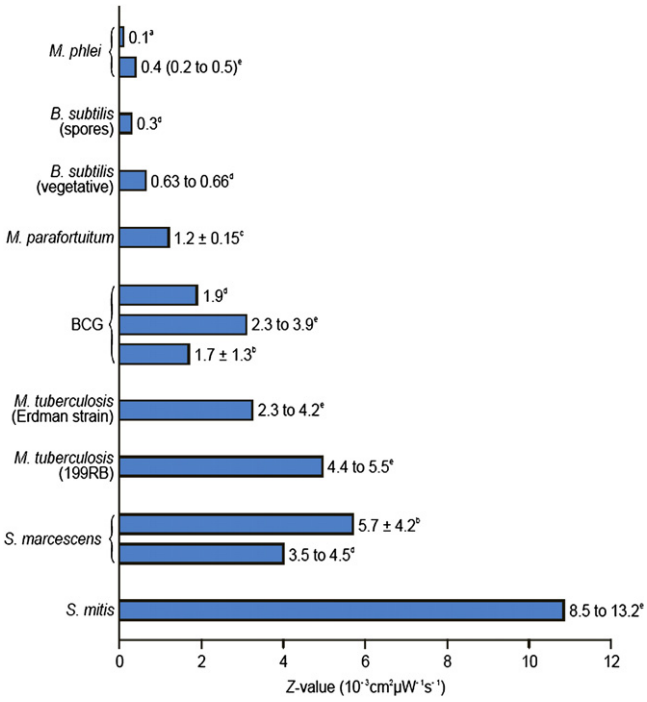

Fig 1. Relative sensitivity of selected airborne microorganism to UVGI. The higher the *z* value, the greater the microorganism's sensitivity to UVGI. The data sources are indicated by superscript letters: (a) Kethley 1973[28]; (b) Ko et al 2000[33]; (c) Miller et al 2002[4]; (d) Peccia 2001[39]; (e) Riley et al 1976.[38] Reprinted with permission.[5]

before the 2003 SARS epidemic, there was strong evidence that ventilation and building finishes are important determinants of the nosocomial transmission of tuberculosis. According to the Centers for Disease Control and Prevention's (CDC) *Guidelines for Environmental Infection Control in Health-Care Facilities*, only TB, measles (rubeola virus), and chickenpox (VZV) should be considered ''true'' airborne infectious diseases.[26] However, other infectious agents, such as SARS CoV, are sometimes called ''opportunistic,'' because they might be transmissible over short distances (eg, 1-2 m), given a favorable environment.[14]

Effectiveness on microbes

All viruses and almost all bacteria (excluding spores) are vulnerable to moderate levels of UVGI exposure, but the magnitude of the effect is extremely species-dependent.[27] Spores, which are larger and more resistant to UVGI than most bacteria, can be effectively removed through high-efficiency air filtration without UVGI. Some UGVI systems are installed in conjunction with high-efficiency filtration. This combination design can be very effective against biological agents in certain situations. Smaller microbes that are difficult to

filter out tend to be more susceptible to UVGI, whereas larger microbes, such as spores, which are more resistant to UVGI, tend to be easier to filter out (Fig 1).[29]

A recent Taiwanese study found that the effectiveness of UVGI depends strongly on the type of virus nucleic acid, and that viruses with dsRNA or dsDNA are significantly less susceptible to UV inactivation.[30] For 90% airborne virus inactivation, the UVGI dose was approximately 2-fold higher for dsRNA and dsDNA viruses than for ssRNA and ssDNA viruses. The microorganism susceptibility factor was the highest for the viruses, similar to that for fragile bacteria, but 13-20 times higher than that for endospore bacteria or fungal spores. The susceptibility factor for the viruses was higher at 55% RH than that at 85% RH, possibly because under high RH, water adsorption onto the virus surface might provide protection against UV-induced DNA or RNA damage.[30]

UVGI APPLICATIONS FOR DISINFECTION OF AIR IN HEALTH CARE FACILITIES

Supplemental control

UVGI has been used as a supplement to mechanical ventilation to inactivate airborne infectious agents to protect the health of building occupants. Upper-room UVGI installations are frequently used to provide ACH equivalent or effective (e-ACH) to that recommended by the CDC for AIIRs. However e-ACH is not acceptable for meeting CDC recommendations as a primary environmental control against *M tuberculosis*.

UVGI generally refers to a UV wavelength of 253.7 nm (UV-C). Exposure to UV light at this wavelength is a practical and cost-effective method of inactivating airborne viruses, mycoplasma, bacteria, and fungi on clean surfaces.[31]

Upper-room air lamps

The most widely used application of UVGI is in the form of passive upper-room fixtures containing UVGI lamps that provide a horizontal layer of UV energy field above the occupied zone. These fixtures are designed to inactivate bacteria that enter the upper irradiated zone, and their efficacy is highly reliant on, among other factors, the airflow field conditions in the room. The survival probability of bacteria exposed to UV irradiance depends on the susceptibility of the target microorganism and the dose and duration of UV-C to which it is exposed.[32] Lamps used to produce UV-C are located relatively high up in the room (8 ft), to prevent exposure to occupants by a specially designed fixture. There are two basic designs: a ''pan'' fixture with UVGI unshielded above the unit to direct the irradiation upward, and a fixture with a series of parallel plates that direct the irradiation outward while preventing the light from reaching the eyes or unprotected skin of the room's occupants. Germicidal activity is dependent on air mixing via convection between the room's irradiated upper zone and the lower patient care zones.[32] This was confirmed in an investigation by Miller et al[4] that involved installation of upper-room UVGI units and evaluation of these units' impact on culturable airborne bacteria. More than 90% of the bacteria detected were inactivated; however, the rate was lower for more-resistant bacteria and fungal spores. That investigation also clearly demonstrated that room air must be mixed for UVGI to effectively inactivate microorganisms. When warm air entered the room via a duct close to the ceiling (which can occur in the winter when the heating system is turned on), the warm air simply ''rested'' on the much cooler air below, and the efficacy of the UVGI system was dramatically diminished because the microbes did not move up for exposure to the UV-C irradiation. No mixing fans were turned on during the experiment, but moderate ventilation was present.

The cleanliness of UV light bulbs and age of UV lamps should be checked periodically (approximately every 6 months) to ensure sufficient UV light intensity for germicidal activity (UV-C). The intensity of germicidal wavelength light decreases with age, and bulb ratings (hours of use) may vary by manufacturer.[13] Upper-room UVGI is often seen as a cost-effective measure to supplement the general ventilation system in a room; however, the combination of the general ventilation system and UV lamps might not necessarily be implemented correctly within a room. For example, if the ventilation rate is too high, the particles may not be sufficiently exposed to the UV-C irradiation to ensure complete inactivation, or if the ventilation system does not provide good mixing within the room, airborne particles containing microbes might not even be exposed to the UV-C irradiation.[13]

A well-designed upper-room UVGI system may effectively kill or inactivate most airborne droplet nuclei containing *Mycobacterium* spp if designed to provide an average UV fluence rate (ie, irradiance from all angles that is incident on a small region of space; a more accurate term than ''UV dose'') in the upper room in the range of 30-50 $\mu W/cm^2$, provided that the other criteria stipulated in the CDC's TB guidelines are met.[2] The fixtures should be installed to provide as uniform a UVGI distribution as possible in the upper room.[5] Schafer et al[33] developed a method to measure fluence rate and used it to verify that this rate varied as much as 3-fold in a typical room, depending on proximity to the lamp, and found that lamp failure was common. This reinforces the need to monitor the efficacy of the lamps used in UVGI fixtures. Under

experimental laboratory conditions with mechanical ventilation rates of up to 6 ACH, the rate at which microorganisms are killed or inactivated by UVGI systems appears to be additive with mechanical ventilation systems in well-mixed rooms.[2]

For other infectious agents, such as SARS-CoV and influenza, the mode of transmission is by droplets, which do not remain suspended in air for long periods of time, but fall out within a 2-m radius from a coughing/sneezing person. Even the most robust HVAC system is unlikely to achieve sufficient air mixing to provide efficient kill of microbes transmitted by droplets. These particles never reach the upper-room UV zone; thus, an alternate method of disinfection is needed.[34]

Escombe et al[35] recently investigated impact of upward-facing UV light fixtures installed in ceilings of a negative-pressure TB isolation ward and ceiling-mounted air ionization fixtures in an animal enclosure chamber, using a guinea pig air sampling model that involved exposure of the animals to exhaust air from the isolation ward. With this animal model, 35% of controls exposed to untreated exhaust air from the TB ward developed TB infection, whereas frequency was reduced to 14% and 9.5% with use of an ionizer and UVGI, respectively. They concluded that ''provided there is adequate mixing of room air, an upper-room UVGI fixture is an effective, low-cost intervention for use in TB infection control in high-risk clinical settings.''[35]

Key variables

Critical factors that affect the efficacy of UVGI include temperature, RH, and lamp output. A number of studies have indicated that the effectiveness of upper-room UVGI systems decreases as humidity increases. For optimal efficiency, RH should be controlled to 60% or less when upper-room UVGI systems are installed. Temperature should be kept between 68°F and 75 °F (20 °C-24 °C). Both of these suggestions are consistent with 2010 Facility Guidelines Institute (FGI) and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) recommendations in ASHRAE Standard 170 (now part of the FGI Guidelines Standards).[36] The ASHRAE Handbook also provides comprehensive recommendations for installation and operation of UVGI systems.[37]

Experimental upper-room UVGI systems used in rooms with aerosolized bacteria (including surrogates of *M tuberculosis*) have shown that the higher the UV fluence rate produced in the upper air of a room, the greater the effectiveness of the system.[4,38,39] Based on the results of experiments with upper-room UVGI systems and aerosolized bacteria in bench-scale reactors, it is apparent that the greater the UV fluence rate in the irradiated zone, the more effective the system.[40,41] However, there appears to be an upper threshold after which an increase in UVGI does not directly correspond to an increase in the system's ability to kill or inactivate microorganisms.[4,13,42,43] Miller et al[4] reported decreased effectiveness of the UVGI system when the UV fixtures were placed on only one side of the room. This is consistent with the findings of Riley and Permutt,[44] who reported that a wider distribution of low-irradiance UV lamps was more efficient compared with the use of one centrally located high-irradiance UV lamp. This suggests that upper-room UVGI systems should be installed to provide the most uniform UVGI distribution in the upper air possible.

Experimental conditions

In most of the studies that form the basis of the irradiance guidelines, the bacteria studied were primarily single cells aerosolized in deionized water. This lack of a mucus coating could possibly make these bacteria more sensitive to UVGI compared with bacteria in droplet nuclei from an infected host.[45] The killing or deactivation of 63% of droplet nuclei in a room by UVGI is equivalent to 1 ACH in terms of reduced total droplet nuclei concentration in the room.[3] This reduction of droplet nuclei by a method other than mechanical ventilation is termed eACH.

AHUs including in-duct applications

UVGI lamps can be installed in a various locations in a HVAC system. One possible location is inside the AHU, typically in front of the cooling coils and drip pan. There are anecdotal reports that this configuration results in energy conservation and maintenance cost savings, but more rigorous study is needed to reproduce and validate these claims. Some manufacturers of these systems have also made claims of reduced incidence of health care-associated infections (HAIs) with the use of UVGI in AHUs. To date, however, there is little, if any, supportive evidence in the peer-reviewed scientific literature. Many of the published investigations rely on environmental surface or air sampling cultures or laboratory-based animal studies for inferential support. Our assessment of the available literature indicates claims of reduced HAIs from AHU-installed UVGI in health care facilities remain unfounded. There is some evidence of fewer complaints related to indoor air quality in buildings with systems containing UVGI inside the AHU.[46] Levetin et al[47] provided some evidence for this by demonstrating a significantly lower concentration of fungal spores on a floor of a building with an in-duct UVGI system compared with a floor in the same building without such a system. The spores recovered in the building were the same as from

insulation material in the ventilation ducts, however. The authors concluded that few spores from the outdoors passed through filters in the AHUs, but that the spores developed when the HVAC system was turned on and off. Notably, they noted that ''as a result, we cannot say that the UV-C radiation had a direct effect on spores in the air stream. The effectiveness of UV-C lamps seemed to be localized, because visual inspection indicated there was conspicuous fungal growth in the downstream duct insulation lining.''[47] UV lamps also can be placed inside supply or return air ducts to disinfect the air before it is supplied to an occupied space or when recirculated.

Air cleaning?

UV irradiation by itself does not clean air. The microorganisms are still there, and in the case of some microorganisms, might still contain the ability to cause noninfectious (eg, allergenic) disease. Although UV potentially can destroy allergenic sites on the surface of a bioaerosol, this ability has yet not been documented or quantified.[47] Bacterial inactivation studies using Bacillus Calmette-Guérin (BCG; a strain of *Mycobacterium bovis*) and *Serratia marcescens* have estimated the effect of UVGI as equivalent to 10-39 ACH.[34] However, another study suggested that UVGI may result in fewer equivalent ACH in the patient-care zone, especially if the mixing of air between zones is insufficient.[48] The use of fans or HVAC systems to generate air movement and good mixing might increase the effectiveness of UVGI by ensuring exposure of airborne microorganisms to the light energy for a sufficient length of time.[35]

UVGI SURFACE DISINFECTION IN HEALTH CARE FACILITIES

UVGI has been used for disinfection of water, but that application is not addressed in this review. It has also been used to disinfect surfaces. One study found that the effectiveness of this application is limited by the low penetrating power of UVGI, and thus it is currently limited to decontaminating surfaces when conventional methods, such as the use of liquid chemical disinfectants, are not feasible.[31]

Some studies also have explored disinfection of medical devices and other high-frequency touch surfaces. Sweeney and Dancer[49] found that UVGI disinfection of computer keyboards without mechanical friction from cleaning had no impact on bioburden for 72% of the 68 keyboards in their study, and concluded that physical cleaning is of greatest importance before the use of UVGI. Kac et al[50] found that UVGI effectively disinfected endocavitary ultrasound probes, but only if used in combination with a surface disinfectant applied with a cloth and with mechanical friction. Interestingly, both of these investigations highlight the adjunctive impact of UVGI following traditional cleaning and disinfection for medical devices and other surfaces, whivch is consistent with use of UVGI for disinfection of air. More recently Rutala et al[51] presented unpublished results of their study of ''no-touch'' full room disinfection with an automated, portable UV-C device that uses mirrors to ''bounce'' UVGI around a room to reach all surfaces, including those not directly exposed to fluence. They reported substantial log reductions in vegetative bacteria (3-4) within 15 minutes of exposure and in spore-forming bacteria, such as *C difficile* (2-3), after 50 minutes of exposure.

ANALYTICAL MODEL FOR UV DOSE EVALUATION USING COMPUTATIONAL FLUID DYNAMICS

An analytical model for evaluating the UV dose in steady-state conditions using the Eulerian system was proposed by Memarzadeh et al.[48] Computational fluid dynamics (CFD) was used to study the efficacy of inactivation of airborne bacteria by upper-room UVGI in a test room. Several UV lamp configurations were used in the model. Compared with available experimental data, the proposed model closely predicts the percentage of particles inactivated by UVGI. The proposed model was used to study the effects of ventilation flow rate and UV fixture configuration on inactivation of airborne bacteria in a test chamber. The Lagrangian system model was also applied in the same test chamber for a similar scenario. This CFD model demonstrates that the percentage of UVGI inactivation is higher when the ventilation flow rate is lower. Increasing the ventilation flow rate from 2 to 6 ACH reduces the residence time of a pass through the UV zone from 24.7 to 8.3 seconds. In the latter case, the dosage is then only ~35% of the total dose received in the former case. For upper-room UVGI to be effective, the aerosolized infectious particles must be moved from the lower part of the room, where they are produced by a person coughing or sneezing, to the germicidal zone in the upper room. Practical considerations prohibit the ideal situation of UVGI cleansing of all infectious particles in a single pass when they move through the upper-room UVGI zone. Another consideration is how rapidly microorganisms proceed through the UVGI zone. A higher frequency of ACH limits the exposure time of the infectious particles to the UVGI and thus is likely to have less effective antimicrobial activity. In practice, the effectiveness of a UVGI installation is determined by the following factors:

- Fixture used to house the UV-C lamp. This determines how much of the radiation discharged from the UV lamp is actually emitted from the fixture and how it is distributed.
- Environmental sustainability issues. Most UV-C lamps use low-pressure mercury, have a limited life span, and require environmental precautions for disposal.
- Distance from the UV-C lamp. The distance of airborne infectious agents from the fixture will determine the irradiance level and thus the germicidal efficacy.
- Airflow pattern. This affects how long the bacteria and viruses are exposed to the UV radiation.
- Humidity. The humidity of the atmosphere is key, because water makes the infectious agent less susceptible to damage from UV radiation. The higher the RH, the less likely an aqueous aerosol will dry out. For maximum effectiveness of UVGI, RH should be $<75\%$.[34]

HUMAN HEALTH CONSIDERATIONS WITH UVGI

According to an American Biological Safety Association position paper, biological effects in humans from overexposure to UV-C radiation vary with wavelength, photon energy, and duration of exposure.[52] In general, adverse effects are limited to the skin and eyes. Erythema (eg, reddening of the skin, as in sunburn) is the most commonly observed skin effect. Chronic exposure to UV radiation can accelerate the skin aging process and increase the risk of skin cancer. The National Toxicology Program (NTP) classifies UV-C as a probable human carcinogen. Excessive exposure to UV-C radiation can adversely affect the eyes, causing photokeratitis and/or conjunctivitis. Based on the current guidelines, repeated exposure at or below the current guideline would not be expected to cause adverse health effects; however, it should be emphasized that UV radiation has been implicated in both skin cancer and cataracts in humans.

Outcome of a case study on UVGI for operating room air disinfection

On May 18, 2007, NIOSH received a request from the Director of Environmental Affairs at Brigham and Women's Hospital (BWH) in Boston, Massachusetts. Some BWH orthopedic surgical staff members were concerned about unspecified skin and eye symptoms, which they attributed to germicidal UV-C radiation produced by ceiling-mounted UVGI lamps in orthopedic operating rooms (ORs). The use of UVGI in orthopedic ORs was investigated by the Occupational Safety and Health Administration (OSHA) on January 19, 2007, in response to a formal complaint submitted after staff discovered that the UVGI lamp controls in an OR had been tampered with and set at an inappropriately high setting. After an inspection, OSHA recommended that BWH provide annual UV-C and personal protective equipment (PPE) training and medical screening for all affected employees, as well as ensure that all affected employees use the required PPE. In July 2008, BWH moved the orthopedic operating suite to an area equipped with laminar airflow and discontinued the use of UVGI for intraoperative infection control. NIOSH investigators recommended the use of alternative infection control technologies, such as laminar airflow.[53]

UVGI DISINFECTION FOR AIR IN OPERATING ROOMS

The use of direct UVGI as an air-cleaning method for intraoperative infection control is a relatively uncommon application that has been used by some surgeons since the 1930s.[54-56] Some evidence suggests that the use of UVGI in this manner might reduce the incidence of surgical site infections by minimizing intraoperative levels of airborne bacterial contaminants. This design differs from upper-room devices in that the UV-C irradiation is directed down to expose the entire OR. Eye protection and other attire are required for those in the OR. The relative efficacy of direct UVGI on intraoperative air quality and prevention of infection has not been well defined, however, because studies that have examined its use did so at a variety of UV intensities in association with other infection prevention methods and surgical techniques. In addition, most studies have been observational, before–after investigations, which are limited by biases and other confounding variables. Investigators have reported that UVGI is usually used not alone, but rather in conjunction with laminar airflow or body exhaust techniques, with discrepancies in wound rates under the same conditions.[56] The CDC recommends against using UVGI to prevent surgical site infections.[26] Overall, for general ventilation effectiveness, there is little advantage to increasing the effectiveness of the UVGI beyond 4-6 ACH. UVGI is effective when at low ACH, and its efficacy diminishes as ACH increases, because the kill rate is dependent on the duration of exposure to the UV dose. With high ACH, exposure time is significantly decreased.

For personnel safety, NIOSH strongly encourages employers to protect employees using a hierarchy of controls approach. The objective of this approach is to minimize the risk of failure of preventive measures, resulting in a hazardous exposure. According to the hierarchy, initial efforts should be made to eliminate the hazardous agent or source of exposure. With regard to intraoperative UVGI use, this could be achieved by substituting other infection prevention methods or

technologies, such as vertical laminar air flow, before implementing direct UVGI inside the OR.[53] It should be noted that a more recent design for the OR uses nonaspirating diffusers with unidirectional airflow over the surgical site but at lower velocities than traditional high-velocity laminar sir flow, thereby minimizing the risk of hypothermia. This design is now required in the 2010 FGI guidelines[36] and is described in detail elsewhere.[57]

DESIGN CONSIDERATIONS

Given the foregoing discussion, we recommend that UVGI system designers take the following considerations into account:

- Apply safety factors to their designs, particularly as they depart from operating modes for which they have performance data and field experience.
- Know the actual lamp output under the most challenging operating conditions.
- Avoid relying solely on design equations to determine the performance of their systems. Actual testing with the contaminants of interest is highly recommended.
- View claims regarding UVGI systems' high level of inactivation of pathogenic bioaerosols with caution. Whereas the microbiological science underlying these conclusions applies to pathogenic bioaerosols as well as environmental organisms, much greater caution is required in the former case. It would be irresponsible to claim a high inactivation rate for a pathogenic bioaerosol without substantial testing. Even with substantial testing, design failures may occur.

USER CONSIDERATIONS WHEN RELYING ON A UVGI SYSTEM FOR DISINFECTION

Health care buildings

Although many laboratory studies have been conducted to analyze the efficacy of UVGI for numerous microorganisms in a range of temperature and humidity conditions, little has been done to evaluate the practical application of UVGI in health care buildings.[3] In fact, Beggs et al[58] concluded that ''the knowledge base that exists on UVGI and its application is relatively small, and health care authorities have few guidelines on which to make decisions.''

Laboratory versus actual conditions

As discussed earlier, potentially infectious droplet nuclei emitted from an infected host might be coated with mucus and consist of more than one bacterium. Study bacteria, aerosolized in deionized water and lacking a mucus coating, may be more sensitive to UVGI compared with bacteria in droplet nuclei from an infected host.[44]

Installation and maintenance

UVGI is associated with human health risks and unpredictable results. UV rays can cause harm to building occupants if not properly installed and maintained. Installation techniques widely vary among manufacturers and currently are not regulated by a governing body to ensure proper efficacy of UVGI after installation.

Manufacturers

UVGI lamp manufacturers (eg, Philips PLD), acknowledge that some important information is not available. For example, regarding to the sizing of UV lamps for installation in ductwork systems, a Philips technical document on UV disinfection states that ''in the calculation…it should be emphasized that it results only in a rough estimation; we did not incorporate the possible effects of humidity and temperature on the killing rate. Philips is not a specialist in that field; we always advise to contact qualified authorities to evaluate the bacteriological aspects.''[59] The use of CFD models and improved distribution studies on UVGI lamps and fixtures is moving the industry in the right direction. The CFD models characterize the room and air distribution in coordination with any UVGI systems applied within the space to evaluate the effectiveness quantitatively.[3] For UVGI applications in AHU and ductwork, maintenance personnel may be at increased risk even if their exposure time to the UVGI irradiation is short, because they will be in close proximity to the UVGI source.

Personnel precautions

Service personnel and occupants are at risk without special care measures. Service staff need to ensure that the system is turned off when working. The need to wear protective clothing and eyewear should be stressed to prevent any possibility of harm to workers. Room occupants may be exposed to higher doses of UVGI irradiation if the fixtures are not located or installed properly within the space. Health care providers are at a greater risk because they occupy the space for longer periods than most patients. UVGI overexposure has the potential to cause unpleasant eye and skin irritations; however, these effects appear to be temporary and have involved no known long-term consequences to date.[60]

RESEARCH NEEDS

Additional areas of research needed to determine the most effective upper-room UVGI systems include UVGI measurements, air mixing, the effect of low humidity, microbial sensitivity, and testing and validation of upper-room UVGI systems. More research is also needed on the ability of UVGI systems to kill or inactivate microorganisms in respirable droplet nuclei of variable sizes and droplet nuclei coated with actual or simulated sputum.[5] Methods for determining whether existing room air mixing is sufficient for UVGI effectiveness are needed, and research should explore whether the use of mixing fans has a negative impact on the intended design of the mechanical ventilation systems or a negative impact on other infection control measures.

Humidity and ventilation

There is some indication that low RH (<25%) might adversely affect the ability of UVGI systems to kill or inactivate airborne bacteria. Additional research is needed in this area. Research in full-scale rooms to better ascertain the effects of high humidity (eg, 80% RH) on airborne microorganisms is needed as well. Experimental research has indicated that mechanical ventilation of up to 6 ACH does not have a significant effect on the effectiveness of upper-room UVGI systems; studies are needed to examine whether mechanical ventilation >6 ACH decreases the effectiveness of upper-room UVGI systems.

Standardization

Tests to determine the relative sensitivity of microorganisms to UVGI are not standardized among laboratories. Laboratory testing guidelines are needed to ensure that these tests are reproducible and reflect real-world situations. Laboratory tests of the efficacy of UVGI upper-room systems should be standardized as well. Protocols for testing and validating upper-room UVGI systems are needed to ensure that the systems perform as designed.[1]

Experimental versus real-world conditions

Guidelines are needed to determine the most practical method for planning effective UVGI systems in a variety of rooms or areas. Theoretically, CFD modeling can be used to evaluate many of the variables associated with installing an upper-room UVGI system and provide an estimate of the UVGI dose received by droplet nuclei. Experiments involving photoreactivation of microorganisms in full-scale test rooms should be conducted, as should tests of the effectiveness of UVGI on airborne bacteria over a wide range of temperatures. In real-world situations, potentially infectious droplet nuclei will vary in size and may be coated with sputum. Both of these factors can decrease the effectiveness of UVGI. Although some laboratory research has been done to evaluate these parameters,[34,44,61] more work is needed to further characterize microbial susceptibility to UVGI based on the size of respirable (up to 5 μm) droplet nuclei and droplet nuclei coated with actual or simulated sputum.

CONCLUSIONS AND DISCUSSION

Data for real-world applications

As this and previous literature reviews have shown, although numerous studies address the efficacy of UVGI, there remains a lack of definitive epidemiologic data demonstrating that these systems prevent HAIs endemic to health care facilities. Also lacking is objective, reproducible evidence of improved energy efficiency of coils and fans with UVGI systems installed in AHUs. The efficacy of an upper-room UVGI application depends strongly on sufficient exposure of microorganisms to UV-C, which can occur if there is good mixing of upper and lower air in the room or area where installed. Furthermore, there are many marketing claims suggesting that such systems, as well as mobile systems, will protect occupants against emerging diseases such as SARS CoV, influenza, *M tuberculosis*, and bioterrorism agents. These claims have not been substantiated by the existing data, however, and must be weighed against the many variables discussed in this literature review. For TB, there is ample laboratory and reasonable evidence from animal studies, but the key question remains the relative role of UVGI in the context of the hierarchy of controls to prevent health care-associated TB.

Bioterrorism

Some of the agents that might be used for bioterrorism, such as anthrax spores, are not very susceptible to UV-C. Because the clinical effectiveness of UV systems may vary, UVGI is not recommended for air management before air recirculation from airborne isolation rooms. It also is not recommended as a substitute for HEPA filtration, local exhaust of air to the outside, or negative pressure.

Portable and in-duct units

The use of UV lamps and HEPA filtration in a single unit offers only minimal infection control benefits over those provided by the use of a HEPA filter alone. Duct systems with UVGI are not recommended as a substitute for HEPA filters when the air from isolation rooms must be recirculated to other areas of the facility. Regular maintenance of UVGI systems, involving keeping

the bulbs free of dust and replacing old bulbs as necessary, is crucial. Safety issues associated with the use of UVGI systems are described in guidelines.

Supplemental engineering controls

When UVGI units are required for air cleaning, as demonstrated by a risk assessment of the AII area, the units should be installed in the exhaust air ducts of the HVAC system to supplement HEPA filtration. When UVGI is used as a supplemental engineering control, fixtures should be installed on the wall near the ceiling or suspended from the ceiling as an upper-air unit, in the air-return duct of an AII room, or in designated enclosed areas or booths for sputum induction.

In summing up the role of UVGI in today's health care facilities, UVGI should continue to be viewed not a routine replacement for ventilation, but rather as a supplement when needed under the conditions and parameters described in this review. It does not appear to have a role in the OR, where air changes are well above 4-6 ACH, or in properly designed AII rooms. Many questions remain regarding how to achieve a balance between utility and safety; hopefully, the necessary research will continue.

References

1. Kowalski WJ, Bahnfleth WP. UVGI design basics for air and surface disinfection. HPAC Eng 2000;72:100-10.
2. Centers for Disease Control and Prevention. Guidelines for preventing the transmission of *Mycobacterium tuberculosis* in health-care settings, 2005. Morb Mortal Recomm Rep 2005;54(RR-17):1-141.
3. First MW, Nardell EA, Chaisson W, Riley R. Guidelines for the application of upper-room ultraviolet germicidal irradiation for preventing transmission of airborne contagion. Part II: design and operation guidance. ASHRAE Trans 1999;105:877-87.
4. Miller SL, Hernandez M, Fennelly K, Martyny J, Macher J, Kujundzic E, et al. Efficacy of ultraviolet irradiation in controlling the spread of tuberculosis. NIOSH final report, Contract 200–97–2602; NTIS publication PB2003-103816. Cincinnati, OH: US Department of Health and Human Services, Centers for Disease Control and Prevention; 2002.
5. Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. Environmental control for tuberculosis: basic upper-room ultraviolet germicidal irradiation guidelines for healthcare settings, 2009. Available from: http://www.cdc.gov/niosh/docs/2009-105/. Accessed January 31, 2010.
6. Centers for Disease Control and Prevention. Update: influenza activity—United States, August 30, 2009-January 9, 2010. MMWR Morb Mortal Wkly Rep 2010;59:38-43.
7. Velayati AA, Masjedi MR, Farnia P, Tabarsi P, Ghanavi J, Ziazarifi AH, et al. Emergence of new forms of totally drug-resistant tuberculosis bacilli: super extensively drug-resistant tuberculosis or totally drug-resistant strains in Iran. Chest 2009;136:420-5.
8. Rastogi VK, Wallace L, Smith LS. Disinfection of *Acinetobacter baumannii*-contaminated surfaces relevant to medical treatment facilities with ultraviolet C light. Mil Med 2007;172:1166-9.
9. Hujer KM, Hujer AM, Hulten EA, Bajaksouzian S, Adams JM, Donskey CJ, et al. Analysis of antibiotic resistance genes in multidrug-resistant *Acinetobacter* sp isolates from military and civilian patients treated at the Walter Reed Army Medical Center. Antimicrob Agents Chemother 2006;50:4114-23.
10. Loivukene K, Sepp E, Adamson V, Mitt P, Kallandi U, Otter K, et al. Prevalence and antibiotic susceptibility of *Acinetobacter baumannii, Pseudomonas aeruginosa* and *Klebsiella pneumoniae* in Estonian intensive care units in comparison with European data. Scand J Infect Dis 2006;38:1001-8.
11. Guidance for control of infection with carbapenem-resistant or carbapenemase-producing *Enterobacteriaceae* in acute care facilities, 2009. Morb Mortal Wkly Rep 2009;58:256–260.
12. Thompson A, Kallen J. Complete restriction of fluoroquinolone use to control an outbreak of *Clostridum difficile* infection at a community hospital. Infect Control Hosp Epidemiol 2009;30:264-72.
13. Memarzadeh F. Assessing the efficacy of ultraviolet germicidal irradiation and ventilation in removing Mycobacterium tuberculosis Available from: http://orf.od.nih.gov/PoliciesAndGuidelines/Bioenvironmental/assessubg_cover.htm Accessed January 31, 2010.
14. Roy CJ, Milton DK. Airborne transmission of communicable infection: the elusive pathway. N Engl J Med 2004;350:1710-2.
15. Fennelly KP, Martyny JW, Fulton KE, Orme IM, Cave DM, Heifets LB. Cough-generated aerosols of *Mycobacterium tuberculosis*: a new method to study infectiousness. Am J Respir Crit Care Med 2004;169:604-9.
16. Bjørn E, Nielsen PV. Dispersal of exhaled air and personal exposure in displacement ventilated rooms. Indoor Air 2002;12:147-64.
17. Bassetti S, Bischoff WE, Walter M, et al. Dispersal of *Staphylococcus aureus* into the air associated with a rhinovirus infection. Infect Control Hosp Epidemiol 2005;26:196-203.
18. Cox CS. The microbiology of air. In: Collier L, Balows A, Sussman M, editors. Topley & Wilson's microbiology and microbial infections. 9th ed. London: Arnold; 1998. p. 339-50.
19. Stephenson EH, Larson EW, Dominik JW. Effect of environmental factors on aerosol-induced Lassa virus infection. J Med Virol 1984;14:295-303.
20. Ijaz MK, Brunner AH, Sattar SA, Nair RC, Johnson-Lussenburg CM. Survival characteristics of airborne human coronavirus 229E. J Gen Virol 1985;66:2743-8.
21. Bean B, Moore EM, Sterner B, Peterson LR, Gerding DN, Balfour HH Jr. Survival of influenza viruses on environmental surfaces. J Infect Dis 1982;146:47-51.
22. Lai MY, Cheng PK, Lim WW. Survival of severe acute respiratory syndrome coronavirus. Clin Infect Dis 2005;41:e67-71.
23. Brankston G, Gitterman L, Hirji Z, Lemieux C, Gardam M. Transmission of influenza A in human beings. Lancet Infect Dis 2007;7:257-65.
24. Han K, Zhu X, He F, Liu L, Zhang L, Ma H, et al. Lack of airborne transmission during outbreak of pandemic (H1N1) 2009 among tour group members, China, June 2009. Emerg Infect Dis 2009;15:1578-81.
25. Li Y, Leung GM, Tang JW, Yang X, Chao CY, Lin JZ, et al. Role of ventilation in airborne transmission of infectious agents in the built environment: a multidisciplinary systematic review. Indoor Air 2007;17:2-18.
26. Centers for Disease Control and Prevention and Healthcare Infection Control Practices Advisory Committee. Guidelines for environmental infection control in healthcare facilities: recommendations of CDC and the Healthcare Infection Control Practices Advisory Committee (HICPAC). Morb Mortal Recomm Rep 2003;52(RR-10):1-42.
27. Fletcher LA, Noakes CJ, Beggs CB, Sleigh PA. The importance of bioaerosols in hospital infections and the potential for control using germicidal ultraviolet irradiation. Proceedings of the First Seminar on Applied Aerobiology, Murcia, Spain, May 2004. Available from: http://www.efm.leeds.ac.uk/CIVE/aerobiology/PDFs/uv-and-airborne-hospital-infection-fletcher.pdf. Accessed January 31, 2010.
28. Kethley TW. Feasibility study of germicidal UV lamps for air disinfection in simulated patient care rooms. Paper presented at: American Public Health Association Conference, Section on Environment; November 7, 1973; San Francisco, CA.
29. Federal Emergency Management Agency. Chemical, biological, and radiological measures. Available from: http://www.fema.gov/pdf/plan/prevent/rms/426/fema426_ch5.pdf. Accessed January 31, 2010.

30. Tseng C-C, Li C- S. Inactivation of virus-containing aerosols by ultraviolet germicidal irradiation. Aerosol Sci Technol 2005;39: 1136-42.
31. Department of the Army. Safety standards for microbiological and biomedical laboratories. Available from: http://www.fas.org/irp/doddir/army/pam385-69.pdf. Accessed January 31, 2010.
32. Memarzadeh F, Jiang J. New research identifies a methodology for minimizing risk from airborne organisms in hospital isolation rooms. ASHRAE Trans 2000;106:731-47.
33. Schafer MP, Kujundzic E, Moss CE, Miller SL. Method for estimating ultraviolet germicidal fluence rates in a hospital room. Infect Control Hosp Epidemiol 2008;29:1042-7.
34. Ko G, First MW, Burge HA. Influence of relative humidity on particle size and UV sensitivity of *Serratia marcescens* and *Mycobacterium bovis* BCG aerosols. Tuber Lung Dis 2000;80:217-28.
35. Escombe AR, Moore DA, Gilman RH, et al. Upper-room ultraviolet light and negative air ionization to prevent tuberculosis transmission. PLoS Med 2009;6:e43.
36. American Society of Heating, Refrigerating, and Air-Conditioning Engineers. Ventilation of health care facilities. ANSI/ASHRAE/ASHE Standard 170. Available from: http://sspc170.ashraepcs.org/index.html. Accessed January 30, 2010.
37. American Society of Heating, Refrigerating, and Air-Conditioning Engineers. Ultraviolet lamp systems. In: ASHRAE Handbook: HVAC Systems and Equipment. Atlanta, GA: ASHRAE; 2008 chap. 16.
38. Miller SL, Macher JM. Evaluation of a methodology for quantifying the effect of room air ultraviolet germicidal irradiation on airborne bacteria. Aerosol Sci Technol 2000;33:274-95.
39. Riley RL, Knight M, Middlebrook G. Ultraviolet susceptibility of BCG and virulent tubercle bacilli. Am Rev Respir Dis 1976;113:413-8.
40. Peccia J, Werth HM, Miller S, Hernandez M. Effects of relative humidity on the ultraviolet-induced inactivation of airborne bacteria. Aerosol Sci Technol 2001;35:728-40.
41. Riley RL, Kaufman JE. Effect of relative humidity on the inactivation of airborne *Serratia marcescens* by ultraviolet radiation. Appl Microbiol 1972;23:1113-20.
42. Beggs CB, Sleigh PA. A quantitative method for evaluating the germicidal effect of upper room UV fields. J Aerosol Sci 2002;33:1681-99.
43. Lidwell OM. Ultraviolet radiation and the control of airborne contamination in the operating room. J Hosp Infect 1994;28:245-8.
44. Riley RL, Permutt S. Room air disinfection by ultraviolet irradiation of upper air: air mixing and germicidal effectiveness. Arch Environ Health 1971;22:208-19.
45. Lai KM, Burge HA, First MW. Size and UV germicidal irradiation susceptibility of *Serratia marcescens* when aerosolized from different suspending media. Appl Environ Microbiol 2004;70:2021-7.
46. Menzies D, Popa J, Hanley JA, Rand T, Milton DK. Effect of ultraviolet germicidal lights installed in office ventilation systems on workers' health and well being: double-blind multiple crossover trial. Lancet 2003;362:1785-91.
47. Levetin E, Shaughnessy R, Rogers CA, Scheir R. Effectiveness of germicidal UV radiation for reducing fungal contamination within air-handling units. Appl Environ Microbiol 2001;67:3712-5.
48. Memarzadeh F, Jiang Z, Xu W. Analysis of efficacy of UVGI inactivation of airborne organisms using Eulerian and Lagrangian approaches. Available from: http://orf.od.nih.gov/PoliciesAndGuidelines/Bioenvironmental/. Accessed January 31, 2010.
49. Sweeney CP, Dancer SJ. Can hospital computers be disinfected using a hand-held UV light source? J Hosp Infect 2009;72:92-4.
50. Kac G, Podglajen I, Si-Mohamed A, et al. Evaluation of ultraviolet C for disinfection of endocavitary ultrasound transducers persistently contaminated despite probe covers. Infect Control Hosp Epidemiol 2010;31:165-70.
51. Rutala WA, Gergen MF, Weber DJ. Room decontamination by ultraviolet radiation. Infect Control Hosp Epidem 2010, in press.
52. Burgener J. Position paper on the use of ultraviolet lights in biological safety cabinets. Appl Biosaf 2006;11:228-30.
53. Sylvain D, Tapp L. UV-C exposure and health effects in surgical suite personnel: health hazard evaluation report. HETA 2007-0257-3082. Available from: http://www.cdc.gov/niosh/hhe/reports/pdfs/2007-0257-3082.pdf. Accessed January 31, 2010.
54. Berg-Périer M, Cederblad A, Persson U. Ultraviolet radiation and ultraclean air enclosures in operating rooms: UV protection, economy, and comfort. J Arthroplast 1992;7:457-63.
55. Miner AL, Losina E, Katz JN, Fossel AH, Platt R. Infection control practices to reduce airborne bacteria during total knee replacement: a hospital survey in four states. Infect Control Hosp Epidemiol 2005; 26:910-5.
56. Ritter MA, Olberding EM, Malinzak RA. Ultraviolet lighting during orthopaedic surgery and the rate of infection. J Bone Joint Surg Am 2007;89:1935-40.
57. Bartley J, Olmsted RN, Haas J. Current views of healthcare design and construction: practical implications of safer, cleaner environments. Am J Infect Control 2010;38(Suppl):S1-12.
58. Beggs CB, Kerr KG, Donnelly JK, Sleigh PA, Mara DD, Cairns G. The resurgence of tuberculosis in the tropics. An engineering approach to the control of *Mycobacterium tuberculosis* and other airborne pathogens: a UK hospital-based pilot study. Trans R Soc Trop Med Hyg 2000;94: 141-6.
59. Van Osdell D, Foarde K. Defining the effectiveness of UV lamps installed in circulating air ductwork. ARTI-21CR/610-40030-01. Available from: www.osti.gov/energycitations/servlets/purl/810964-SRS2Dd/native/810964.pdf. Accessed January 31, 2010.
60. Kujundzic E, Matalkah F, Howard CJ, Hernandez M, Miller SL. UV air cleaners and upper-room air ultraviolet germicidal irradiation for controlling airborne bacteria and fungal spores. J Occup Environ Hyg 2006;3:536-46.
61. First M, Rudnick SN, Banahan KF, Vincent RL, Brickner PW. Fundamental factors affecting upper-room ultraviolet germicidal irradiation, part I: experimental. J Occup Environ Hyg 2007;4:321-31.