

UV Air Cleaners and Upper-Room Air Ultraviolet Germicidal Irradiation for Controlling Airborne Bacteria and Fungal Spores

Elmira Kujundzic,¹ Fatimah Matakah,¹ Cody J. Howard,²
Mark Hernandez,¹ and Shelly L. Miller²

¹Department of Civil, Environmental and Architectural Engineering, University of Colorado at Boulder, Boulder, Colorado

²Department of Mechanical Engineering, University of Colorado at Boulder, Boulder, Colorado

In-room air cleaners (ACs) and upper-room air ultraviolet germicidal irradiation (UVGI) are engineering control technologies that can help reduce the concentrations of airborne bacteria and fungal spores in the indoor environment. This study investigated six different types of ACs and quantified their ability to remove and/or inactivate airborne bacteria and fungal spores. Four of the air cleaners incorporated UV lamp(s) into their flow path. In addition, the efficacy of combining ACs with upper-room air UVGI was investigated. With the ventilation system providing zero or six air changes per hour, the air cleaners were tested separately or with the upper-room air UVGI system in operation in an 87-m³ test room. Active bacteria cells and fungal spores were aerosolized into the room such that their numbers and physiologic state were comparable both with and without air cleaning and upper-room air UVGI. In addition, the disinfection performance of a UV-C lamp internal to one of the ACs was evaluated by estimating the percentage of airborne bacteria cells and fungal spores captured on the air filter medium surface that were inactivated with UV exposure. Average airborne microbial clean air delivery rates (CADR_m) varied between 26–981 m³hr⁻¹ depending on the AC, and between 1480–2370 m³hr⁻¹, when using air cleaners in combination with upper-room air UVGI. Culturing, direct microscopy, and optical particle counting revealed similar CADR_m. The ACs performed similarly when challenged with three different microorganisms. Testing two of the ACs showed that no additional air cleaning was provided with the operation of an internal UV-C lamp; the internal UV-C lamps, however, inactivated 75% of fungal spores and 97% of bacteria cells captured in the air filter medium within 60 min.

Keywords air disinfection, bioaerosols, upper-room air UVGI

Address correspondence to: Prof. Shelly L. Miller, Department of Mechanical Engineering, 427 UCB, Boulder, CO 80309-0427; e-mail: shelly.miller@colorado.edu.

INTRODUCTION

Indoor and outdoor air contains suspended biological particulate matter (bioaerosols) that can pose a threat to public

health. Airborne transmission of infectious agents resulting in disease has been well documented.^(1–5) The possibility for adverse health effects associated with bioaerosols has prompted an effort to design appropriate engineering control technologies to remove and/or inactivate disease-causing agents from indoor air. In addition to reducing the incidence of respiratory diseases, the application of air cleaning technologies may also reduce the likelihood of airborne disease transmission if pathogenic microorganisms were intentionally released.^(6,7) Engineering control technologies designed to reduce the concentration of bioaerosols within an indoor environment, to protect those who come into close contact with infectious persons, and to prevent bioaerosols from spreading throughout a facility include in-room air cleaning and upper-room air ultraviolet germicidal irradiation (UVGI).

Commercially available low-pressure, mercury-vapor lamps used for UVGI applications emit nonionizing electromagnetic radiation with a substantial amount of spectral power in the UV-C wavelength of 254 nm.^(8,9) UV-C radiation that penetrates to microbial DNA may cause damage sufficient to interrupt cell replication. Upper-room air UVGI is achieved by suspending lamps from the walls or ceiling; the bottom of the lamp is usually shielded to direct radiation upward above a predetermined height in order to maximize UV radiation exposure to airborne microorganisms in the upper part of the room, while minimizing radiation exposure to persons in the lower part of the room.^(10–12) Studies have been performed evaluating the performance of upper-room air UVGI for inactivating bioaerosols.^(11–16)

In-room air cleaning has been used to effectively reduce indoor particle concentrations in many settings^(17–23) and can be achieved by operating devices that circulate room air through fiber filter medium or other technologies designed to collect particles from the incoming air. These devices can be stand-alone or mounted on the ceiling or walls. New generation cleaning devices also incorporate UV-C lamps in their design

with the objective of inactivating microorganisms as they pass through the air cleaner, or inactivating bioaerosols trapped on air filter medium surfaces. It has been suggested that some bacteria and fungal spores captured in air filter medium may be able to survive over prolonged time periods under certain environmental conditions and retain potential for microbial growth.^(24,25)

Information on the efficacy of engineering control technologies is needed to provide a rational basis for developing strategies to reduce the incidence of bioaerosol-related health problems. To assess the impact of a control that targets airborne biological agents, especially those that incorporate UVGI, it is useful to challenge a device with a bioaerosol similar to those that cause symptoms and diseases in realistic settings. The overall objective of this study was to conduct experiments to quantify the rate at which bioaerosols are removed and/or inactivated by six ACs (some of which contain UV lamps) and by ACs combined with the operation of an upper-room air UVGI system. UV-C lamp performance was also evaluated for one of the ACs by estimating the percentage of bacteria cells and fungal spores captured on the air filter medium surface that was inactivated upon UV exposure.

METHODS

Test Room and Air Cleaners

A full-scale test room established at the Joint Center for Energy Management's Larson Building Systems Laboratory, University of Colorado at Boulder, as previously described,^(12,16,26) was used for this study. An 87-m³ room housed inside the laboratory was used for testing. The temperature and relative humidity (RH) for all experiments were maintained at ambient room conditions: 20°C to 25°C and 20% to 30% RH. The test room has an as-built infiltration rate of 0.1–0.3 air changes per hour (ACH or hr⁻¹). It is equipped with a computer-controlled ventilation system. During testing, the ventilation's supply and exhaust airflow were balanced to achieve exhaust airflow greater than the supply, such that there was a negative pressure of 12 Pa within the room relative to the surrounding laboratory. The negative pressure was continuously monitored and maintained using pressure gauges and ventilation system feedback-control loops.

During testing, air cleaners were located near the wall or at the center of the test room. The location of an air cleaner in a room does not impact its performance if the room air is well mixed.⁽²²⁾ Six ACs were tested: three combination air cleaners containing both fibrous air filter medium and UV lamp(s), two ionizers (one with and one without a UV-C lamp), and one electrostatic precipitator. UV lamps within air cleaners may result in the inactivation of airborne microorganisms through either or both of the following two scenarios: (1) by sufficiently exposing airborne microorganisms not retained on filter medium surfaces (i.e., during "blow-by") to UV light, or (2) by sufficiently exposing airborne microorganisms immobilized on filter medium surfaces to UV light.⁽¹⁹⁾

Characteristics of the ACs are presented in Table I. Airflow rates for most of the air cleaners were independently measured at a National Institute for Occupational Safety and Health (NIOSH) laboratory.⁽²⁷⁾

The HEPA-UV cleaner (H_{UV}) contained a high-efficiency particulate air (HEPA) filter and UV lamps. The unit prefilters air using an extended filter surface and an electrostatic air filter. Air then enters an irradiated chamber containing one UV-A/UV-B medium pressure metal halide quartz lamp (400 W) and eight UV-C lamps (15 W each). The irradiated particles are then collected on a HEPA filter where they are again irradiated by UV-C lamps.

The ceiling-mounted HEPA-UV cleaner (cH_{UV}) was a prototype of a new generation of high-volume, ceiling-mounted AC modified with two UV-C lamps (36 W each). UV-C lamps are located on both sides of a HEPA filter. The air is drawn first past the HEPA filter medium and then through the UV-C lamps.

A second prototype air cleaner was also tested in this study, which includes both electrostatic filtration technology and a UV-C lamp (E_{UV}). Particle-laden air is pulled through an electrically charged air filter before being released into the general room air. The air filter is irradiated on the upstream side with one UV-C lamp (25 W). The performance of the UV-C lamp for inactivating captured microorganisms on the filter medium was evaluated in separate set of experiments.

The ionizer-UV cleaner (I_{UV}) combines ionization air cleaning technology with a single UV-C lamp (15 W). Airborne particles are electrically charged and captured on oppositely charged stainless steel plates. This unit does not have a blower or a fan.

The negative ion-generator (N) contains a high-voltage cathode that generates electrons that attach to air molecules generating ions with a negative charge. The ions can collide with airborne particles, charging the particles. The charged particles released into the air can attach to surfaces or can attract positive particles so that they coagulate and grow in size until they are large enough to settle and subsequently be removed by general cleaning methods (e.g., vacuuming or dusting).

The electrostatic precipitator (EP) contains an ionizer. As particles pass through the ionizer section, they are given an intense positive charge. These charged particles are then collected on cell plates that are located inside the EP. The cleaned air is redistributed into the room through an outlet diffuser.

A modern UVGI system (Lumalier, Memphis, Tenn.) was installed in the test room and consisted of five fixtures, four mounted in each of the corners of the room, and one hung from the center of the ceiling. The center fixture was rated at 72 W and had four lamps. The corner fixtures were rated at 36 W each and contained two lamps installed with parabolic aluminum reflectors on the back of the fixtures. Each fixture was equipped with concentric black louvers of 1.9 cm spacing. The fixtures were installed so that the lower edge was located 2.1 m above the floor, and the top was 10 cm below the ceiling. This placement created a 30-cm-wide band of UVGI in the upper level of the room. In a previously performed set of experiments, the UVGI fluence rate distribution in the test room

TABLE I. Characteristics of Tested Air Cleaners

Air Cleaner Type	HEPA Air Cleaner with UV-A,B,C Lamps (H_{UV})	Ceiling-Mounted HEPA Air Cleaner with UV-C Lamps (cH_{UV})	Electrostatic Filter with UV-C Lamp (E_{UV})	Ionizer with UV-C Lamp (I_{UV})	Negative Ion Generator (N)	Electrostatic Precipitator (EP)
Manufacturer	Halogenetic Irradiation Technology, Inc.	Honeywell	Phototype	Sharper Image ^A	Quorum Int.	United Air Specialists, Inc.
Manufacturer-specified airflow rates ($m^3 hr^{-1}$)	934	1,700	476	NS	NS	255–578
Measured airflow rate ($m^3 hr^{-1}$) ^B	856	NM	476	46	41	127–207
Intake position	Top	Bottom	Back	Back	Back	Left-right
Exhaust position	Front	Sides	Front	Front	Top	Right-left
Dimensions (m)	$1.09 \times 0.79 \times 0.56$	$1.22 \times 0.61 \times 0.58$	$0.94 \times 0.3 \times 0.43$	$0.74 \times 0.28 \times 0.19$	$0.28 \times 0.25 \times 0.13$	$0.3 \times 0.38 \times 0.48$
Weight (kg)	91	67	12	5	2	18
Purchase cost	\$6250	\$2500	NA	\$500	\$340	\$722
Mounting options	Portable	Ceiling	Portable	Portable	Portable	Portable/ceiling

Note: NS = not specified; NM = not measured; NIOSH facility no longer available for use; NA = not applicable (prototype).

^ARetailer.

^BIndependently measured at NIOSH facility (see Ref. 27).

was evaluated using spherical actinometry.⁽²⁸⁾ To measure the fluence rate in the upper zone of the room, actinometers were suspended at 20 evenly spaced locations 2.3 m from the floor and exposed to UVGI for 30 min. UVGI fluence rate was estimated to be $44 \pm 20 \mu\text{W}/\text{cm}^2$ at 216 W (all room lamps on) and $20 \pm 8 \mu\text{W}/\text{cm}^2$ at 108 W (half of the room lamps on).^(12,16)

Test Bioaerosols

Mycobacterium parafortuitum (American Type Culture Collection, ATCC 19689) was aerosolized during most of the experiments. *M. parafortuitum* is a nonmotile, rod-shaped bacterium 2–4 μm long.⁽²⁹⁾ It grows rapidly on standard bacterial culture medium and produces smooth, pale yellow colonies that disperse readily in water. This bacterium was used in this study because its cells have been used as nonpathogenic surrogates for tuberculosis in other bioaerosol studies.^(12,16,30) *Micrococcus luteus* was aerosolized for a subset of experiments in which the performance of the EP was tested. *M. luteus* (ATCC 4698) is a Gram-positive bacterium with spherical cells 0.9–1.8 μm in diameter that can often occur in tetrads of four cells.⁽³¹⁾ It produces yellow to cream white pigmented colonies on standard bacterial culture medium. *Aspergillus versicolor* (ATCC 52173) was also aerosolized for a subset of experiments in which the performance of the I_{UV} and E_{UV} were tested. *A. versicolor* was used in this study because its spores have been successfully used as subpathogenic fungus surrogates in past bioaerosol research.^(32,33) *A. versicolor* spore dimensions were measured in this study using microscopy. Spore diameters ranged from 5 μm to 7 μm .

Bacteria were grown on soybean-casein digest agar (SCDA; Difco Laboratories, Detroit, Mich.) at 37°C. Just before aerosolization, bacteria cells were removed from agar plate surfaces by aseptic scraping with a sterile glass rod and were suspended in a 15-mM phosphate buffer solution (PBS; 10 mM sodium phosphate buffer; 5 mM NaCl; pH 7.2). Fungus was grown on malt extract agar (MEA; Difco) at 24°C. Just before aerosolization, *A. versicolor* spores were removed from plate surfaces by shaking with 3-mm sterile glass beads and suspended in sterile water with addition of 0.1% Tween 80 (Sigma, St. Louis, Mo.).

Bioaerosol Generation

Test bioaerosol was generated using a six-jet Collison nebulizer (CN 25; BGI Inc., Waltham, Mass.) with a 250-mL reservoir. The nebulizer was located outside the test room in an adjacent room housed within the laboratory. A biosafety cabinet (Nuair Inc., Plymouth, Minn.) was installed in this adjacent room for storage of bioaerosol generation supplies. The nebulizer was operated at 138 kPa, generated by a compressed air cylinder in series with an air supply system that includes a dehumidifier, a HEPA filter, and a regulator (model 3074, TSI Inc., St. Paul, Minn.). The bioaerosol was delivered from the atomizer discharge port into the test room at 12.5 L/min through 2.5 m of flexible tubing with a 1.6 cm inner diameter.

Bioaerosol was generated from liquid suspensions achieving room air concentrations between 10^8 – 10^{12} bacterial cells per m^3 or approximately 10^6 fungal spores per m^3 . The volumetric airflow rate of the suspension leaving the nebulizer ranged between 0.12–0.33 mL/min. Test bioaerosol was released approximately 1.5 m above the floor. Bioaerosol was generated continuously to raise the concentration in the room to a suitable level for detection (usually 30 min for bacteria and 75 min for fungi). No ventilation was provided during this period, and two box fans (48 cm diameter) were turned on to ensure mixing. Once the bioaerosol concentration reached the desired level, generation ceased and the concentration was allowed to decay.

The location of the aerosol source with respect to the ventilation supply and exhaust air is an important factor that influences the effectiveness of in-room engineering control technologies.⁽²²⁾ Bioaerosol was generated in the center of the room between the ventilation exhaust and supply airflow in accordance with the Centers for Disease Control and Prevention recommendation that specifies that clean air first flows to less contaminated areas, then flows across the infectious source and into the exhaust.⁽¹⁰⁾

Bioaerosol Sampling

Airborne bacteria cells were sampled with all-glass liquid impingers (AGI-30, Ace Glass Inc., Vineland, N.J.). Airborne fungal spores were sampled with swirling aerosol collectors (BioSampler; SKC Inc., Eighty Four, Pa.). Airborne bacteria cells and fungal spores were sampled at one room location. Previous research showed that under the current test room configuration with mixing fans operating, the room is well mixed and the bioaerosol concentration within the room can be represented by a few samples.⁽³⁴⁾ Bioaerosol samplers were positioned in the breathing zone, 1.6 m above the floor, below the ventilation exhaust outlet. Before each experiment, bioaerosol samplers were completely disassembled; washed thoroughly with ethanol and distilled, deionized water; and autoclaved at 203 kPa (2 atm) and 120°C for 15 min. AGI-30s collected bacteria cells in 30 mL of sterile 15 mM PBS. BioSamplers collected fungal spores in 20 mL of sterile 15 mM PBS.

For the *M. parafortuitum* experiments, air was sampled five times during the decay period. Two AGI-30s were operated simultaneously to collect duplicate samples for 30 sec to 20 min, depending on the experimental scenario.

For the *A. versicolor* experiments, the air was sampled for 30 min. More time was needed for fungal spore sampling because the airborne concentration that could be initially achieved in the room was much lower for fungal spores as compared with the bacteria cells. Air samples were collected three times sequentially during the decay period. Two BioSamplers were operated simultaneously to collect duplicate samples.

All air samples were collected at the airflow rate of 12.5 L/min with a high-flow sampling pump (model 1023-1 01 Q; Gast Manufacturing Inc., Benton Harbor, Mich.) regulated with rotameters (model 7400, King Instruments

Inc., Garden Grove, Calif.). The pump and rotameters were calibrated using a primary flow meter (Dry Cal; DC-Lite, Butler, N.J.).

Bioaerosol Quantification

Three independent methods were used for bioaerosol quantification: (1) culturing, (2) direct microscopy, and (3) optical particle counting.

Culturing

Concentrations of culturable heterotrophic bacteria and fungal spores were determined by plating of liquid-capture air samples and expressed as colony forming units (CFUs) per cubic meter of air sampled. Nondiluted liquid was plated onto nutrient-rich SCDA or MEA medium for bacteria cells and fungal spores, respectively, using a spiral-dispensing method (Spiral Biotech Inc., Bethesda, Md.) according to manufacturer's recommendations. Plates were incubated at 37°C for 2–3 days for *M. parafortuitum* and 1 day for *M. luteus*. For *A. versicolor*, plates were incubated at 24°C for 7–10 days. All colonies were counted. All plating was performed in indirect dimmed light, and all incubations were carried out in the dark to control for potential photoreactivation. At least three replicates of each sample were plated.

Direct Microscopy

Number concentrations of total bacteria cells were determined using direct microscopy.^(30,35) Fungal spores in-room number concentrations, however, could not be determined using this method because the detection limit was too high. Detection limit for direct microscopic evaluation of fungal spores was approximately 10⁴ number fungal spores/mL. Direct microscopy was used only to determine the number concentration of fungal spores in solution prepared for aerosolization. Bacteria cells were stained and enumerated with 4',6-diamidino-2-phenylindole (DAPI), a DNA-binding fluorescent stain. Fungal spores were stained with acridine orange (AO), also a DNA-binding fluorescent stain. Solutions containing bioaerosols were stained and passed through 25-mm, 0.22- μ m (pore diameter), and 0.4- μ m polycarbonate membrane filters for bacteria cells and fungal spores, respectively. Microorganisms retained on the filter surface were mounted using low fluorescence immersion oil containing an antifadent (CitiFluor Ltd., Leicester, England), and were examined under 1100 \times magnification using a Nikon Eclipse E400 epifluorescence microscope fitted with a mercury lamp and polarizing filters. Between 5 and 10 random microscopic fields were counted per slide. All counts were reported as the average of all microscopic fields counted. In accordance with the statistical criteria previously reported, counts from aliquots having coefficients of variation greater than 30% were discarded, and new sample aliquots were stained and counted until the distribution of microorganisms immobilized was judged as uniform by these criteria.⁽³⁵⁾

Optical Particle Counting

An optical particle counter (OPC, model 237B; Pacific Scientific Instruments Inc., Grants Pass, Ore.) was used to monitor the number of particles in a size range between 0.3 μ m to >5 μ m (six size bins: 0.3–0.5, 0.5–0.7, 0.7–1, 1–2, 2–5, and >5 μ m). The OPC collected particles for 30 seconds every minute at a sampling airflow rate of 2.83 L/min. Before experiments, OPC calibration was accomplished by the manufacturer.

Ozone Measurements

The I_{UV} air cleaner was evaluated for ozone generation. The I_{UV} was turned on for a period of 12 hours in the test room, during which time ozone reached steady-state concentrations. No mechanical ventilation was provided (the natural infiltration rate was 0.3 h⁻¹), and two box fans were turned on the high setting to ensure well-mixed conditions within the room. Ozone concentrations were measured continuously every minute using a UV photometric ozone analyzer (model 49C; Thermo Environmental Instruments Inc., Franklin, Mass.). The analyzer has a detection limit of 1 ppb, and it is suitable for monitoring ozone in the temperature range between 5°C and 45°C. The ozone analyzer was calibrated against a custom lab-built UV ozone sensor that works on the same principles as the ozone analyzer. Based on a series of calibrations, the ozone concentrations detected by the ozone analyzer were accurate to within 5%.

Experimental Protocol

For each experiment, bioaerosol was generated continuously until the concentration in the room reached a suitable level for detection. Once the bioaerosol concentration reached the desired level, generation ceased, the AC and/or upper-room air UVGI were turned on, and air sampling was initiated. The concentration within the room decreased over time once generation ceased. Mixing fans were on during the decay period. Observation periods varied between 5 min and 270 min, depending on the rate at which the AC removed bioaerosol. Observation periods also varied depending on the room ventilation rate. Experiments involving the N, EP, and H_{UV} air cleaners were performed at two mechanical ventilation rates: zero and six air changes per hour; all other ACs were tested at zero air changes per hour.

All experiments involving upper-room air UVGI were performed at zero air changes per hour and in the dark to control for any potential photoreactivation.

Although the cH_{UV} air cleaner is to be installed on the ceiling, it was tested in this study by placement on the floor. Ceiling installation could affect room airflow patterns and air cleaner performance.⁽²⁰⁾ However, because the experiments in this study were conducted under well-mixed conditions, the placement of the cH_{UV} did not impact the outcome of the experiments.

For two units, the I_{UV} and E_{UV}, experiments were designed to explore whether the internal UV-C lamps had any additional

TABLE II. Experimental Scenarios

Experimental Scenario	Air Cleaner Configuration (UV Lamp Engagement)	Test Bioaerosol	Ventilation (ACH, hr ⁻¹)	Upper-Room Air UVGI Level	Number and Type of Analysis ^A
H _{UV} -MP-0	Internal UV-A,B,C	<i>M. parafortuitum</i>	0	0	3D, 2(D + C + OPC)
H _{UV} -MP-6	lamps on for	<i>M. parafortuitum</i>	6	0	3D, 1C
H _{UV} -MP UVGI@100%	all experiments	<i>M. parafortuitum</i>	0	100%	2(D + C)
H _{UV} -MP UVGI@50%		<i>M. parafortuitum</i>	0	50%	2(D + C)
cH _{UV} -MP-0	Internal UV-C lamps on	<i>M. parafortuitum</i>	0	0	3(D + OPC)
E _{UV} OFF-MP-0 ^B	UV-C lamp off	<i>M. parafortuitum</i>	0	0	1(D + C)
E _{UV} ON-MP-0	UV-C lamp on	<i>M. parafortuitum</i>	0	0	1(D + C)
E _{UV} OFF-AV-0	UV-C lamp off	<i>A. versicolor</i>	0	0	2C
E _{UV} ON-AV-0	UV-C lamp on	<i>A. versicolor</i>	0	0	2C
I _{UV} OFF-MP-0 ^B	UV-C lamp off	<i>M. parafortuitum</i>	0	0	2(D + C)
I _{UV} ON-MP-0	UV-C lamp on	<i>M. parafortuitum</i>	0	0	2(D + C)
I _{UV} OFF-AV-0	UV-C lamp off	<i>A. versicolor</i>	0	0	2C
I _{UV} ON-AV-0	UV-C lamp on	<i>A. versicolor</i>	0	0	2C
N-MP-0		<i>M. parafortuitum</i>	0	0	3D, 1C
N-MP-6		<i>M. parafortuitum</i>	6	0	3D
EP-MP-0 ^B		<i>M. parafortuitum</i>	0	0	4D, 1C
EP-MP-6		<i>M. parafortuitum</i>	6	0	3D
EP-ML-0		<i>M. luteus</i>	0	0	2C
EP-MP UVGI@100%		<i>M. parafortuitum</i>	0	100%	2(D + C)

^ANumber denotes the number of times that the experiment was repeated.

^BEP, I_{UV}, and E_{UV} tested on high setting.

air cleaning effect by inactivating airborne bacteria cells and fungal spores as they passed through the device. Experiments were performed with the UV-C lamp in operation and without the lamp in operation.

Experimental scenarios are given in Table II. Scenarios are named according to the air cleaner that was tested, the bioaerosol that was used (MP for *M. parafortuitum*, ML and for *M. luteus*, AV for *A. versicolor*), and the ventilation rate within the room during the experiments (zero or six ACH or hr⁻¹). The EP, I_{UV}, and E_{UV} were tested on the manufacturers' high setting. In Table II, the experiments conducted with the upper-room air UVGI system operating at 100% available UVGI are denoted as UVGI@100% (216 W, all room lamps on), and at 50% available UVGI are denoted as UVGI@50% (108 W, half of the room lamps on).

Analysis type is also given in Table II. Analysis type refers to whether the bioaerosol samples were subsequently analyzed by direct microscopy (D), culturing (C), or particle counting (OPC). Most of the analyses were done using direct microscopy or culturing. In a few experiments, both direct microscopy and culturing were used to analyze the same sample volume; these runs are denoted as D + C.

Completely Mixed Room Model

The clean air delivery rate (CADR) was employed to describe air cleaner performance. The clean air delivery rate is the airflow rate that represents the effective amount of particle-clean air produced by the air cleaner.⁽²¹⁾ Theoretically

it is equal to the single-pass efficiency of a device (fractional removal of pollutants from the air stream as it passes through the device) multiplied by the airflow rate through the device.⁽³⁶⁾ The Association of Home Appliance Manufacturers (AHAM) has a certification program for labeling particulate air cleaners that provides retail labeling the CADR for removing dust, tobacco smoke, and pollen.⁽³⁷⁾ For this study a modification of the AHAM test method was used to determine the CADR for microbiological aerosols, termed CADR_m.⁽¹⁷⁾

A completely mixed room model was used to estimate the removal rate of the air cleaning technologies as previously described.^(16,20) The removal/inactivation rate (R) is defined here as the CADR_m for airborne bacteria cells or fungal spores associated with the operation of the air cleaner (or the upper-room air UVGI system) divided by the room volume in which it has been applied.

According to the completely mixed room model, the bioaerosol concentration as a function of time is described by the following equation.⁽¹¹⁾

$$\ln C(t) = \ln C_0 - (R_0 + R_D + R_V + R_{\text{mAC}} + R_{\text{UVGI}})t \quad (1)$$

where C(t) is the concentration of bioaerosol at time t (number m⁻³ or CFU/m³), C₀ is the concentration of bioaerosol at time t = 0 (number m⁻³ or CFU/m³), R₀ is the removal rate of bioaerosol due to natural die-off, R_D is the removal rate due to deposition onto surfaces, R_V is the removal rate of bioaerosol due to ventilation, R_{AC} is the removal rate

of bioaerosol due to air cleaner operation, and R_{UVGI} is the inactivation rate of bioaerosol due to upper-room air UVGI. All removal/inactivation rates are expressed in air changes per hour (ACH or hr^{-1}). This equation can be applied to a material balance on total and culturable number of cells/spores. For example, if applied to culturable number all removal rates were included. For total number of particles, R_O and R_{UVGI} would not apply. Using data derived from direct microscopy analysis (or OPC) gives an estimate of $(R_D + R_V + R_{AC})$ if air cleaner was running or $(R_D + R_V)$ if air cleaner was turned off, since direct microscopy gives a measure of the total number of airborne microorganisms. Using data derived from culturing analysis gives an estimate of $(R_O + R_D + R_V + R_{AC})$ with air cleaner operating or $(R_O + R_D + R_V + R_{AC} + R_{UVGI})$ with air cleaner and upper-room air UVGI operating, since culturing gives a measure of the number of colony forming units of selected airborne microorganisms. In the controlled experiments conducted here, specific microorganisms were grown on nutrient medium, thus the number of microorganisms suspended in the air that were estimated by direct microscopy were directly related to estimates made by culturing.

The removal rates $(R_O + R_D + R_V)$ were estimated by conducting an experiment using the decay protocol in which no ACs or upper-room air UVGI were operated. All other rates were estimated by conducting a decay experiment with ACs and/or upper-room UVGI in operation. Removal and inactivation rates were estimated using least-squares linear regression to fit removal/inactivation decay data, according to Eq. 1 and then differenced. The CADR_m was estimated by multiplying the observed bioaerosol removal/inactivation rate, R_{AC} and R_{UVGI} , by the volume of the test room (87 m^3).

Experimental Protocol to Evaluate UV-C Lamp Performance

UV-C lamp performance in the E_{UV} air cleaner was evaluated by estimating the percentage of microorganisms captured on the air filter medium surface that were inactivated by time-integrated UV exposure. Duplicate experiments were conducted using both the vegetative cells of bacterium *M. parafortitium* and the spores of the fungus *A. versicolor*. Active bacteria cells and fungal spores were generated in such manner that their numbers and physiologic state were comparable with and without the UV-C lamp in operation; culturable concentrations up to 1.5×10^6 and 4.6×10^4 CFU/mL in eluted solution were achieved for bacteria cells and fungal spores, respectively.

Experiments were designed to collect and analyze five separate pieces of air filter medium surface that were loaded with microorganisms and subsequently exposed to UV for varying lengths of time. Prior to testing, five square pieces were precut in the air filter medium (each roughly 8 cm by 7 cm). This precut air filter medium was then placed tightly inside the air cleaner for testing. At the start of each experiment the air cleaner was engaged but the UV-C lamp kept off. Bioaerosol was generated continuously upstream and directly into the inlet of the air cleaner for 60–120 min (the air cleaner was 0.3–1 m

away from the generation source). Aerosolization was ceased and the UV-C lamp was then turned on for a period of 30 min. After that, the first precut filter piece was removed from the air filter medium and was replaced with a new one. A new piece was placed inside so that the filter medium remained intact. The UV-C lamp was turned on for another 30 min. After that the second filter piece was removed from the air filter medium and was replaced with a new one. Three more air filter medium pieces were exposed to UV in this manner for 30-min segments for total exposure times of 90 min, 120 min, and 150 min. This experiment was then repeated with the UV-C lamp turned off.

Immediately following the test, under aseptic conditions, the filter medium pieces were placed in glass beakers with 100–200 mL of PBS and eluted for 1 hour in a sonication bath (Fisher Scientific) at room temperature. This eluent was analyzed by culturing and/or direct microscopy as previously explained. The above-described elution technique (the use of ultrasound) could not recover all bioaerosol attached on the air filter medium.⁽³⁸⁾ However, tests showed that the elution procedure yielded consistent results for air filter medium prepared under identical conditions and eluted more than enough microorganisms for rigorous statistical evaluation.

UV-C lamp performance was defined as the fraction of the concentration of culturable bacteria cells, normalized to the total concentration of bacteria cells that survived UV-C lamp exposure as compared with otherwise identical conditions without UV exposure:

$$\text{Inactivation} = \left(1 - \frac{C_{UVon}/D_{UVon}}{C_{UVoff}/D_{UVoff}} \right) \times 100\% \quad (2)$$

where $C_{UVon/off}$ is the bacterial concentration obtained by culturing with the UV-C lamp on/off (CFU m^{-3}); $D_{UVon/off}$ is the total concentration of bacteria obtained by direct microscopy with the UV-C lamp on/off (number m^{-3}).

During fungal spore analysis, an equation similar to Eq. 2 was used to calculate the UV-C lamp performance, except that the culturable fungal spore concentrations were not normalized to the total concentration of fungal spores. Total concentrations could not be determined due to fungal spore concentrations being below the method detection limit of direct microscopy.

RESULTS AND DISCUSSION

Air Cleaners Effective in Removing Bioaerosol

Clean air delivery rates of the air cleaners ranged more than two orders of magnitude (Table III) when challenged with microbiological aerosol. T-tests assuming unequal variances ($\alpha = 0.05$) showed that there was no significant difference between bioaerosol quantification methods, type of bioaerosol, ventilation rates, or internal UV-C lamp operation. Averaged clean air delivery rates with their standard deviations are presented in Table III.

TABLE III. Clean Air Delivery Rates for Air Cleaners

Experimental Scenario	CADRM (m ³ hr) ^A	Total Number of Experiments	Average CADRM (Std. Dev.) (m ³ hr)
H _{UV} -MP-0	773; 1,090; 1,237; 675; 703; 606 (OPC); 675 (OPC); 1,221 (C); 1,235 (C)	13	933 (244)
H _{UV} -MP-6	957; 1,072; 742; 1,149 (C)		
cH _{UV} -MP-0	904; 802; 993; 1,170 (OPC); 1,021 (OPC); 993 (OPC)	6	981 (123)
E _{UV} OFF-MP-0 ^B	72; 229 (C)	8	155 (67)
E _{UV} ON-MP-0	121; 261 (C)		
E _{UV} OFF-AV-0	125 (C); 102 (C)		
E _{UV} ON-AV-0	127 (C); 200 (C)		
I _{UV} OFF-MP-0 ^B	30 (C); 69 (C)	10	26 (17)
I _{UV} ON-MP-0	21; 36 (C); 20; 26 (C)		
I _{UV} OFF-AV-0	17 (C); 5 (C)		
I _{UV} ON-AV-0	13 (C); 23 (C)		
N-MP-0	32; 25; 23; 37 (C)	7	31 (8)
N-MP-6	21; 42; 39		
EP-MP-0 ^B	551; 663; 652; 533; 778 (C)	10	529 (139)
EP-MP-6	520; 418; 361		
EP-ML-0	467 (C); 343 (C)		

^ARemoval rate determined by direct microscopy unless noted by a “C” or “OPC”, which indicates that culturing or optical particle counter was used.

^BEP, I_{UV} and E_{UV} tested on high setting.

Different Bioaerosol Quantification Methods Revealed Same Air Cleaner Performance

In this study, three independent methods of quantifying bioaerosol (culturing, direct microscopy, and optical particle counting) were performed. There was no significant difference in estimating removal rates using these respective types of analyses (t-test: assuming unequal variances, $\alpha = 0.05$). For example, for experiment cH_{UV}-MP-0, the clean air delivery rate using direct microscopy was in the range between 802–993 m³hr⁻¹, when determined using optical particle counting, the clean air delivery rate was in the range between 993–1170 m³hr⁻¹.

Because there were no significant differences between performance indices determined using culturing, direct microscopy, or optical particle counting, these results suggest that for the microorganisms used in this study the rate of natural die-off, R_O, was negligible compared with the other removal rates.

Air Cleaners Performed Similarly for Different Bioaerosols

The data from this research showed no significant difference in the EP CADRM observed using *M. parafortuitum* as compared with that observed for the removal of *M. luteus* (t-test: assuming unequal variances, $\alpha = 0.05$). The CADRM obtained from challenge tests of the fungus *A. versicolor* were not significantly different from the CADRM for bacterium *M. parafortuitum* when challenging both the I_{UV} and E_{UV} air cleaning units (t-test: assuming unequal variances, $\alpha = 0.05$). This finding suggests that when these units are operated in

a multipass fashion, in which indoor air laden with biological particles passes through the air cleaner multiple times, differences in particle size or cellular morphology may not significantly impact performance where intact microbiological cells and spores are involved. Similar findings were also reported previously, when comparing air cleaner removal rates as determined using airborne *B. subtilis* spores and tracer salt particles.⁽²⁰⁾

Ventilation Did Not Impact Air Cleaner Performance

Three air cleaners were tested under two different room ventilation scenarios. A rate of six ACH provided by the test room’s ventilation system did not significantly impact the CADRM of the air cleaners (t-test: assuming unequal variances, $\alpha = 0.05$) as expected. Theoretically, all removal rates are independent and additive in a completely mixed room. Situations may occur in which, in a poorly mixed room, airflow from ventilation systems could disturb air cleaner performance.

No Additional Air Cleaning with UV-C Lamps

Testing of the I_{UV} and E_{UV} demonstrated that the internal UV-C lamps did not provide any additional air cleaning benefits because no significant differences in the CADRM were observed between experiments with or without the UV-C lamp engaged (t-test: assuming unequal variances, $\alpha = 0.05$).

Most Airflow Rate Efficiencies Less Than 100%

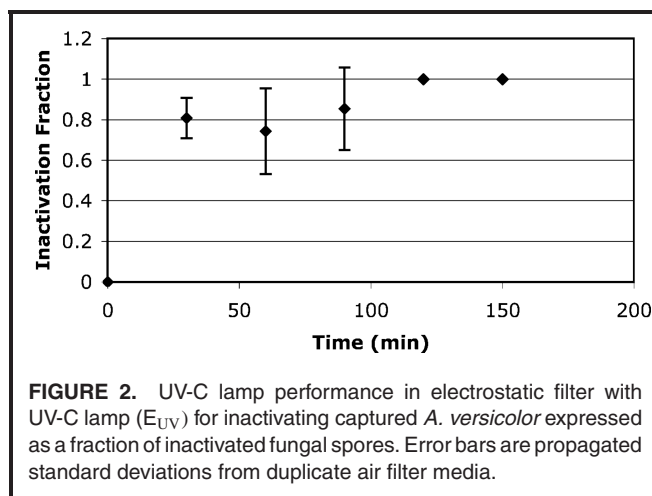
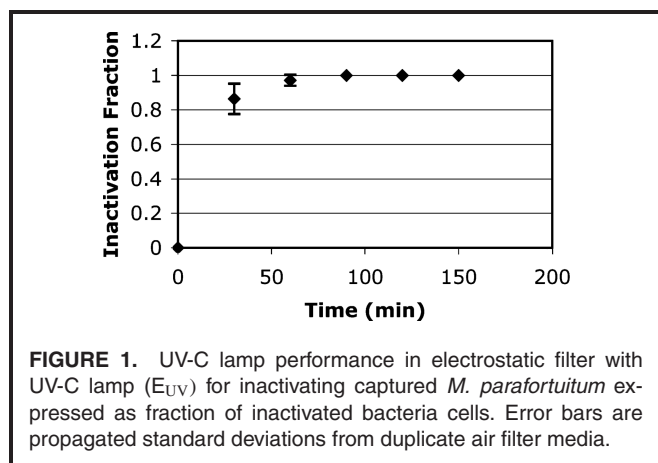
As judged by CADRM, the performance reported by manufacturers was different from that observed under the conditions tested. These departures are reported as manufacturers airflow

rates normalized by the CADR observed (reported as %). In all cases this ratio was less than 100%. For N and I_{UV}, the measured airflow rate was used for the calculation, since the manufacturer did not report the airflow rate for these units (see Table I). The relative efficiencies of the cH_{UV} cleaner and N were at 58% and 77%, respectively. The EP had a relative efficiency of 85%. The I_{UV} and E_{UV} had relative efficiencies of 56% and 36%, respectively. The H_{UV} cleaner had the highest efficiency near 100%.

UV-C Lamps Inactivated Bioaerosol Retained on the Air Cleaner Filter Medium Surface

Experiments investigating effects of the UV-C lamp inside the E_{UV} showed that the lamp inactivated bacteria cells and fungal spores captured on the air filter medium surface. Tests with filter-immobilized *M. parafortuitum* showed that it took 60 min to inactivate 97% of culturable bacteria cells retained on the air filter medium (Figure 1). Exposure for 90 min completely inhibited the recovery of culturable bacteria cells from the air filter medium. Tests with the fungal spores of *A. versicolor* showed that 75% inactivation of fungal spores on the air filter medium took approximately 60 min (Figure 2); exposures at 120 min completely inhibited the recovery of culturable fungal spores from the air filter medium. The uncertainties reported here were determined by duplicate exposed and tested air filter medium as well as from multiple assay quantification.

In a previously published study,⁽³⁹⁾ researchers challenged different air filter media with pure cultures of bacteria: *Escherichia coli* and *M. luteus*. The air filter face velocity was kept at 1 m/sec, and RH was between 30% and 60%. The viability of bacteria cells recovered declined on air filter media within the observation period (60 min). In a polyester air filter medium, the inactivation was about 96% for *E. coli*, whereas the inactivation of *M. luteus* was notably lower (~40%). The decline rate was strongly dependent on air filter medium and type of bacterium employed. Gram-positive bacteria (e.g., *M. luteus*) were more resistant to



environmental stress factors than Gram-negative bacteria (e.g., *E. coli*).⁽³⁹⁾

Air Cleaning via ACs and Upper-Room Air UVGI Removal/Inactivation Rates Are Additive

A series of experiments investigating the operation of air cleaners in conjunction with the operation of an upper-room air UVGI system showed that this combination of controls can remove/inactivate airborne bacteria at very high rates. These controls were applied in combination with each other. Table IV provides the clean air delivery rates observed.

Data from this study showed that removal/inactivation rates using air cleaning via ACs in combination with upper-room air UVGI are additive, as would be expected under completely mixed conditions. When isolating ACs, the average (\pm propagated standard deviation) CADR_m for the EP and H_{UV} cleaner was $529 \pm 139 \text{ m}^3\text{hr}^{-1}$ and $933 \pm 244 \text{ m}^3\text{hr}^{-1}$, respectively. Using the same test room and operating the total available power to the upper-room air UVGI, a previous study⁽¹⁶⁾ reported the CADR_m for *M. parafortuitum* to be $1392 \pm 157 \text{ m}^3\text{hr}^{-1}$. Summing these rates, the CADR_m for the EP plus upper-room air UVGI was expected to be $1921 \pm 148 \text{ m}^3\text{hr}^{-1}$, which agrees well with the average of the CADR_m found in this study (Table III): $1889 \pm 344 \text{ m}^3\text{hr}^{-1}$. Similarly, the CADR_m for the H_{UV} plus upper-room air UVGI

TABLE IV. Clean Air Delivery Rates for Upper-Room Air UVGI

Experimental Scenario ^A	Air Cleaner + UVGI CADR _m (m ³ hr ⁻¹)	Average CADR _m (m ³ hr ⁻¹)
EP-MP UVGI@100% ^B	2061; 1717	1889
H _{UV} -MP UVGI@100%	2242; 2503	2373
H _{UV} -MP UVGI@50%	1538; 1421	1480

Note: All experiments were performed using direct microscopy and culturing.

^AThe ventilation rate provided to the test room was 0 air changes per hour.

^BEP tested on high setting.

was expected to be $2325 \pm 201 \text{ m}^3\text{hr}^{-1}$, which agrees with the average of the CADR_m found in this study (Table IV): $2373 \pm 261 \text{ m}^3\text{hr}^{-1}$.

When the upper-room air UVGI was decreased, the CADR_m was also decreased accordingly. In the H_{UV} experiments, when the upper-room air UVGI was decreased by 50%, the averaged clean air delivery rates subsequently decreased by 38%.

Ionizer Air Cleaners Generate Ozone

The results of the tests measuring ozone during the operation of the ionizer equipped with a UV-C lamp (I_{UV}) showed that the steady-state ozone concentration was 33 ppb. The U.S. Food and Drug Administration prohibits devices that result in more than 50 ppb of ozone in the air of occupied enclosed spaces, such as homes, offices or vehicles, or that result in any releases of ozone in places occupied by the ill or infirm.⁽⁴⁰⁾

Previous testing in a 44-m³ test room showed that the negative-ion generator (N) used in this study generated ozone at concentrations up to 22 ppb.⁽²⁷⁾ The EP was also tested previously, and 4 ppb of ozone was generated during its use.⁽⁴¹⁾

Cleaned Room Volume Varies by Almost Three Orders of Magnitude

Another way of interpreting air cleaner performance is to estimate the volume of space that can be cleaned at a threshold efficiency level.⁽³⁶⁾ This interpretation is similar to what AHAM uses in its labeling program for air cleaners.⁽³⁷⁾ A completely mixed room model was used in this analysis. Table V summarizes the room volume in which the operation of an AC or AC in combination with upper-room air UVGI reduces the concentration by 80% compared with otherwise identical conditions without the controls, assuming an air exchange rate of 1 hour and a deposition rate of biological particulate matter of 0.3 hr^{-1} .⁽⁴²⁾

TABLE V. Room Volume in Which the Bioaerosol Concentration is Reduced by 80% with Air Cleaner and/or Upper-Room Air UVGI

Air Cleaner Type	Averaged CADR _m (m ³ hr ⁻¹)	Room Volume (m ³)
H _{UV}	933	179
H _{UV} UVGI@100%	2373	456
cH _{UV}	981	189
E _{UV}	155	30
I _{UV}	26	5
N	31	6
EP	529	102
EP UVGI@100%	1889	363

Note: Room volume in which the bioaerosol concentration is reduced by 80% with air cleaner and/or upper-room air UVGI, compared with otherwise identical conditions without controls.

The cH_{UV} was the most efficient air cleaner with respect to volume (189 m³) in comparison with the other air cleaners, whereas the N and I_{UV} units were the least efficient in this context. Combining an AC with upper-room air UVGI more than doubled the room volume that could be cleaned.

Air cleaner performance depends mainly on the volume of the room in which it is applied; its usefulness for cleaning also depends on how much ventilation the space is receiving. For example, if the air volume that needs to be cleaned is 100 m³ and CADR of the air cleaner is 900 m³ h, 9 hr⁻¹ can be achieved by using this air cleaner. When compared with a typical home air exchange rate (0.2 hr⁻¹) significant improvement in indoor air quality can be achieved. On the other hand, when applying air cleaner with the low CADR, for example 26 m³hr⁻¹, only 0.26 hr⁻¹ is achieved by operating this air cleaning unit in the same volume that is not significant improvement when compared with typical air exchange rate of the home.

CONCLUSIONS

Transmission of infectious diseases through inhalation of airborne bacteria and fungal spores is a public health problem that may pose substantial risks to health care workers and a general risk to the public. Air cleaning via ACs and upper-room air UVGI are engineering control technologies that can reduce the spread of infectious bioaerosols through the indoor environment. This research showed that air cleaners alone or combined with upper-room air UVGI can remove/inactivate bioaerosol at significant rates, which can be linearly superposed. In high-exposure environments such as hospitals, homeless shelters, animal shelters, and correction facilities, it is of great importance to combine different engineering controls, such as air cleaning and upper-room air UVGI if additional removal and/or inactivation of biologically derived airborne contaminants is necessary.

ACKNOWLEDGMENTS

The authors thank Millie P. Schafer, NIOSH, for her assistance, and for proposing the study of in-room air cleaning in combination with upper-room air UVGI. The authors also thank Leroy Mickelsen, NIOSH, for his assistance. The authors are grateful to Daniel Veronica, and the Joint Center for Energy Management for providing essential equipment and helping operating the test facility. We are grateful to Jennifer Jeffers for her help with laboratory work, and we acknowledge the help and support of Jay Julos.

This study was supported by funds provided by the Center for Disease Control and Prevention, the National Institute for Occupational Safety and Health, and the Shaklee Corporation.

REFERENCES

1. Hopewell, P.C.: Factors influencing the transmission and infectivity of *Mycobacterium tuberculosis*: Implications for clinical and public health

- management. In *Respiratory Infections*, M.A. Sande, L.D. Hudson, R.K. Root (eds.). New York: Churchill Livingstone, 1986. pp. 191–216.
2. **Klontz, K.C., N.A. Hynes, R.A. Gunn, M.H. Wilder, M.W. Harmon, and A.P. Kendal:** An outbreak of influenza A/Taiwan/1/86 (H1N1) infections at a naval base and its association with airplane travel. *Am. J. Epidemiol.* 129:341–348 (1989).
 3. **Behrman, A.J., and F.S. Shofer:** Tuberculosis exposure and control in an urban emergency department. *Ann. Emerg. Med.* 31:370–375 (1998).
 4. **Sutton, P.M., M. Nicas, F. Reinisch, and R. Harrison:** Evaluating the control of tuberculosis among healthcare workers: Adherence to CDC guidelines of three urban hospitals in California. *Infect. Control Hosp. Epidemiol.* 19:487–493 (1998).
 5. **Li, Y., X. Huang, I.T.S. Yu, T.W. Wong, and H. Qian:** Role of air distribution in SARS transmission during the largest nosocomial outbreak in Hong Kong. *Indoor Air* 15:83–95 (2005).
 6. **Miller, J.D.:** Defensive filtration. *ASHRAE J.* 44:18–28 (2002).
 7. **Brickner, P.W., R.L. Vincent, M. First, E. Nardell, M. Murray, and W. Kaufman:** The application of ultraviolet germicidal irradiation to control transmission of airborne disease: Bioterrorism countermeasure. *Public Health Rep.* 118:99–114 (2003).
 8. **American Industrial Hygiene Association (AIHA):** *Nonionizing Radiation Guide Series: Ultraviolet Radiation*. Akron, Ohio: AIHA, 1991.
 9. **Shechmeister, I.L.:** Sterilization by ultraviolet irradiation. In *Disinfection, Sterilization and Preservation*. S.S. Block (ed.). Philadelphia: Lea & Febiger, 1991. pp. 553–565.
 10. **Center for Disease Control and Prevention (CDC):** *Guidelines for Preventing the Transmission of Mycobacterium tuberculosis in Health-Care Facilities*. *MMWR* 43(R-13):1–132 (1994).
 11. **Miller, S.L., and J.M. Macher:** Evaluation of a methodology for quantifying the effect of room air ultraviolet germicidal irradiation on airborne bacteria. *Aerosol Sci. Technol.* 33:274–295 (2000).
 12. **Xu, P., E. Kujundzic, J. Peccia, et al.:** Impact of environmental factors on efficacy of upper-room air ultraviolet irradiation for inactivating airborne Mycobacteria. *Environ. Sci. Technol.* 39:9656–9664.
 13. **Green, F.C., and P.V. Scarpino:** The use of ultraviolet germicidal irradiation (UVGI) in disinfection of airborne bacteria. *Environ. Eng. Policy* 3:101–107 (2002).
 14. **Ko, G., M.W. First, and H.A. Burge:** The characterization of upper-room ultraviolet germicidal irradiation in inactivating airborne microorganisms. *Environ. Health Perspect.* 110:95–101 (2002).
 15. **Macher, J.M., L.E. Alevantis, Y.L. Chang, and K.-S. Liu:** Effect of ultraviolet germicidal lamps on airborne microorganisms in an outpatient waiting room. *Appl. Occup. Environ. Hyg.* 7:505–513 (1992).
 16. **Xu, P., J. Peccia, P. Fabian, et al.:** Efficacy of ultraviolet germicidal irradiation of upper-room air in inactivating airborne bacterial spores and Mycobacteria in full-scale studies. *Atmos. Environ.* 37:405–419 (2003).
 17. **Foarde, K., E. Myers, J. Hanley, D. Ensor, and P. Roessler:** Methodology to perform clean air delivery rate type determinations with microbiological aerosols. *Aerosol Sci. Technol.* 30:235–245 (1999).
 18. **Cheng, S.Y., C.J. Lu, and T.R. Chen:** Efficiency of a portable indoor air cleaner in removing pollens and fungal spores. *Aerosol Sci. Technol.* 29:92–101 (1998).
 19. **Kujundzic, E., L.T. Angenent, D.A. Zander, D.E. Henderson, S.L. Miller, and M. Hernandez:** Effects of ceiling-mounted HEPA-UV air filters on airborne bacteria concentrations in an indoor therapy pool building. *J. Air Waste Manage. Assoc.* 55:210–218 (2005).
 20. **Miller-Leiden, S., C. Lobacsio, W. Nazaroff, and J. Macher:** Effectiveness of in-room air filtration and dilution ventilation for tuberculosis infection control. *J. Air Waste Manage. Assoc.* 46:869–882 (1996).
 21. **Offermann, F., R.G. Sextro, W.J. Fisk et al.:** Control of respirable particles in indoor air with portable air cleaners. *Atmos. Environ* 19:1761–1771 (1985).
 22. **Rutala, W.A., S.M. Jones, J.M. Worthington, P.C. Reist, and D.J. Weber:** Efficacy of portable filtration units in reducing aerosolized particles in the size range of *Mycobacterium tuberculosis*. *Infect. Control Hosp. Epidemiol.* 16:391–398 (1995).
 23. **Shaughnessy, R.J., E. Levetin, J. Blocker, and K.L. Sublette:** Effectiveness of portable indoor air cleaners: Sensory testing results. *Indoor Air* 4:179–188 (1994).
 24. **Kemp, S.J., T.H. Kuehn, D.Y.H. Pui, D. Vesley, and A. Streifel:** Filter collection efficiency and growth of microorganisms on filters loaded with outdoor air. *ASHRAE Trans. Part 1*:228–238 (1995).
 25. **Maus, R., A. Goppelsroder, and H. Umhauer:** Survival of bacterial and mold spores in air filter media. *Atmos. Environ.* 35:105–113 (2001).
 26. **Kreider, J.F., and M.J. Brandemuehl:** A university laboratory for testing commercial building HVAC systems. *ASHRAE J.* 3:47–50 (1995).
 27. **National Institute for Occupational Safety and Health (NIOSH):** *Evaluation of the Ability of Commercially Available Portable Air Cleaners to Remove Bioaerosols* by A. Rumble, P.A. Jensen, C.F. Green, R.L. Mickelsen, and J.J. Whalen (EPHB 222-056, DART 03-149). Cincinnati, Ohio: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, and NIOSH, 2003.
 28. **Rahn, R.O., P. Xu, and S.L. Miller:** Dosimetry of room-air germicidal irradiation using spherical actinometry. *Photochem. Photobiol.* 70:314–318 (1999).
 29. **Wayne L.G., and G.P. Kubica:** Genus *Mycobacterium*. In *Bergey's Manual for Systematic Bacteriology*, N.R. Krieg and J.G. Holt (eds.). Baltimore: Williams & Wilkins, (1986). pp. 1436–1457.
 30. **Peccia, J., H. Werth, S.L. Miller, and M. Hernandez:** Effects of relative humidity on the ultraviolet induced inactivation of airborne bacteria. *Aerosol Sci. Technol.* 35:728–740 (2001).
 31. **Kocur, M.:** Genus *Micrococcus*. In *Bergey's Manual for Systematic Bacteriology*. N.R. Krieg and J.G. Holt (eds.). Baltimore: Williams & Wilkins, 1986. pp. 1004–1007.
 32. **Reponen, T., K. Willeke, V. Ulevicius, A. Reponen, and S.A. Grinshpun:** Effects of relative humidity on the aerodynamic diameter and respiratory deposition of fungal spores. *Atmos. Environ.* 30:3967–3974 (1996).
 33. **Gorny, R.L., T. Reponen, S.A. Grinshpun, and K. Willeke:** Source strength of fungal spore aerosolization from moldy building material. *Atmos. Environ.* 35:4853–4862 (2001).
 34. **Xu, P., and S.L. Miller:** Factors influencing effectiveness of ultraviolet germicidal irradiation for inactivating airborne bacteria: Air mixing and ventilation efficiency. In *Proceedings of the 8th International Conference on Indoor Air Quality and Climate—Indoor Air '99*, Edinburgh, Scotland, Vol. 2, pp. 665–670 (1999).
 35. **Hernandez, M., S.L. Miller, D. Landfear, and J.M. Macher:** A combined fluorochrome method for quantification of metabolically active and inactive airborne bacteria. *Aerosol Sci. Technol.* 30:145–160 (1999).
 36. **Nazaroff, W.W.:** Effectiveness of air cleaning technologies. In *Proceedings of Healthy Buildings 2000*. O. Seppänen and J. Säteri (eds.), Vol. 2, pp. 49–54. SIY Indoor Air Information, Helsinki, 2000.
 37. **Association of Home Appliance Manufacturers ANSI/AHAM:** *Standard Method for Measuring Performance of Portable Household Electric Cord-Connected Room Air Cleaner (AC-1-220)*. [Standard] Washington, D.C.: 2002.
 38. **Wang, Z., T. Reponen, K. Willeke, and S. Grinshpun:** Survival of bacteria on respiratory filters. *Aerosol Sci. Technol.* 30:300–338 (1999).
 39. **Maus, R., A. Goppelsroder, and H. Umhauer:** Viability of bacteria in unused air filter media. *Atmos. Environ.* 31:2305–2310 (1997).
 40. **Food and Drug Administration (FDA):** *Code of Federal Regulations*. 2002 ed. Title 21. Vol. 8.
 41. **Wysmuller, S.M.:** “Reducing Childhood Exposure to Indoor Allergens Using Environmental Interventions in Grade Schools and Residencies.” MS thesis, University of Colorado, Boulder, 2002.
 42. **Thatcher, T.L., A.C.K. Lai, R. Moreno-Jackson, R.G. Sextro, and W.W. Nazaroff:** Effects of room furnishings and air speed on particle deposition rates indoors. *Atmos. Environ.* 26:1811–1819 (2002).