Evaluating Portable Air Cleaner Removal Efficiencies for Bioaerosols

Principal Investigator:
Shelly L. Miller
University of Colorado at Boulder
Department of Mechanical Engineering
Campus Box 427
Boulder, CO 80309-0427
Phone: 303-492-0587
Fax: 303-492-3498
E-mail: shelly.miller@colorado.edu

Co-Investigator:
Mark Hernandez
University of Colorado at Boulder
Department of Environmental Engineering
Campus Box 428
Boulder, CO 80309-0428
Phone: 303-492-5991
Fax: 303-492-7317
E-mail: mark.hernandez@colorado.edu

Research Staff:
Elmira Kujundzic, Cody Howard

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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 (Hopewell, 1986; Behrman et al., 1998; Sutton et al., 1998). Efforts to design and optimize appropriate systems to remove or inactivate causative agents are underway. Transmission of *Mycobacterium tuberculosis* is a classic example of airborne contagion. The possibility for adverse health effects associated with bioaerosols including disease transmission has prompted an effort to design appropriate systems and methods to remove causative agents.

The Centers for Disease Control and Prevention (CDC) specifies a combination of administrative, engineering, and personal respiratory protection measures to achieve infection control (CDC, 1994). Engineering controls include direct source control using local exhaust ventilation, maintenance of pressure differences between isolation/treatment rooms and adjacent areas, dilution and removal of contaminated air by mechanical ventilation, in-room air filtration, and ultraviolet germicidal air irradiation (UVGI). These controls are designed to reduce the concentration of bioaerosols within the local environment, to protect those who come into close contact with infectious persons, and to prevent bioaerosols from spreading throughout a facility.

Despite the fact that filtration has been used to reduce indoor pollutant concentrations in many settings, and that filtration has been shown to be effective in controlling a number of indoor airborne contaminants, little is known about the use of filtration with regard to decreasing the risk of infectious diseases. There is also a need to explore the effectiveness of combining filtration with other engineering controls such as UVGI. Information on the efficacy of engineering controls is needed to provide a rational basis for developing strategies for reducing the transmission of infectious diseases. For many of the control strategies, there are numerous factors that can

influence their performance, and information on their efficacy is lacking. To assess the impact of control strategies that target airborne infectious agents, it is necessary to challenge them with a bacterial aerosol similar to those that transmit diseases in realistic settings.

The overall objective of this study was to conduct experiments to quantify the rates at which bioaerosols are removed and/or inactivated by three portable air cleaners (PACs), and by the PACs combined with the operation of an upper-room air UVGI system. Filtration has been used to reduce indoor pollutant concentrations in many settings and it has been shown to be effective in controlling a number of airborne contaminants. Chamber studies have been performed evaluating the efficiency of PACs challenged with biological and non-biological aerosols (Foarde, 1999; Miller et al., 1999; Miller-Leiden et al., 1996; Morton, 1999). Commercially available low-pressure mercury-vapor lamps used for UVGI applications emit nonionizing electromagnetic radiation with a predominant wavelength of 254 nm (AIHA, 1991). UVGI that penetrates to microbial DNA may cause damage sufficient to interrupt cell replication. UVGI can be used for air disinfection in an open configuration irradiating room air. Studies have been performed evaluating efficiency of UVGI to inactivate bioaerosols (Macher et al., 1992; Miller and Macher, 2000; Peccia et al., 2001; Xu et al., 2002).

MATERIALS AND METHODS

Test Chamber

A full-scale simulated health-care room established at the University of Colorado at Boulder, as previously described (Miller et al., 1999), was used for this study (Figure 1). Two 89-cubic meter (m^3) chambers are housed inside the laboratory. One of these rooms was used for the test room. The room has insulated walls, a raised floor, plenum ceiling, one door and no windows. The floor-to-ceiling height is 2.4 m and contains 37 m^2 of clear floor area. The room is

capable of maintaining a stable temperature in the range 15–35°C and relative humidity in the range of 50% to 90%.

The test room has a natural infiltration rate of 0.1–0.3 air changes per hour (ACH). It is equipped with a computer controlled ventilation system that delivers a minimum of 2 ACH and a maximum of 8 ACH of high-efficiency-particulate-air (HEPA) filtered outside air through two circular diffusers located in the ceiling. Air is exhausted through two ports also located in the ceiling. To minimize particles exiting the test room, HEPA filters were installed within the exhaust ducting. The mechanical ventilation system was operated to maintain negative pressure within the test room. Two box fans were used to ensure complete mixing within the test room.

During testing, the room supply and exhaust airflow were balanced to achieve an exhaust flow greater than the supply such that a negative pressure of 12 Pa was achieved 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.

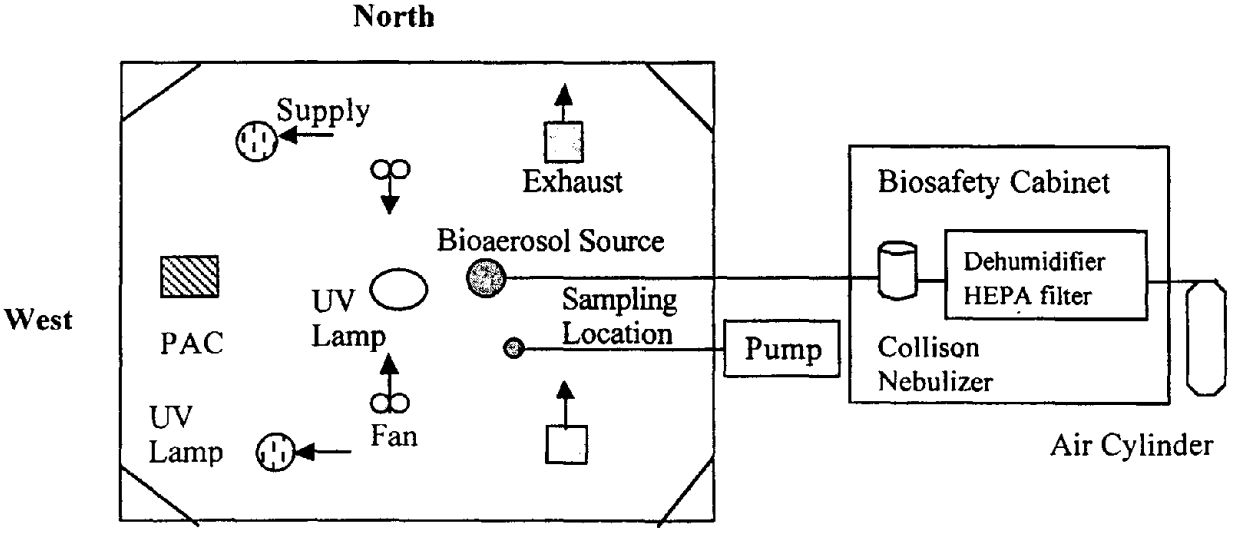

Figure 1. Schematic of the test chamber (top view) set up for portable air cleaner/UVGI studies.

PACs were located on the west wall during testing (Figure 1). The three PACs that were evaluated are summarized in Table 1. The tested PACs covered a wide range of configuration and prices. The characteristics of the PACs as specified by the manufacturer are presented in Table 1.

Table 1. Characteristics of Portable Air Cleaners

PAC Type	Negative Ion Generator (N)	Electrostatic precipitator (E)	HEPA filter with internal UV lamps (H)
Airflow rate as specified by manufacturer (cfm)	Not Specified	Variable (150–340)	550
Measured airflow rate (cfm)[a]	24	75–122	504
Equivalent air-exchange rate (ACH)[b]	0.46	1.4–4.2	9.6
Airflow pattern	Back-flow	Back-flow	Top-flow
Intake position	Back	Left-right	Top
Exhaust position	Top	Right-left	Bottom-front
Dimensions (cm)	28 x 25 x 13	30 x 38 x 48	109 x 79 x 56
Weight (kg)	2	18	91
Cost	$340	$722	$6250
Mounting options	Portable	Portable/Ceiling	Mobile

[a] Personal communication, NIOSH Internal Report, Jun 2001

[b] Based on 89 m^3 test chamber volume and measured airflow rates

A modern UVGI system (Lumalier, Memphis, TN) is installed in the chamber and consists of five luminaries, four mounted in each of the corners of the room and one hung from the center of the ceiling (Figure 1). The manufacturer rated the lamps within the luminaries at 18 watts (W). The center luminary was rated at 72 W, consisting of four lamps. The corner lamps were rated at 36 W each containing two lamps installed with parabolic aluminum reflectors on the back of the luminaries. Each luminary is equipped with concentric black louvers of 1.9 cm

spacing. The luminaries were installed so that the lower edge was located 2.2 m above the floor and the top was 3 cm below the ceiling. This placement created a 30 cm wide band of UVGI in the upper level of the room, with the lower edge at approximately 2.1 m above the floor. The UVGI system was operated for more than 100 hours before experiments were conducted.

Microorganisms

Mycobacterium parafortuitum (American Type Cultur Collection (ATCC) No. 19689) was aerosolized during most of our experiments. This Gram-positive organism is similar in size to *Mycobacterium tuberculosis* (1–4 μm in length). *M. parafortuitum* is a non-motile, rod-shaped bacteria 2–4 μm long. It grows rapidly on standard bacterial culture media and produces smooth pale yellow colonies that disperse readily in water (Bergey's Manual of Determinative Bacteriology, 1994). It has been shown to have similar high susceptibility to UVGI as *Mycobacterium bovis* BCG (Xu et al., 2002).

We initially planned to do a subset of experiments with *Escherichia coli*, which proved difficult. This Gram-negative bacterium is extremely sensitive to being aerosolized, that is, stress induced on the bacterium during the aerosolization process or by being suspended in the air (which is a lower relative humidity environment than it normally experiences) can cause harm to the bacterium. Therefore we had difficulty aerosolizing and elevating its airborne concentration in our 89-m^3 chamber. During our initial experiments, we were able to detect low levels of *E.coli* without any control measure operating. When a PAC or the UVGI system, however, was operated, we could not detect any *E. coli*. Similar results were seen in a study conducted by Miller and Macher (2000). To alleviate these problems, *Micrococcus luteus*, an organism that is hardier and can withstand aerosolization, was used instead of *E. coli*. This microorganism has been used in previous bioaerosol studies (Miller and Macher, 2000). *M. luteus* (ATCC 4698) is

Gram-positive microorganism with spherical cells 0.9–1.8 μm in diameter that can often occur in clusters of four. It produces yellow to cream white pigments on standard bacterial culture media. It appears to be reasonably susceptible to UVGI (Miller and Macher, 2000).

Bioaerosol Generation

Test bioaerosol was generated using a six-jet Collison nebulizer with a large reservoir (CN 25, BGI, Inc.). The nebulizer was located outside of the test room, in an adjacent chamber housed within the laboratory. A biosafety cabinet was installed in this adjacent chamber for storage of bioaerosol generation supplies. The nebulizer was operated at 138 kPa (20 psia), 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.). The bioaerosol was delivered from the atomizer discharge port into the test room at 12.5 L min^{-1} through 3 meters of flexible tubing with a 1.3-cm inner diameter.

Bioaerosol was generated from liquid suspensions achieving room air concentrations of 10^8–10^{12} bacterial cells m^{-3}. The volumetric flow rate of the suspension leaving the nebulizer ranged from 0.12–0.33 ml min^{-1}. Test bioaerosol was released approximately 1.5 m above the floor.

Bioaerosol was generated continuously to raise the bioaerosol concentration in the room to a suitable concentration for detection (usually 30 minutes). No ventilation was provided during this period and the box fans 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 controls (Miller-Leiden et al., 1996). Aerosol generation was located in the center of the room between the

ventilation exhaust and supply airflow, in accordance with the CDC's recommendation, which specifies that clean air first flows to less contaminated areas, then flows across the infectious source and into the exhaust (CDC, 1994).

Bioaerosol Sampling

Airborne bacteria were sampled with AGI-30 impingers at one room location. Our previous research showed that under the current test chamber configuration with mixing fans operating, the room is well mixed and the bioaerosol concentration within the room can be represented by a few samples (Xu et al., 1999). Impingers were positioned in the breathing zone, 1.6 m above the floor, below the ventilation exhaust outlet (Figure 1). Impingers collected bacteria in 30 ml of sterile, phosphate buffered solution. The pump and rotameters were calibrated using a primary flow meter (Dry Cal, DC-Lite, Butler, NJ).

Bioaerosol was collected five times sequentially during the decay period. Two impingers were operated simultaneously to collect duplicate samples for 30 seconds to 20 minutes, depending on the experimental scenario, at 12.5 L min^{-1} with a high-flow sampling pump regulated with rotameters.

Bioaerosol Quantification

Two independent methods were used for bioaerosol quantification: culturing and epifluorescent direct microscopy in accordance with previously described methods (Hernandez et al., 1999, Peccia et al., 2001). Culturable plate counts (usually termed Colony-forming Units or CFUs) represent the number of cells in a sample capable of forming colonies on a suitable agar medium. Direct microscopic counts (also termed total counts) represent the number of both living and dead bacterial cells collected in a sample (Madigan et al., 2000). All microbiology work was done in the Environmental Microbiological Laboratory at the University of Colorado at Boulder.

For culturing, concentrations were quantified by plating of the impinger liquid onto tryptic soy agar using a spiral-plating machine (Spiral Plater Model D, Spiral Biotech, MD). At least three replicates of each sample were plated. Plates were incubated at 37°C for 2–3 days for *M. parafortuitum* and 1 day for *M. luteus*. All colonies were described and counted. All plating was performed in indirect dimmed light and all incubations were carried out in the dark to control for photoreactivation.

For epifluorescent microscopy, a sensitive biological stain, 4'6-diamidino-2-phynyldole (DAPI), was used to measure the total number of airborne microorganisms in accordance with previously described methods (Hernandez et a., 1999). Cells were incubated in DAPI for 1 min at room temperature and then filtered through 25-mm diameter, 0.2 μm, black polycarbonate filters (Poretics Inc., CA). Mounted filters were examined under 1100x magnification using Nikon Eclipse E400 epifluorescent microscope (Hernandez et al., 1999). Five random fields were usually counted per slide. All direct counts are reported as the average of the number of fields.

Experimental Protocol

Decay scenario experiments were performed (Xu et al., 2002). In a typical decay scenario, an infectious person has been present in a room for a time but departs before a susceptible person enters; therefore the infectious aerosol concentration decreases with time after the infectious person leaves.

For each experiment bioaerosol was generated continuously until the bioaerosol concentration in the room reached a suitable level for detection. No ventilation was provided during this period and the box fans were turned on to ensure mixing. Once the bioaerosol concentration reached the desired level, generation ceased, the PAC and/or UVGI were turned on, and sampling was initiated. The concentration within the room decreased over time once

generation ceased and the rate at which it decayed depended on the experimental scenario. Mixing fans were on during the decay period. Decay time periods varied between 5 to 120 minutes, in which the longer decay periods occurred while testing PACs with low removal rates, such as the NIG, and the shorter decay periods occurred while testing PACs with high removal rates, such as the HEPA-UV. Decay periods also varied depending on the ventilation rate. Experiments were performed at two ventilation rates: zero and six ACH. All experiments involving UVGI were performed in the dark to control for photoreactivation.

Experimental scenarios are given in Table 2. Scenarios are names according to the bioaerosol that was used (MP for *M.parafortuitum*, ML and for *M.luteus*), the filter that was tested (E for ESP, N for NIG, or H for HEPA-UV, see Table 1), and the ventilation rate within the room during the experiments (0 or 6 ACH). Note that the ESP was tested on the high setting. In addition, for the HEPA-UV filter experiments, we tested the filter with the internal lamps on (designated "ON") or off (designated "OFF). The last two experiments described in Table 2 were conducted with the UVGI system operating, which is denoted in the table as UVGI-100 for 100% operation (all lamps on) and UVGI-50 for 50% operation (half of the lamps on).

Experiments were not conducted in any particular order. Dates for experiments and analysis type are also given in the table. Analysis type refers to whether the collected bioaerosol samples were subsequently assayed by culturing or by direct microscopy. We did most of our analyses using direct microscopy. A few experiments were also analyzed using culturing to compare with direct microscopy results. For runs that are denoted as having D + C, only one experiment was actually run; the samples were then split into two volumes, culturing was performed on one volume, and microscopy was performed on the other volume. Experiments are repeated at least twice with some experiments being repeated 3–5 times.

Table 2. Experimental Scenarios

Experimental Scenario[a]	PAC Type	Ventilation (ACH)	UVGI Level	Date and Type of Analysis[b]
MP-E-0	ESP	0	0	06/11/01 (1D); 06/13/01 (2D+1C); 07/18/01 (1D)
MP-E-6		6	0	07/16/01 (2D); 07/23/01 (1D)
ML-E-0		0	0	01/25/02 (2C)
MP-E UVGI-100	ESP with UVGI system operating	0	100%	07/09/01 (1D+1C); 09/26/01 (1D+1C); 10/10/01 (1D+1C)
MP-N-0	NIG	0	0	05/18/01 (1D); 06/18/01 (2D), 09/25/01 (1C)
MP-N-6		6	0	07/25/01 (2D); 07/30/01 (1D)
MP-H OFF-0	HEPA-UV with lamps physically removed	0	0	06/20/01 (1D); 06/27/01 (2D)
MP-H OFF-6		6	0	08/08/01 (2D); 08/13/01 (1D)
MP-H ON-0	HEPA-UV with lamps on	0	0	05/21/01 (2D); 06/04/01 (1D)
MP-H ON-6		6	0	08/01/01 (2D+1C); 08/06/01 (1D)
MP-H ON-0 UVGI-100	HEPA-UV with lamps on and UVGI system operating	0	100%	10/03/01 (2D+2C)
MP-H ON-0 UVGI-50		0	50%	10/16/01 (2D+2C)

[a] MP – *M.parafortuitum*; ML – *M.luteus*; E – ESP; N – NIG; H denotes HEPA-UV

[b] C – culturing; D – direct microscopic analysis

Completely Mixed Room Model

The equivalent air-exchange rate of operating a PAC with UVGI was determined using a completely mixed room model. An equivalent air-exchange rate is defined as the volumetric loss rate associated with a control measure (or combination of measures), such as an air cleaner, divided by the volume of the room where the control has been applied. The equivalent air-exchange rate is useful for describing the rate at which bioaerosols are removed by means other than ventilation and for directly comparing all removal mechanism rates. According to the completely mixed room model, the rate of change of the bacterial aerosol concentration with time during the decay period is given by (Miller and Macher, 2000):

$$C(t) = C_0 e^{-(ACH_0 + ACH_V + ACH_{PAC} + ACH_{UVGI})t} \quad (1)$$

where C(t) is the concentration of bioaerosols at time t (# m^{-3} or CFU m^{-3}), C_0 is the concentration of bioaerosols at time t=0 (# m^{-3} or CFU m^{-3}), ACH_O is the loss rate of culturable bacteria due to other removal processes, including deposition, exfiltration and natural die-off, ACH_V is the loss rate of culturable bacteria due to ventilation, ACH_{pac} is the loss rate of culturable bacteria due to filtration via PACs, and ACH_{UVGI} is the loss rate of culturable bacteria due to UVGI. All loss rates are expressed in air changes per hour (h^{-1}). The concentration of bioaerosols was measured sequentially during the decay period, and the log form of equation (1) was linearly fit to the data:

$$\ln C(t) = \ln C_0 - (ACH_O + ACH_V + ACH_{PAC} + ACH_{UVGI})t \quad (2)$$

The equivalent air-exchange rate $ACH_v + ACH_O$ is estimated by conducting an experiment using the decay protocol in which no PACs were operated nor was the UVGI system turned on.

For most of our experiments with the PACs, we used direct microscopy to analyze our samples. The decay rate determined by direct microscopy gives an estimate of $ACH_O + ACH_v + ACH_{PAC}$, since direct microscopy gives a measure of the total number of bacteria-containing

particles are in the air. We also conducted a few PAC experiments using culturing, which also gives an estimate of $ACH_O + ACH_v + ACH_{PAC}$, since culturing gives a measure of the number of colony-forming units of bacteria-containing particles are in the air. Since we are conducting controlled experiments with a known type of bacteria, we are able to specifically grow on agar plates everything that is culturable in the air. Thus microscopy is directly related to culturability. This is most likely only true in well-controlled experiments such as these conducted here. Knowing $ACH_v + ACH_O$ and using equation (2), we can estimate ACH_{PAC} by subtraction.

For experiments in which we operated the UVGI system in addition to the PACs we needed to use both the results from direct microscopy and culturing to estimate the equivalent air-exchange rate parameters. Culturing is the only means by which we can estimate the rate at which UVGI inactivates organisms; therefore culturing gives an estimate of $ACH_O + ACH_v + ACH_{PAC} + ACH_{UVGI}$. Direct microscopy will only give an estimate of $ACH_O + ACH_v + ACH_{PAC}$. Knowing $ACH_v + ACH_O$ and using equation (2), we can estimate ACH_{PAC} or $ACH_{PAC} + ACH_{UVGI}$ by subtraction. ACH_{UVGI} can be determined subtracting the rate determined by culturing from the rate determined by microscopy.

RESULTS AND DISCUSSION

The PAC bioaerosol equivalent air-exchange rates are presented for each experiment and type of analysis in Table 3. These equivalent air-exchange rates were estimated using least-squares linear regression to fit a line to the decay data, according to equation 2, and then differenced. The standard error of the regression coefficient (with errors propagated) is provided in parentheses as an estimate of the uncertainty in the equivalent air exchange rate (Montgomery and Runger, 1999). Rates are derived using data from the direct microscopy analyses, except for those denoted by "C", which designates culturing analysis. The last column of Table 3 provides the average

equivalent air-exchange rate (and propagated standard error) estimated for each PAC experimental scenario. The average is over all analysis types and experiment replicates. The standard error for the average was calculated using propagation of errors. Appendix I provided details about error propagation.

Figure 2 is an illustrative example of the regression of the data used to extract the equivalent air-exchange rates. In Figure 2, the linear regression equations are shown for the MP-E-0 experiment, without and with the air cleaner operating. Without the PAC operating, the slope of the line is 0.00978 x 60 = 0.588 h^{-1}, giving an estimate of $ACH_O + ACH_V$. With the PAC operating, the slope of the line is 0.1129 x 60 = 6.77 h^{-1}, giving an estimate of $ACH_O + ACH_V + ACH_{PAC}$. The equivalent air-exchange rate for the ESP filter, ACH_{PAC}, tested under the experimental scenario MP-E-0 is the difference between these two slope values: 6.77 – 0.588 = 6.19 h^{-1}.

The raw data for the PAC experiments are provided in Appendix II as well as the calculations for the standard error of the regression coefficients.

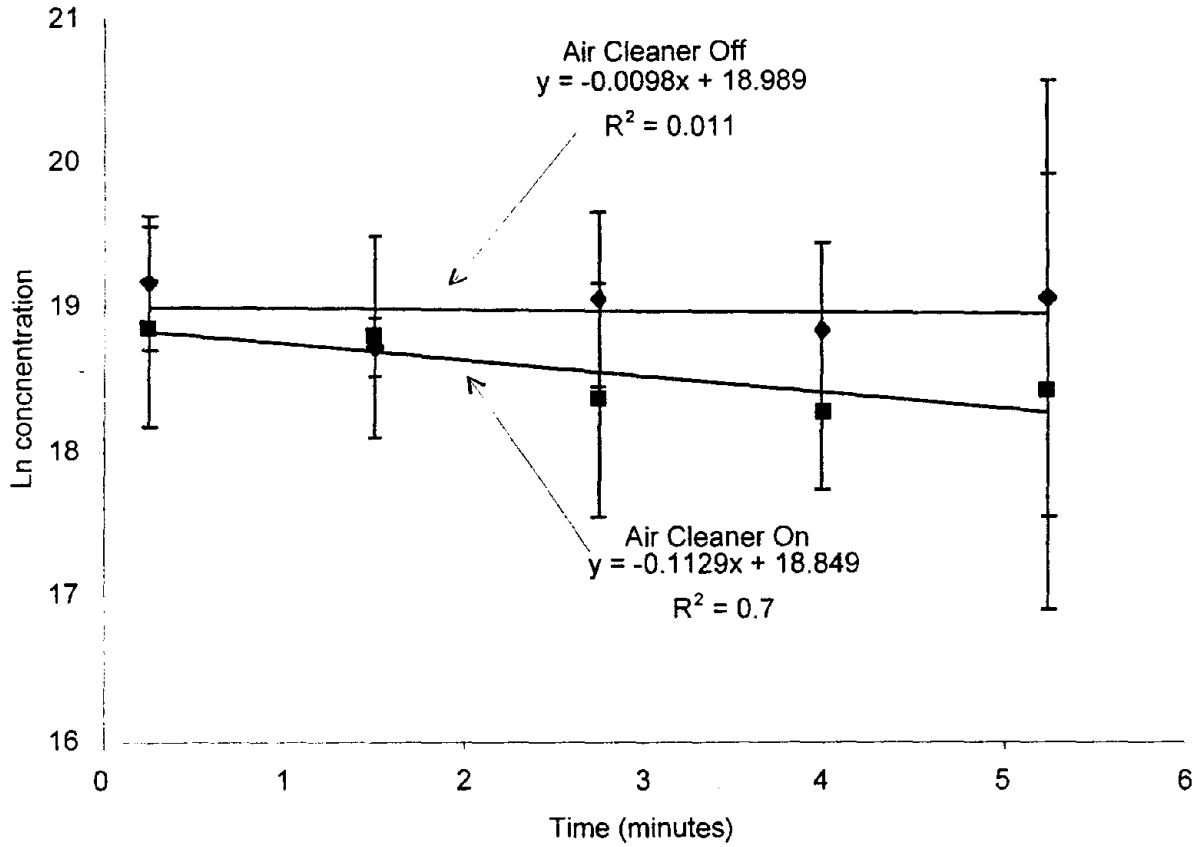

Figure 2. Plot of the natural log of total bioaerosol concentration (# m^{-3} as determined by microscopy) versus time for as MP-E-0 decay experiment. Two experiments were conducted, one without and one with the air cleaner operating. Also shown are the least-squares linear regression equations used to derive the equivalent air-exchange rate in Table 3.

Table 3. PAC Bioaerosol Equivalent Air Exchange rates

Experiment ID	Equivalent Air-Exchange Rate for Each Experiment and Analysis Type (Standard Error) [ACH, h^{-1}] [a, b]	Average Equivalent Air-Exchange Rate (Standard Error) [ACH, h^{-1}] [c]
MP-E-0[d]	6.36 (0.63); 7.72 (1.16); 7.31 (1.42); 6.19 (4.11); 8.32 (0.95) C	7.18 (0.93)
MP-E-6	6.03 (2.04); 4.88 (3.99); 4.47 (3.51)	5.13 (1.90)
ML-E-0	5.36C (2.86); 3.95 (1.45) C	4.66 (1.60)
MP-N-0	0.360 (0.078); 0.288 (0.075); 0.270 (0.054)	0.335 (0.061)
MP-N-6	0.246 (2.312); 0.486 (2.126); 0.450 (3.805); 0.420 (0.21) C	0.394 (1.65)
MP-H OFF-0	3.80 (2.70); 2.60 (0.37); 2.39 (0.91)	2.93 (0.96)
MP-H OFF-6	3.81 (4.57); 4.08 (4.90); 3.40 (1.91)	3.76 (2.32)
MP-H ON-0	8.86 (0.66); 12.2 (2.5); 14.1 (2.6)	11.7 (1.2)
MP-H ON-6	10.6 (2.1); 12.0 (2.1); 8.58 (3.46); 12.6 (1.0) C	10.9 (1.2)

[a] ACH determined by direct microscopy unless noted by a "C", which indicates culturing was used
[b] Standard error determined by linear regression analysis
[c] Standard error determined by propagation of errors
[d] ESP tested on high setting

The NIG unit was not effective in removing bioaerosols. Although this might indicate that negative ion generators do not work for this application, it should also be noted that the unit we tested was small with very low airflow rates, and it may not have been the right size for our test chamber. The HEPA-UV unit was very effective at removing bioaerosols, especially with the UV lamps on.

The air-exchange rates measured in our decay experiments agree reasonably with those calculated based on the measured volumetric airflow rate divided by the test room volume, as detailed in Table 2. The measured rates are 0.335–0.394 h^{-1} for the NIG compared to the calculated rate of 0.46 h^{-1}; for the ESP, the measured rates are 4.66–7.18 h^{-1} compared to the calculated rate of 4.2 h^{-1} (ESP on high); and for the HEPA-UV, the measured rates are 10.9–11.7 h^{-1} compared with the calculated rate of 9.6 h^{-1}.

Culturing and direct counts showed comparable equivalent air-exchange rates (paired t-test; α=0.05). For example, in experiment MP-H UV ON-6, the equivalent air-exchange rate using culturing was 12.6 (1.0) h^{-1} and using direct counts the value of 12.0 (2.1) h^{-1} was obtained.

A ventilation rate of 6 ACH provided by the chamber's ventilation system did not significantly impact the equivalent air-exchange rates of the portable air-cleaners, as expected (paired t-test; α=0.05). For example, an equivalent air-exchange rate of 6.36 (0.63) h^{-1} was estimated for experiment MP-E-0 with zero ventilation compared to 6.03 (2.04) h^{-1} for experiment MP-E-6 with 6 ACH ventilation. Thus we can calculate an overall average equivalent air-exchange rate for each filter, averaging across ventilation rates: 5.66 h^{-1} for the ESP, 0.365 h^{-1} for the NIG, 3.35 h^{-1} for the HEPA-OFF, and 10.4 h^{-1} for the HEPA-ON.

There was no significant difference in the equivalent air-exchange rates obtained for the ESP using *M. parafortuitum* compared to *M. luteus* (paired t-test; α=0.05).

There was a significant difference in the equivalent air-exchange rates for the HEPA-UV ON compared to the HEPA-UV OFF experiments (paired t-test; α=0.05). This discrepancy in performance could be due to a number of factors: (1) the airflow by-passed the HEPA filter when the lamps were removed reducing the equivalent air-exchange rate; (2) the airflow through the filter was altered when the lamps were removed. Thus, we conducted a few more experiments to determine if physically removing the lamps from the unit changed the internal pattern of airflow and this change caused the unit to perform differently.

To test this hypothesis, the filter unit was reconfigured so that the lamps could be turned off with a switch instead of by removing them from the system. Experiments were repeated with this new configuration. The experimental protocol was the same as in previously described experiments except that we used a surrogate, non-biological aerosol (phosphate buffer solution particles) instead of a bioaerosol since previous experiments have shown that for filtration, performance is similar for biological and non-biological particles (Miller-Leiden et al., 1996). Also, we measured the concentration decay using an Optical Particle Counter (Met One, Pacif. Sci Inst., Grants Pass, Oregon), which counted the total number of particles between 0.3 and > 5 μm, instead of doing microscopy.

First, we tested the filter in the HEPA-UV ON configuration, and then with the HEPA filter on and the UV lamps off (both with the lamps removed and turned off by the switch). Measured equivalent air-exchange rates, and in parentheses the standard error of regression coefficients, are presented in Table 4. Although it appears as though the equivalent air-exchange rates with the UV lamps on are slightly higher than those with the UV lamps off, there was no statistically significant difference (paired t-test; α=0.05) between the sets of experiments, suggesting that our hypothesis was not correct. Also, a test was done in which the HEPA filter was removed from the unit and the

UV lamps were left inside and operating. The results showed that the equivalent ACH due to the UV lamps was roughly one ACH. Our opinion is that more analyses should be performed on the HEPA-UV filter to better understand the discrepancies mentioned above.

Table 4. Equivalent Air-Exchange Rates (standard error) of HEPA-UV with Non-Biological Aerosol

HEPA filter on, UV lamps on	**HEPA filter on, UV lamps off**
7.79 (0.45)	4.27 (0.37)[a]
5.89 (0.34)	4.41 (0.19)[a]
5.48 (0.32)	4.70 (0.33)[b]
	3.97 (0.23)[b]

[a]UV lamps were removed from unit
[b]UV lamps were turned off using the switch

The results discussed above pertain to our experiments with PACs. We also conducted a series of experiments investigating the effectiveness of PACs in conjunction with the operation of a UVGI system. As described in the methods section of this report, these experiments were conducted using the same protocol as the PAC experiments, except that when the filters were turned on, the UVGI system was also turned on.

Table 5 and 6 summarize the results of experiments with UVGI in combination with filtration by portable air cleaners. Table 5 provides the equivalent air-exchange rates estimated for all replicate experiments and Table 6 provides the average equivalent air-exchange rates over all repeat experiments. Also in Table 6, estimates are made of the ACH due to PACs only and UVGI only. These individual rates for the PACs and UVGI system were calculated as explained in the "Completely Mixed Room Model" section of this report. In Table 6, propagated standard error in the regression coefficients are provided with the average air-exchange rate of replicate runs.

Figure 3 is an example of the linear regression of the data used to derive the results in Table 5. In Figure 3, the linear regression equations are shown for the MP-E UVGI-100 experiment, without and with the air cleaner and UVGI system operating. Without the PAC and UVGI operating, the slope of the line is 0.0249 x 60 = 1.49 h^{-1} and 0.0101 x 60 = 0.606 h^{-1} for direct microscopy (total) and culturing data respectively (these are estimates of $ACH_O + ACH_V$). With the PAC and UVGI system operating, the slope of the line is 0.1714 x 60 = 10.3 h^{-1} and 0.405 x 60 = 24.3 h^{-1} for direct microscopy ($ACH_O + ACH_V + ACH_{PAC}$) and culturing data ($ACH_O + ACH_V + ACH_{PAC} + ACH_{UVGI}$) respectively. The equivalent air-exchange rate for the PAC + UVGI, $ACH_{PAC} + ACH_{UVGI}$, is the difference between the two slope values for culturing: 24.3 – 0.606 = 23.7 h^{-1}. The equivalent air-exchange rate for the PAC only, ACH_{PAC}, is the difference between the two slope values for direct microscopy: 10.3 – 1.49 = 8.8 h^{-1}. To estimate the equivalent air-exchange rate for the UVGI only, we subtract ACH_{PAC} from $ACH_{PAC+UVGI}$: 23.7 – 8.8 = 14.9 h^{-1}.

The raw data for the UVGI plus PAC experiments are provided in Appendix III as well as the calculations for the standard error of the regression coefficients.

The average equivalent air-exchange rates for MP-E UVGI-100 and MP-H ON UVGI-100, in which the PACs were operated in combination with 100% UVGI, are quite high, 22 – 27 h^{-1}. When the UVGI was decreased by 50%, the equivalent air-exchange rate subsequently decreased.

The rates for just the PACs as determined in these experiments are comparable to the rates estimated in the PAC only experiments. For the ESP filter, the average ACH is 7.2 h^{-1} from the PAC plus UVGI experiments, which agrees with the average ACH of 5.66 h^{-1} from the PAC only experiments. For the HEPA-UV filter, the average ACH is 10.4 h^{-1} from the PAC plus UVGI experiments, which agrees with the average ACH of 11.3 h^{-1} from the PAC only experiments.

The average equivalent air-exchange rate for just the UVGI system as determined in these experiments is 15–17 h^{-1}. This equivalent air-exchange rate due to UVGI is agrees well with estimates from a previous study for *M. parafortuitum*. Peng et al. (2002) measured a rate of 16± 1.8 ACH for all lamps operating in decay experiments with *M. parafortuitum*. For experiment MP-H ON UVGI-50, the average UVGI equivalent air-exchange rate was roughly half of the rates for MP-E UVGI-100 and MP-H ON UVGI-100, due to the application of only 50% UVGI.

Table 5. Equivalent air-exchange rates (standard error) of UVGI in combination with filtration by portable air cleaners for all replicate decay experiments

Experimental Scenario	$ACH_{PAC}+ACH_{UVGI}$	ACH_{PAC}	ACH_{UVGI}
MP-E UVGI-100	23.7 (9.8) 21.9 (4.0) 19.9 (4.0)	8.79 (2.5) N/A 5.69 (1.8)	14.9 (10.1) N/A 14.2 (4.4)
MP-H ON-0 UVGI-100	25.7 (8.3) 28.6 (7.4)	9.40 (2.8) 11.9 (5.8)	16.3 (8.8) 16.7 (9.4)
MP-H ON-0 UVGI-50	17.6 (11.0) 16.2 (3.1)	10.4 (1.2) 9.20 (2.9)	7.20 (11.1) 7.00 (4.3)

Table 6. Average equivalent air-exchange rates (standard error) of UVGI in combination with filtration by portable air cleaners, for PACs only, and for UVGI only

Experimental Scenario	$ACH_{PAC}+ACH_{UVGI}$	ACH_{PAC}	ACH_{UVGI}
MP-E UVGI-100	21.8 (3.8)	7.24 (1.5)	14.6 (5.5)
MP-H ON-0 UVGI-100	27.2 (5.6)	10.7 (3.2)	16.5 (6.4)
MP-H ON-0 UVGI-50	16.9 (5.7)	9.80 (1.6)	7.10 (6.0)

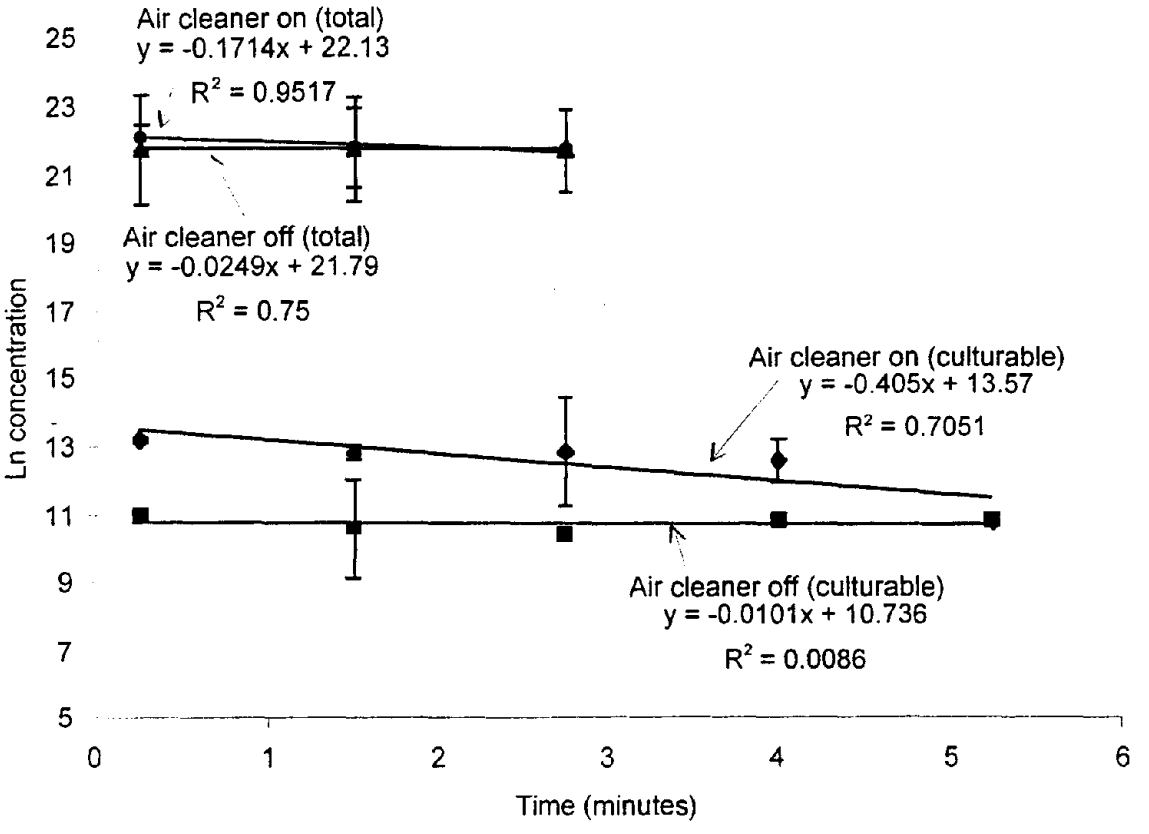

Figure 3. Plot of the natural log of total and culturable bioaerosol concentration (# m^{-3} as determined by microscopy and CFU m^{-3} as determined by culturing) versus time for a MP-E UVGI-100 decay experiment. Two experiments were conducted, one without and one with the air cleaner plus UVGI operating. Also shown are the least-squares linear regression equations used to derive the equivalent air-exchange rate in Tables 5 and 6.

CONCLUSIONS AND IMPLICATIONS

Transmission of infectious diseases, such as TB, through inhalation of airborne bacteria is a public health problem that may pose substantial risks to healthcare workers and a general risk to the public. Air filtration and applied UVGI are engineering control methods that can prevent the spread of bioaerosols through indoor environments. Observed and reported data showed that it is essential to ensure a low risk for transmission of infection through high-risk settings.

The experimental results of this study showed that filtration alone and in combination with UVGI can remove/inactivate airborne bacteria at reasonable rates. Equivalent air-exchange rates in the range of 5–12 ACH can be achieved using PACs, depending on the type of air cleaner. Additionally, one air cleaner tested did not have any effect on airborne bacteria (NIG). These air-exchange rates are comparable with previous studies (Miller-Leiden et al., 1996). Operating UVGI in conjunction with the PACs added an additional 7–17 ACH, depending on the number of lamps operating. This additional equivalent air-exchange rate due to UVGI is comparable with previous studies (Peng et al., 2002).

Completion of the proposed research significantly improved our understanding of the efficacy of PACs and combination of PACs and UVGI against biological aerosols. Observed data showed that portable cleaners could be used to enhance the rate of bioaerosol inactivation due to UVGI and vice versa.

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APPENDIX I

ERROR PROPAGATION FOR AIR CLEANER EQUIVALENT AIR-EXCHANGE RATES

To estimate the equivalent air-exchange rate for a PAC, two experiments were conducted. One experiment consisted of aerosolizing bacteria into the test chamber and allowing it to decay without an air cleaner operating. The 2nd experiment was a repeat of the first except that the air cleaner was turned on and operated throughout the decay period. To estimate the equivalent air-exchange rate, linear regression was performed on data from both experiments according to equation 2 (see Figure 2). The overall PAC air-exchange rate (ACH_{PAC}) was the difference between the rate derived with ($ACH_{PAC\ On}$) and without the air cleaner ($ACH_{PAC\ Off}$):

$$ACH_{PAC} = ACH_{PAC\ On} - ACH_{PAC\ Off} \qquad (AI.1)$$

Each rate estimated by linear regression has its own uncertainty (U) associated with it. This uncertainty is the standard error in the regression coefficient. To find the overall uncertainty in ACH_{PAC}, we must propagate the uncertainties in the rates used to calculated ACH_{PAC}:

$$U_{ACH_{PAC}} = \sqrt{\left(\frac{\partial ACH_{PAC}}{\partial ACH_{PAC\ On}} U_{ACH_{PAC\ On}}\right)^2 + \left(\frac{\partial ACH_{PAC}}{\partial ACH_{PAC\ Off}} U_{ACH_{PAC\ Off}}\right)^2} \qquad (AI.2)$$

Substituting in the partial derivatives we find the uncertainty in the PAC equivalent air-exchange rate is:

$$U_{ACH_{PAC}} = \sqrt{U_{ACH_{PAC\ On}}^{\ 2} + U_{ACH_{PAC\ Off}}^{\ 2}} \qquad (AI.3)$$

ERROR PROPAGATION FOR AVERAGE EQUIVALENT AIR-EXCHANGE RATE

All PAC experiments were repeated from two to five times to get an idea of the repeatability of the estimated equivalent air-exchange rates. Average equivalent air-exchange rates were calculated from the results of the repeated experiments and errors were propagated according to the following method.

$$AVG = \frac{ACH_{PAC_1} + ACH_{PAC_2} + \ldots + ACH_{PAC_N}}{N}$$

$$AVG = \frac{1}{N} ACH_{PAC_1} + \frac{1}{N} ACH_{PAC_2} + \ldots + \frac{1}{N} ACH_{PAC_N} \qquad (AI.4)$$

The uncertainty in the average is calculated using propagation of errors:

$$U_{AVG} = \sqrt{(\frac{\partial AVG}{\partial ACH_{PAC_1}} U_{ACH_{PAC_1}})^2 + ... + (\frac{\partial AVG}{\partial ACH_{PAC_N}} U_{ACH_{PAC_N}})^2} \quad \text{(AI.5)}$$

Substituting in the partial derivatives we find the uncertainty in the Average PAC equivalent air-exchange rate is:

$$U_{AVG} = U_{AVG} = \sqrt{(\frac{1}{N} U_{ACH_{PAC_1}})^2 + ... + (\frac{1}{N} U_{ACH_{PAC_N}})^2} \quad \text{(AI.6)}$$