

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

April, 2002

INTRODUCTION

Indoor and outdoor air contains suspended biological particulate matter (bioaerosols) that can pose a threat to public health through infectious diseases. The possibility for disease transfer associated with bioaerosols has prompted an effort to design appropriate systems and methods to remove causative agents.

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 increased incidence of tuberculosis (TB) in US, since 1985, has been shown to be the greatest in immigrants from TB-endemic parts of the world, persons with HIV infectious, the homeless population, certain minorities, illegal drug users, and those persons with low socioeconomic status.

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 negative pressure differences between tuberculosis 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 have 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 uses 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 in removing bioaerosols.

The overall objective of this study was to conduct experiments to quantify the rates at which three portable air cleaners (PACs) remove bioaerosols and to explore the effects of filtration via PACs combined with UVGI. 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 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 three configurations: (1) enclosed in mechanical ventilation system ducts, (2) enclosed in locally recirculating units, and (3) in an open configuration irradiating room air. Studies have been performed evaluating efficiency of UVGI in inactivating bioaerosols in many settings (Macher et al., 1992, Miller and Macher, 2000, Xu et al., 2002).

MATERIALS AND METHODS

Test Chamber

A simulated, full-scale health-care room, established at the Joint Center for Energy Management's Larson Building Systems Laboratory, University of Colorado at Boulder, as previously described (Miller et al., 1999) was used for this study. Two 90-m³ 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 m² 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%. PACs were located on the west wall (Figure 1). The three PACs that were evaluated during the course of this research study are summarized in Table 1.

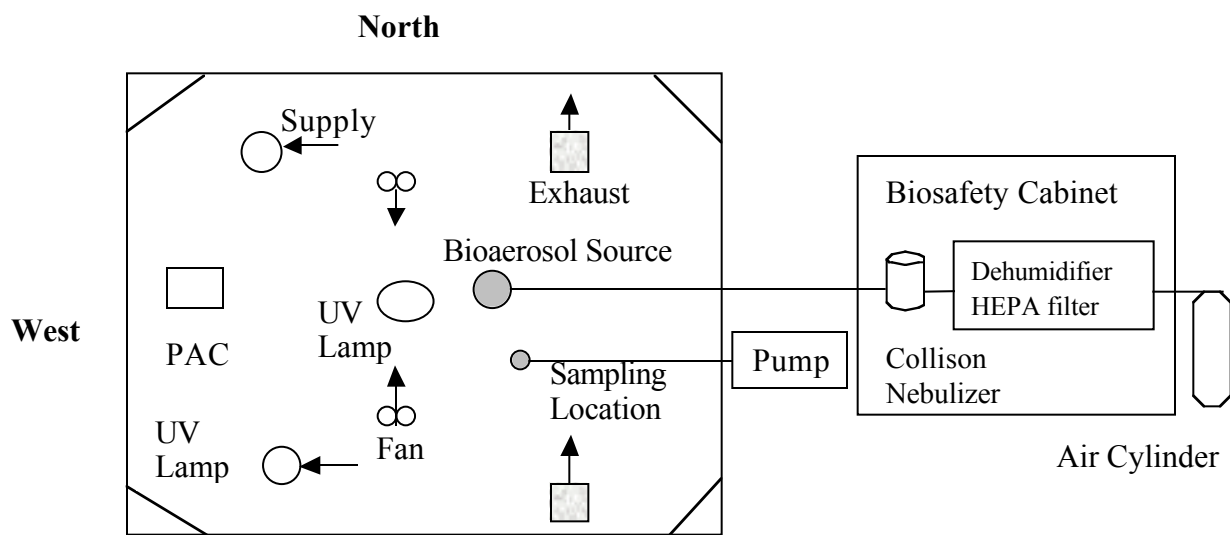


Figure 1. Test chamber (top view) set up for portable air cleaner/UVGI studies

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.

The UVGI system (Lumalier, Memphis, TN) consisted 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 W. The center luminary was rated at total of 72 W, consisting of four lamps. The corner lamps were rated at a 36 W each containing two lamps installed with parabolic aluminum reflectors on the back of the luminaries. Each luminary was 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 lower edge at approximately 2.1 m above the floor. The UVGI system was operated for more than 100 h before experiments were conducted.

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.

Microorganisms

Mycobacterium parafortuitum (ATCC 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 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 proposed to do a subset of experiments with *Escherichia coli*, which proved difficult. Because this Gram-negative bacterium is extremely sensitive to being aerosolized, we

had difficulty aerosolizing and elevating its airborne concentration in our 90-m³ room. During our initial experiments, we were able to detect low levels of *E.coli* without any control measure operating; when filtration or UVGI, however, was operated, we could not detect any *E. coli*. Similar results were seen in a study conducted by Miller and Macher (2000). To elevate these problems, *Micrococcus luteus*, an organism that can withstand aerosolization, was used instead of *E. coli*. This microorganism has been used in previous aerosol 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

The 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 aerosol 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.

The bacterial particles were generated from suspensions containing more than 10⁹ bacterial cells/m³. The volumetric flow rate of the suspension leaving the nebulizer ranges from 0.12–0.33 ml min⁻¹. The test aerosol was released approximately 1.5 m above the floor.

Bioaerosol was generated continuously to raise the bioaerosol concentration in the room to a suitable level for detection (usually 30 min). 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 was 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, 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 room configuration with mixing fans operating, the room is well mixed and the concentration within the room can be represented by a few samples (Xu et al., 1999). Samplers were positioned in the breathing zone, 1.6 m above the floor, below the ventilation exhaust outlet. Aerosol 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. Ten (five samples in duplicate) 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 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, colony) count represents the number of cells in the sample capable of forming colonies on a suitable agar medium. Direct microscopic count represents both living and dead bacterial cells (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. A spiral-plating machine (Spiral Plater Model D, Spiral Biotech, MD) was used. Plates were incubated at 37°C and for 2-3 days for *M. parafortuitum* and 1 day for *M. luteus*. All colonies were described and counted.

For epifluorescent microscopy, sensitive biological stain, 4'6-diamidino-2-phenylidole (DAPI), was used to measure the total numbers of airborne microorganisms. Mounted filters were examined under 1100x magnification using Nikon Eclipse E400 epifluorescent microscope (Hernandez et al., 1999).

Experimental Protocol

The experiments that were performed were based on a decay scenario (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. Decay time varied between 5 to 120 minutes depending on the experimental scenario. 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 and the concentration was allowed to decay, mixing fans were on all the time, the PAC and/or UVGI was turned on and sampling was initiated. Experiments were performed at two ventilation rates: zero and six ACH.

The tested PACs covered a wide range of configuration and prices. The characteristics of used PACs specified by manufacturer are presented in Table 1. Experimental scenarios are given in Table 2.

Table 1. Characteristics of PACs Specified by Manufacturer

PAC Type	Negative Ion Generator (NIG)	Electrostatic precipitator (ESP)	HEPA filter with internal UV lamps (HEPA-UV)
Air Flow (cfm)	Not Specified	Variable (125-335)	550
Pattern	Back-flow	Back-flow	Top-flow
Intake Position	Back	Left-right	Top
Exhaust Position	Top	Right-left	Bottom-front
Dimensions (cm)	28x25x13	30x38x48	43x31x22
Weight (kg)	2	18	91
Cost	\$340	\$722	\$6250
Mounting Options	Portable	Portable/Ceiling	Mobile

Table 2. Experimental Scenarios

Experimental Scenario ^a	PAC Type	Ventilation (ACH)	UVGI	Number of Repeats
MP-ESP-0 MP-ESP-6 ML-ESP-0 MP-ESP-UVGI	ESP	0 6 0	0 0 0 100%	5 (1C, 4D) 3D 2(C) 3 (C, D)
MP-NIG-0 MP-NIG-6	NIG	0 6	0 0	4 (1C, 3D) 3D
MP-HEPA-UV OFF-0 MP-HEPA-UV OFF-6	HEPA-UV with lamps physically removed	0 6	0 0	3D 3D
MP-HEPA-UV ON-0 MP-HEPA-UV ON-6 MP-HEPA-UV ON-UVGI-1 MP-HEPA-UV ON-UVGI-2	HEPA-UV with lamps on	0 6 0 0	0 0 100% 50%	3D 4 (1C, 3D) 4 (C, D) 3 (C, D)

^a MP - *M.parafortuitum*; ML - *M.luteus*

^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 and expressed as an equivalent air-exchange rate. 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):

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

where $C(t)$ is the concentration of bioaerosols at time t ($\# \text{ m}^{-3}$ or CFU m^{-3}), C_0 is the concentration of bioaerosols at time $t=0$ ($\# \text{ m}^{-3}$ or CFU m^{-3}), ACH_0 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 bioaerosols due to ventilation, ACH_{pac} is the loss rate of bioaerosols due to filtration via PACs, and ACH_{uv} is the loss rate of bioaerosols due to UVGI. All loss rates are expressed in air changes per hour. The concentration of bioaerosols was measured sequentially during the decay period and the log form of equation (1) was linearly fit to the data:

$$\ln C(t) = \ln C_0 - (\text{ACH}_0 + \text{ACH}_v + \text{ACH}_{\text{pac}} + \text{ACH}_{\text{uv}})t \quad (2)$$

Knowing the equivalent air-exchange rate by ACH_v and ACH_0 and using equation (2), we can estimate ACH_{pac} or $\text{ACH}_{\text{pac}} + \text{ACH}_{\text{uv}}$. The decay rate determined by direct microscopy gives an estimate of $\text{ACH}_0 + \text{ACH}_v + \text{ACH}_{\text{pac}}$, and by culturing gives $\text{ACH}_0 + \text{ACH}_v + \text{ACH}_{\text{pac}} + \text{ACH}_{\text{uv}}$. A baseline for each experiment was performed in which no UVGI or filtration was applied to determine $\text{ACH}_v + \text{ACH}_0$. Subsequent individual decay rates are estimated by subtraction.

RESULTS AND DISCUSSION

In Table 3, the PAC bioaerosol equivalent air-exchange rates expressed as equivalent air-exchange rates are presented, as well as the summary of bioaerosol average equivalent air-exchange rates of each evaluated PACs expressed as an equivalent air-exchange rate. Standard error of the regression coefficient for each obtained value of ACH is listed in parentheses.

Culturing and direct counts showed comparable equivalent air-exchange rates (paired t-test; $\alpha=0.05$). For example, in experiment MP-HEPA UV ON-6, the equivalent air-exchange rate using culturing was 12.5 h^{-1} and using direct counts the value of 12.0 h^{-1} was obtained.

Results showed that the negative ion generator was not effective in removing biological aerosols and the HEPA-UV was the most effective in removing/inactivating bioaerosols. A

ventilation rate of 6 ACH provided by ventilation system did not significantly impact the equivalent air-exchange rates of the portable air-cleaners, as expected (paired t-test; $\alpha=0.05$). There was no significant difference in the ACH obtained for the ESP using *M. parafortuitum* compared to *M. luteus* (paired t-test; $\alpha=0.05$).

Table 3. PAC Bioaerosol Equivalent Air Exchange rate for each Experiment and Analysis Type

Experiment ID	ACH (Standard Error) for Each Experiment and Analysis Type [h^{-1}] ^{a, b}	Average ACH (Standard Error) [h^{-1}] ^c
MP-ESP-0	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-ESP-6	4.88 (3.99); 4.47 (3.51); 6.03 (2.04)	5.13 (1.90)
ML-ESP-0	5.36C (2.86); 3.95 (1.45) C	4.66 (1.60)
MP-NIG-0	0.360 (0.078); 0.288 (0.075); 0.270 (0.054)	0.335 (0.061)
MP-NIG-6	0.246 (2.312); 0.486 (2.126); 0.450 (3.805); 0.420 (0.21) C	0.394 (1.65)
MP-HEPA-UV OFF-0	3.80 (2.70); 2.60 (0.37); 2.39 (0.91)	2.93 (0.96)
MP-HEPA-UV OFF-6	3.81 (4.57); 4.08 (4.90); 3.40 (1.91)	3.76 (2.32)
MP-HEPA-UV ON-0	8.86 (0.66); 12.2 (2.5); 14.1 (2.6)	11.7 (1.2)
MP-HEPA-UV 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

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; $\alpha=0.05$). Our hypothesis was that in

the HEPA-UV OFF experiments, in which the UV lamps were physically removed from the unit, there was a change in the internal pattern of airflow and this change caused the unit to perform differently. To test this hypothesis, the filter unit was configured so that the lamps could be turned off without removing them from the system. Experiments were repeated with this new configuration. We used a surrogate, non-biological aerosol (phosphate buffer solution particles) instead of microorganisms, and we measured the concentration decay using an Optical Particle Counter (Met One, Pacif. Sci Inst., Oregon). We added a switch to the PAC, which could be used to turn off UV lamps without physically removing it from filter unit and a new configuration was tested again. First, we tested the filter in the HEPA-UV ON configuration, and then with the HEPA filter on and the UV lamps off (but not removed). Results (Table 4) showed that there was no significant difference (paired t-test; $\alpha=0.05$) 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.

Table 4. Equivalent air-exchange rates of HEPA-UV with Non-biological Aerosol

HEPA filter on, UV lamps on	HEPA filter on, UV lamps off
7.79	4.27 ^a
5.89	4.41 ^a
5.48	4.70 ^b
	3.97 ^b

^aUV lamps were removed from unit

^bUV lamps were turned off using the switch

Our opinion is that more analysis should be performed on the HEPA-UV filter to understand the discrepancies mentioned above.

Summary results of average equivalent air-exchange rates of UVGI in combination with filtration by portable air cleaners are presented in Table 3.

Table 3. Average (standard error) equivalent air-exchange rates (h^{-1}) of UVGI in combination with filtration by portable air cleaners

Experimental Scenario	$\text{ACH}_{\text{PAC}} + \text{ACH}_{\text{UV}}$	ACH_{PAC}	ACH_{UV}
MP-ESP-UVGI	22 (3.8)	7.2 (1.5)	15 (5.5)
MP-HEPA-UV ON UVGI-1	27 (5.6)	11 (3.2)	17 (6.4)
MP-HEPA-UV ON UVGI-2	17 (5.7)	9.8 (1.6)	7.1 (6.0)

As expected, the average UVGI equivalent air-exchange rates for MP-ESP-UVGI and MP-HEPA-UV ON UVGI-1, in which the PACs were operated in combination with 100% UVGI, were comparable. For experiment MP-HEPA-UV ON UVGI-2, the average UVGI equivalent air-exchange rate was roughly half of the rates for MP-ESP-UVGI and MP-HEPA-UV ON UVGI-1, due to the application of only 50% UVGI.

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. 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 experimental results of this study showed that filtration alone and in combination with UVGI can remove/inactivate airborne bacteria. Equivalent air-exchange rates in the range of 5-12 ACH can be achieved using PACs, depending on the type of air cleaner. These air-exchange rates due to 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 equivalent air-exchange rate due to UVGI is comparable with previous studies, which measured a rate of 16 ± 1.8 ACH for all lamps operating (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. This research further demonstrated a full-scale laboratory approach for evaluating filtration as engineering infection control in indoor environments.

ACKNOWLEDGEMENTS

The authors thank Leroy Mickelsen, NIOSH, for his assistance. The authors also thank Millie P. Schafer, Ph.D., NIOSH, for her assistance and for proposing the PAC + upper air UVGI studies. We are grateful to the Joint Center for Energy Management for providing essential equipment and operating the test facility. This study was supported by funds provided by the Centers for Disease Control and Prevention, National Institute of Occupational Safety and Health through contracts 200-97-2602 and PO-36755-R-00077B5D.

REFERENCES

- AIA 1987. Committee on Architecture for Health. Guidelines for Construction and Equipment of Hospital and Medical Facilities, Washington, D.C, The American Institute of Architects Press.
- AIHA 1991. Nonionizing Radiation Guide Series. Ultraviolet Radiation, American Industrial Hygiene Association, Akron, OH.
- Behrman, A.J. and Shofer, F.S. 1998. Tuberculosis Exposure and Control in an Urban Emergency Department. *Ann. Emerg. Med.*, Vol.31, pp. 370-375.
- Bergey's Manual of Systematic Bacteriology. 1986. Vol. 1. Baltimore, MD. Williams and Wilkins.
- CDC 1994. Guidelines for Preventing the Transmission of *Mycobacterium tuberculosis* in Health-care Facilities. *MMWR* Vol. 43 (RR-13): 1-132.
- Foarde, K., Myers, E., Hanley, J., Ensor, D., Roessler, P. 1999. Methodology to Perform Clean Air Delivery Rate Type Determinations with Microbiological Aerosols. *Aerosol Science & Technology*, Vol. 30, pp. 235-245.
- Hernandez, M., Miller, S.L., Landfear, D., Macher, J. 1999. A Combined Fluorochrome Method for Quantification of Metabolically Active and Inactive Airborne Bacteria. *Aerosol Science & Technology*, Vol. 30, pp. 145-160.
- Hopewell, P. 1986. Factors Influencing the Transmission and Infectivity of *Mycobacterium tuberculosis*: Implications for Clinical and Public Health Management. In *Respiratory Infections*, Sande, M. A., Hudson, L. D. and Root, R. K., eds. New York: Churchill Livingstone, pp. 191-216.

- Madigan, M., Martiniko, J., Parker, J. 2000. Brock Biology of Microorganisms. Ninth Edition. Prentice Hall, Upper Saddle River, NJ.
- Macher, J.M., Alevantis, L.E., Chang, Y.L., Liu, K.S. (1992): Effect of Ultraviolet Germicidal Lamps on Airborne Microorganisms in an Outpatient Waiting Room. *Applied Occup. Environ. Hyg.* Vol. 7, No. 8, pp. 505-513.
- Miller, S.L. and Macher, J. 2000. Evaluation of a Methodology for Quantifying the Effect of Room Air Ultraviolet Germicidal Irradiation on Airborne Bacteria, *Aerosol Science & Technology*, Vol. 33, pp. 274-295.
- Miller-Leiden, S., Lobacsio, C., Nazaroff, W., Macher, J. 1996. Effectiveness of In-room Air Filtration and Dilution Ventilation for Tuberculosis Infection Control. *Journal of the Air and Waste Management Association*, Vol. 46, pp. 869-882.
- Miller S.L., Xu. P., Peccia, J. et al. 1999. Effects of Ultraviolet Germicidal Irradiation of Room Air on Airborne Bacteria and *Mycobacteria*. *Proceedings of the 8th International Conference on Indoor Air Quality and Climate - Indoor Air '99*, Vol. 2. pp. 665-670.
- Morton, A., Watkins, D., Jensen, P., Mickelsen, R., Johnston, O., Shulman, S. 1999. Evaluation of Portable Air Cleaners Challenged with Non-Biological and Biological Aerosols. *Proceedings of the American Industrial Hygiene Association*, paper#59, Fairfax, VA.
- Peccia, J, Werth, H., Miller, S.L., Hernandez, M. 2001. Effects of Relative Humidity on the Ultraviolet Induced Inactivation of Airborne Bacteria. *Aerosol Science and Technology*, Vol. 35, pp. 728-740.
- Sutton, P. M., Nicas, M., Reinisch, F. et al. 1998. Evaluating the Control of Tuberculosis among Healthcare Workers: Adherence to CDC Guidelines of Three Urban Hospitals in California. *Infect. Control Hosp. Epidemiol.*, Vol. 19, pp. 487-493.

- Xu, P. and Miller, SL.. 1999 Factors Influencing Effectiveness of Ultraviolet Germicidal Irradiation for Inactivating Airborne Bacteria: Air Mixing and Ventilation Efficiency. *Proceedings of the 8th International Conference on Indoor Air Quality and Climate - Indoor Air '99*, Vol. 2. pp.393-398., Edinburgh, Scotland.
- Xu, P., Peccia, J., Fabian, P. et al. 2002. Efficacy of Ultraviolet Germicidal Irradiation of Upper-room Air in Inactivating Airborne Bacterial Spores and *Mycobacteria* in Full-scale Studies, *Atmospheric Environment*, submitted.