J. Microbiol. Biotechnol. (2007), **17**(10), 1622–1628

JOURNAL OF MICROBIOLOGY AND BIOTECHNOLOGY

Removal of *Serratia marcescens* Aerosols Using an Electrostatic Precipitator Air-Cleaner

KO, GWANGPYO[1]* AND HARRIET BURGE[2]

[1]*Department of Environmental Health, Institute for Health and Environment, School of Public Health, Seoul National University, Seoul 110-799, Korea*
[2]*Department of Environmental Health, Harvard School of Public Health, Boston, MA, 02115, U.S.A.*

Received: March 5, 2007 Accepted: May 1, 2007

Abstract We characterized the efficacy of an electrostatic precipitator (ESP) air-cleaner in reducing the concentration of *Serratia marcescens* in an enclosed space. We used an experimental room (4.5×3×2.9 m) in which electrostatic air-cleaners were located. Two air-cleaners enhanced the equivalent ventilation rates in the chamber by about 3.3 air changes per hour (ACH) over the 2 ACH provided by the mechanical ventilation system. Natural die-off of the organisms provided an additional equivalent of 3 ACH, so that the total ventilation rate with the ESP air-cleaners was 8.3 ACH. We also examined whether the ESP air-cleaners altered the deposition of *Serratia marcescens* aerosols on the experimental room surfaces. We did not find any significant differences in the number of colony forming units recovered from surfaces with and without the air-cleaners. We installed UV lights inside the ESPs and determined if UV light, in addition to electrical fields, increased the efficacy of the ESPs. The presence of UV light inside the ESP reduced *S. marcescens* aerosols by approximately 2 ACH. Finally, a box model indicates that the efficiency of the air-cleaner increases for both biological and nonbiological particles at ventilation rates of 0.2–1, which are typical for residential settings.

Keywords: Bioaerosols, electrostatic precipitator, UV, indoor air quality

Air-cleaners are commonly recommended for protection against particulate air contaminants [2, 19]. Currently available air-cleaners for removing particulates are mechanical filters, electronic air-cleaners or electrostatic precipitators (ESPs), inertial separators, cyclones, or louvers, and hybrid devices that contain two or more of these particle removal devices [16]. Air-cleaner efficacy depends on the flow rate and particle collection efficiencies, which are primarily functions of the type and structure of air-cleaners, operating conditions, and particle characteristics.

Typically, air-cleaners are recommended for patients with asthma or hypersensitivity pneumonitis and are installed in various high-risk settings to reduce exposure to various infectious agents, especially for immunocompromised patients. However, evidence is equivocal on the ability of these units to decrease total concentrations of biological aerosols [6, 13, 14, 20]. In addition, because most air-cleaners make a significant amount of noise compared with the amount of air they move, many people fail to use them routinely. We tested the Quadra ESP air-cleaner, designed and marketed by The Sharper Image. This ESP air-cleaner circulates air electronically and operates very silently because it lacks a mechanical motor. These characteristics might result in high compliance. We tested the efficacy of the ESP air-cleaner in reducing airborne bacteria using *Serratia marcescens* as a surrogate for potentially infectious Gram-negative bacteria. Diseases that may be caused by Gram-negative bacteria include Legionnaires' disease, whooping cough, and some pneumonias [1, 5, 11]. Controlling these types of aerosols is especially important in light of the increasing number of immunocompromised people.

Materials and Methods

Bacterial Culture and Preparation of Cell Stocks

Serratia marcescens was obtained from the American Type Culture Collection (ATCC 8195) and maintained on nutrient agar (NA) slants (DIFCO, Detroit, MI, U.S.A.) at room temperature [12]. A loopful of cells was inoculated into 100 ml of nutrient broth (NB) and cultured at 25°C for 24 h with agitation (200 rpm). Aliquots of 1 ml of cultured cells were placed in 1.5-ml Eppendorf tubes, washed twice with 1 ml of phosphate-buffered saline (PBS; pH 7.4), and harvested by centrifugation at 1,500 rpm for 10 min. Harvested cells were stored at −20°C for later experiments.

*Corresponding author
Phone: 82-2-3668-7881; Fax: 82-2-762-9105;
E-mail: gko@snu.ac.kr

Several of these cell aliquots were sampled, serially diluted, and cultured on NA to appropriate dilutions for aerosolization. A cell pellet was suspended in 150 ml of PBS to a cell concentration of approximately 10^6 colony forming units (CFU) per ml. Fetal calf serum (FCS; DIFCO) was added to a final concentration of 10% to simulate the protein concentration of saliva (3.5 mg/ml; [18]). A six-jet Collison nebulizer was initially loaded with about 70 ml of cell suspension, and additional suspension was added to the nebulizer as needed [14]. Nutrient agar plates were loaded into a six-stage Andersen culture plate impactor (Andersen Sampler Inc., Atlanta, GA, U.S.A.) for the experiments. Colonies of *S. marcescens* were counted after incubation for 48 h at room temperature.

Description of the Experimental Facility

The same experimental chamber was used in a previous study [10]. The facility was built on the roof of a four-story building in an urban setting in Boston, about 19 m from the ground (Fig. 1). The facility is 15.6 m^2 (5.2×3 m) with a ceiling height of 2.9 m. It contains an experimental chamber (4.5×3 m) and an anteroom (0.7×3 m) separated by a partition and an interior door. Interior wall and ceiling surfaces are finished with vinyl-covered sheet rock, and the floor is a composite. The facility has an exterior door to the anteroom and three double-insulated glazed windows. The interior door separating the anteroom from the chamber was sealed with vinyl tape during the experiments. Ventilation of the chamber is through an upper room supply grill and a lower room air exhaust grill, both fitted with HEPA filters to prevent microbiological contamination of the supply air and to prevent release of microbiological agents into the exhaust air. The mechanical ventilation rate was adjusted to approximately 50 cubic feet per minute (CFM) for two air changes per hour (ACH). The air exchange rate was measured in the exhaust duct using a hot wire anemometer (model 8360, TSI Inc., St. Paul, MN, U.S.A.) and checked using the decay rate of a tracer gas (SF_6). The chamber is essentially airtight and the air exchange rate estimated by mechanical ventilation was almost identical to the decay of the tracer gas. The room was always maintained under negative pressure relative to the anteroom and exterior, using a balance of supply and exhaust, and was checked by a smoke test. During the experiments, temperature, relative humidity (RH), and negative pressure in the room chamber were continuously monitored in front of the exhaust duct by an electrical sensor (Humeter 50Y, VAISALA, Woburn, MA, U.S.A.). The temperature and RH were maintained at 21°C and 50% respectively. A 20-inch box fan (Cyclone model number 3510, Lasko, Franklin, TN, U.S.A.) was located in the center of the room.

Aerosol Generation and Sampling Devices

Aerosols were generated by a six-jet Collison nebulizer (CN-38, BGI, Waltham, MA, U.S.A.). The nebulizer was located outside the test room, and the aerosols were introduced to the center of the chamber through a permanently installed stainless steel pipe. A multi-perforated stainless steel hollow sphere was connected to the end of the steel pipe, thereby projecting condensation nuclei-like particles more or less uniformly throughout the chamber. Particle deposition in the aerosol supply line (approximately 1.5 m in length) is expected to be negligible compared with the number of cells aerosolized (less than 1%; [3]).

The sampling line through which all samples were collected penetrated an exterior wall and was sealed airtight to the structure at the point of entry and the inner wall surface. A sampling line was permanently installed at the exhaust grill through sampling ports, and all other parts of the sampling devices were located outside the chamber.

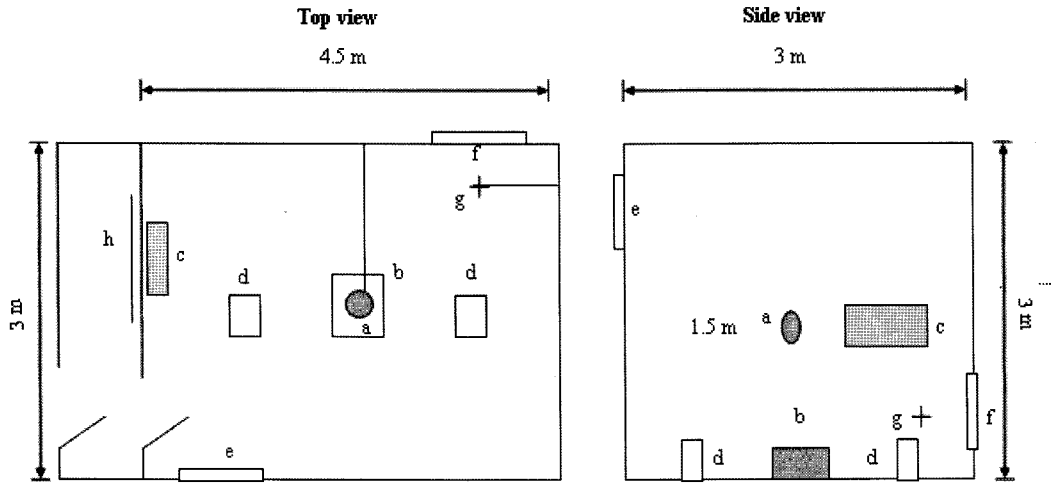

Fig. 1. Diagram of the experimental room.
a, aerosol generator; b, box fan; c, humidifier; d, air cleaner; e, air supply grill; f, air exhaust grill; g, sampling device.

An outer tube was sealed airtight to the inner and outer facility walls. An inner tube, approximately 1.5 m long, had O-ring seals attached at appropriate intervals to assure that two O-rings were always inside the outer tube, providing a double seal between the facility interior and exterior. The sampling line was fit with a six-stage Anderson culture plate impactor and other sampling devices. The discharge of the sampler was fit with flat HEPA filter material to remove microorganisms not recovered by the Andersen sampler. A high static pressure pump was connected to the sampling device at the downstream end and provided the desired sampling rate, which was monitored by both a venturi meter and a rotameter. Loss of bacterial aerosols during transport through the sampling line is expected to be negligible [3].

ESPs with and without UV Fixtures

The ESP air-cleaners tested were commercially available units provided by The Sharper Image (model #S1637, The Sharper Image Corp., San Francisco, CA, U.S.A.). The direction of airflow was tested using smoke tubes and was approximately laminar. Airflow rates were measured at 36 different points across the exit grills of each air-cleaner by a hot wire anemometer (8360, TSI Inc., St. Paul, MN, U.S.A.) and then averaged. When the switch was set at high, the average velocity through the exit grill was 143 feet per minute (fpm), and the flow rate through the grill was approximately 58 CFM. Two ESP air-cleaner units were placed in the experimental chamber. In addition, the commercially available unit was modified with a UV light to test the effect of UV light on the efficacy of the ESP air-cleaner. This modified unit can be run with either ESP only or both ESP and UV light. The average velocity through the exit grill of the ESP air-cleaner with UV light was 168 fpm and the flow rate was approximately 64 CFM. One ESP air-cleaner with a UV light was placed in the experimental chamber.

Efficacy of the Electrostatic Air-Cleaner in Reducing Airborne Microorganisms

The mechanical ventilation rate was maintained at 2 ACH. *Serratia marcescens* cells were aerosolized by the six-jet Collison nebulizer, which generated aerosols with 2 mm mass median particle diameter (MMD; [15]). Air pressure for the nebulizer was maintained at 138 kPa (20 psi). Bacterial aerosols were generated at a rate of 1.5×10^6 CFU/min and introduced into the chamber as described above. Air was mixed during experiments by operation of the floor fan. Air containing the microbial aerosols was pulled from the chamber into the sampling line at a flow rate of 1 CFM and then into the Andersen culture plate impactor. The concentration of airborne culturable microorganisms was determined from the total volume of sampled air and the number of resulting colonies. Because most sampled cells (>95%) were recovered on the fifth stage of the Andersen sampler, corresponding to a particle size range of 1.1–2.1 μm, and because particles in this size range present the greatest risk for airborne infection, only the second and fifth stages were loaded with agar plates. The colonies recovered from the second stage plate would be large clumps of organisms (>4.7 μm), whereas colonies recovered from the fifth stage would be the remaining small particles from 1.1 to 4.7 μm. Only data from the fifth stage were used for analysis.

The efficacy of the air-cleaners in reducing the concentration of culturable microorganisms in the air was tested under transient aerosol conditions. Aerosols were generated for 90 min, stopped at time=0, and then concentrations of airborne microorganisms were measured at 0, 5, 10, and 15 min with and without the air-cleaners. All experiments were performed at 2 ACH, the minimum ventilation rate at which we could maintain pressure relationships in the chamber. Each experimental condition was repeated six times for the commercially available ESP and four times for the ESP modified with a UV light. A positive hole conversion factor was used to adjust for the probability of multiple impactions at each site on the culture plates [4].

Deposition of Airborne Microorganisms onto Surfaces with and without the ESP Air-Cleaner

Bacterial aerosols were generated at a rate of 1.5×10^6 CFU/min and introduced into the room chamber for 90 min. After stopping nebulization, we waited for 5–5.5 h with or without the air-cleaners operating. We then entered the experimental chamber, wearing protective equipment, and took 20 surface samples from the walls and floor using Rodac plates (4-1034-2, Becton Dickinson Labware, Lincoln Park, NJ, U.S.A.). Each experiment was performed on a different day, and the experiments were repeated six times (three experiments with ESP-on and three experiments with ESP-off). Ultraviolet germicidal irradiation (LIND-24-EVO-2PM, Atlantic Ultraviolet, Hauppauge, NY, U.S.A.) was applied to the floor and walls at least overnight before beginning each experiment, to kill any remaining microorganisms previously introduced into the chamber during other experiments.

Data Analysis and Risk Models

Data were manipulated in Excel and statistical tests were performed using S-plus (Mathsoft Inc, Seattle, WA, U.S.A.). The slopes of aerosol decay curves were estimated from a regression with an assumption of 100% recovery at time=0. The slopes of the aerosol decay curves with and without air-cleaners were defined as $K_{air\text{-}cleaner}$ and K_o, respectively. The equivalent ventilation rate was defined as the amount of ventilation that would produce the same effect as the air-cleaner in our experimental setting. The effect of the air-

Table 1. Recovery of *Serratia marcescens* aerosols in a room with 2 ACH, with or without two air-cleaners (ACs; N=6 for each condition).

		AC-off (mean±SE)[a]		AC-on (mean±SE)	
		Recovered CFU[b]	Percent recovery[c]	Recovered CFU	Percent recovery
Elapsed time (min)	0	336±122	100±0	310±72	100±0
	5	111±73	31.9±10.2	67±28	21.5±6.8
	10	46±19	13.5±2.9	16±8	5.0±1.9
	15	22±17	6.2±3.4	3±2	0.8±0.7
Equivalent ventilation rate (ACH)		5.0±0.2		8.3±0.2	

[a]Two air-cleaners were operated simultaneously in the experimental chamber (4.5×3×3 m).
[b]The number of colony forming units (CFU) recovered during 3-min samples at a flow rate of 1 cubic feet per minute.
[c]100% at time=0.

cleaners ($K_{air\text{-}cleaner}-K_o$) was expressed as the equivalent ventilation rate (ACH) attributable to the air-cleaner.

The effect of the air-cleaners was extrapolated to different ventilation conditions (0.1 and 1 ACH) using box models. The steady-state condition (constant ventilation and aerosol generating rate) was estimated using Eq. (1).

$$C=G/([Q+D+A]\times V) \quad (1)$$

where C is the steady-state concentration (CFU/m^3), G is the generation rate of aerosols (CFU/h), Q is the mechanical ventilation rate (h^{-1}), D is the rate of decay of culturable airborne microorganisms (h^{-1}), A is the equivalent ventilation rate due to the air-cleaner (h^{-1}), and V is the volume of the room (m^3).

In addition to estimating the microbial concentration under steady-state conditions with and without the air-cleaner, we estimated the time required for a 99% reduction in aerosol concentrations after stopping nebulization using Eq. (2).

$$C(t)=C_0\exp(-[Q+A]\times t) \quad (2)$$

where C(t) is the concentration at time t, C_0 is the initial concentration (CFU/m^3), Q is the ventilation rate (h^{-1}), A is the equivalent ventilation rate due to the air-cleaner (h^{-1}), and t is the elapsed time (h) after nebulization.

RESULTS

Percent Recovery and Particle Size Distribution

No *S. marcescens* colonies were collected on stages 1 through 4 of the Andersen sampler. An average of 35 colonies were found on stage 5, and 3 on stage 6. More than 90% of the recovered cells were from the fifth stage in all experiments, representing an aerodynamic diameter range from 1.1 to 2.1 μm.

Decay Curves of *S. marcescens* Aerosols with and without Air-Cleaners

The efficacy of the air-cleaners was calculated from stage 5 colony counts only. The number of recovered CFUs at time=0 over all experiments was 324±98 (mean±SD). Colony counts were performed for each experimental condition over time (Table 1). Equivalent ventilation rates provided by the air-cleaners and natural die-off of the aerosols were also determined (Table 1). These data indicate that the air-cleaners significantly reduce the concentration of bacterial aerosols over the natural decay rate, and each unit adds an equivalent of 1.6 ACH under our experimental conditions.

Surface Recovery with and without ESP Air-Cleaners

The experimental results of surface sampling with and without ESP air-cleaners were summarized (Table 2). The

Table 2. Recovery of *Serratia marcescens* aerosols in a room with 2 ACH, with or without UV light inside ESP air cleaners (N=8 for each condition).

		AC without UV (mean±SE)[a]		AC with UV (mean±SE)	
		Recovered CFU[b]	Percent recovery[c]	Recovered CFU	Percent recovery
Elapsed time (min)	0	335±255	100±0	375±359	100±0
	5	137±141	36.4±10.7	172±225	31.4±21.6
	10	76±79	18.9±10.0	73±115	12.6±8.9
	15	37±31	10.8±5.3	43±91	5.7±8.3
Equivalent ventilation rate (ACH)		9.4±0.5		11.7±0.4	

[a]Two air-cleaners were operated simultaneously in the experimental chamber (4.5×3×3 m).
[b]The number of colony forming units (CFU) recovered during 3-min samples at a flow rate of 1 cubic feet per minute.
[c]100% at time=0.

Table 3. Numbers of *Serratia marcescens* recovered from surfaces in a room with or without electrostatic air-cleaners.

Air-cleaners[a]	Replicate	Recovered CFU[b]
On	1	11
	2	10
	3	6
Off	1	16
	2	16
	3	8

[a]Two electrostatic air-cleaners were running simultaneously in the experimental chamber (4.5×3×3 m) under a ventilation rate of 2 ACH.
[b]Total number of colony forming units (CFU) recovered from 10 surface samples by Rodac plates. The surface samples were taken 5–5.5 h after aerosolization of *Serratia marcescens* into the room.

number of recovered CFUs on 20 Rodac plates was 11, 10, and 6 in experiments with the air-cleaners operating, and 16, 16, and 8 in experiments without air-cleaners. Air-cleaner operation did not significantly change the number of CFUs recovered from surfaces.

Decay Curves of *S. marcescens* Aerosols with UV Light Inside ESP Air-Cleaners

The number of recovered CFUs at time=0 over all experiments ranged from 66 to 499 on stage 5. Equivalent ventilation rates provided by the ESP air-cleaner with and without UV light (Table 3) indicate that UV light significantly reduced the concentration of bacterial aerosols. The efficacy of the ESP with and without UV light in our experimental settings was 2.6 and 0.6 ACH higher than without the ESP, respectively.

Extrapolation to Different Conditions Using Box Models

We used box models to estimate the incremental efficacy of the air-cleaners at steady-state conditions (Table 4). Percent reductions in *S. marcescens* aerosols were estimated to 89.2, 62.3, and 45.2 at 0.2, 1, and 2 ACH, respectively. We also estimated the reduction in total particle concentrations assuming that all particles remain airborne until removed by the room ventilation (*i.e.*, gravitational settling and surface interception are considered negligible compared with removal by ventilation; Table 4). Percent reductions in particulates were estimated to 34.0, 29.2, and 24.8 at 0.2, 1, and 2 ACH, respectively. Finally, we used the box models to estimate the time under transient conditions that would be needed to reach 1% of the original aerosol concentration (Table 4). When an air-cleaner was present, the estimated time required for 99% reduction of *S. marscensns* aerosols in the experimental chamber was reduced by 35%, 29%, and 25% at 0.2, 1, and 2 ACH, respectively.

DISCUSSION

The ESP air-cleaners tested clearly augmented background ventilation rates, reducing culturable bacterial levels by nearly an order of magnitude over that achieved by death and physical decay factors. Particles in indoor air are generally removed by ventilation, impaction, diffusional deposition, electrostatic deposition, interception, and gravitational deposition. These are all physical mechanisms, and the efficiency with which particles are removed is highly dependent on their aerodynamic size (a combination of size, shape, and density of the particle). Ventilation is one of the most important means of particle removal. Without recirculation, particle-laden air is replaced (diluted) with clean fresh air, assuming that similar particles are not present in the fresh air. The rate of removal depends on the ventilation rate. When recirculation is used, particle concentrations also depend on the particle collection efficiency of the ventilation system. Ventilation can remove airborne particles over a very broad size range. These physical mechanisms apply to biological particles, and the efficiency of removal is controlled by the same factors. However,

Table 4. Extrapolation of the effects of an electrostatic air-cleaner at different air exchange rates.

	Agent	Room ventilation rate (ACH)		
		0.2	1	2
Percent reduction due to an air-cleaner at a steady state[a]	Particulates	89.2	62.3	45.2
	Serratia marcescens	34.0	29.2	24.8
Time required for 99% reduction under transient conditions (min)[b]				
Air-cleaner off	Particulates	2760	277	138
Air-cleaner on	Particulates	158	104	75
Air-cleaner off	*S. marcescens*	89	69	55
Air-cleaner on	*S. marcescens*	58	49	41

[a]Concentrations were estimated using the formula $C=G/(Q+D+A)$, where C is the concentration (CFU/m^3), G is the aerosol generation rate (CFU/h), Q is the ventilation rate of the room (m^3/h), D is the rate of die-off (m^3/h), and A is the equivalent ventilation rate due to the air-cleaner (m^3/h).
[b]Time required for 99% reduction after stopping nebulization. An air-cleaner is assumed to produce 1.6 equivalent ACH in reducing airborne microorganisms. The concentrations were estimated from $C(t)=C_0\exp(-[Q+A]/Vt)$, where C(t) is the concentration at time t, C_0 is the initial concentration (CFU/m^3), Q is the ventilation rate of the room (m^3/h), A is the equivalent air exchange rate due to the air cleaner (m^3/h), V is the volume of the room, and t is the elapsed time after nebulization.

some biological particles must be living to cause human health problems in a building. This type of particle includes viruses, bacteria, and some fungal spores. Thus, as particulate organisms die, they are, for all practical purposes, removed from the aerosol.

Our chamber was continuously ventilated with HEPA-filtered air (no recirculation) at 2 ACH. The culturable particle removal rate under these circumstances was equivalent to 5 ACH without the air-cleaners operating. This additional 3 ACH represents a combination of all of the physical removal rates, other than ventilation and the death rate of the cells. When two air-cleaners were added to this system, the effective ventilation rate increased to 8.3 ACH (Table 1). The additional 3.3 ACH can be attributed to the effects of the air-cleaners.

The particles may have remained in the room, but could no longer be detected by measurement methods that use viability (culture) as a means for detection. If we had used particle counts, the results might have been quite different, but not as biologically relevant if infection risk is of concern. The rate of loss of infectivity (as measured by culturability) appears much higher in typical buildings than loss related to physical mechanisms of aerosol removal. For example, the estimated settling velocity of unit density (1 g/cm^3) spherical airborne particles sized 1, 2, and 5 μm at standard conditions (20°C and 1 atm) is 3.5E-3, 1.3E-2, and 7.8E-2 (cm/s), respectively. With these settling velocities, it takes about 7.9 h, 2.1 h, and 36 min, respectively, for particles to fall 1 m. In comparison, the half-life of culturable *Serratia marcescens* aerosols (without air cleaning) is 10–15 min [7]. Noninfectious agents such as biological toxins and allergens are less likely to be subject to biological inactivation; these particles are more likely to be removed by physical mechanisms.

The augmentation of removal rates provided by the air-cleaners could have been caused by particle trapping, increasing the death rate of cells in the aerosols or increasing the rate of electrostatic attachment to surfaces in the chamber [9]. To examine whether the ESP air-cleaners increased physical deposition on surfaces, we collected surface samples following aerosolization of bacteria with and without the air-cleaner operating. There were no significant differences in recoveries attributable to air-cleaner operation. To examine changes in the death rate, we modified the ESP with UV light and examined if the presence of germicidal 254 nm UV light inside the ESP increased the efficacy of the ESP in removing infectious *S. marcescens* aerosols. The increased efficiency with germicidal UV light (Table 3) indicated that the ESP is likely to have little or no effect on the viability of airborne bacteria. Instead, UV light inside the ESP air-cleaner increased its efficacy by killing airborne bacteria that were not trapped. We estimated that the efficiency of inactivation increased from 23% to almost 100% (Table 3). The 100% collection efficiency of the ESP with UV light indicates that all *S. marcescens* in incoming air were either trapped by electrical force or killed by UV light.

The collection efficiency of each air-cleaner type was estimated to be 23%–71%. Collection efficiency is a function of flow rate, the strength of the electrical field, and the area of the collecting plates [8, 17]. The different collection efficiencies may result from the different amounts of dust on the collecting plates or variability among experiments.

In our experimental settings, the decay of the tracer gas (SF_6) matched the nominal mechanical ventilation rate. This implies that natural ventilation was almost negligible in our chamber and that the mechanical system is likely the dominating physical mechanism for removing airborne particles.

A constant rate of decay was assumed in the regression model. This assumes a uniform distribution of aerosolized bacteria in the room and equal susceptibility of airborne microorganisms to environmental stressors. Our results followed the expected exponential decay pattern of the *S. marcescens* aerosols reasonably well, suggesting that our assumptions were likely valid. The system may produce different results for microbial aerosols with subpopulations of more- or less-resistant organisms.

The results from our risk models suggest that the effects of the air-cleaners in removing airborne microorganisms would be greater under a lower air exchange rate. The augmentation provided by the air-cleaners is likely to be higher for nonbiological than biological particles because of the higher natural decay rates for living aerosols. It should be noted that the estimated effect of the air-cleaners on nonbiological fine particles might be somewhat overestimated at 0.2 ACH, because other physical mechanisms might no longer be negligible.

In conclusion, ESP air-cleaners can increase the effective air exchange rate in poorly ventilated buildings by 1.6 ACH. The efficacy of these units can be increased by adding UV light inside the ESP air-cleaner. These units show promise in reducing the tight building effects that are increasingly common in energy-efficient houses. Furthermore, they are likely to reduce exposure to some infectious biological particles.

REFERENCES

1. Aintablian, N., P. Walpita, and M. H. Sawyer. 1998. Detection of *Bordetella pertussis* and respiratory synctial virus in air samples from hospital rooms. *Infect. Control Hosp. Epidemiol.* **19:** 918–923.
2. American Lung Association. 1997. *Residential Air Cleaning Devices: Types, Effectiveness and Health Impact.* Washington, D.C.
3. Anand, N. K. and A. R. McFarland. 1989. Particle deposition in aerosol sampling lines caused by turbulent diffusion and gravitational settling. *Am. Ind. Hyg. Assoc. J.* **50:** 307–312.

4. Andersen, A. A. 1958. New sampler for the collection, sizing and enumeration of viable airborne particles. *J. Bacteriol.* **76:** 471–484.
5. Cordes, L. G., D. W. Fraser, P. Skaliy, C. A. Perlino, W. R. Elsea, G. F. Mallison, and P. S. Hayes. 1980. Legionnaires' disease outbreak at an Atlanta, Georgia, country club: Evidence for spread from an evaporative condenser. *Am. J. Epidemiol.* **111:** 425–431.
6. Cornet, M., V. Levy, L. Fleury, J. Lortholary, S. Barquins, M. H. Coureul, E. Deliere, R. Zittoun, G. Brucker, and A. Bouvet. 1999. Efficacy of prevention by high-efficiency particulate air filtration or laminar airflow against *Aspergillus airborne* contamination during hospital renovation. *Infect. Control Hosp. Epidemiol.* **20:** 508–513.
7. Cox, C. S. 1989. Airborne bacteria and viruses. *Science Progr.* **73:** 469–499.
8. Kam, S. K., K. H. Kang, and M. G. Lee. 2005. Removal characteristics of ethyl acetate and 2-butanol by a biofilter packed with Jeju scoria. *J. Microbiol. Biotechnol.* **15:** 977–983.
9. Kang, H. S., J. K. Lee, M. H. Kim, and D. H. Park. 2006. Effect of electrochemical oxidation potential on biofilter for bacteriological oxidation of VOCs to CO_2. *J. Microbiol. Biotechnol.* **16:** 399–407.
10. Ko, G., M. W. First, and H. A. Burge. 2001. The characterization of upper room ultraviolet germicidal irradiation in inactivating airborne microorganisms. *Environ. Health Perspect.* **110:** 95–101.
11. Kuru, T. and J. P. Lynch. 1999. Nonresolving or slowly resolving pneumonia. *Clin. Chest Med.* **20:** 623–651.
12. Kwak, J., D. H. Lee, Y. D. Park, S. B. Kim, J. S. Maeng, H. W. Oh, H. Y. Park, and K. S. Bae. 2006. Polyphasic assignment of a highly proteolytic bacterium isolated from a spider to *Serratia proteamaculans*. *J. Microbiol. Biotechnol.* **16:** 1537–1543.
13. Lajcikova, A., Z. Mathauserova, and K. Klanova. 2000. Effect of recirculation air cleaners on indoor air quality in a children's home. *Central Eur. J. Public Health* **8:** 182–185.
14. Lee, Y. H. and B. U. Lee. 2006. Inactivation of airborne *E. coli* and *B. subtilis* bioaerosols utilizing thermal energy. *J. Microbiol. Biotechnol.* **16:** 1684–1689.
15. May, K. R. 1973. The collison nebulizer: Description, performance, and application. *J. Aerosol Sci.* **4:** 235.
16. McDonald, B. and M. Ouyang. 2000. Air cleaning-particles, pp. 9.1–9.28. *In* J. D. Spengler, J. M. Samet, and J. F. McCarthy (eds.), *Indoor Air Quality Handbook.* McGraw-Hill, New York, NY.
17. Offerman, F. J., R. G. Sextro, and W. J. Fisk. 1985. Control of respirable particles in indoor air with portable air cleaners. *Atmos. Environ.* **19:** 1761–1771.
18. Theunissen, H. J., N. A. Lemmens-den Toom, A. Burggraaf, E. Stolz, and M. F. Michel. 1993. Influence of temperature and relative humidity on the survival of *Chlamydia pneumoniae* in aerosols. *Appl. Environ. Microbiol.* **59:** 2589–2593.
19. U.S. Environmental Protection Agency. 1990. Residential air cleaning devices - a summary of available information. EPA-400-I-90-002.
20. Wood, R. A., E. F. Johnson, M. L. Van Natta, P. H. Chen, and P. A. Eggleston. 1998. A placebo-controlled trial of a HEPA air cleaner in the treatment of cat allergy. *Am. J. Respir. Crit. Care Med.* **158:** 115–120.