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Effectiveness of In-Room Air Filtration and Dilution Ventilation for Tuberculosis Infection Control

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ABSTRACT

Tuberculosis (TB) is a public health problem that may pose substantial risks to health care workers and others. TB infection occurs by inhalation of airborne bacteria emitted by persons with active disease. We experimentally evaluated the effectiveness of in-room air filtration systems, specifically portable air filters (PAFs) and ceiling-mounted air filters (CMAFs), in conjunction with dilution ventilation, for controlling TB exposure in high-risk settings. For each experiment, a test aerosol was continuously generated and released into a full-sized room. With the in-room air filter and room ventilation system operating, time-averaged airborne particle concentrations were measured at several points. The effectiveness of in-room air filtration plus ventilation was determined by comparing particle concentrations with and without device operation. The four PAFs and three CMAFs we evaluated reduced room-average particle concentrations, typically by 30% to 90%, relative to a baseline scenario with two air-changes per hour of ventilation (outside air) only. Increasing the rate of air flow recirculating through the filter and/or air flow from the ventilation did not always increase effectiveness. Concentrations were generally higher near the emission source than elsewhere in the room. Both the air flow configuration of the filter and its placement within the room were important, influencing room air flow patterns and the spatial distribution of concentrations. Air filters containing efficient, but non-high efficiency particulate air (HEPA) filter media were as effective as air filters containing HEPA filter media.

IMPLICATIONS

Recirculating air filtration systems can be used to augment ventilation as a technique to reduce airborne concentrations of *Mycobacterium tuberculosis*, and therefore to reduce the transmission of tuberculosis, a major public health problem. The use of in-room air filtration systems in hospital isolation/treatment rooms is often an economically attractive alternative to increasing ventilation rates. The experimental results reported in this paper indicate that air filtration in conjunction with dilution ventilation can yield moderate to good reductions in airborne bacterial contamination; however, in high-risk settings, these engineering controls should not be relied upon as the sole or even the primary means of TB infection control.

INTRODUCTION

The worldwide occurrence of tuberculosis (TB) is very high. The World Health Organization (WHO) estimates that in 1990, 8 million people developed TB worldwide and 2 to 3 million died.[1,2] After decades of decline, TB incidence recently increased in the United States:[3] between 1985 and 1991, the rate of new TB cases increased 18%.[4] In addition to increased incidence, multidrug-resistant strains of the causative agent, *Mycobacterium tuberculosis (M. tb)*, have become more prevalent. There is recent evidence that the incidence of TB in some areas of the U.S. has stabilized;[5,6] nevertheless, it continues to pose a serious public health threat.

TB is transmitted by inhalation of small airborne particles, sometimes termed "droplet nuclei," that carry viable *M. tb* and mucus. Droplet nuclei are thought to have diameters ranging from 1 to 5 μm.[7] Particles of this size settle slowly, and most emitted into indoor air remain suspended until removed by ventilation or filtration.[8-10] These particles are generated mainly by coughing or sneezing of persons who have active pulmonary or laryngeal TB. Infection can occur when a susceptible person inhales an *M. tb*-carrying particle that subsequently deposits deep in the lungs.[9] Persons who become infected with *M. tb* have an approximate 10% lifetime risk of developing active TB.[11,12]

Transmission of *M. tb* is a recognized risk in hospitals and other congregate living sites, including correctional facilities and homeless shelters.[13-17] Persons at risk in these settings include health care workers, patients, inmates, residents, volunteers, and visitors. Infection control is achieved by a combination of administrative and engineering methods. Engineering controls include direct source control with local exhaust ventilation, maintenance of negative pressure differences between TB isolation/treatment rooms and adjacent areas, dilution and removal of contaminated air with mechanical ventilation, in-room air filtration, ultraviolet

germicidal air irradiation, and respiratory protective equipment. These controls are designed to reduce the concentration of droplet nuclei within the local environment, to protect those who come into close contact with infectious persons, and to prevent *M. tb*-carrying particles from spreading throughout a facility.[11,18-20]

Ventilation is a primary engineering infection-control technique. Outside air is mechanically supplied to the room and air that may contain infectious particles is exhausted to the outside environment. Until recently, TB isolation rooms were recommended to have a minimum total air flow of 6 air-changes per hour (*ACH*) with at least 2 *ACH* being outdoor air, and with the room air directly exhausted to outdoors (the air-exchange rate, expressed as *ACH*, is defined as the total volume of air entering per hour divided by the volume of the room).[21-23] In their 1994 guidelines for preventing TB transmission, the Centers for Disease Control and Prevention (CDC) recommended that at least 6 *ACH* should be provided for existing TB isolation rooms; where feasible, this air flow rate should be increased to ≥12 *ACH* by adjusting or modifying the ventilation system or by using auxiliary means; and at least 12 *ACH* should be provided for newly constructed or renovated isolation rooms.[11] The CDC guidelines do not explicitly state how much of the air flow should be constituted by outside air. Many isolation rooms currently receive less than the recommended 6 *ACH*[11,16,24] and renovating facilities to achieve ventilation rates of 6 to 12 *ACH* can be expensive. Auxiliary means to remove droplet nuclei from room air may be attractive: As defined by the CDC, these include the "recirculation of room air through fixed high efficiency particulate air (HEPA) filtration systems or portable air cleaners."

In a recirculating air filter, a built-in fan draws particle-laden room air through filter media, blowing treated air back into the room. For indoor applications, filtration units can be grouped into two categories: portable air filters (PAFs) designed to be located on the floor or a table, and ceiling-mounted air filters (CMAFs). In addition to reducing first costs associated with ventilation-system retrofits, the use of filter-recirculated air as an alternative to increasing ventilation rates can reduce the energy requirements for heating and cooling.

Despite the fact that ventilation and filtration have been used to reduce indoor pollutant concentrations in many settings,[25-28] and that filtration has been shown to be effective in controlling a number of indoor airborne contaminants,[29-32] little is known about its uses with regard to decreasing the risk of TB infection. The need for research on the use of engineering control methods for reducing transmission of *M. tb* has frequently been expressed.[11,18,33-34] In particular, there is a need to explore the effectiveness of different levels of ventilation or filtration and the efficacy of combining ventilation and filtration.

Two papers have been published that explore filtration- and/or ventilation-based engineering controls to reduce TB exposures. Marier and Nelson[35] reported on a stand-alone unit containing ultraviolet lights and ultra-low penetration air filter media that was effective in removing bacterial particles from the air. Rutala et al.[36] studied four commercially-available PAFs in a test chamber and a hospital isolation room. Their investigation showed that PAFs were effective in removing airborne mineral oil particles and that the location of the unit did not affect performance.

Our two-phase study more broadly investigated the many factors that influence the effectiveness of filtration and dilution ventilation for TB infection control while emphasizing practical issues of concern. During the first phase, we investigated the air-cleaning effectiveness of filtration using PAFs in conjunction with different levels of dilution ventilation. We extended our investigation in the second phase to include CMAFs. In addition, based on our phase-one findings, we expanded our objectives to include not only determining the effectiveness of filtration plus ventilation, but also to determine whether improved effectiveness was due to filter design, a higher recirculating filter air flow rate, or increased ventilation rates. In our investigation, we explored spatial and temporal variability of airborne particle concentrations, aspects that were not addressed in previous research. Our study was not designed to determine which specific air filter was the most effective, but rather to provide information that may help to answer the general questions, "how effective are engineering controls for TB infection control" and "what factors govern effectiveness?"

In this paper, we first present the theoretical framework that was used to guide the design and evaluation of experimental results. Then the test facility and experimental methods are described. Finally, the results are discussed, with particular emphasis on their significance for TB infection control in high-risk settings.

THEORETICAL CONSIDERATIONS

In evaluating the performance of a room air filter, it is important to distinguish *single-pass efficiency* from *effectiveness*. The former parameter characterizes the likelihood that a particle will be removed from air that passes through a filter. The latter parameter describes the impact of device operation on room air concentrations; it is the more relevant indicator for infection control. The effectiveness of in-room air filtration depends on single-pass filter efficiency. However, it also depends on the air flow rate through the filter, and on other features of the indoor environment, particularly the relative positions of the source, control device, and receptor, and the indoor air flow patterns.

The single-pass filter efficiency, η_F, is defined by the following equation and illustrated in Figure 1:

$$\eta_F = \frac{C_{in} - C_{out}}{C_{in}} \quad (1)$$

where: C_{in} = concentration of particles in air as it enters the device

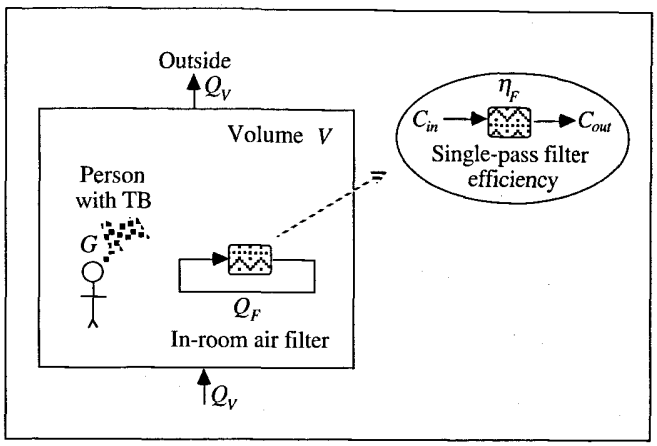

Figure 1. Schematic diagram of the completely-mixed room model for a TB isolation room.

C_{out} = concentration of particles in air as it leaves the device

The single-pass filter efficiency is a function of particle size and of the media used in the device.[37] Minimum single-pass efficiency occurs in the accumulation mode of the particle size distribution, typically at a particle diameter of about 0.3 μm.[10] HEPA filters are essentially 100% efficient: they have a single-pass efficiency of ≥99.97% for 0.3 μm particles.[38,39] However, the use of HEPA media does not ensure a high effectiveness for infection control.

To initiate infection, airborne particles containing *M. tb* must be transported from persons who have active TB to susceptible persons. Although infection theoretically can be caused by emission of only one droplet nucleus, the greater the concentration of these particles in the air breathed by the receptor, the greater the risk of infection.[4,34] The concentration of infectious particles in a room occupied by a person with TB depends on the rate at which they are generated by the source, the volume through which they are distributed within the room, and the rate at which they are removed by ventilation or filtration. Other factors that could affect the concentration include the rate at which particles are inactivated by desiccation or by the presence of ultraviolet germicidal irradiation. These factors were not considered in this study.

Although departures from perfect mixing will prove to be key factors in filter effectiveness, a mathematical model based on the assumption of a completely-mixed room (CMR) serves as a useful evaluation tool.[40-42] The CMR model is formulated from a material balance applied to a pollutant in indoor air, assuming that the pollutant concentration is uniform throughout the volume of the space. As applied in this study, the model is schematically represented in Figure 1. Particles carrying *M. tb* are emitted from a person with TB. Ventilation air flows through the room, serving to reduce the indoor particle concentrations; the air-exchange rate due to ventilation is denoted ACH_V. In this application, ventilation is provided by clean, outside air, (i.e., no *M. tb*-carrying particles enter the room with the ventilation air). Particles carrying *M. tb* may also be removed from room air by filtration. Normalizing the rate of recirculating, filtered air flow by the room volume yields an "equivalent" air-exchange rate, ACH_F, for air filtration. Gravitational settling and other deposition mechanisms for the 1 to 5 μm *M. tb*-carrying particles are negligible, compared with removal by ventilation or filtration at the rates considered here.[10] The rate of change of the indoor airborne droplet nuclei concentration with time is given by:

$$\frac{dC(t)}{dt} = \frac{G}{V} - (ACH_V + \eta_F ACH_F)C(t) \qquad (2)$$

The symbols have the following definitions:

$C(t)$ = concentration (# m^{-3}) of airborne *M. tb*-carrying particles at time t (h)
G = emission rate of droplet nuclei (# h^{-1})
V = room volume (m^3)
$ACH_V = Q_V / V$ = air-exchange rate due to ventilation (h^{-1})
Q_V = room ventilation rate (m^3 h^{-1})
$ACH_F = Q_F / V$ = air-exchange rate due to in-room air filtration (h^{-1})
Q_F = recirculating air flow rate through the filter (m^3 h^{-1})
η_F = single-pass filter efficiency of air filter

Assuming that the governing parameters are constant in time, Equation 2 is solved subject to the initial condition that $C(t) = 0$ at $t = 0$. The resulting equation describes how the droplet nuclei concentration evolves:

$$C(t) = \frac{G}{(ACH_V + \eta_F ACH_F)V}\left(1 - e^{-(ACH_V + \eta_F ACH_F)t}\right) \qquad (3)$$

For exploring the effectiveness of air filtration and dilution ventilation, we considered two scenarios under which an individual might be exposed to TB; these scenarios are denoted *transient* and *steady-state*. In the transient scenario, both the infectious person and the susceptible person enter an initially clean room simultaneously; the concentration of droplet nuclei increases with time. In the steady-state scenario, the infectious person has been present in the room long before the susceptible person enters; the droplet nuclei concentration is constant, as determined by a balance between the rates of generation and removal.

The average transient concentration, C^T, over an exposure period 0-T is determined from the CMR model as the time-weighted average of the concentration predicted by Equation 3:

$$C^T = \frac{1}{T}\int_0^T C(t)dt \qquad (4)$$

The steady-state concentration, C^S, is described by Equation 3 in the limit $t \to \infty$:

$$C^S = \frac{G}{(ACH_V + \eta_F ACH_F)V} \qquad (5)$$

For practical applications, it is important to explore effectiveness under both transient and steady-state concentrations to delimit the range of situations that are encountered. To this end, we compared the particle concentration (transient or steady-state) associated with a baseline scenario to one with ventilation/filtration controls. All factors (except for the level of controls) were kept constant between the two cases. The airborne particle concentration in the baseline scenario was used to normalize the aerosol concentrations observed in any other scenario. For example:

$$Z_{A,\,norm} \equiv \frac{C_{A,\,filter}}{C_{baseline}} \qquad (6)$$

where: $Z_{A,norm}$ = normalized concentration of particles during scenario A with filtration

$C_{baseline}$ = concentration of particles during baseline scenario

$C_{A,filter}$ = concentration of particles during scenario A with filtration

The effectiveness, E, can be determined directly from the normalized concentration:

$$E \equiv 1 - Z_{A,\,norm} = 1 - \frac{C_{A,\,filter}}{C_{baseline}} \qquad (7)$$

For example, if the normalized concentration for a filtration scenario is 0.3, then the effectiveness of in-room filtration is 70% relative to the baseline scenario.

According to the CMR model, the effectiveness of air filtration plus ventilation in preventing person-to-person transmissions is independent of receptor position (i.e., where the susceptible person is located in the room); however, if the room air is not thoroughly mixed, effectiveness will vary with position. The CMR model also predicts that the effectiveness is less in a transient exposure scenario than in a steady-state scenario (Figure 2).

These theoretical considerations served as a framework for our experimental investigation. Effectiveness was experimentally evaluated by comparing both transient and steady-state particle concentrations measured under baseline conditions to those measured with an air filter operating and/or with ventilation. In either case, we assumed that exposure lasts 30 minutes. For all model predictions and experimental measurements reported in this paper, the baseline scenario had a ventilation rate of 2 ACH_V outside air and no air filtration.

EXPERIMENTAL MATERIALS AND METHODS

Test Facility

Experiments were conducted at the Indoor Air Quality Research House located at the Richmond Field Station of the University of California, Berkeley. The test facility is a two-story, wood-frame structure, within which three rooms on the ground floor have been retrofitted to reduce the infiltration rate to less than 0.1 *ACH*.[25] One of these rooms, 36 m³ in volume and similar in size to many TB isolation rooms, was used for the experiments (Figure 3). The floor is covered with linoleum and the walls and ceiling are painted sheetrock or plywood. The two interior doors to the room were closed and sealed during the tests. The east wall has a window to the outdoors that was covered during the tests. The room was furnished with two tables, a heated mannequin seated in a chair, and two lamps; the mannequin and the lamps generated thermal plumes which influenced indoor air mixing.

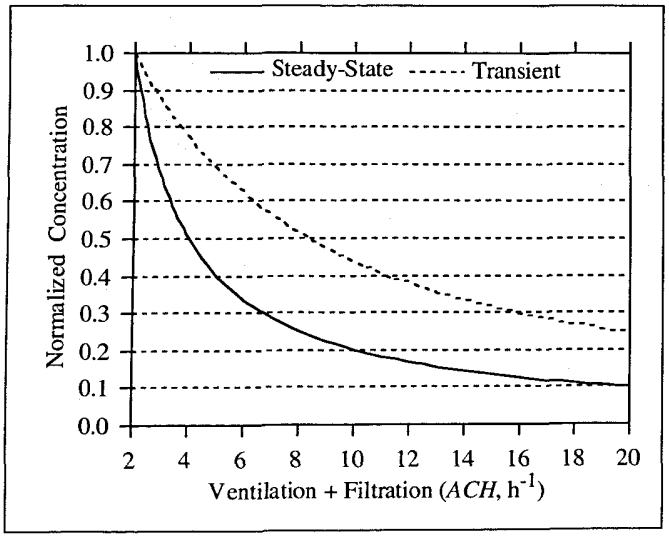

Figure 2. Completely-mixed room model predictions of transient and steady-state concentrations normalized by a baseline scenario under varying ventilation and filtration conditions. Baseline scenario was 2 ACH_V. Steady-state concentrations were calculated according to Equation (5); transient concentrations were time-weighted averages over the period 0 to 30 minutes (Equation 4). Single-pass filter efficiency was assumed to be 100%.

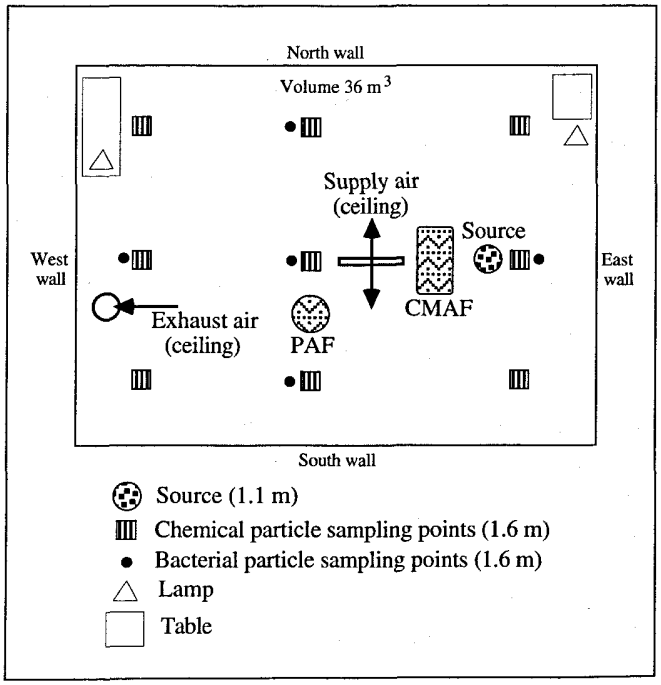

Figure 3. Configuration of test room (plan view). Height above the floor is given in parentheses.

Table 1. Characteristics of in-room air filters.

Code Name	Model and Manufacturer	Type of Filter Medium	Manufacturer-Specified Air Flow Rates (m^3 h^{-1})	Price
		Portable Air Filters		
EC	Enviracaire® 11500, Honeywell Environmental Air Control, Inc., Hagerstown, MD	HEPA 99.97% efficient at 0.3 μm	125 to 250	$169
MC	MediClean® 200, MediClean Corporation, Millbrae, CA	95% efficient at 0.3 μm	65, 160, 335	$299
WM*	Microcon® WallMAP, Biological Controls, Inc., Eatontown, NJ	HEPA 99.97% efficient at 0.3 μm	250 to 485	$1,000
JR	Microcon® Junior, Biological Controls, Inc., Eatontown, NJ	HEPA 99.97% efficient at 0.3 μm	170 to 670	$1,600
		Ceiling-Mounted Air Filters		
EC14	Enviracaire® 14006, Honeywell Environmental Air Control, Inc., Hagerstown, MD	HEPA 99.97% efficient at 0.3 μm	300, 470	$690
UGP	UltraGuard Plus, Airo Clean, Inc., Exton, PA	HEPA 99.97% efficient at 0.3 μm	500, 840, 1175	$1,985
EM†	ElectroMedia 50C, It's All About Clean Air Glasgow, KY	60% efficient at 0.3 μm	250 to 420	$1,600-1,800

* Wall-mounted air filter.

† The filter medium is sandwiched between patented 20 kV electrically charged wires that create an elecrostatic field. Particle removal may be enhanced due to the forces that are exerted on particles in an electrostatic field.[10]

Characteristics of the In-Room Air Filters

Four PAFs and three CMAFs, all commercially available, were selected for testing based on their rated capacity to recirculate air and on the investigators' access to the units. The tested filters covered a wide range of configurations and price (Table 1). Each of the units employed pleated fibrous filters. One PAF (MC) and one CMAF (EM) used non-HEPA media; each of the others used HEPA media. The size and inlet/outlet configurations of the units are depicted in Figure 4. Although one of the PAFs was a wall-mounted filter (WM), it was included in the PAF category since it was roughly the same size and design. One of the CMAFs (UGP) was a two-piece unit with the inlet connected to the outlet by 3-m long x 0.25-m diameter ducting; all of the other devices were single-piece units with inlet and outlet air streams in close proximity to one another.

During the experimental runs, the PAFs were located near the center of the room, in accordance with the manufacturers' recommendations (Figure 3). The WM filter was attached to the south wall. CMAFs were attached to the ceiling near the particle generation source. The inlet of the two-piece UGP was attached to the ceiling near the source; the outlet was attached at the opposite end of the room; and the connecting ducting was installed through the ceiling.

We tested the filters as they arrived from the manufacturer, without any preconditioning, similar to the manner in which customers might operate the filters. It is uncertain how conditioning might have influenced the effectiveness results, since the performance of fiber filter units changes over time: as more particles accumulate within the filter media, the single-pass efficiency usually increases until clogging takes place.[10,37] However, the recirculating air flow rate will tend to decrease with loading.[37] The net effect is not expected to be large until substantial loading of the filter media has occurred. Most manufacturers recommend yearly replacement of the filter media. For TB infection control purposes, the filter must be disposed of

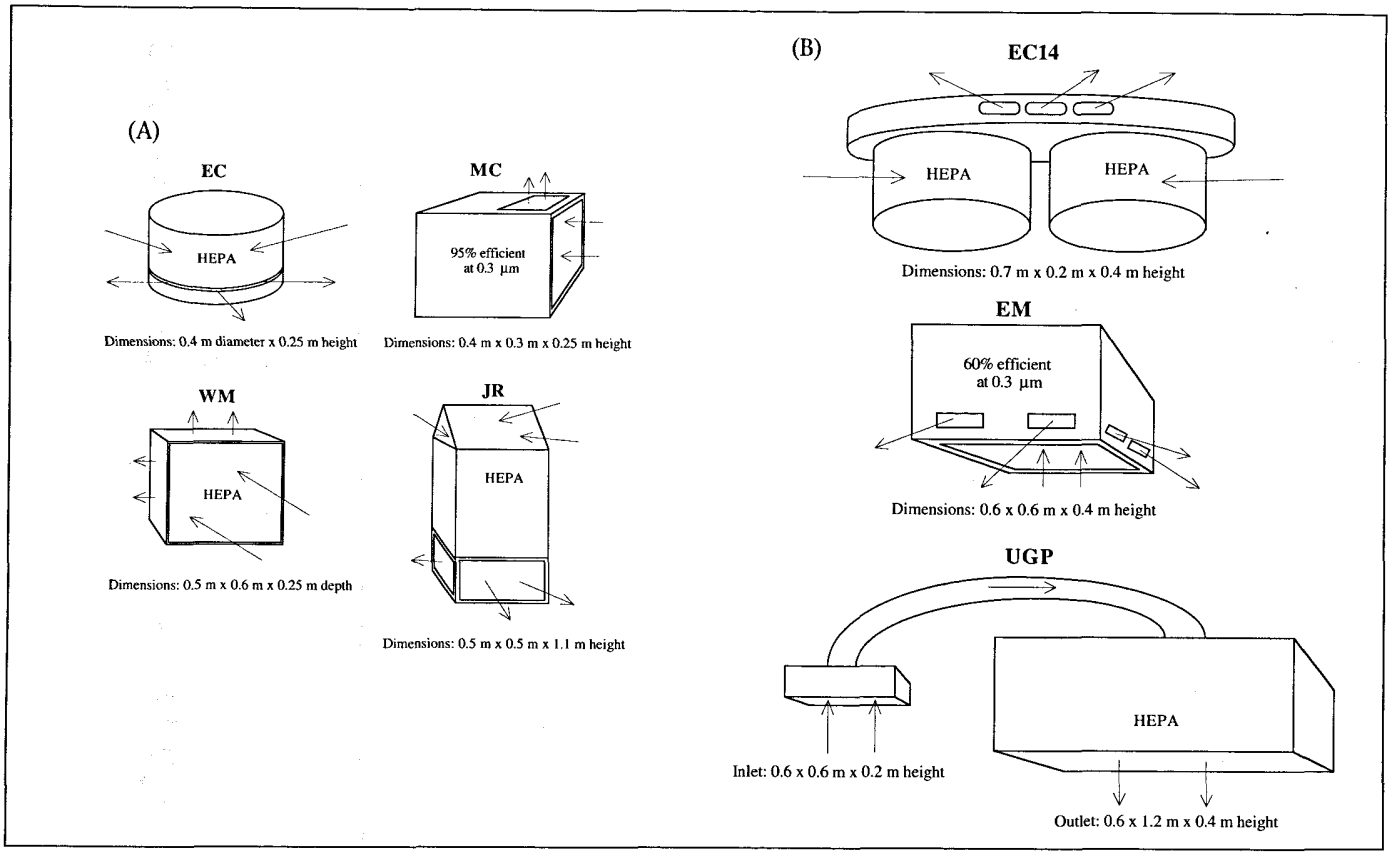

Figure 4. Schematic of inlet/outlet and air flow characteristics for the (A) portable air filters and (B) ceiling-mounted air filters.

according to the proper procedures, since it potentially contains viable *M. tb.*

Ventilation and Filtration Conditions

The effectiveness of in-room air filtration and dilution ventilation for reducing the room air concentration of droplet nuclei-sized particles was tested under a wide range of flow conditions, as summarized in Table 2.

In many cases, the target ACH_F did not match the available settings on the air filters. In these cases, power to the units was provided by variable transformers. The appropriate transformer settings were determined by two types of air flow tests: "orifice plate" and "tracer gas." In the orifice-plate method, the air filtration unit discharged into a large, airtight plenum from which air was separately extracted by an auxiliary fan. In turn, the auxiliary fan discharged to a 20-m straight pipe containing an orifice plate. Air flow generated by the auxiliary fan was adjusted to the desired target value, as determined by measuring the pressure drop across the orifice plate. Then the power to the air filtration unit was adjusted to yield atmospheric pressure in the plenum. At this setting, air flow through the filter matched the target value. In the tracer-gas method, air containing a known mole fraction of SF_6 was injected at a constant rate by means of a mass-flow controller (Matheson, Model 8274) into the inlet of the filter. The outlet of the filter was connected to a plenum that was open to the atmosphere. The concentration of SF_6 was measured in the plenum with a gas chromatograph equipped with an electron capture detector (Lagus Applied Technology). The air flow rate was determined by mass balance based on the steady-state SF_6 concentration in the plenum. The uncertainty in air flow through the filters was typically 10%, based on repeated measurements of flow rates over the course of a few days at the target transformer settings.

We determined that the filters provided the manufacturer-specified air flow rate to within 20%, with one exception. The MC at its maximum setting delivered an air flow rate of 3 ACH_F, 65% lower than specified by the manufacturer. By removing the activated carbon cartridge in the MC, we were able to achieve an air flow rate of 3.6 ACH_F.

The test room was equipped with a mechanical ventilation system that delivered a maximum of 220 $m^3 h^{-1}$ (6 ACH_V) of HEPA-filtered outside air through a ceiling-mounted slot diffuser near the middle of the room (Figure 3). Air was exhausted opposite the particle emission source through a 0.15-m opening in the ceiling connected through a duct to an exhaust fan. Although this supply and exhaust configuration is common, it differs from the CDC recommendation: For improved ventilation effectiveness, the air supply and exhaust should be located such that clean air first flows to less contaminated areas, and then flows across the infectious source and into the exhaust.[11]

Supply and exhaust air flow rates through the ventilation system were monitored continuously during the experiments by measuring the pressure drop across orifice

Table 2. Number and type of experimental scenarios.

Code Name*	Ventilation Rate, ACH_V (h^{-1})	Filtration Rate, ACH_F (h^{-1})	# Runs	
			Chemical Particles	Bacterial Particles
V	2†	0	3[a]	3[b]
	6	0	2[a]	2[b]
Portable Air Filters				
EC	0	4	0	1[a]
	2	4	2[a]	2[b]
	6	4	2[a]	0
MC††	0	3.6	0	1[a]
	2	3.6	2[a]	2[b]
	6	3.6	2[a]	0
WM	0	4	0	1[a]
	2	4	1[a]	2[b]
	6	4	1[a]	0
JR	0	4	0	1[a]
	2	4	1[a]	2[b]
	6	4	1[a]	0
Ceiling-Mounted Air Filters				
EC14	0	6	2	0
	0	12	1	0
	2	10	1	0
	6	10	1	0
UGP	0	12	2	0
	2	10	1	0
	6	10	2	0
	0	20	2	0
EM	0	6	1	0
	0	10	1	2
	0	12	2	0
	0	18	1	0
	2	10	1	0
	6	10	1	0
	2	18	1	0

* Refer to Table 1 for definition of filter code names.
† Baseline scenario.
a One run measured transient concentrations only.
b Two runs measured transient concentrations only.
†† The MC at its maximum setting delivered an airflow rate of only 3 ACH_F, 65% lower than the maximum manufacturer-specified flow rate. During testing, we operated the MC at 3.6 ACH_F by removing the activated carbon cartridge.

plates with a micromanometer (MP20S, Neotronics, Ltd.). Constant-injection SF_6 tracer gas measurements were used to verify the ventilation air flow rates during the experiments. The measured air flow rates provided by the ventilation system were within 10% of the target value.

Test Aerosol Generation and Sampling

Two distinct test aerosols were generated for the experiments: one contained nonviable chemical particles and a second contained viable bacterial particles. The chemical particles consisted of oleic acid (molecular weight 282 g $mole^{-1}$; specific gravity 0.89; viscosity 25.6 g m^{-1} s^{-1}), tagged with a fluorescent dye, uranine (sodium fluorescein): the particles were generated from a solution consisting of volumetric fractions of 49% isopropyl alcohol, 49% oleic acid, and 2% (20 g L^{-1}) uranine in distilled water.[43] The bacterial particles were generated from a suspension of *Bacillus subtilis* in sterile, distilled water, containing 10^7 viable colony-forming units (CFUs) per ml. *B. subtilis* is a rod-shaped, spore-forming bacterium, common in nature, with a diameter of 0.7 to 0.8 μm and a length of 2 to 3 μm. The aerodynamic diameter of *B. subtilis* ranges from 1 to 1.4 μm, comparable to the aerodynamic diameter of *M. tb*, which ranges from 0.3 to 1.4 μm.

The particles were generated using a six-jet Collison nebulizer (CN) with a large reservoir (CN 25, BGI, Inc.) located outside of the test room. The nebulizer was operated at 20 psia, generated by a compressed air cylinder in series with an air supply system that included a dehumidifier, a HEPA filter, and a regulator (Model 3074, TSI, Inc.). The aerosol was delivered from the CN discharge port into the test room at 2.4 L min^{-1} through 2.9 meters of flexible tubing with a 1.3-cm inside diameter. To ensure a stable particle size distribution over the course of the experiment, the particle solution or suspension in the CN was replenished every 30 minutes.

An electrically heated mannequin (80 W) was seated on a chair in the test room, simulating the presence of a person infected with TB. The test aerosol was released near the mannequin's head through a dispersion bottle located 1.1 m above the floor. The discharge velocity of the test aerosol from the dispersion bottle was measured at 45 cm s^{-1} using an omnidirectional air velocity transducer (Model 8470, TSI, Inc.). This is less forceful than the reported discharge from a sneeze or a cough: The peak velocity from sneezing or coughing approaches 100 m s^{-1} and 16-48 m s^{-1}, respectively.[7]

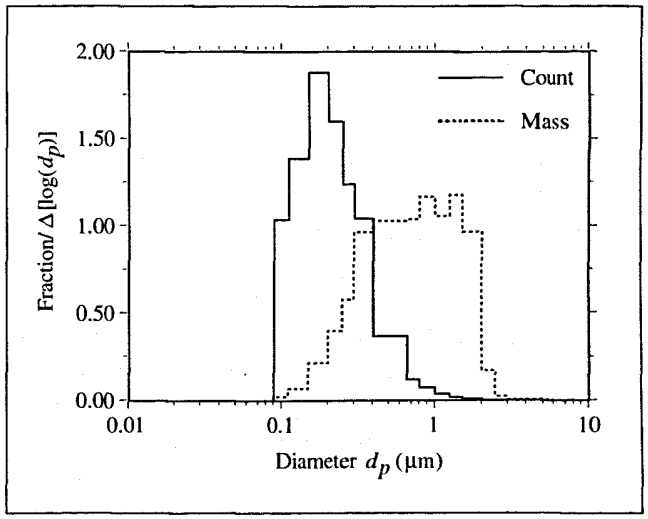

Figure 5. Particle size frequency distribution for the chemical aerosol as a function of particle diameter. The form of the figure is such that the area under a curve between two particle sizes is proportional to the fraction of total particles within those size limits. The mass fraction profile is based on a presumed particle density of 0.89 g cm^{-3}. The count median diameter is 0.2 μm with a GSD of 1.7. The mass median diameter is 0.7 μm with a GSD of 2.0.

Figure 5 depicts the size distribution for the generated chemical aerosol measured with an optical particle counter (LAS-X, PMS Inc.). The mass distribution had a median diameter of 0.7 μm with a geometric standard deviation (GSD) of 2.0; the number distribution had a median diameter of 0.2 μm with a GSD of 1.7. The size distribution of the bacterial aerosol was measured with a 6-stage multiple-hole impactor (Grasby Anderson). For this aerosol, 98% of the particles had aerodynamic diameters ranging from 1.1 to 3.3 μm; the number distribution had a median diameter of 1.3 μm with a GSD of 1.3.

A large proportion of the test particles were found to have diameters less than 1 μm. The test results for air filtration effectiveness might therefore be slightly low, because infectious droplet nuclei are thought to have aerodynamic diameters of 1 to 5 μm, and filtration efficiency is better for these larger particles. However, given the nature of the test protocol, and the relatively high single-pass particle removal efficiency of most PAFs and CMAFs, the results are unlikely to be significantly different than if all the test particles were larger than 1 μm in diameter.

To experimentally characterize the spatial distribution of particles, concentrations were measured at many room locations using integrated filter samples (Figure 3). Sampling points were positioned in the "breathing zone," 1.6 m above floor level. During experiments with chemical particles, nine room locations were sampled; bacterial particle concentrations were sampled at five locations. Constant-flow air samplers or personal-sampling pumps were employed. Air was drawn through 25-mm diameter filters housed in filter holders (Gelman and Costar) at 2 to 4 L min^{-1}. Chemical particles were sampled on mixed-cellulose ester membrane filters with a 0.8 μm pore size (AAWP25, Millipore). Bacterial particles were collected on polycarbonate membrane filters with a 0.4 μm pore size (110607, Costar). The constant-flow air samplers were calibrated before each experiment using a Gillibrator (Gillian Instrument Corp.). Two blank filters were installed in the room as a part of the quality assurance protocol. In addition, one blank filter was brought to the test facility but not installed in the test room.

Each experimental run had a duration of two hours. At the beginning of each experiment, the ventilation and filtration conditions were established and the test room was sealed to reduce infiltration. Particle generation and aerosol sampling were then started simultaneously. To characterize the temporal variability of particle concentrations, four 30-minute samples were collected sequentially at each sampling point. For a few experiments, to improve temporal resolution, two 15-minute samples were collected at the start of the experiment. Only the first 30-minute sample was collected during a subset of the PAF experiments (Table 2). Evaluation of the transient scenario was based on the first 30-minute sample; evaluation for the steady-state scenario was based on the final 30-minute sample.

The chemical aerosol concentration sampled at each room location was determined by first extracting the fluorescent-tagged oleic acid from the membrane filters with 5 ml of buffer solution (sodium phosphate, 0.05 M). The amount of fluorescein in the extract solution was then measured using a Turner 112 fluorometer with narrow bandpass filters (excitation at 436 nm, emission at 515 nm). The fluorometer was calibrated with standards made from the particle solution used during each experiment.

The bacterial aerosol concentration sampled at each room location was determined by first washing the bacteria from the filters with 10 ml sterile distilled water with 0.02% tween. The filters were vortexed in the wash solution for 1 minute, then diluted and plated onto casein soy peptone agar. The number of CFUs was determined after incubating the plates at 37 °C for 24 hours.

RESULTS AND DISCUSSION

To evaluate the effectiveness of in-room air filtration and dilution ventilation, experiments conducted with controls were normalized to the results from a baseline scenario in which ventilation was provided at 2 ACH_V and no filtration unit was operated. The room-average particle concentration measured at nine locations (for the chemical tracer) or five locations (for the bacterial tracer) for the baseline scenario was used to normalize the measured concentrations in all other tests. Comparisons of normalized concentrations between scenarios determined what levels of filtration and ventilation were most effective. The significance of differences between scenarios was evaluated by means of the paired *t* test.

Figure 6 illustrates the evolution of particle concentrations for three experimental scenarios. Each line segment in

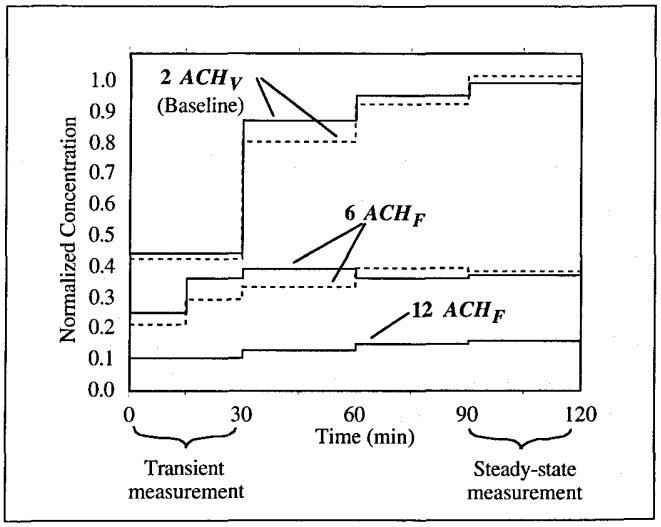

Figure 6. Evolution of the normalized room-average concentrations for the baseline scenario of 2 ACH_V and two in-room filtration experiments with the EC14 operating at 6 and 12 ACH_F. Concentrations are measured with sequential integrated filter samples. The solid and dashed lines represent duplicate experiments.

the figure represents the average of the concentrations measured at nine room locations (room average), normalized by the room-average concentration measured during the last 30 minutes of the baseline scenario. During the 6 and 12 ACH_F scenarios, steady state was reached in about an hour; for the 2 ACH_V scenario, it took two hours to approach steady state.

To evaluate measurement reproducibility, experiments were repeated for several scenarios (Table 2). In comparing repeated runs, room-average concentrations differed by less than 20%. Figure 6 shows sequential-in-time measurements for two specific experiments that were duplicated; for these experiments, the steady-state room-average concentrations differed by less than 2%.

The following subsections highlight key findings, emphasizing infection control aspects. For those scenarios with multiple experiments, results are presented as the average of the repeated runs. Except where noted, results are presented for experiments conducted with chemical particles.

Filtration Effectiveness for Chemical and Bacterial Aerosols

Figure 7 summarizes the results of six experiments conducted separately with both chemical and bacterial test aerosols. Differences between the two types of experiments were not statistically significant. The finding of comparable efficacy is not surprising, because the major factor affecting particle capture by a filter is its aerodynamic diameter, which is determined by the particle's density, shape, and physical diameter.[10] Particles having similar aerodynamic diameters will be filtered with similar effectiveness regardless of whether or not they carry a viable bacterium.[44]

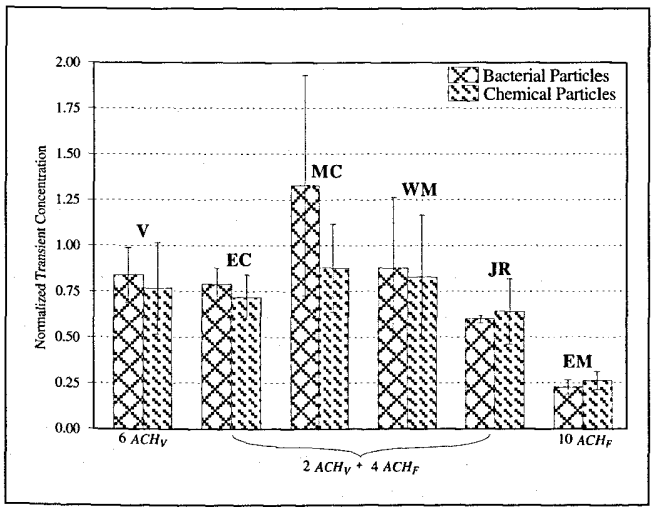

Figure 7. Normalized transient concentrations for experiments with chemical and bacterial aerosols. Each shaded bar represents the room-average concentration measured during scenarios with ventilation only (V), with PAFs (EC, MC, WM, JR), and with a CMAF (EM). Error bars represent the standard deviation of the concentrations measured at different room locations. The difference between the chemical and bacterial particle values was not statistically significant at the 0.05 level using a paired *t* test.

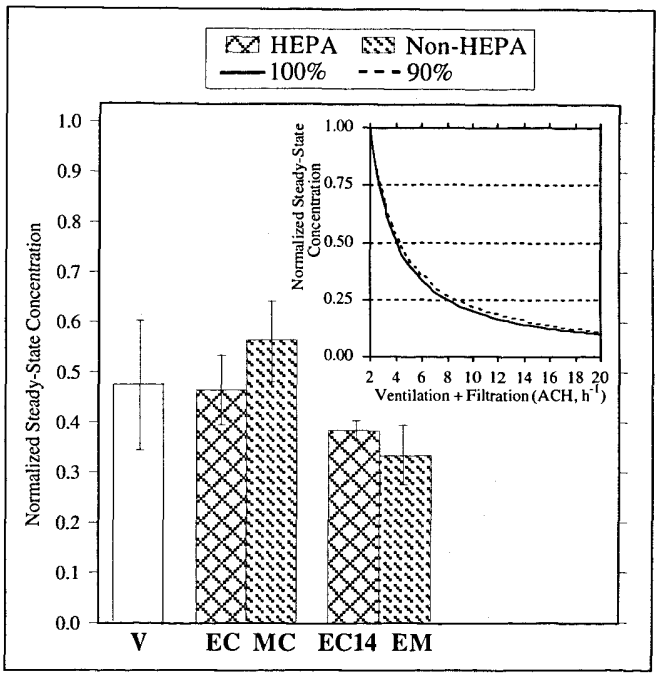

Figure 8. Normalized steady-state concentrations for several experiments showing the effectiveness of in-room filtration using a HEPA filter as compared to a non-HEPA filter. Theoretical predictions from the completely-mixed room model for 2 ACH_V + variable ACH_F using a 100% and 90% efficient filter are represented by the solid and dashed lines, respectively. Each bar represents the room-average concentration measured during the 6 ACH_V (V), the PAFs operated at 2 ACH_V + 4 ACH_F (EC, MC at 3.6 ACH_F), and the CMAFs operated at 6 ACH_F only (EC14, EM). Error bars represent the standard deviation of the concentrations measured at 9 room locations. The difference between the non-HEPA and HEPA experimental values was not statistically significant at the 0.05 level using a paired *t* test.

Strict HEPA Filtration Not an Important Factor Governing Effectiveness

Figure 8 compares the effectiveness of using in-room air filters with non-HEPA media to those using HEPA media. We did not observe any statistically significant difference in experimental performance between these classes of filter materials. The theoretical curves in Figure 8, based on the CMR model, show that the effectiveness of air filtration using a filter with a single-pass efficiency of a 100% is not much different from the effectiveness of a 90% efficient filter.

These findings illustrate the importance of distinguishing between filter efficiency and device effectiveness. Although HEPA filters permit far less particle penetration than lower-grade filter media, this attribute is not especially important in the present application, which might be characterized as an open-path configuration. Droplet nuclei emitted into the room are unconfined. That is, the particles are not restricted to a distinct path from the source, through a filter, to the receptor. The key to engineering good TB infection control is to interrupt the transport of *M. tb* from the source (e.g., patient) to the receptor (e.g., health care worker). Even perfect single-pass efficiency is irrelevant if the emitted droplet nuclei bypass the filter and are transmitted directly to the breathing zone of a susceptible person.

In addition, the supermicron diameter of droplet nuclei makes them much easier to remove from air than 0.3 μm-diameter particles.[37] Filters that are rated according to their removal of 0.3 μm particles from gas streams will tend to have higher than reported efficiency against *M. tb.* Furthermore, HEPA media usually has more resistance to flow than lower-efficiency media, due to more tightly packed, smaller fibers.[10] Thus it is possible that for a given fan size, the air flow rate in a unit will be higher with non-HEPA media and the overall effectiveness will be increased. For example, the EM manufacturer provided two types of filter inserts to be used in the unit, one with HEPA media and one made of media 60% efficient at 0.3 μm. We operated the unit at the same high setting with both types of inserts, and determined that the recirculating air flow rate was reduced by roughly 50% when the HEPA media insert was used. With this unit, we observed improved effectiveness using the non-HEPA media insert due to the increased air flow.

There are circumstances in which maximum single-pass filter efficiency is essential to achieve maximum effectiveness. For example, when filters in ventilation ducts are used in a single-pass configuration to clean the air exhausted from a TB isolation room, single-pass efficiency is key in controlling transmission. Maximum filter efficiency is also important in source-control applications that attempt to capture emitted droplet nuclei near the source before they are distributed throughout the room.

Ceiling-Mounted Air Filter Design Influence on Room Air Flow Patterns and Effectiveness

The spatial distribution of airborne particle concentrations varied markedly among runs with CMAFs. Similar results were not observed for the PAFs. Figure 9 compares the spatial distribution of steady-state concentrations measured during CMAF tests at 12 ACH_F. The height of each bar represents the normalized concentration measured in the breathing zone at the indicated location (Figure 3). Two of the units (EC14 and EM) produced fairly uniform concentrations throughout the room, whereas one unit (UGP) created large concentration gradients.

These differences are explained by the distinct air flow patterns generated by each unit. With the two-piece UGP operating, most of the particles were removed from the zone near the source before they dispersed throughout the room (Figure 9A). For this specific positioning of control device inlet close to the emission source (outlet was opposite the source), the filter acted effectively as a local exhaust unit, capturing particles from the zone where their concentration was high. The room-average effectiveness of the device at 12 ACH_F was 96%, much higher than predictions based on the CMR model (83%). With the EC14 operating, particles were mixed uniformly throughout the test space, resulting in less overall particle removal (Figure 9B); the measured effectiveness of this unit (84%) matched the predictions from the CMR model. The behavior of the EM appeared to lie between these two limits (Figure 9C). The measured concentration distribution appeared completely mixed, but the overall room average was lower than that predicted by a CMR model. With an effectiveness of 95%, it is likely that more particles were removed near the source by this unit before they dispersed throughout the room.

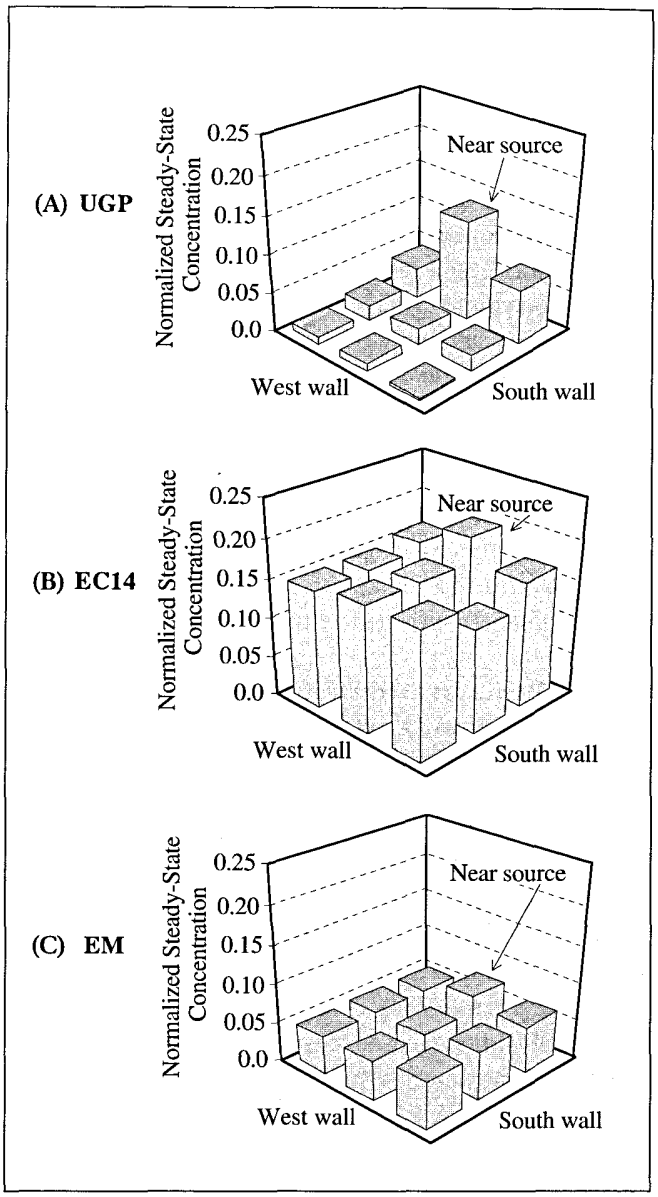

Figure 9. Normalized steady-state concentrations measured in the breathing zone during experiments with the CMAFs operating at 12 ACH_F with no ventilation: (A) UGP; (B) EC14; and (C) EM. The height of the bars represents the concentration measured at that location. Refer to Figure 3 for test room and sampling layout.

Particle Concentrations Elevated Near the Source

The spatial variation in droplet-nuclei concentration can be an important factor for infection control, particularly in facilities where health care workers often work near their patients. A "near-field effect," in which the concentration

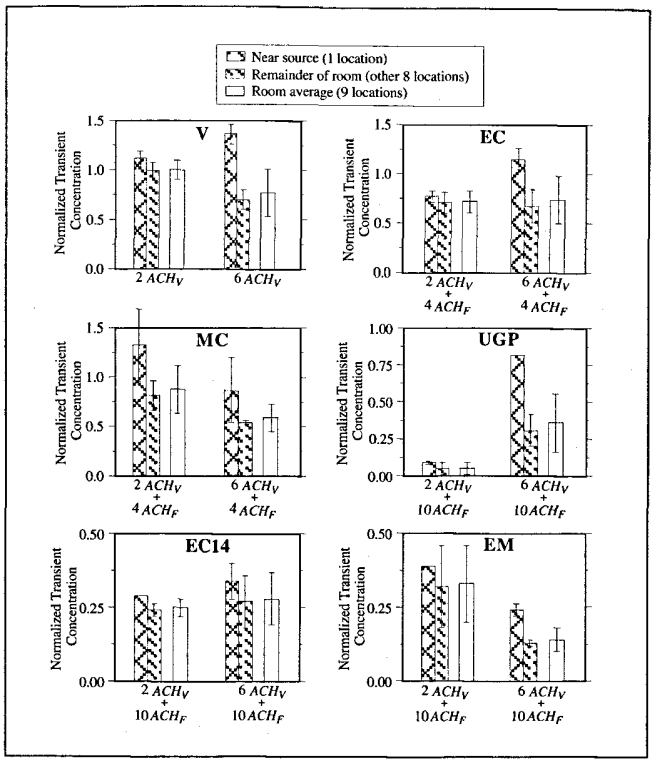

Figure 10. Normalized transient concentrations for several experiments illustrating the near-field effect. Experiments include ventilation only (V), ventilation + PAFs (EC, MC), and ventilation + CMAFs (UGP, EC14, EM). Each frame shows results for two air flow scenarios, and the height of the bars represents three types of measurements: (1) near emission source; (2) remainder of the room (average of 8 locations); and (3) room average (average of 9 locations), for one type of filter or ventilation only. Error bars represent the standard deviation (SD) of two measurements at the near-source location, the SD of concentrations measured at 8 room locations, or the SD of concentrations measured at 9 room locations. Error bars are not shown for SDs less than 0.01. The difference between near "near-source" and "far-field" values was statistically significant at the 0.05 level using a paired *t* test. Note that the vertical scale varies from frame to frame.

is higher near the source than the average of the other sampling points, was observed in each experiment. The magnitude of this effect varied among experimental conditions. The near-field effect was generally more pronounced for the transient scenario, probably because the room concentration was still evolving during this period. Figure 10 summarizes the near-field effect observed during transient conditions. Each frame presents results from runs under two different air flow conditions.

The largest near-field effect was observed at 6 ACH_V. The near-field effect diminished when ventilation was augmented with in-room filtration, as can be seen by comparing the 2 ACH_V + 4 ACH_F scenario using EC with the 6 ACH_V scenario. These two conditions each yielded roughly 25% effectiveness when evaluated on the basis of room-average concentrations. The near-source concentration was almost twice as high as the average for the rest of the room for the 6 ACH_V case, whereas the near-source concentration was only 10% higher than the rest-of-room average for the 2 ACH_V + 4 ACH_F EC scenario. Perhaps providing recirculating air flow (instead of ventilation only) promoted better mixing within the room.

More Total Air Exchange Not Always More Effective

The CMR model predicts that an increase in filtration and/or ventilation air flow rates always yields improved effectiveness, but with diminishing improvement as the total *ACH* becomes large. We observed experimentally that higher air flow rates did not always increase effectiveness; rather, in some cases, effectiveness was decreased. Figure 11 illustrates this finding by presenting results of duplicate runs for two UGP scenarios. Effectiveness stayed the same or worsened when the UGP air flow rate increased from 12 to 20 ACH_F. The large standard deviations represented by the error bars in Figure 11 are due to the large spatial variation in concentrations measured during tests with the UGP (Figure 9A).

The UGP, EC14, and EM frames in Figure 10 also show that increasing the total air flow rate for the CMAF scenarios from 12 to 16 *ACH* (2 ACH_V + 10 ACH_F to 6 ACH_V + 10 ACH_F) did not always result in better effectiveness. Based on room-average concentrations, increasing total air flow from 12 to 16 *ACH decreased* the UGP effectiveness from 95% to 64%, probably because the effective local exhaust air flow pattern was disrupted by the higher ventilation flow rate. The same change in flow conditions yielded a slight decrease in EC14 effectiveness (not statistically significant), from 75% to 72%, whereas the EM effectiveness increased from 67% to 86%.

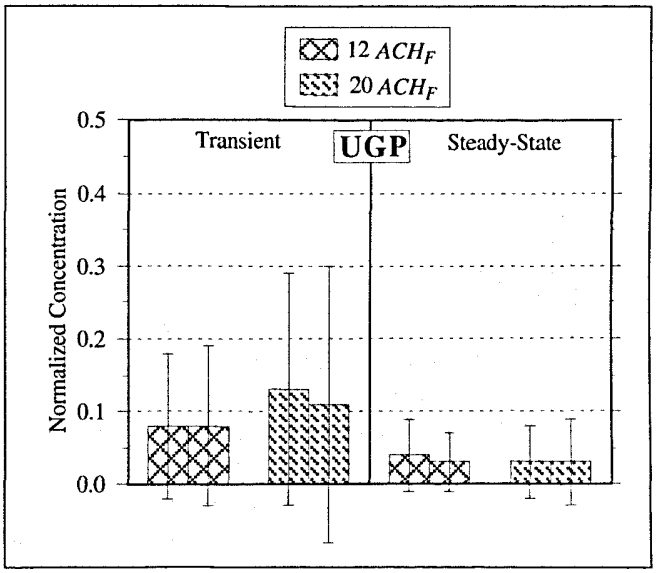

Figure 11. Normalized transient and steady-state concentrations for experiments with the UGP, demonstrating that increasing the ACH_F from 12 to 20 did not increase effectiveness. Each frame shows results for duplicate experiments of two scenarios. Error bars represent the standard deviation of the concentrations measured at 9 room locations. The difference between 12 and 20 ACH_F values was not statistically significant at the 0.05 level using a paired *t* test.

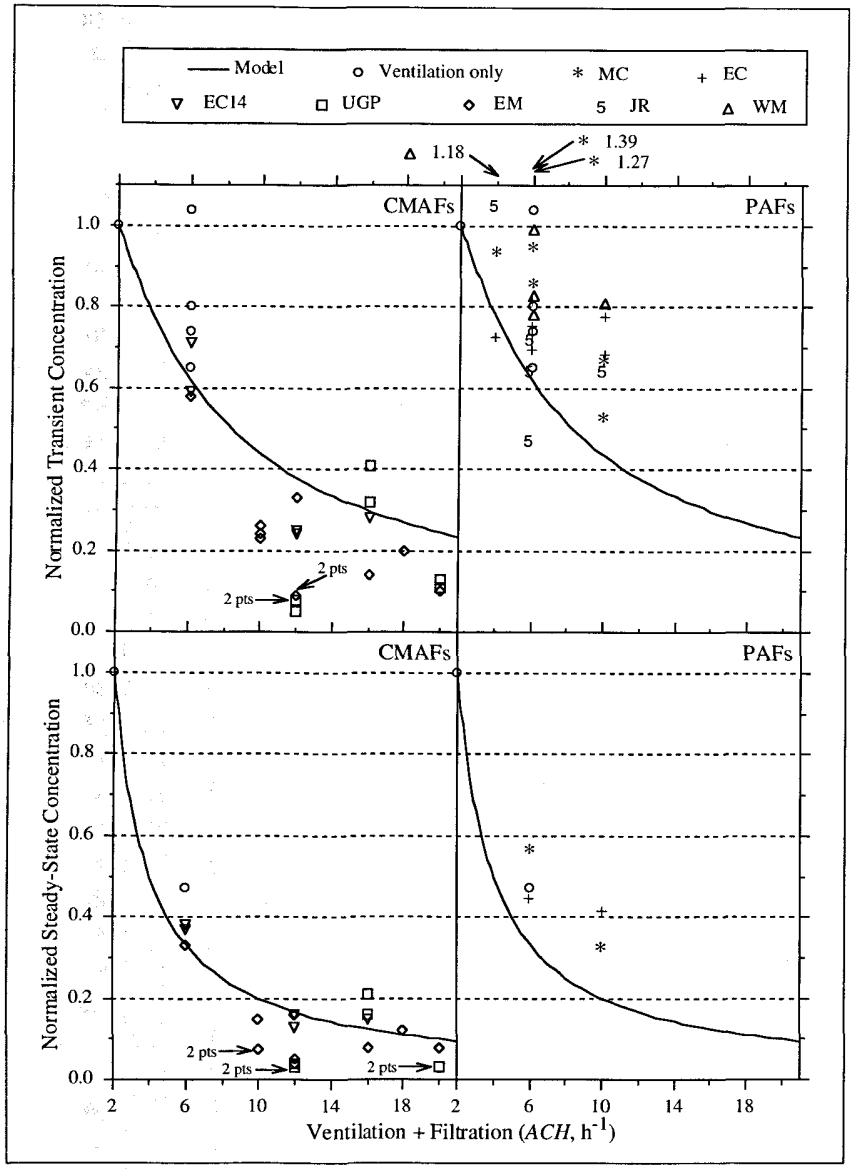

Figure 12. Normalized transient and steady-state concentrations for all experiments. Theoretical predictions from the completely-mixed room model are represented by the solid lines. The top frames represent transient concentrations, while the bottom frames show steady-state concentrations. The left- and righthand sides show ceiling-mounted air filter and portable air filter results, respectively. Each point on the figure represents the room-average concentration measured during a single experiment with the chemical or the bacterial aerosol. Values off-scale are indicated by arrows; two points with the same value are also indicated.

PAF results are shown in the EC and MC frames of Figure 10. The EC frame shows that the overall room-average effectiveness decreased slightly, from 28% to 26%, when the total air flow rate was increased from 6 to 10 *ACH* (2 ACH_V + 4 ACH_F to 6 ACH_V + 4 ACH_F). The MC frame shows that the effectiveness increased from 12% to 41% in response to the same change. This large increase for the MC unit may have resulted because under low-ventilation conditions, the air filter generated an ineffective short-circuiting flow pattern that was disrupted as the higher ventilation rates drove the room air towards becoming more uniformly mixed.

It is difficult to draw generalized conclusions from our findings, since in some cases, effectiveness increased with increasing *ACH*, and in other cases the opposite was observed. The results do suggest that uniform mixing cannot be assumed. However, uniform mixing is not desirable, if one can capture pollutants at higher-than-average concentrations. To optimize effectiveness in designing and deploying filtration and ventilation systems for airborne infection control, particular attention should be given to the spatial relationships among the particle source (e.g., TB patient), particle receptor (e.g., health care worker), and the air supply and return locations for the ventilation and filtration systems.

Filtration Effectiveness Good, but Not Great

Normalized room-average concentrations measured during all experiments are summarized in Figure 12. Each point in the figure corresponds to room-average measurements for a single experiment, including both bacterial and chemical particle runs (summarized in Table 2). The upper and lower graphs present data for transient and steady-state scenarios, respectively. Note that the points are plotted against total *ACH*; for example, the 12 ACH_F scenario and 2 ACH_V + 10 ACH_F scenario are both plotted at 12 *ACH*. Also shown in Figure 12 are predictions of the CMR model.

Figure 12 captures core findings from this study. In-room air filtration was effective in reducing airborne particle concentrations, both in conjunction with ventilation and independently. However, the effectiveness was not nearly as great as the single-pass efficiency of a HEPA filter. At best, 96% effectiveness was achieved: this performance was attained under steady-state conditions with the UGP operating at 20 ACH_F. At worst, for transient conditions using 2 ACH_V + 4 ACH_F with the MC, the average effectiveness obtained with the chemical particle runs was 12% and the average effectiveness for the bacterial particle runs was -33% (worse performance than baseline). For most runs, the effectiveness ranged from 30% to 90%.

Figure 12 shows that the CMR model predicted the performance for CMAFs reasonably well. In some cases, effectiveness was better (normalized concentrations were lower) than predictions, most likely due to capturing test particles at high concentration from the buoyant plume above the source mannequin. In other cases, most notably the ventilation-only 6 ACH_V scenario, the model predicted better effectiveness than was realized experimentally. The ventilation

exhaust was located at the opposite end of the room, ceiling level, from the particle source. It seems likely, especially in light of the strong performance of the UGP, that positioning the ventilation exhaust nearer to the source would yield more effective particle removal. These findings support the CDC's recommendation that the ventilation exhaust be located near the more contaminated area of the room. Furthermore, as the ventilation increased from 2 to 6 ACH_V, a larger near-field effect was seen (see Figure 10), again indicative of poor mixing. The use of CMAFs (EC14, EM) to provide 6 ACH_F resulted in a more uniform room concentration and 10% to 20% better effectiveness as compared to 6 ACH_V, probably due to better mixing.

A troublesome finding is that filtration using PAFs plus ventilation was not as effective as predicted by the CMR model. In fact, the results for the 6 ACH_V + 4 ACH_F scenario (10 *ACH* total) are strikingly similar to those for the 2 ACH_V + 4 ACH_F scenario (6 *ACH* total). Our study of PAFs was not robust enough to determine the exact cause of this effect; still, there are at least two possible explanations: (1) these units underperformed because of short-circuiting of air flow through the recirculating air filters with nearly coincident supply and exhaust; and (2) the effectiveness of PAFs was masked by the worsening effects of increasing the ventilation from 2 to 6 ACH_V. CMAFs with similarly coincident flow geometry (EC14, EM) performed well, perhaps because they were better positioned to capture particle emissions from the thermally buoyant source.

CONCLUSIONS

Many factors influence the effectiveness of in-room air filtration for TB infection control. The CMR model presents a simplified description in which effectiveness depends only on flow rates (ventilation and filtration), single-pass filter efficiency, and time (transient versus steady state). The CMR model yields analytical expressions that quantitatively capture the dependence of effectiveness on these factors. One limitation of the CMR model, important for the present application, is that it assumes perfect mixing and therefore does not capture effects of imperfect mixing.

One aspect of the experiments that reflects imperfect mixing is the observation of higher particle concentrations near the source than in the rest of the room. In many high-risk settings where a susceptible person may work in close proximity to an infectious person, controlling near-field concentrations may be at least as important as controlling room-average values.

Because of imperfect mixing, many of our experimental results departed substantially from the CMR model predictions. Significantly, effectiveness could be better than predicted. The key is to capture droplet nuclei in high concentrations near the source before they are dispersed throughout the room. Positioning an air-filter inlet or ventilation exhaust register close to a patient helps to achieve this goal. Also, CMAFs may offer systematic advantages over PAFs because the inlet is elevated and the droplet nuclei source is buoyant.

Capturing the pollutant near the source with filtration or ventilation requires knowing the location of the source. TB patients are not always confined to beds, and they can spend time in other parts of the room. In addition, infection may occur before the patient is suspected of having TB and placed in an isolation room.[11] To control the spread of infection generated by patients who have unrecognized TB, dilution ventilation and filtration aided by good mixing may be more reliable than attempting to capture droplet nuclei at higher than room-average concentrations.

The objective of this study was to investigate the effectiveness of in-room air filtration with dilution ventilation for controlling TB infection. Although this study was broad in scope, there were many issues that we did not address; these should be considered in future investigations. The location of the ventilation supply and exhaust in our test chamber was fixed at ceiling level, with the supply in the middle of the room and the exhaust opposite the source. Locating the exhaust port nearer the source may have provided greater effectiveness. Future studies should be conducted in a room with adjustable supply/exhaust location configurations (i.e., with the exhaust located near the source, or with the supply port near the floor). Future studies of filtration plus ventilation effectiveness should also include operating PAFs at their full range of air flow rates. To gain further insight into the potential for TB infection control by engineering methods, additional research is needed on air flow patterns in rooms and their influence on pollutant transport and dispersion. Modeling tools, such as computational fluid dynamics, can aid in exploring these factors.[27,45] Experimental investigations of air flow patterns can be conducted with the use of a sonic vector anemometer.[46]

Compared with a base case condition of 2 ACH_V, this study shows that ventilation plus recirculating air filtration can achieve reductions of droplet nuclei concentrations, and therefore the risk of infection, with effectiveness typically ranging from 30% to 90%. Given the frequently reported occurrence of TB outbreaks in health care settings, this degree of protection may not suffice. Complementing room air cleaning with source-oriented controls, such as treatment booths and receptor-oriented controls such as respiratory protection devices, appears essential to ensure a low risk for TB infection in high-risk settings.

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