A VENTILATION-FILTRATION UNIT FOR RESPIRATORY ISOLATION

Robert L. Marier, MD; Tim Nelson

See also pages 681, 686, 689, 694, and 723.

ABSTRACT

OBJECTIVE: **The development of a new method for achieving respiratory isolation in hospitals, clinics, and residential facilities, in response to the increasing risk of transmission of tuberculosis and the limitations of the currently available isolation systems.**

DESIGN: **Ultraviolet (UV) light and ultra-low-penetration air filtration were combined with a ventilation unit and adapted for use in modular isolation rooms or for conversion of existing rooms.**

RESULTS: **The ventilation-filtration unit efficiently cleared bacterial aerosols and particles >0.2 µm from the air, maintained required negative pressures and airflows, and provided directional airflow within rooms (*Infect Control Hosp Epidemiol* 1993;14:700-705).**

INTRODUCTION

One of the most pressing problems facing healthcare facilities today is the potential for aerosol transmission of tuberculosis to patients and hospital staff.

Recent surveys conducted by the Centers for Disease Control and Prevention (CDC) indicate that few hospitals have effective respiratory isolation facilities.[1] Delayed diagnosis and isolation of patients with tuberculosis has been associated with an increase in tuberculin skin test conversions among healthcare workers and outbreaks of tuberculosis in hospitals.[2-7] These outbreaks have been associated with significant morbidity and mortality among healthcare workers.

According to the CDC, protection of patients and staff depends on a hierarchy of controls including, in order of importance, identification and treatment of infection, and isolation of patients.[8] Isolation rooms must maintain negative pressure with respect to the hallway and must provide at least six room air changes per hour. Airflow within the room should sweep infectious particles away from healthcare workers, creating relatively safe workspaces. Exhaust should be vented to the outside away from other intakes or

From the Louisiana State University School of Medicine and the Medical Center of Louisiana, Charity Hospital (Dr. Marier), New Orleans, Louisiana, and Component Systems Inc (Mr. Nelson), Cleveland, Ohio.

The authors thank Drs. Donald Greer and Aileen Janey, Ms. Janice Chatlain, Ms. Denise Sciro, Ms. Joell Bowab, and the staff of C600 (the Medical Center of Louisiana and LSU Medical School in New Orleans) for their assistance in this project.

Component Systems Inc manufactured the ventilation-filtration unit and provided support for this evaluation.

Preliminary reports were presented at the World Congress on Tuberculosis, Bethesda, Maryland, November 20, 1992, and at the International Conference of the American Lung Association and the American Thoracic Society, Miami, Florida, May 19, 1992.

Address reprint requests to Robert L. Marier, MD, Louisiana State University School of Medicine, 1532 Tulane Ave., New Orleans, LA 70112.

93-OA-043. Marier RL, Nelson T. A ventilation-filtration unit for respiratory isolation. Infect Control Hosp Epidemiol *1993;14:700-705.*

should be filtered with a high-efficiency particulate air (HEPA) filter and recirculated.[8] Ultraviolet (UV) light may be used in areas where ventilation is impractical.[9-11]

This article reports the development and testing of a unit that removes bacterial aerosols from the air and is capable of maintaining negative pressure, high air exchange rates, and directional airflows in isolation rooms. The unit may be used to convert existing areas for the purpose of isolating patients or containing aerosols produced during sputum induction and other procedures.

METHODS

Design of the Ventilation-Filtration Unit

The unit is 24 in wide, 48 in high, and 16 in deep (nominal) and weighs 103 lbs. The housing is made of 20-gauge steel. A centrifugal fan provides variable volumes of airflow through the unit. The fan is adjustable from 150 to 640 cu ft/min in its low-speed mode and provides up to 850 cu ft/min in a highspeed mode. This high-speed mode is designed to automatically activate when a door switch or air pressure sensor detects room entry or egress, and compensates for pressure changes. Air is pulled through a prefilter (pleated disposable type, of 30% efficiency by standard ASHRAE [American Society of Heating, Refrigeration, and Air-Conditioning Engineers] methodology; Airguard Industries, Louisville, KY) and is directed around a 22W, high-intensity UV lamp located within the unit's fan cabinet. The location of the lamp places the airstream in close proximity to the UV light and provides continuous irradiation of interior surfaces of the unit. The lamp was illuminated for all experiments. Final filtration is provided by an ultra-low-penetration air (ULPA) filter (Filtra Corp, Hawthorne, NJ) rated by the manufacturer at an efficiency of 99.9995% for particles 0.12 μm or larger.

Testing the Filtration Capabilities of the Unit

A chamber was constructed to facilitate filtration testing of the unit (Figure 1). A nebulizer (ULTRA-NEB 99, DeVelbiss Health Care Inc, Somerset, PA) was used to produce aerosols and was positioned at the intake of the ventilation-filtration unit. The chamber was placed inside a test room that permitted control of temperature and pressure (Figure 1). Room temperatures were recorded using a digital thermometer (Electro-Therm model SH66A, Cooper Instrument Corp, Middlefield, CT) and were held at 96°F. Airflow through the unit was measured using a bolometer (Alnor, Skokie, IL) and was set at 850 cu ft/min, which is the maximum setting of the fan. Particle counts were recorded using a particle counter (LASAIR model 210, Particle Measuring Systems Inc,

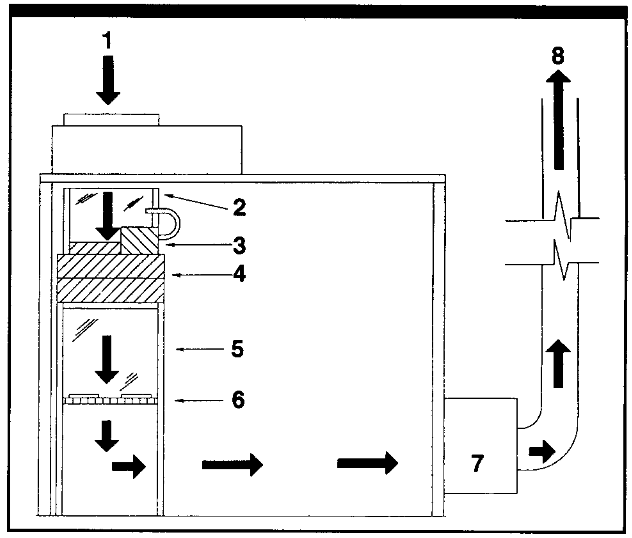

FIGURE 1. The ventilation-filtration unit and test chamber in the test room (side view): 1) supply air; 2) intake (mixing) chamber; 3) nebulizer; 4) ventilation-filtration unit; 5) test chamber; 6) perforated grid with culture plates and location of particle counter probe; 7) exhaust fan for room; 8) exhaust air to outdoors.

Boulder, CO) with an isokinetic probe capable of measuring particles from 0.2 to 10 μm. The counter was set to calculate continuously the particle counts per cu ft/min. The output of the counter was recorded. In various experiments, the system was tested with the filter and with UV light either present or absent.

Suspensions of *Enterobacter cloacae* and *Mycobacterium vaccae* in normal saline were prepared from Mueller-Hinton 48-hour subcultures and adjusted to one McFarland standard containing, by quantitative subculture, approximately $1 \cdot 10^8$ and $1 \cdot 10^{10}$ bacteria, respectively, in 40 mL saline. Mueller-Hinton culture plates (150 mm BBL, Matheson Scientific, Houston, TX) were used for isolation of bacteria.

The nebulizer was filled with distilled water (40 mL), and the water or bacterial suspensions were aerosolized at the maximum setting for 30 minutes. Particles below the unit were counted every five minutes for 30 minutes, or culture plates were exposed for 30 minutes. Following exposure, plates were incubated at 35°C for 48 hours, and colonies were counted. Experiments were done in duplicate (eight plates per experiment). Approximately 10% of the filtered air was sampled.

Testing the Ventilation Capabilities of the Unit

In order to test the ability of the ventilation-filtration unit to maintain the required pressures and airflows and to further test the ability of the system to clear particles from the air, an isolation room of approximately 1,140 cu ft was constructed (Figure 2). The air supply for the room was pulled from an anteroom, through an adjustable louver over the room

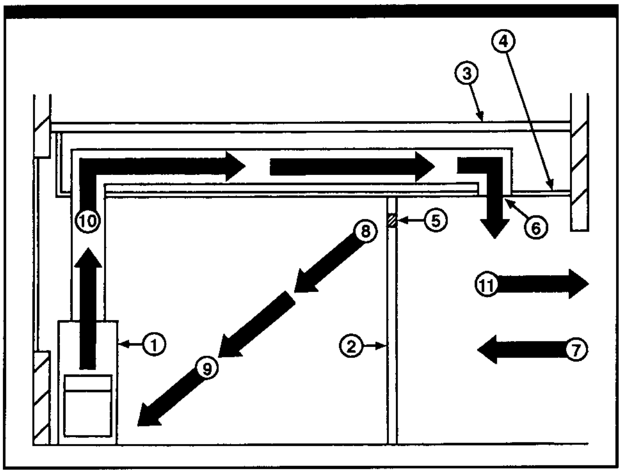

FIGURE 2. The ventilation-filtration unit in an isolation room (side view): 1) ventilation-filtration unit; 2) interior partition; 3) existing ceiling; 4) suspended, gasketed tile ceiling; 5) adjustable vane, dampered louver; 6) ceiling air diffuser or grille; 7) outside air from corridor; 8) filtered and fresh air entering isolation room near ceiling; 9) air being pulled toward floor by ventilation-filtration unit; 10) filtered air being ducted back to the anteroom; 11) filtered air returning to corridor.

door, to the floor-level intake of the ventilation-filtration unit across the room. The air was filtered and returned to the anteroom. A door switch was installed on the door to the anteroom in order to activate the unit's high-speed fan mode automatically when the door was opened. The switch was disabled for certain experiments, as noted, in order to measure the escape of particles from the room without activation of the high-speed fan.

Particle counters, as described above, were placed inside the room at the air intake of the ventilation-filtration unit and outside the door leading from the anteroom to the isolation room. Particles were generated in the center of the isolation room using a fog/smoke machine (model 1500, Rosco Laboratories, Hollywood, CA) and the number of particles (1 μm) inside and outside the room were counted over time under various conditions. The particle generator, counters, and the ventilation-filtration unit itself were controlled from outside the room. The significance of differences between groups of measurements was determined by means of a two-sample *t* test.

Baseline particle counts were determined before the particle generator was turned on. After the baseline conditions were determined, the particle generator was turned on. When the 1 μm particle counts inside the room reached approximately $1{\cdot}10^6$ particles/cu ft, the particle generator was turned off. Particle counting continued for six minutes inside and outside the room. The door leading out of the room was opened at the three-minute mark in all experiments.

TABLE 1
PARTICLE REMOVAL BY THE VENTILATION-FILTRATION UNIT

Particle Size (μm)	Particles/cu ft/min Below VF Unit: Filter Absent Mean	Filter Absent SD	Filter Present Mean
0.30	299,000	199,000	0
0.50	192,000	147,000	0
0.70	245,000	158,000	0
1.00	243,000	160,000	0
2.00	139,000	167,000	0
3.00	2,000	3,300	0
5.00	1,000	3,000	0

VF = ventilation-filtration

In separate experiments, the following conditions with respect to the fan settings were studied: 1) fan off; 2) fan on at low speed; and 3) fan on at low speed, increasing to high speed when the door was opened. These fan settings accomplished 0, 10, and 44 room air changes per hour, respectively. Each experiment was repeated three times, and the particle counts at each time point were averaged for the purpose of statistical analysis.

RESULTS

The first and second experiments were done in the test chamber and were designed to measure the clearance of particles and bacteria by the ventilation-filtration unit (Figure 1). Under the test conditions described, it was observed that a range of particles from 0.30 to 5 μm was produced by the nebulizer with most particles ≤1 μm in diameter, and that the particles and bacteria were cleared by the unit (Tables 1 and 2).

The third set of experiments was done in the isolation room and was designed to measure the clearance of particles inside the room and the escape of particles from the room under various conditions (Figure 2). The baseline particle count was 520,000 particles/cu ft, with most particles <5 μm (Table 3).

Particle counts inside the room remained constant over the six-minute sampling period with the fan turned off; opening of the door after three minutes did not affect room particle counts (Table 4). With the fan on at low speed for six minutes, particle counts fell significantly compared with baseline levels; the counts fell more quickly and were significantly lower when the fan switched to high after three minutes.

As noted, the door switch was disabled in some experiments to keep the high-speed fan from coming

TABLE 2
BACTERIAL AEROSOL REMOVAL BY THE VENTILATION-FILTRATION UNIT

	Bacterial Counts Below VF Unit*	
Bacteria	**Filter Absent**	**Filter Present**
Enterobacter cloacae	525	0
Mycobacterium vaccae	130,800	0

VF = ventilation-filtration
* Total number of colonies identified on culture plates

TABLE 3
BASELINE PARTICLE COUNTS IN ISOLATION ROOM

	Particles/cu ft/min	
Particle Size (μm)	**Mean**	**SD**
0.30	145,737	3,355
0.50	348,285	3,619
1.00	13,571	572
2.00	11,644	792
5.00	713	40
10.00	134	113
Total	520,084	

on automatically. Particle counts outside the room increased significantly when the door was opened either with the fan off or with the fan on at low speed, but not with the fan on at high speed (Table 5).

Finally, particle counts outside the room were lower with the fan on at either setting than with the fan off (Table 5). This was attributed to the return of filtered air to the anteroom outside the door.

DISCUSSION

These results demonstrate the effectiveness of the ventilation-filtration unit in removing bacterial aerosols and particles from the air. The ventilation-filtration unit lowered particle counts both inside and outside the room and prevented the escape of particles when the door was opened (automatically activating the unit's high-speed fan mode).

The size of the room is an important consideration in the installation and operation of the ventilation-filtration unit. The unit has an adjustable fan that provides from 150 to 640 cu ft/min in the low-speed mode and up to 850 cu ft/min in the high-speed mode. The fan must be set at the time of installation to achieve the necessary room air changes per hour, given the size of the room in question.

It is essential to monitor the performance of the filter and to change the filters on a periodic basis because over time particulate matter will accumulate on the filter, reducing airflow. It should be noted, however, that while the airflow may decrease, the filtration actually increases under these circumstances, with less and less penetration of particulate material.

The unit uses an ULPA filter, which according to the manufacturer is 10 times more efficient than HEPA filtration in removing particles from the air. ULPA filtration was chosen instead of HEPA filtration because of the greater efficiency and minimal cost differential. However, the need for ULPA filtration, rather than HEPA filtration, has not been demonstrated, and HEPA filters are used widely in laboratory settings to remove *Mycobacterium tuberculosis* from the air.

It should be noted that the independent effect of the UV light included in this system was not tested. This will be the subject of further study. The UV light was included primarily to decontaminate the interior surfaces of the unit.

There are a number of other engineering issues that must be considered in the design and use of a ventilation system for an isolation room. The first and most important relates to the ability of an isolation room to maintain the required airflows. Existing isolation rooms originally constructed to provide six air changes and negative room air pressure, as recommended by the CDC, may appear to be safe when tested using a smoke stick. This test will indicate the direction of airflow, but does not indicate the volume of airflow or degree of negative pressure.

If the testing is done with bathroom exhausts operating properly, the bathroom doors open, and the hallway doors closed, the room may appear to perform adequately. However, if the bathroom exhaust system is not operating properly or is turned off for maintenance at a later point in time, or if the bathroom doors are closed or the hallway doors are open, the isolation room may not perform adequately.

Indeed, we found in our own studies that an open door allowed significant numbers of particles to escape into the corridor even with use of the low-speed fan, which provided 10 room air changes per hour. This was prevented when the automatic high-speed fan mode was activated, which increased the airflow from approximately 10 air changes per hour to more than 40 air changes per hour when the door was opened.

In addition, isolation rooms that may have performed adequately when first constructed now may not if there have been changes in the hospital's heating, ventilation, and air conditioning (HVAC) system that have changed the air supply to the room. These effects are not easily measured without specialized equipment. Moreover, unpredictable changes in outdoor wind conditions may close louvers and shut

TABLE 4
EFFECT OF THE VENTILATION-FILTRATION UNIT ON PARTICLE COUNTS INSIDE THE ISOLATION ROOM

	Counts of 1 μm Particles/cu ft/min Inside Room						
	Fan Off Throughout		Fan Low Throughout		Fan Low, Then High*		
Time (min)	Mean	SD	Mean	SD	Mean	SD	*P*†
1	944,045	244,814	924,526	270,062	1,133,333	57,735	NS
2	1,016,463	236,636	1,166,667	57,735	947,275	91,322	NS
3	1,007,152	423,586	808,877	173,852	552,501	43,973	NS
Door opened							
4	972,538	198,008	499,715	103,895	231,111	39,956	0.01
5	1,071,353	313,439	289,201	91,214	118,330	59,372	0.05
6	918,784	281,794	245,309	56,717	74,222	63,092	0.02
P‡	NS		0.01		0.001		

* For this setting only, fan switched from low to high when door was opened following obtaining of 3 minute readings.
† Significance of difference between fan low and fan high.
‡ Significance of difference between particle counts at 1 and 6 minutes

TABLE 5
EFFECT OF THE VENTILATION-FILTRATION UNIT ON PARTICLE COUNTS OUTSIDE THE ISOLATION ROOM

	Counts of 1 μm Particles/cu ft/min Inside Room						
	Fan Off Throughout		Fan Low Throughout		Fan Low, Then High*		
Time (min)	Mean	SD	Mean	SD	Mean	SD	*P*†
1	10,917	7,166	789	215	855	369	NS
2	12,212	7,166	877	402	1,094	653	NS
3	11,980	4,286	415	138	534	219	NS
Door opened							
4	104,956	43,212	31,691	12,080	3,086	2,375	0.01
5	122,195	22,455	18,571	5,454	3,031	2,429	0.01
6	89,038	54,537	15,960	5,744	3,238	2,878	0.03
P‡	0.02		0.01		NS		

* For this setting only, fan switched from low to high when door was opened following obtaining of 3 minute readings.
† Significance of difference between fan low and fan high.
‡ Significance of difference between particle counts at 1 and 6 minutes.

down window exhaust units, causing the isolation rooms to "go positive." This suggests that effective ventilation should not depend on unreliable hospital HVAC systems or window exhausts. One alternative is to recirculate filtered air with a ventilation-filtration unit such as the one described.

A second engineering issue involved in the design and use of a ventilation-filtration unit for isolation rooms relates to increased demand on the hospital HVAC system if all of the air is exhausted outdoors. The HVAC systems in many facilities may not be able to maintain comfortable conditions under these conditions. Uncomfortable conditions may reduce the level of patient compliance with respiratory isolation. Moreover, the energy costs associated with exhausting large amounts of conditioned air are not insignificant, especially if a number of rooms are involved.[12]

The ability to recirculate exhaust air from isolation rooms may be important from a practical perspective as well as from the perspective of compliance with federal, state, and local regulations relating to environmental discharges. Isolation rooms may be needed in areas of the facility where access to exhaust ducts or outdoor walls is unavailable. Alternatively, isolation rooms may have access to outdoor walls or windows, but nearby intake vents, operable windows, or people may make safe outdoor exhaust impossible or even illegal.[8]

In addition, current national fire protection and building codes dictate that if air intake penetrations are made through ceilings or walls that are fire barriers, costly, permanent automatic damper systems must be installed. As an alternative, inexpensive movable partitions constructed of fire-safe materials can be installed at the entrance to the isolation room, creating a vestibule or anteroom (Figure 2). Recirculated air then can be supplied from louvers located in the partition above the door and all code requirements can be met without penetrating the fire wall.

A final consideration in the design and use of a ventilation system for isolation rooms relates to safety inside the room itself. Transmission of tuberculosis has been associated with average concentrations of bacteria in the range of 0.0001 particles/cu ft.[10] Large numbers of droplet nuclei may be associated with coughing (5,000 particles) and sneezing (1 million particles),[13] although most of these particles are probably not infectious in patients with tuberculosis given the relatively low transmission rates associated with this disease. Most of the particles associated with coughing are less than 10 μm in diameter and remain airborne as droplet nuclei.[13]

Directional airflow may create safer workspaces by sweeping potentially infectious aerosols in the area of the patient away from the worker if the clean air supply is located above the door behind the worker and the return is located below and behind the patient. This design is recommended by the CDC.[8]

Portable filtration devices that recirculate air within an isolation room by discharging filtered air through grills at the top or bottom of the device actually may create unsafe conditions by generating turbulence that might carry infectious aerosols toward the healthcare worker. Moreover, there is the potential problem of local recirculation around the portable device itself, which might render it ineffective.

In conclusion, a properly designed and installed ventilation-filtration unit appears to be an appropriate method for achieving effective respiratory isolation in healthcare facilities.

REFERENCES

1. Rudnick J, Kroc K, Manangan S, et al. How prepared are U.S. hospitals to control nosocomial transmission of tuberculosis? Presented at the World Congress on Tuberculosis; November 16-19, 1992.
2. Haley CE, McDonald RC, Rossi L, Jones WD Jr, Haley RW, Luby JP. Tuberculosis epidemic among hospital personnel. *Infect Control Hosp Epidemiol* 1989;10:204-210.
3. Centers for Disease Control. Nosocomial transmission of multidrug-resistant TB to health care workers and HIV-infected patients in an urban hospital—Florida. *MMWR* 1990;39:718-722.
4. Centers for Disease Control. Nosocomial transmission of multidrug-resistant tuberculosis among HIV-infected persons—Florida and New York, 1988-91. *MMWR* 1991;40:585-591.
5. Fischl MA, Uttamchandani RB, Daikos GL, et al. An outbreak of tuberculosis caused by multiple drug-resistant tubercle bacilli among patients with HIV infection. *Ann Intern Med* 1992;117:177-183.
6. Pearson ML, Jerb JA, Thomas RF, et al. Nosocomial transmission of *Mycobacterium tuberculosis* and risk to patients and healthcare workers. *Ann Intern Med* 1992;117:191-196.
7. Kent J, Valway S, Onorato I. Epidemiologically linked outbreaks of multi-resistant tuberculosis (MDRTB), New York State, 1990-1992. Presented at the World Congress on Tuberculosis; November 16-19, 1992.
8. Centers for Disease Control. Guidelines for preventing the transmission of tuberculosis in health-care settings, with special focus on HIV-related issues. *MMWR* 1990;39:1-29.
9. Allen HF. Air hygiene for hospitals. *JAMA* 1959;170:261-267.
10. Riley RL, Mills CC, O'Grady F, Sultan LU, Wittstadt F, Shivpuri DN. Infectiousness of air from a tuberculosis ward. *Am Rev Respir Dis* 1962;85:511-525.
11. Riley RL, Nardell EA. Clearing the air. The theory and application of ultraviolet air disinfection. *Am Rev Respir Dis* 1989;139:1286-1294.
12. Higher energy prices fuel hospital inflation. *AHA News* April 8, 1991.
13. Duguid JP. The size and the duration of air carriage of respiratory droplets and droplet nuclei. *Journal of Hygiene* 1946;44:471-480.