

# FACTORS INFLUENCING EFFECTIVENESS OF ULTRAVIOLET GERMICIDAL IRRADIATION FOR INACTIVATING AIRBORNE BACTERIA: AIR MIXING AND VENTILATION EFFICIENCY

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## ABSTRACT

As a result of the recent resurgence in tuberculosis incidence, there has been increased interest in using ultraviolet germicidal irradiation (UVGI) of room air to reduce exposures to infectious agents. This paper presents results of experimental studies investigating how air mixing and ventilation influences the efficacy of UVGI for inactivating airborne bacteria. Tracer gas—SF<sub>6</sub>—and tracer particles generated by nebulization of a salt solution were injected into a full-scale room. The particles simulate an aerosol carrying an infectious agent generated by persons coughing or sneezing. The tracer gas was used to study the room airflow patterns. The concentration of the gas and particles was measured over time with a gas chromatograph and an optical particle counter. Using these data, the air mixing and ventilation efficiency were characterized. The results showed that the room air was not necessarily well mixed and the ventilation efficiency were not necessarily close to unity under higher air-exchange rates (6 air changes per hour), depending on the thermal conditions within the room.

## INTRODUCTION

The transmission of tuberculosis (TB) in healthcare settings is a recognized hazard, and recent outbreaks involving multidrug-resistant strains of *Mycobacterium tuberculosis* has heightened concern [1]. In response, the Centers for Disease Control and Prevention (CDC) issued comprehensive guidelines for controlling TB transmission in health-care facilities [1]. The CDC recommended that at least 6 air changes per hour (ACH, h<sup>-1</sup>) be provided for existing TB isolation rooms and, where feasible, this air flow rate should be increased to greater than 12 ACH. This increase in air-exchange rate could be accomplished by adjusting or modifying the ventilation system or by using auxiliary controls. One auxiliary engineering control method proposed by the CDC is ultraviolet germicidal irradiation (UVGI) of room air [1].

Irradiation is accomplished by mounting germicidal lamps to walls or suspending them from ceilings above the people inhabiting the rooms. This arrangement is designed to protect people from over-exposure to the UV radiation while providing enough exposure to airborne microorganism in rooms. These germicidal lamps emit UV-C radiation at a predominant wavelength of 254 nm.

In 1954, the use of UV radiation in classrooms to prevent measles was studied. Results showed that UV radiation was efficient in preventing measles from spreading where children were exposed [2]. Riley et al. conducted decay experiments in a full-sized room to determine the equivalent air-exchange rate of room air UV irradiation on *Mycobacterium bovis BCG* [3].

Results showed that the bacteria were inactivated at an exponential rather than linear rate under the UV exposure.

Despite the fact that ventilation is a primary engineering control technique and that UVGI is being recommended and used for controlling TB transmission, little is known about the efficacy of combining ventilation and UVGI. Our research group is experimentally investigating the effectiveness of UVGI of room air for inactivating airborne bacteria. To better understand some of the many factors that influence UVGI effectiveness, including ventilation rate, we conducted a study to characterize the mixing and ventilation efficiency of the test room in which the UVGI experiments are underway. These experiments were designed to investigate the following:

- Is the room well-mixed under different ventilation rates?
- How efficiently are airborne microorganisms removed by ventilation?
- What is the vertical concentration gradient within the test room?

To study the room airflow patterns, tracer gas was injected into the test room. Tracer gas, however, may not exactly represent airborne microorganisms, such as *Mycobacterium parafortuitum* aerosolized during our UVGI experiments, or *Mycobacterium tuberculosis* emitted by an infectious patient in a TB isolation room. Riffat & Cheong [4] showed that there was a difference between the distribution of particle and gas-phase concentrations in a room. Thus, tracer particles were generated to simulate airborne microorganisms. Time-averaged tracer gas and particle concentrations were measured at many points. Mixing and ventilation efficiency were determined by calculating the parameters air change effectiveness and pollutant removal effectiveness respectively. The vertical concentration gradient was characterized by comparing the measured concentrations in the upper and lower portions of the room.

## METHODS

**Test facility.** Experiments were conducted in a full-size, simulated healthcare room at the Joint Center for Energy Management's Larson Building System Laboratory, University of Colorado (Figure 1). The test facility is a 90-m<sup>3</sup> chamber located inside the laboratory with a floor to ceiling height of 2.4 m and a clear floor area of 6×6 m. The room is ventilated by a computer controlled air handling system, which can vary the air-exchange rate in the room from 0 to 8 ACH. Two high efficiency particulate air (HEPA) filters were installed in both supply and exhaust ducts. Two supply air diffusers are located on one side of ceiling and two exhaust outlets were located on the opposite side of the ceiling. There were two box fans (40 W) positioned near the walls to promote mixing.

The germicidal lamp system (Lumalier, Memphis, TN) consists of five luminaries: four mounted in each of the corners of the room and one hung from the center of the ceiling. The UV lamps generate a band of UV radiation with a width of 30 cm in the upper level of the room.

To characterize the distribution of tracer gas and particles in the upper and lower portions of the room, samples were collected at 5 locations. One sample (A) was collected near the source. Four samples were evenly distributed in the room, two in the upper zone (B, D) measuring the concentration in the upper level and at the exhaust, and two in the lower level of the room (C, E) measuring the concentration at breathing level (1.3 m).

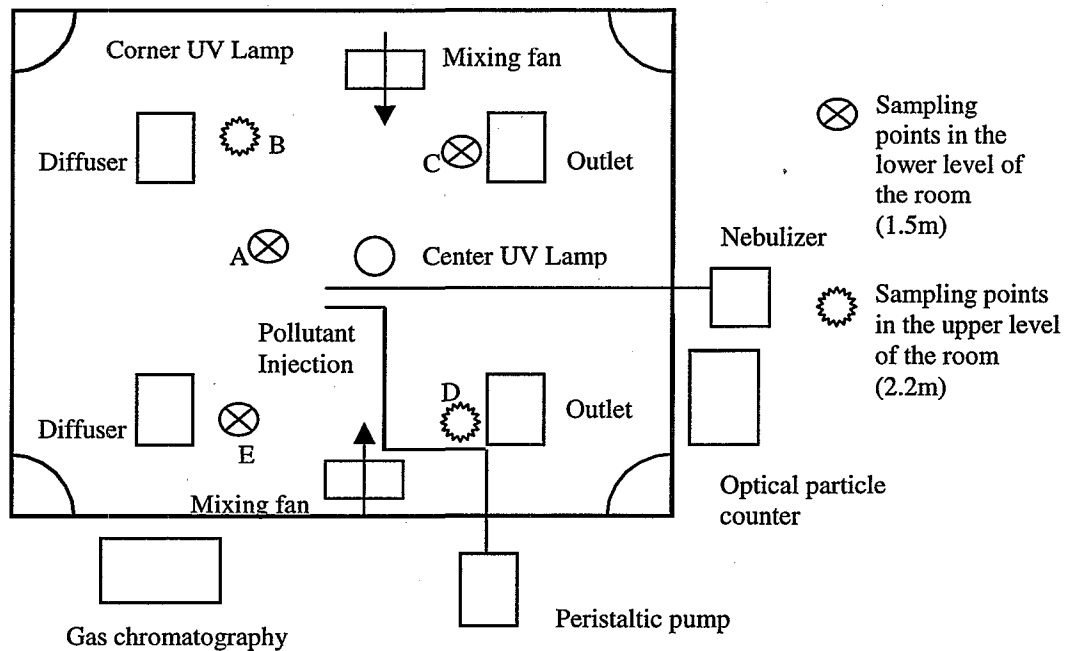


Figure 1. Layout of the test chamber and equipment

Tracer gas (17.6% SF<sub>6</sub> in He) was delivered into the room from a bag connected to a peristaltic pump (Cole-Parmer, IL). Tracer gas concentrations were measured by gas chromatography (Model 101, Lagus Applied Technology, CA). Tracer particles were generated from 2% salt solution using a six-jet Collison nebulizer (CN 25 BGI, Inc., MA). The particle concentrations were measured with a laser optical particle counter (Particle Measurement System Inc., CO). To measure multiple concentrations at five locations, a solenoid valve was put in line with the particle counter to automatically switch sampling every three minutes.

**Test conditions and procedures.** To investigate the airflow patterns, experiments were conducted varying with airflow rate, supply air temperature, and use of the mixing fans. Test conditions are summarized in Table 1. Experiment 6 is labeled as “summer conditions” because the supply air is cooler than room air. Similarly, experiment 7 is called “winter conditions”.

Table 1. Experimental conditions of tests

No.	0 ACH		3 ACH	6 ACH			
	1	2	3	4	5	6	7
Mixing fan	on	off	off	on	off	off	off
Room Temp. °C	21	21	21	21	21	21	21
Supply air Temp. °C	N/A	N/A	21	21	21	12	32

Before starting every experiment, the ventilation system was turned on, purging the room with HEPA-filtered air, and conditioning the room air to 21 °C. When the ventilation rate, system supply air, and room air temperature were stable, the tracer gas injection pump and the nebulizer were turned on. Each experiment lasted five hours after the injections were started, measuring the concentration profile from zero to steady state. After five hours, the injections were turned off and decay process was measured for another hour.

## DATA ANALYSIS

**Pollutant removal efficiency (PRE)** [5]. Pollutant removal efficiency expresses the effectiveness of ventilation in removing the contaminants generated in a room. Since HEPA filters were installed in the supply air ducts, the particle concentration entering the room with the ventilation was assumed to be zero. Likewise, the outside concentration of tracer gas was treated as zero. The efficiency for both particles and gas was determined by:

$$PRE = C_e / C_i \quad (1)$$

where PRE is the pollutant removal efficiency at the location of interest,  $C_e$  is the pollutant concentration measured in the exhaust air (D), and  $C_i$  is the room-averaged pollutant concentration measured in the four evenly distributed sampling points (B, C, D, E). The room ventilation more efficiently removes pollutants if the value of the PRE is higher. PRE is equal to one when the room is completely mixed.

**Air change effectiveness (ACE)** [5]. To characterize mixing within the room, we use another index, called air change effectiveness, or air change efficiency. Air change effectiveness was determined by:

$$ACE = \tau_{\text{exhaust}} / \tau_{\text{room}} \quad (2)$$

where  $\tau_{\text{exhaust}}$  is the age of the exhaust air,  $\tau_{\text{room}}$  is the average air age of the four evenly distributed sampling points in the room. The age of air of these points was determined by a tracer gas decay method:

$$\tau = \int_0^{\infty} t \cdot C(t) / \int_0^{\infty} C(t) \quad (3)$$

where  $C(t)$  is the concentration measured during the decay period. The higher the air change effectiveness, the better the room air is mixed. Air change effectiveness is equal to unity for completely mixed room and its maximum value is 2.

## RESULTS

Using the analysis method described above, the air change effectiveness and pollutant removal efficiency for each test was calculated (Tables 2 and 3). PRE was not calculated for experiments 1-2 since steady state was never reached for these tests.

Table 2. Data analysis for tracer gas tests

Experiment No.	1	2	3	4	5	6	7
Mean concentration in upper zone (ppm)	119	112	82.4	36.0	35.0	24.0	19.0
Mean concentration in lower zone (ppm)	152	162	115	52.0	49.0	27.0	249
Air change effectiveness	0.92	0.86	1.0	1.1	1.0	1.2	0.33
Pollutant removal efficiency	N/A	N/A	0.95	0.79	0.88	0.81	0.14

Table 3. Data analysis for tracer particle tests.

Experiments No.	1	2	3	4	5	6	7
Mean concentration in upper zone ( $\times 10^6/\text{m}^3$ )	98.8	96.1	445	161	185	200	83.5
Mean concentration in lower zone ( $\times 10^6/\text{m}^3$ )	100	98.4	617	255	229	247	336
Air change effectiveness	1.2	1.1	0.94	0.81	0.85	0.95	0.31
Pollutant removal efficiency	N/A	N/A	0.95	0.79	0.88	0.60	0.24

**Tracer gas results.** The concentrations presented in Tables 2 and 3 are time-weighted average (TWA) concentrations from the 2nd to the 5th hour (steady state for experiments 3-7). The TWA tracer gas concentration in the lower zone was always higher than in the upper zone. This is reasonable since the injection was located in the lower zone. For experiments 1-6, in which mixing was relatively good, the largest difference between the upper and lower zone occurred during the experiment 2 (0 ACH without fan), which is about 50%. There is a significant difference for experiment 7 (6 ACH winter condition); the concentration in the lower zone is about 20 times higher than that in upper zone, which indicates a large vertical concentration gradient.

Generally speaking, the room was well mixed in most cases. The air change effectiveness is close to unity, from 0.86 to 1.19 in tests 1-6 and is still 0.86 even when there was no ventilation and no mixing fans. The pollutant removal efficiency is also close to unity for tests 1-6. For experiment 7, both the air change effectiveness and PRE are low, only 0.3 and 0.1 respectively.

**Comparison of tracer particles and tracer gas.** The optical particle counter counts particle diameters from 0.1 to 10  $\mu\text{m}$ . We used the 0.4  $\mu\text{m}$  particle counts to calculate all the parameters in Table 2, since the majority of the particles generated by the nebulizer are around this size [6]. The results from the particle and tracer gas tests were generally comparable. The air change effectiveness and pollutant removal efficiency varied similarly for the different test conditions. For example, the mixing for the winter condition was poor, determined by the low air change effectiveness in both the tracer gas and particle test.

For 0 ACH, the percent difference in TWA concentrations between the upper and lower zones was 50% for the tracer gas test compared to only 2% for particle test, suggesting that the particles and tracer gas were distributed differently. But for the 3 ACH and 6 ACH tests, the percent difference was smaller. It was likely that when the air-exchange rate was low, diffusion and natural convection were the dominant pollutant transport mechanisms. Therefore, particles behaved differently when compared with the gas phase pollutants.

## DISCUSSION

A primary objective of this study was to determine the mixing conditions and ventilation efficiency of the test chamber we are using to evaluate the efficiency of germicidal lamp systems. In our full-size simulated healthcare room, the mixing and ventilation efficiency were good when the room was mechanically ventilated, except under winter conditions when

the buoyancy effects most likely caused the supply air to short circuit directly to the exhaust. Similar results have been shown in previous studies by Fisk et al [7] and Olesen and Seeler [8] in which rooms were mostly completely mixed when the supply air was either cooler or close to room air temperature. Therefore, in wintertime, when mixing can worsen, special techniques should be applied to enhance mixing and ensure the effectiveness of UVGI.

The concentration in the lower portion of the room was higher than the upper portion of the room, where germicidal lamps are installed in our chamber and the UVGI is concentrated. Although the room was approximately well mixed, based on the value of the air change effectiveness from tests 1-6, the difference between the two concentrations was 10-20%. Future investigations will be undertaken to address whether such a room is sufficiently mixed to inactivate airborne bacteria with UVGI when the air change effectiveness is close to one and a small vertical concentration gradient exists.

## ACKNOWLEDGMENTS

We appreciate the assistance of John Martyny for providing technical advice and the tracer gas measurement equipment. We also thank Erik Jeannette for technical help in setting up the experiments. This work was supported by the Centers for Disease Control and Prevention.

## REFERENCES

1. Centers for Disease Control and Prevention. 1994. Guidelines for preventing the transmission of Mycobacterium tuberculosis in health-care facilities. *Morbidity and Mortality Weekly Reports*, Vol. 43(RR-13), pp. 1-132.
2. Medical Research Council. 1954. *Special report series no.283. Disinfection with Ultra-violet Irradiation of Classrooms: Its Effects on Illness in School-Children*. London: Medical research Council.
3. Riley R L, Knight M, and Middlebrook G. 1976. Ultraviolet susceptibility of BCG and Virulent Tubercle Bacilli. *American Review of Respiratory Diseases*. Vol. 115, pp. 413-418.
4. Riffat S B and Cheong K W. 1993. Measurement of ventilation and aerosol particles in buildings. *International Journal of Energy Research*. Vol. 17, pp. 45-55.
5. Claude A R and Luk V. 1991. Airflow Patterns Within Buildings - Measurement Techniques. . *International Energy Agency*. pp. IV.4.
6. Miller-Leiden S, Lobascio C, Nazaroff W W and Macher J M. 1996. Effectiveness of in-room air filtration and dilution ventilation for tuberculosis infection control. *Journal of the Air & Waste Management Association*. Vol. 46, pp. 869-882.
7. Fisk W J, Faulkner D, Pih D, McNeel PJ, Bauman F S and Arens E A. 1991. Indoor air flow and pollutant removal in a room with task ventilation. *Indoor Air*. Vol. 1(3), pp. 247-262.
8. Olesen B W. and Seelen J. 1992. Field measurements of air changer effectiveness using tracer gas techniques, *Proceedings of IAQ '92: Environment for People*. Atlanta, GA, American Society of Heating, Refrigerating, and Air conditioning Engineers. pp. 301-308.