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Influence of ceiling fan’s speed and direction on efficacy of upper-room, ultraviolet germicidal irradiation: Experimental

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ABSTRACT

Increasing a ceiling fan’s speed from its lowest setting of 61 rpm, which resulted in 0.77 m³/s of airflow, to its highest setting of 176 rpm, which resulted in 2.5 m³/s of airflow, or having the fan blow either upward or downward had no statistically significant effect on the efficacy of upper-room ultraviolet germicidal irradiation (UVGI). This outcome suggests that air circulation due to the ceiling fan was sufficient and that any additional increase would not improve efficacy. Numerous experimental studies on upper-room UVGI in which fans were used to provide air mixing have been published. However, none have quantified the air movement produced by these fans or described their tests in sufficient detail to allow results to be compared to predictions using computational fluid dynamics (CFD). The present work provides the required information. In addition to the usual boundary conditions needed for CFD, we made experimental measurements of UV susceptibility of the microorganisms used in the upper-room UVGI tests. We measured UV susceptibilities for Mycobacterium parafortuitum and Bacillus atrophaeus spores to be 0.074 and 0.018 m²/J, respectively. In a previous publication, we reported the spatial distribution of fluence rate, which is also needed for predicting efficacy from CFD. In a companion paper referred to as Part II, upper-room UVGI efficacy was predicted by both Eulerian and Lagrangian CFD and compared to the experimental results from the present study.

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1. Introduction

Upper-room ultraviolet germicidal irradiation (UVGI) is a commonly used engineering control technology to reduce the likelihood of airborne disease transmission in congregate settings such as hospitals, homeless shelters, and prisons [1]. It is particularly well suited for control of tuberculosis (TB), which is spread from person to person exclusively by airborne transmission [2]. Other diseases that are believed, at least in part, to be transmitted through the airborne route can also potentially be controlled by upper-room UVGI (e.g., common cold [3], influenza [4], severe acute respiratory syndrome (SARS) [5], and smallpox [6]). In addition, upper-room UVGI can also reduce the concentration of airborne Bacillus anthracis spores, an infectious agent that has been used by terrorists [7].

In upper-room UVGI’s usual configuration, specially designed fixtures containing low-pressure mercury lamps producing 254-nm ultraviolet (UV) radiation are mounted on a wall or suspended from the ceiling, typically at a height of about 8 ft (2.4 m). In order to minimize UV radiation reaching the lower room where it is potentially hazardous to occupants, the fixtures utilize horizontal, closely spaced, deep louvers to collimate the UV beam and cause it to rise about three to five degrees from the horizontal. A concern with upper-room UVGI arises because the UV beam remains in the upper room and an infected person exhales infectious particles into the lower room. Thus, sufficient vertical air mixing is crucial for bringing infectious particles to the upper room where they are irradiated and inactivated and then returning the air to the lower room where it can be safely breathed by non-infected people. Recognizing that natural convection may not always provide a dependable source of vertical air mixing, NIOSH recommends the use of ceiling fans as a means to assure that vertical air mixing is adequate [8].

Because of the importance of air mixing, we conducted an experimental study to evaluate the influence of a ceiling fan’s speed and direction on the efficacy of upper-room UVGI. In addition to quantifying how much mixing is required for upper-room UVGI to be efficacious, this work was also designed to provide other researchers engaged in modelingupper-room UVGI using...
computational fluid dynamics (CFD), or other methods, with experimental data that they could use for validation of their simulations. Although numerous journal articles using CFD to predict the performance of upper-room UVGI have been published previously, experimental measurements of efficacy needed for validation have been very limited [9–12]. In addition, besides the usual boundary conditions required for modeling, such as room dimensions and supply and exhaust airflow rate and location, predicting upper-room UVGI efficacy requires knowledge of the UV susceptibility of the airborne organisms being inactivated and the UV fluence rate field in the upper room. UV susceptibilities were measured in the present study, and the UV fluence rate field was measured and modeled using a computer-aided design tool in a prior study [13]. Using all of this information, efficacy of upper-room UVGI was predicted using CFD and compared to the experimental results in a companion paper [14].

2. Materials and methods

2.1. Bacteria preparation and generation of bioaerosol

We used two different bacteria as microbiological test aerosols: Bacillus atrophaeus spores and Mycobacterium parafortuitum (ATCC 19686). B. atrophaeus spores are relatively harmless and often used as surrogates for the bacterial spores that cause anthrax. They are also used as decontamination control organisms because of their high resistance to various sterilization methods [15]. M. parafortuitum is also relatively harmless and of the same genus as Mycobacterium tuberculosis, the bacteria causing TB.

A suspension of B. atrophaeus spores was provided by The Baker Company (Sanford, ME). This suspension was diluted to a concentration of approximately \(10^8\) colony forming units (CFUs) per mL with phosphate-buffered saline (PBS) solution (0.8% NaCl, 0.02% KH₂PO₄, 0.115% Na₂HPO₄, and 0.02% KCl) and stored as 1-mL aliquots at \(-80^\circ\)C until needed.

Dry-reeled M. parafortuitum (ATCC, Manassas, VA) was reconstituted in 1 mL of tryptic soy broth (Bacto, Difco Laboratories, Detroit, MI). Then, 0.25 mL of this reconstituted was added to 200 mL of tryptic soy broth, and allowed to incubate at 37 °C in an Orbital Shaker (VWR, Radnor, PA) at 175 rpm for 16 h. This suspension was divided into 50 mL of PBS solution and again centrifuged. The resulting four pellets were combined and referred to as a 1-mL aliquot at \(-80^\circ\)C until needed.

To produce a test bioaerosol, HEPA-filtered air at a pressure of 15 psig (101 kPa) was supplied to a six-jet Collison nebulizer (model VHP 100P, Steris Corp., Mentor, OH) and then ventilated overnight. The test chamber, which is 9.74 ft (2.97 m) wide by 15.1 ft (4.60 m) long with a 10.0 ft (3.05 m) ceiling height, was designed to simulate a one-patient hospital room. A schematic diagram of the test chamber showing Cartesian coordinates for the locations of the chamber’s corners and other prominent features is shown in Fig. 1. This detailed diagram is provided so that others can compare our experimental results with their predictions using CFD or other simulation methods.

The chamber has a dedicated computer-controlled heating, ventilating, and air conditioning (HVAC) system that maintains the chamber at 70 °F (21 °C) and provides an air exchange rate of 6 h⁻¹. Conditioned outdoor air flows through a high efficiency particulate air (HEPA) filter and, as shown in Fig. 1, then flows through a supply air grille and enters the chamber near the ceiling in the upper corner of a long wall. It exits through the exhaust air grille near the floor in the lower corner of the other long wall farthest from where the supply air enters, and then flows through a second HEPA filter prior to being exhausted outdoors high above surrounding buildings. In order to prevent exfiltration of contaminated air, the chamber is kept at a negative pressure of 0.01–0.05 in. w. (12.5–25 Pa) by exhausting about 10 cfm (4.7 L/s) more air than is supplied to the chamber. The 13.5 in. (343 mm) square opening for the supply air grille contains 12 equally spaced horizontal louvers. The 10 louvers farthest from the door make an angle of roughly 30° with the face of the grille such that the air is directed away from the door. The 9 louvers closest to the adjacent door are essentially perpendicular to the face of the grille. The opening for the exhaust air grille is 19 in. (483 mm) wide and 10.8 in. (274 mm) high. It contains 16 equally spaced horizontal louvers.

A three-speed, reversible, five bladed, 52 in. (1.3 m) ceiling fan (model 28415, Hunter Fan Company, Memphis, TN) hangs from the center of the ceiling with the blades 8.9 ft (2.7 m) above the floor. This fan operates at 61, 107, or 176 revolutions per minute (rpm), drawing 66 W of electricity at 176 rpm. The manufacturer measured the rate at which air is moved by this fan to be 1630, 3050, and 5500 cfm (7.8, 14.2, and 27.4 m³/s).

2.2. Simulated one-patient hospital room

2.2.1. Room-size test chamber

We measured efficacy of upper-room UVGI in a 2000 ft³ (56.6 m³) stand-alone structure containing an interior partition that separates a 1470 ft³ (41.7 m³) test chamber from a 530 ft³ (15.0 m³) control room containing a biological safety cabinet and a control panel for remotely operating equipment inside the test chamber. Prior to entering the test chamber, it was decontaminated with vaporized hydrogen peroxide (Biodectomant System Model VHP 100P, Steris Corp., Mentor, OH) and then ventilated overnight.

The test chamber, which is 9.74 ft (2.97 m) wide by 15.1 ft (4.60 m) long with a 10.0 ft (3.05 m) ceiling height, was designed to

Fig. 1. Three-dimensional diagram of the room-size test chamber (not to scale). Cartesian coordinates in meters for the chamber and locations of supply and exhaust air grilles and the back of the UV fixtures are specified. (The origin is located at the back lower corner of the chamber.)
5250 cfm (0.77, 1.4, and 2.5 m$^3$/s) respectively, based on methodology published by U.S. EPA [16]. Further details for this fan are given in a companion paper [14]. We did not conduct experimental tests without a ceiling fan operating because upper-room UVGI efficacy may vary significantly depending on the amount of mixing caused by heat sources (such as people, computers, and radiators), HVAC systems, differences in indoor and outdoor temperatures, and wind velocity [17–19].

The test chamber contained two Hygreaire model LIND 24-EVO UV fixtures (Atlantic Ultraviolet Corp., Hauppauge, NY), which were mounted with their bottom surfaces at a height of 8 ft (2.4 m) above the floor. In Appendix A, a diagram of this fixture with dimensions is given in Fig. A.1. Each fixture contains one 25-W tubular lamp with a parabolic reflector close to the lamp’s backside. UV radiation exiting the fixture must pass between 2 ft (0.61 m) wide, 3 in. (76 mm) deep, horizontal louvers spaced 1/4 in. (6.4 mm) apart. The two fixtures were staggered so that they did not directly face each other. As shown in Fig. 1, one fixture was mounted on one short wall and the other fixture on the other short wall, such that one side of each fixture was 2 ft (0.60 m) away from a different long wall. The UV emission rate of each fixture, which was 0.47 W, and the UV fluence rate field produced by these fixtures were measured in a prior study [13]. However, because the location where each fluence rate was measured was not previously specified, Appendix A gives fluence rates and corresponding locations in Table A1 and Fig. A.2, respectively.

2.2.2. Testing methods in room-size chamber

Pairs of experimental tests were done under identical conditions except that for one test the two UV fixtures were turned on for 15 min whereas for the other test they were turned off prior to introduction of airborne bacteria into the test chamber. For both tests, the ceiling fan was operating at the same speed and direction and the air exchange rate was maintained at 6 h$^{-1}$. In order to evaluate experimental error, all test pairs were replicated three or four times.

The test bioaerosol generated by the Collison nebulizer located in the biological safety cabinet was discharged directly into a 1.0-in. (25 mm) diameter stainless steel (SS) tube that extended from the biological safety cabinet through the chamber wall to the center of the chamber. The aerosol was discharged at a height of 5 ft (1.5 m) above the floor through a hollow, 3-in. (76 mm) diameter, SS sphere having 25 equally spaced 1/8 in. (3.2 mm) diameter holes.

If the air in the chamber was well mixed, then after 40 min of supplying aerosol and outdoor air at 6 h$^{-1}$, the bacteria concentration would be expected to be greater than 98% of its steady-state value. Thus, we assumed that after 40 min steady-state conditions had essentially been established and sampling was begun. The sampling point was directly in front of the midpoint of the exhaust air grille. Samples were withdrawn at the rate of 28.3 L/min sampling point was directly in front of the midpoint of the exhaust air grille. Samples were withdrawn at the rate of 28.3 L/min through a 1.0-in. (25 mm) diameter SS tube leading back to the biological safety cabinet in the control room. Depending on expected concentrations, the samples were collected for various sampling times using a single-stage Andersen biological impactor (Thermo Electron, Smyrna, Ga.) onto tryptic soy agar contained in petri dishes. Samples were taken in triplicate. Petri dishes were incubated at 37 °C, and colonies were counted the next morning for B. atrophaeus spores and after four days for M. parafortuitum. Colony counts were adjusted to account for the likelihood that more than one organism had passed through the same hole [20].

2.2.3. Calculations and important parameters

The efficacy of upper-room UVGI under steady-state conditions can be expressed using any of the following metrics: 1) fraction or percentage surviving, 2) fractional or percentage reduction, and 3) equivalent air exchange rate. The fraction surviving (S) is defined as the ratio of the steady-state concentration of culturable airborne bacteria at the exhaust air grille with the UVGI turned on (C$^{UV}$) to the steady-state concentration at the exhaust air grille with the UVGI turned off (C$^{noUV}$):

$$S = \frac{C^{UV}}{C^{noUV}}$$  (1)

For the purpose of specifying UVGI efficacy, either fraction surviving or fractional reduction, which is equal to $1 - S$, can be used. A more useful measure of efficacy is equivalent air exchange rate, which is defined in terms of the air exchange rate. For our purposes, air exchange rate ($\lambda$) is defined as the volumetric flow rate of bacteria-free air entering the chamber ($Q$) divided by the chamber volume ($V$):

$$\lambda = \frac{Q}{V}$$  (2)

If we assume that the following three conditions exist, the airborne concentration of culturable bacteria would be inversely proportional to air exchange rate: 1) well-mixed room air, 2) steady state, and 3) no removal or inactivation processes other than dilution ventilation with bacteria-free air. For these conditions, if the air exchange rate is doubled, the airborne culturable bacteria concentration in the room will be halved. If there is also an inactivation process such as upper-room UVGI, the equivalent air exchange rate for UVGI can be defined as the additional increase in air exchange rate that would be necessary under the three conditions specified above to obtain the same viable airborne bacteria concentration without UVGI. For example, if the air exchange rate is 6 h$^{-1}$ and upper-room UVGI reduced the viable airborne bacteria concentration by a factor of four, a hypothetical air exchange rate of 24 h$^{-1}$ would result in the same concentration. Thus, the equivalent air exchange rate attributable to UVGI is the difference between this hypothetical air exchange rate and the actual air exchange rate—that is, 18 equivalent air changes per hour. This result can also be calculated from the following equation [21]:

$$\lambda_{eq} = \frac{1 - S}{S^2} \lambda$$  (3)

where $\lambda_{eq}$ is equivalent air exchange rate attributable to UVGI. Equivalent air exchange rate is an outcome parameter whose effect most people understand—that is, analogous to air exchange rate under the conditions specified above, for every doubling of equivalent air exchange rate, the concentration of viable bacteria is halved and the risk is reduced accordingly.

Another important parameter is the ceiling fan’s air turnover rate ($\lambda_{fan}$), which is defined in a similar way as air exchange rate:

$$\lambda_{fan} = \frac{Q_{fan}}{V}$$  (4)

where $Q_{fan}$ is the airflow rate attributable to the ceiling fan, which provides air circulation between the lower and upper room. To meet Energy Star qualification for US EPA’s voluntary energy conservation program, ceiling fan manufacturers must measure and report $Q_{fan}$ using a prescribed procedure [16].

Another parameter of primary importance to upper-room UVGI is the room’s UV dosing rate ($D$):

$$D = \frac{E}{V}$$  (5)

where $E$ is the UV emission rate for all of the UV fixtures in a room. For our experimental test chamber with two Hygreaire UV fixtures, the dosing rate is 22 mW/m$^3$. 

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It would appear that by using equivalent air exchange rate, air turnover rate, and UV dosing rate, which are all normalized by room volume, scale-up—that is, adjusting for different size rooms—would be straightforward and that simple guidelines could be recommended. However, whether these parameters can be used successfully for scale-up purposes needs to be demonstrated by either experimental studies or by computational fluid dynamics.

2.3. Measurement of UV susceptibility of bacteria

2.3.1. Bench-top chamber

We measured the UV susceptibility of M. parafortuitum and B. atrophaeus spores, the test bacteria used for studies done in the simulated patient hospital room, in a one-pass bench-top chamber designed specifically for this purpose. This chamber had been used previously to measure the UV susceptibility of other bacteria and viruses [22–25]. The chamber and associated apparatus, which are shown in a schematic diagram in Fig. 2, were located in a biological safety cabinet to minimize the possibility that aerosol would escape from the chamber into the room or that stray organisms would enter the chamber. The chamber is divided into two zones: 1) a mixing zone containing baffles to induce mixing and drying of the bacteria-containing droplets and 2) an exposure zone where bacteria are exposed to a known constant UV irradiance. Relative humidity and temperature were measured with an Omega

\[ t = \frac{V}{Q} \]  

The dose (D) received by the bacteria can be calculated based on the average of the 30 irradiance measurement made in the exposure zone (I) and the exposure time:  

\[ D = IT \]  

2.3.2. Testing methods for bench-top chamber

The test bioaerosol generated by a Collison nebulizer along with room air that had been dried and HEPA filtered flowed through the mixing zone and then through the exposure zone. Downstream of the chamber, 12.5 L/min of irradiated aerosol flowed through each of two liquid impingers (SKC Biosamplers, SKC, Inc., Eighty Four, PA) connected in parallel. Each impinger contained 20 mL of PBS solution. Air leaving the impingers passed through a single HEPA filter prior to entering a pump, which maintained an airflow rate of 25 L/min through the system. Pairs of two-minute samples were collected in the impingers. For one sample, bacteria were exposed to UVGI, whereas the other sample was prevented from receiving UV exposure by covering the quartz window. Between samples, the aerosol bypassed the impingers and flowed at 25 L/min directly to the HEPA filter before being exhausted. The impingers were thoroughly rinsed with deionized water between samples.

After sampling for M. parafortuitum, 50 μL of the contents of one of the impingers was mixed with 50 μL of PBS solution. This mixture was plated in triplicate on tryptic soy agar, whereas for B. atrophaeus spores, 100 μL of the undiluted contents of one impinger was plated in triplicate on tryptic soy agar. After incubation at 37 °C, the colonies were counted and the concentrations in CFU/m³ were calculated. The inactivation of both M. parafortuitum and B. atrophaeus spores due to UVGI was assumed to follow the equation for exponential decay [22,23]:  

\[ \frac{C_{\text{UV}}}{C_{\text{noUV}}} = \exp(-zD) \]  

where \( C_{\text{UV}} \) and \( C_{\text{noUV}} \) are concentrations of bacteria when they are exposed and not exposed to UVGI, respectively, all else being the same. When the logarithms of experimental values of \( C_{\text{UV}}/C_{\text{noUV}} \) are plotted against dose, a straight line should be obtained. The slope of this straight line is equal to \( z \), the UV susceptibility of the bacteria.

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Fig. 2. Schematic diagram of the one-pass bench-top chamber and associated apparatus used to measure the UV susceptibility (z) of M. parafortuitum and B. atrophaeus spores.
3. Results

3.1. Upper-room UVGI efficacy

For the purpose of allowing others to compare our experimental results with their predictions using CFD, Table B1 in Appendix B lists the fraction surviving for all tests conducted during this study. Based on Equation (3), fraction surviving can be converted to equivalent air exchange due to upper-room UVGI, which is used in our analysis to follow.

Fig. 3 shows the influence of the ceiling fan’s air turnover rate on the equivalent air exchange rate attributable to upper-room UVGI when *M. parafortuitum* is the test bioaerosol. The three available fan speeds in rpm are indicated at the top of this plot. Each data point is the mean for four independent tests, and the error bars correspond to the standard error of the mean. The two linear regression lines corresponding to the fan blowing air up or down, however, are based on 12 independent tests (four replicates for each of three fan speeds). The effect of the fan’s air turnover rate on equivalent air exchange rate for the fan blowing up or down is minimal, as suggested by the near-zero slopes and coefficients of determination ($R^2$) of 0.0007 and 0.0308, respectively.

Similarly, Fig. 4, in which the mean and standard error of the mean for three or four independent tests are plotted, shows the effect of changing the fan’s air turnover rate on equivalent air exchange rate due to upper-room UVGI for *B. atrophaeus* spores. The linear regression lines corresponding to the fan blowing air up and down are based on 10 and 9 independent tests, respectively. Although greater than for the tests using *M. parafortuitum*, the influence of the fan’s air turnover rate on the equivalent air exchange rate does not show a strong correlation for either the fan blowing up or down ($R^2$ of 0.25 and 0.53, respectively). For the fan blowing down, the equivalent air exchange rate increases with increasing air turnover rate, whereas, for the fan blowing up, the equivalent air exchange rate decreases with increasing air turnover rate.

A one-way analysis of variance (ANOVA) was used to determine if changing the fan’s air turnover rate and/or direction had a statistically significant effect on the equivalent air exchange rate attributable to upper-room UVGI. The null hypothesis that the equivalent air exchange rate is the same for the fan blowing up or down and for changes in air turnover rate over the range of 66–214 h$^{-1}$, which corresponds to 61–176 rpm, could not be rejected at 95% confidence level for both *M. parafortuitum* ($p = 0.51$) and *B. atrophaeus* spores ($p = 0.12$).

3.2. Measurement of UV susceptibility in bench-top chamber

In Fig. 5 for *M. parafortuitum* and in Fig. 6 for *B. atrophaeus* spores, the logarithm of the ratio of concentration when bacteria are exposed to UV to the concentration when there is no UV exposure is plotted against the logarithm of UV dose for tests made in the one-pass bench-top chamber. Based on Equation (8), the 17 data points in Fig. 5 and 19 data points in Fig. 6 should both fall on straight lines whose slopes have magnitudes equal to the UV susceptibility of *M. parafortuitum* and *B. atrophaeus* spores, respectively. Based on these slopes, the means and 95% confidence intervals for UV susceptibility of *M. parafortuitum* and *B. atrophaeus* spores are 0.074 ± 0.011 m$^2$/J and 0.018 ± 0.0017 m$^2$/J, respectively. The UV susceptibility of *M. parafortuitum* is about four times that of *B. atrophaeus* spores.

4. Discussion

4.1. Effect of fan speed and direction on efficacy of upper-room UVGI

A one-way ANOVA could not distinguish a difference in outcome at 95% confidence level for any of the three available fan speeds or for the fan blowing up or down. Therefore, for the purpose of upper-room UVGI efficacy, the air in the room can be considered to be well mixed when this ceiling fan is operating under the
conditions tested. This result is fortuitous because ceiling fans can cause drafts that interfere with the comfort of room occupants [26], particularly at higher speeds when the fan is blowing downward. These statements, however, need to be tempered with the caveat that experimental error may be obscuring trends.

Over the range tested, if the fan’s speed did have a significant influence on upper-room UVGI then the equivalent air exchange rate versus the air turnover rate for both M. parafortuitum and B. atrophaeus spores would be expected to show similar trends. However, this is not what we observed. Based on the regression lines shown in Figs. 3 and 4, when the fan was blowing up and the air turnover rate was increased by changing the fan speed from low to high, the equivalent air exchange rate for M. parafortuitum decreased by 3%, whereas for B. atrophaeus spores, it increased by 52%. When the fan was blowing down and the air turnover rate was increased, the equivalent air exchange for M. parafortuitum (Fig. 3) decreased by 13%, whereas for B. atrophaeus spores (Fig. 4), it increased by 78%. Thus, the trends for M. parafortuitum and B. atrophaeus spores when the fan is blowing up or when the fan is blowing down contradict each other.

The inherent variability in microbiological aerosolization and sampling can be large and may be the explanation for these observations.

For both the fan blowing up and down, an increasing equivalent air exchange rate with increasing air turnover rate was anticipated because the greater the mixing, the more effective upper-room UVGI would be expected to be, all else being the same. Mixing promotes uniform irradiation of bacteria, which minimizes the likelihood of bacteria being over-irradiated—a bacterium can only be killed once—or exiting the chamber with little or no exposure to the UV beam. This expectation, however, was not supported by the experimental data, suggesting that once there is sufficient air mixing, then increasing fan speed may not improve upper-room UVGI efficacy.

4.2. UV susceptibility of M. parafortuitum and B. atrophaeus spores

We determined the UV susceptibility for M. parafortuitum, which was based on 17 independent tests, and for B. atrophaeus spores, which was based on 19 independent tests, to be equal to 0.074 m²/J and 0.018 m²/J, respectively. We believe that these values are likely to be more reliable than other published values of UV susceptibilities for two reasons: 1) We used apparatus specifically designed for measuring the UV susceptibility of bacteria and virus and 2) as far as we are aware, our measurements are based on far more independent tests than most, if not all, of the other UV susceptibilities that have been reported in the scientific journals.

Rentschler [27] (as reported by Brickner et al. [28]) measured a susceptibility of 0.019 m²/J for Bacillus subtilis spores, which is very close to the 0.018 m²/J that we measured for B. atrophaeus spores—previously known as B. subtilis var. niger spores [15]. Miller et al. [18] measured a susceptibility of 0.12 m²/J and Peccia [29] measured 0.16 m²/J (as reported by Miller et al. [18]) for M. parafortuitum, both somewhat higher than the 0.074 m²/J that we measured. However, their measurements were determined from experimental tests done in chambers that were assumed to be well mixed. Thus, in their tests, bacteria were not exposed to constant fluence rates and exposures times were not constant. For the UV susceptibilities measured in the present study, both fluence rate and exposure time were approximately the same for all exposed bacteria.

Miller et al. also observed similar upper-room UVGI efficacy for M. parafortuitum and Mycobacterium bovis (BCG), which they suggested indicated that these mycobacteria behave similarly to UV exposure [18]. Earlier research by Riley et al. showed a similar response to UVGI for BCG and virulent M. tuberculosis [30]. Thus, it is tempting to state that the UV susceptibilities of M. parafortuitum and virulent M. tuberculosis are not very different, although further confirmation is necessary in order to feel confident that M. parafortuitum is a reasonable surrogate for virulent M. tuberculosis in experimental studies.

5. Conclusions

Increasing the ceiling fan’s speed from its lowest setting of 61 rpm to its highest setting of 176 rpm, which results in an increase in the fan’s air turnover rate from 66 to 214 h⁻¹, or having the fan blow up or down had no statistically significant effect on upper-room UVGI efficacy. This observation suggests that the air circulation provided by the ceiling fan is sufficient and that an increase in fan speed will not improve upper-room UVGI efficacy. However, as the air turnover rate is decreased below 66 h⁻¹, at some point mixing would likely become insufficient and upper-room UVGI efficacy would suffer.

Although the results from many experimental studies on upper-room UVGI in which fans were used to provide air mixing have been published, none quantified the level of mixing or described it in sufficient detail to allow experimental results to be compared to predictions using computational fluid dynamics. The present work provides the information required to make these comparisons. In addition to the usual boundary conditions needed for CFD such as room dimensions, airflow rates, etc., the present study provides experimental measurements of UV susceptibility for M. parafortuitum and B. atrophaeus spores, the microorganisms for which upper-room UVGI efficacy studies were done and reported in this paper. The spatial distribution of fluence rate in the upper room, which is also needed for CFD predictions of upper-room UVGI, is available from a previous publication [13]. In a companion paper with the same title as the present paper, but referred to as Part II, the efficacy of upper-room UVGI was predicted from simulations using both Eulerian and Lagrangian CFD [14]. These predictions were made without knowledge of the results from the present experimental study. After these predictions were made, they were compared to the experimental results from the present study.

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Appendix A. UV fixtures.

Fig. A.1 is a diagram with dimensions of the Hygeaire model LIND 24-EVO UV fixture (Atlantic Ultraviolet Corp., Hauppauge, NY), which was used in the present study. The front face of this fixture slants 4° from the vertical such that the louvers, which are perpendicular to this face, slant upward by 4° causing the UV beam to rise slightly.

Fluence rates in the upper room are given in Table A1. In comparison, fluence rates outside the collimated UV beam in the remainder of the room are small and would not be expected to contribute very much to inactivation of airborne bacteria. For each of six heights specified in Table A1, the location of specific fluence rates in the corresponding horizontal plane are indicated in Fig. A.2 by the filled-in circles. These circles are at the center of 0.6-m squares and are designated in Table A1 and Fig. A.2 by row, which are labeled A, B, C, D, E, F, and G, and by column, which are labeled 1, 2, 3, 4, and 5. For simplicity, the space within 6 in. (0.15 m) of both short walls was ignored.

Table A1
Measured fluence rates in μW/cm² within the UV beam in the upper room of the test chamber. See Fig. A2 for locations of these fluence rates.a

| Height (H) | 1  | 2  | 3  | 4  | 5  | 1  | 2  | 3  | 4  | 5  |
|-----------|----|----|----|----|----|----|----|----|----|----|
| H = 7 ft (2.13 m) |   |    |    |    |    | A  | 0.49 | 0.75 | 0.66 | 0.64 | 0.56 | A  | 14.77 | 17.63 | 20.04 | 21.11 | 21.27 |
| H = 8.5 ft (2.59 m) |   |    |    |    |    | B  | 0.68 | 0.87 | 0.84 | 0.76 | 0.65 | B  | 17.85 | 21.29 | 25.57 | 27.48 | 26.80 |
| H = 7.5 ft (2.29 m) |   |    |    |    |    | C  | 0.78 | 0.85 | 0.85 | 0.84 | 0.76 | C  | 25.79 | 30.36 | 34.71 | 34.35 | 31.53 |
| H = 8 ft (2.44 m) |   |    |    |    |    | D  | 0.84 | 0.87 | 0.87 | 0.87 | 0.87 | D  | 38.34 | 48.27 | 50.41 | 48.27 | 38.14 |
| H = 9 ft (2.74 m) |   |    |    |    |    | E  | 0.76 | 0.84 | 0.85 | 0.85 | 0.78 | E  | 31.53 | 34.35 | 34.71 | 30.36 | 25.79 |
| H = 9.5 ft (2.90 m) |   |    |    |    |    | F  | 0.65 | 0.76 | 0.84 | 0.87 | 0.68 | F  | 26.80 | 27.48 | 25.57 | 21.29 | 17.85 |
| Height (H) | 1  | 2  | 3  | 4  | 5  | 1  | 2  | 3  | 4  | 5  |
| H = 7 ft (2.13 m) |   |    |    |    |    | A  | 0.56 | 0.64 | 0.66 | 0.75 | 0.49 | A  | 21.27 | 21.11 | 20.04 | 17.63 | 14.77 |
| H = 8.5 ft (2.59 m) |   |    |    |    |    | B  | 0.65 | 0.76 | 0.84 | 0.87 | 0.68 | B  | 26.80 | 27.48 | 25.57 | 21.29 | 17.85 |
| H = 7.5 ft (2.29 m) |   |    |    |    |    | C  | 0.76 | 0.85 | 0.85 | 0.84 | 0.76 | C  | 25.79 | 30.36 | 34.71 | 34.35 | 31.53 |
| H = 8 ft (2.44 m) |   |    |    |    |    | D  | 0.84 | 0.87 | 0.87 | 0.87 | 0.87 | D  | 38.34 | 48.27 | 50.41 | 48.27 | 38.14 |
| H = 9 ft (2.74 m) |   |    |    |    |    | E  | 0.76 | 0.84 | 0.85 | 0.85 | 0.78 | E  | 31.53 | 34.35 | 34.71 | 30.36 | 25.79 |
| H = 9.5 ft (2.90 m) |   |    |    |    |    | F  | 0.65 | 0.76 | 0.84 | 0.87 | 0.68 | F  | 26.80 | 27.48 | 25.57 | 21.29 | 17.85 |

For additional details, see previous publication [8].

b Based on symmetry (rather than direct measurement).
Appendix B. Fraction surviving for upper-room UVGI tests.

Measured fraction surviving for all upper-room UVC tests done in the room-size chamber are listed in Table B1. These values can be converted to equivalent air exchange rate using Equation (3).

Table B1
Fraction surviving for upper-room UVC tests.

| Fan speed (rpm) | Fan blowing up | Fan blowing down |
|-----------------|----------------|-----------------|
| 61              | 107            | 176             |
| M. parafortuitum |                |                 |
| Test# 1         | 0.62           | 0.29            |
| # 2             | 0.39          | 0.32            |
| # 3             | 0.23          | 0.30            |
| B. atrophaeus spores | 0.407       | 0.603          |
| Test# 1         | 0.580         | 0.612           |
| # 2             | 0.366         | 0.722           |
| # 3             | 0.407         | 0.603           |
| # 4             | 0.718         | 0.612           |

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