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# Eggcrate UV: a whole ceiling upper-room ultraviolet germicidal irradiation system for air disinfection in occupied rooms

**Abstract** A novel whole ceiling upper-room ultraviolet germicidal irradiation (UVGI) system [eggcrate ultraviolet (UV)] has been developed that incorporates open-cell 'eggcrate'-suspended ceiling panels and bare UV lamps with a ceiling fan. Upper-room UVGI is more effective for air disinfection than mechanical ventilation at much lower installation and operating costs. Conventional upper-room UVGI fixtures employ multiple tightly spaced horizontal louvers to confine UV to the upper-room. These louvered fixtures protect occupants in the lower-room from UV-induced eye and skin irritation, but at a major cost to fixture efficiency. Using a lamp and ballast from a conventional upper-room UVGI fixture in the eggcrate UV system, the germicidal efficacy was markedly improved even though the UV radiation emitted by the lamp was unchanged. This fundamental change in the application of upper-room UVGI air disinfection should permit wider, more effective application of UVGI globally to reduce the spread of airborne infection.

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Key words: Airborne disease transmission; Upper-room ultraviolet germicidal irradiation; Infection; Bioaerosol; Air disinfection; Whole ceiling ultraviolet germicidal irradiation system; Eggcrate ultraviolet.

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**Practical Implications**
The novel whole ceiling ultraviolet germicidal irradiation system maximizes the germicidal potential of ultraviolet lamps in the upper-room while assuring air mixing and occupant safety. This promising new technology has the potential to transform infection control of airborne disease transmission by providing efficient, economical in-room air disinfection.

## Introduction

Person-to-person airborne transmission of diseases, including tuberculosis, small pox, severe acute respiratory syndrome (SARS), and pandemic influenza, is a major public health concern (Dias et al., 2012; Tellier, 2006). More than 1 billion people are infected with diseases via airborne transmission annually (WHO, 2009, 2012). Engineering control of airborne infectious agents is an important strategy for reducing airborne transmission of disease. The current WHO tuberculosis (TB) infection control plan includes engineering controls such as natural and mechanical ventilation, upper-room ultraviolet germicidal irradiation (UVGI) air disinfection, and air filtration (Hodgson et al., 2012) (Scano, 2009). Of these, upper-room UVGI has some unique advantages; it has the potential to process large quantities of room air relatively inexpensively, rapidly, and without noise. Additionally, UVGI can supplement natural and mechanical ventilation systems. Use of mechanical ventilation alone, except under ideal conditions, is an inefficient method of particle removal. Natural ventilation may not always be reliable depending on ambient conditions, and may not be practical in cold climates. Filtration room air cleaners rarely produce the necessary equivalent air changes required for effective air disinfection, are noisy, and often reprocess the same local air (short-circuiting).

However, the application of upper-room germicidal air disinfection has been limited by current fixture designs. In the usual configuration, upper-room UVGI, specially designed fixtures containing low-pres-

sure mercury lamps producing 254-nm ultraviolet radiation (UV) are mounted on an upper wall or suspended from the ceiling. In order to minimize UV radiation reaching the lower-room where it can potentially lead to eye or skin irritation of room occupants, modern fixtures utilize closely spaced, deep louvers to collimate the UV beam so it is nearly parallel to the ceiling (Nardell and Riley, 1992). Unfortunately, while successfully preventing daily 8-h exposures greater than the 6 mJ/cm$^2$ threshold limit value guideline, these louvers severely restrict the amount of UV radiation emitted by the fixture (ACGIH, 2010). Standard gonioradiometry measurements used by the lighting industry have shown that 96–99% of the UV radiation emitted by the lamps never exits the fixtures (Rudnick et al., 2012). Nevertheless, in rooms <3 m high, these severely UV-restricting louvers have been necessary for the safe application of upper-room UVGI.

Because the UV irradiation is confined to the upper-room while contagious people exhale infectious particles in the lower-room, adequate air mixing between the upper- and lower-room is essential. Vertical air movement is crucial for bringing infectious particles to the upper-room where they are irradiated, rendered noninfective, and returned to the lower, occupied portion of the room (Zhu et al., 2013). Recognizing that natural convection, although often ample, may not reliably provide sufficient vertical air exchange, National Institute for Occupational Safety and Health (NIOSH) recommends the use of ceiling fans as a means to assure that vertical air exchange is adequate (NIOSH, 2009).

Herein, we present a novel approach to upper-room germicidal air disinfection that eliminates tightly louvered fixtures in favor of bare lamps located above a suspended ceiling with open-cell 'eggcrate' panels and a ceiling fan (termed 'eggcrate UV' or 'eggcrate UVGI'). This system is designed to eliminate the need for louvers and maximize UV emission into the upper-room, while protecting room occupants from overexposure to UV radiation. The bare lamps irradiate air throughout the upper-room. The large open area of the widely available eggcrate ceiling panels helps to minimize airflow resistance while the panel depth prevents both the direct UV rays and much of the reflected UV radiation from reaching the lower-room. We compare air disinfection efficacy, UV irradiance levels in the lower-room, and air mixing for the eggcrate UV system against conventional louvered fixtures in this proof-of-concept study.

## Materials and methods

### Experimental chamber

Experimental tests were conducted in a room-size chamber; all aerosolization and sampling were carried out in a Class II Type A1 biosafety cabinet as described elsewhere (First et al., 2007). The chamber, which has a 3.0 m by 4.6-m floor and a 3.0-m-high ceiling, is equipped with a computer-controlled heating, ventilation, and air-conditioning system. Supply air enters the chamber through a high-efficiency particulate air (HEPA) filter just below the suspended ceiling. Exhaust air is removed from the opposite wall of the lower-room and passes through a second HEPA filter to prevent microorganisms used during experiments from being released into the outdoor environment. The air exchange rate was maintained at six air changes per hour (ACH). A negative pressure of approximately 12 Pa was maintained in the chamber to prevent microorganisms used in the tests from being released into the outdoor environment and antechamber. A ceiling fan with five 52″ blades (model #28415, Hunter Fan Company, Memphis, TN, USA) is mounted in the center of the ceiling.

### Conventional upper-room UVGI

Atlantic Ultraviolet Hygeaire fixtures, Model LIND 24-EVO (Atlantic Ultraviolet, Hauppauge, NY, USA), shown in Figure 1a, were mounted on the wall of the experimental chamber adjacent to locations A2 and G4 (Figure 2) at a height of 2.3 m. For experiments using only one lamp, the fixture adjacent to G4 was turned on. For experiments using two lamps, both figures were turned on. Although the UV output of these lamps is adjustable, the lamps were always operated at their highest UV output. During all experimental tests using these fixtures, the ceiling fan was operated at high speed blowing up.

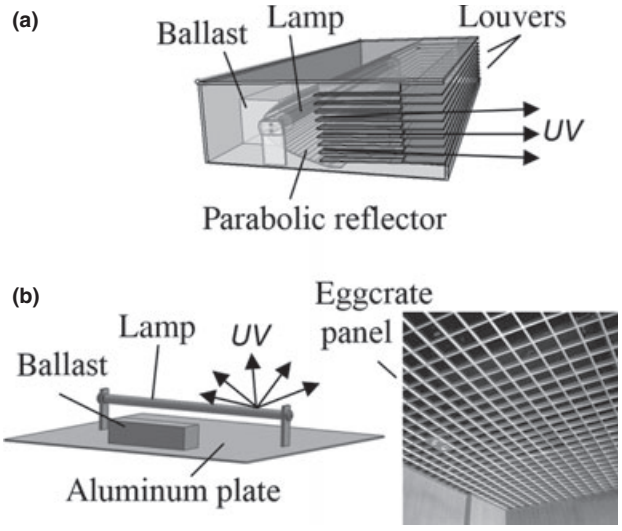


**Fig. 1** Schematics of (a) conventional wall mounted ultraviolet (UV) fixture, (b) the bare UV lamp with electrical components mounted on aluminum plate (left) and suspended eggcrate panels (right)

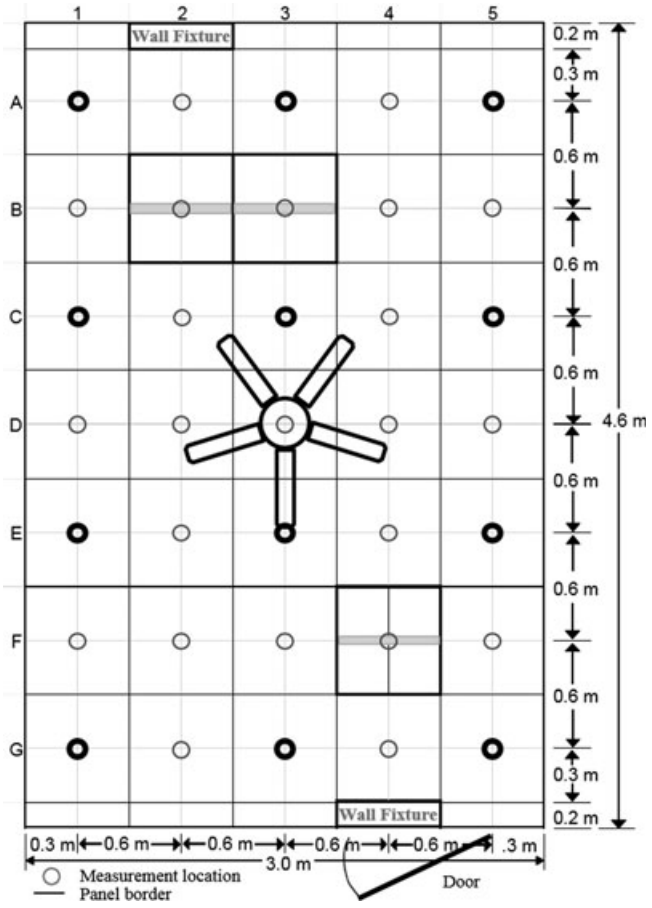


**Fig. 2** Measurement grid within the experimental chamber. Lamps for eggcrate ultraviolet (UV) are at locations B3 (single UV lamp location) and B2 and F2 (two UV lamp locations). Radiometer measurements were made at each of the 35 circles (O) within the grid. Anemometer measurements were made at each of the 12 bold circles (**O**) within the grid

### Upper-room Eggcrate UVGI

Black plastic eggcrate ceiling panels (Thincell™ TC Economy eggcrate panels; SLP Lighting, Fenton, MO, USA), typically used for lighting, were inserted into a 2.4-m-high-suspended ceiling in which 0.61 m (2 ft) square fiberglass ceiling tiles are normally placed. The commercially available open-cell plastic panels have a thickness of 7.75 mm and 14.6-mm × 14.6-mm square openings, which result in a total open area of 82.5% per panel.

The eggcrate UV fixtures were constructed using components identical to those used in the conventional fixtures described above [8.5 W single-pin low-pressure UV mercury vapor lamp, Surelite ballast, and single-pin sockets (Atlantic Ultraviolet)]. These components were mounted on a 0.61 m (2 ft) square aluminum, 3-mm-thick mirror-polished 5052 aluminum alloy plate such that the lamp was 50 mm above the plate, as shown in Figure 1b. The grid suspension of the drop ceiling in which the aluminum-plate-mounted fixture was placed provides a 25-mm lip above the aluminum plate.

For experimental tests using one-lamp, the prototype fixture mounted on the 0.61 $m^2$ plate was placed on top of an open-cell panel at location B3 shown in Figure 2. For experiments using two-lamps, the fixtures and plates were placed at location B2 and F4 of Figure 2. In all experiments, a double layer of open-cell panels were placed on top of the four panels adjacent to the fixture(s) to minimize lower-room irradiance.

### Bioaerosol tests

A concentrated stock of *Bacillus atrophaeus* (*B. atrophaeus*) spores (ATCC 9372) was provided by The Baker Company (Sanford, ME, USA). The spores were prepared by diluting the stock to a concentration of $10^8$ colony-forming units (CFUs) per ml in a phosphate-buffered saline (PBS) solution. *Mycobacterium parafortuitum* (*M. parafortuitum)* was purchased from ATCC (ATCC #19686), cultured in tryptic soy broth overnight at 37°C, and diluted to $10^8$ CFUs per ml in PBS. One millilitre aliquots of these bacterial suspensions were stored at −80°C until used.

A six-jet Collison nebulizer (CN-25; BGI Inc., Waltham, MA, USA) located in the biologic safety cabinet in the antechamber was filled with 75 ml of PBS containing $2 \times 10^7$ CFU of either *B. atrophaeus* spores or *M. parafortuitum* stock. Filtered compressed air at 105 kPa was used to aerosolize the suspension through a 25 mm inner diameter stainless steel pipe and then through a spherical diffuser located in the center of the chamber at a height of 1.5 m. Sampling was carried out after operating conditions had remained constant for 40 min. At six ACH, assuming the air in the chamber was well mixed, we would expect to have reached >98% of steady-state conditions after 40 min.

Sampling was performed by drawing air from the center of the exhaust grille at a rate of 28.3 l/min through a 25 mm inner diameter stainless steel pipe leading to a N6 single-stage viable Andersen impactor (Thermo Fischer Scientific, Franklin, MA, USA), which was located in the biologic safety cabinet. During sampling, spores were deposited directly on the surface of a tryptic soy agar Petri dish. Samples of *B. atrophaeus* spores were incubated for 1 day at 37°C, and samples containing *M. parafortuitum* were incubated for 4 days at 37°C prior to counting colonies on each plate. Colony counts were adjusted to account for the likelihood that more than one organism had passed through the same hole (Macher, 1989). Five- and 3-min samples were taken in triplicate for UV 'on' and UV 'off', respectively. The bacterial suspension in the nebulizer was replaced with a fresh 75 ml bacterial suspension between UV 'on' and UV 'off' tests. The

order of the UV 'on' vs. UV 'off' experiments was randomized.

### Irradiance measurements

Eye-level UV irradiance measurements in the lower-room were taken using an International Light Technologies photometer (Model IL1400; International Light Technologies, Peabody, MA, USA) and sensor (Model SEL240) that responds to UV radiation in the range of 180–300 nm in order to evaluate potential human exposures. The floor of the chamber was divided into a grid, as specified in Figure 2, by five columns (labeled 1–5) and seven rows (labeled A–G). Thirty-five irradiance measurements, each separated from each other by 0.61 m, as indicated by circles in Figure 2, were taken to measure lower-room irradiance. The sensor with its face oriented vertically was attached to a tripod such that the center of the sensor's face was at a height of 1.73 m, which corresponds to the 95th percentile for male eye height in the USA (First et al., 2005). At each of the 35 measurement locations, the sensor was rotated 360° in the horizontal plane to determine the maximum irradiance reading, which was the value recorded. After maximum irradiances at all 35 locations were measured, this procedure was repeated twice to evaluate experimental error. In addition, in order to measure vertical irradiance, measurements were taken with the face of the sensor horizontal and facing upward at a height of 1.83 m, which corresponds to the 85th percentile for the top of the head of a man (CDC/NCHS, 2012).

### Vertical air speed

A Windsonic ultrasonic anemometer (Model 200-7000; Gill Instruments Ltd, Lymington, UK), which can measure air speed simultaneously in two perpendicular directions, was used to measure vertical air speed with and without the open-cell ceiling panels in place while the ceiling fan was operated. In order to collect vertical and horizontal airflow simultaneously, the anemometer was mounted with the face perpendicular to the floor on top of a tripod at a height of 1.83 m and centered at locations corresponding to columns 1, 3, 5 and rows A, C, E, G in Figure 2. At each location, the average velocity was measured for 1 min and logged digitally. After a full set of measurements were taken, the procedure was repeated two more times.

### Data analysis

The fraction of surviving organisms ($f$), which is defined by Equation 1, was calculated as:

$$f = \frac{C_{\mathrm{UV}}}{C_{\mathrm{noUV}}} \tag{1}$$

where $C_{\mathrm{UV}}$ is the concentration of culturable bacteria in CFUs from samples with the UV lamps turned on, and $C_{\mathrm{noUV}}$ is the concentration of CFUs from the matched test with UV lamps turned off. The deposition of particles on the surfaces of the chamber, the sampling apparatus, and the eggcrates or conventional fixtures would be the same for both UV 'on' and UV 'off' conditions; therefore, the relative losses are normalized through the use of the fraction of surviving organisms.

Under steady-state conditions with no removal or inactivation processes other than dilution ventilation with clean air, airborne viable pathogen concentration is inversely proportional to the air exchange rate in a well-mixed room. For example, if the air exchange rate is doubled, the viable pathogen concentration in the room will be reduced by half. If there is also an inactivation process such as upper-room UVGI, then the equivalent air exchange rate for this process can be defined as the additional increase in air exchange rate that would be necessary to obtain the same viable pathogen concentration without UVGI. For example, if the air exchange rate is six ACH and upper-room UVGI further reduced the viable pathogen concentration by a factor of four, an air exchange rate of 24 ACH would result in the same concentration. Thus, the equivalent air exchange rate attributable to upper-room UVGI would be 18 equivalent air changes per hour ($\mathrm{ACH_{UV}}$). This result can also be calculated from the following equation:

$$\lambda_{\mathrm{e}} = \frac{1-f}{f}\lambda \tag{2}$$

where $f$ is fraction surviving, $\lambda$ is air exchange rate, and $\lambda_{\mathrm{e}}$ is equivalent air exchange rate (First et al., 2007). For experiments performed in this study, $\lambda$ was maintained at six ACH.

For each operating condition, bioaerosol tests were performed in triplicate on three separate days and the mean and standard deviation of the fraction surviving were calculated. The minimum, maximum, median, 25th percentile, and 75th percentile, were analyzed to compare the lower-room irradiance in the chamber. Two-tailed, unpaired, Student's $t$-tests were used to determine statistical significance of differences of sample conditions.

## Results

### Germicidal efficacy

The percentage of *B. atrophaeus* spores inactivated by one conventional louvered UVGI fixture containing one-lamp was 12% (Figure 3a). When used in the

eggcrate UV configuration, a single-bare UV lamp, identical to the lamp in the conventional louvered fixture, resulted in a 62% inactivation of *B. atrophaeus* spores. The use of a two conventional fixtures resulted in inactivation of 37% of *B. atrophaeus* spores whereas two bare lamps in the eggcrate UV setup yielded an 82% inactivation of *B. atrophaeus* spores. The differences in the mean values of inactivation percentages are statistically significant ($P < 0.0005$) between conventional louvered fixtures and eggcrate UV.

As seen in Figure 3b, inactivation of *M. parafortuitum* was more effective than inactivation for *B. atrophaeus* spores. One conventional UVGI fixture inactivated 55% of *M. parafortuitum*, and two of these fixtures inactivated 63%. One- and two-lamp setups in the eggcrate UV system inactivated 84% and 91% of *M. parafortuitum*, respectively. The differences in the mean values were statistically significant ($P < 0.001$) between the conventional and eggcrate fixtures for each number of lamps.

Equivalent air exchange rates were calculated for each test condition based on Equation 2 and plotted in Figure 4. For *B. atrophaeus* spores, one conventional louvered fixture provided an air exchange rate of <1.0 $ACH_{UV}$ and two conventional louvered fixtures provided air exchange rates of 3.5 $ACH_{UV}$. In contrast, one UV lamp in the eggcrate UV configuration provided 10 $ACH_{UV}$ and the addition of a second lamp provided 26 $ACH_{UV}$. The equivalent air exchange rates of *B. atrophaeus* provided by the eggcrate UV were statistically significantly different ($P < 0.00005$) compared with equivalent air exchange rates provided by conventional UVGI. *Mycobacterium parafortuitum* spores were more susceptible to UVGI in both configurations. For *M. parafortuitum*, conventional upper-room UVGI fixtures resulted in 8 and 10 $ACH_{UV}$ for one and two fixtures, respectively, whereas the eggcrate UV configuration led to air exchange rates of 33 and 62 $ACH_{UV}$, respectively. These mean values were statistically significantly different ($P < 0.05$) compared with conventional and eggcrate UV for both single and double lamps.

### Vertical air velocity measurements

Without regard to whether the air flowed upward or downward, the average vertical air speeds with and without the eggcrate ceiling in place are shown in Table 1. The suspended ceiling reduced vertical airflow by 31% compared to without the suspended ceiling.

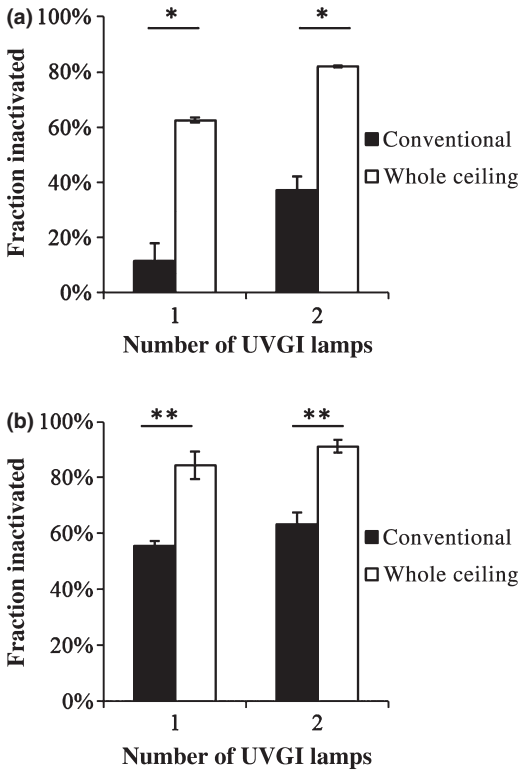


**Fig. 3** Germicidal efficacy of conventional fixtures and the eggcrate UV system at inactivating (a) *Bacillus atrophaeus* spores and (b) *Mycobacterium parafortuitum* in steady-state conditions. Error bars indicate standard deviations. *Indicates $P < 0.0005$. **Indicates $P < 0.001$

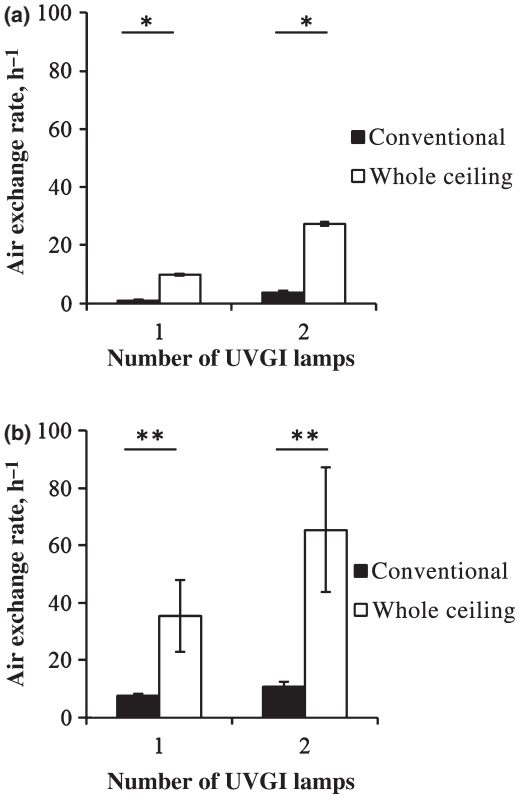


**Fig. 4** Equivalent air exchange rate provided by conventional fixtures and the eggcrate UV system for (a) *Bacillus atrophaeus* spores and (b) *Mycobacterium parafortuitum* at steady-state conditions. Error bars indicate standard deviations. *Indicates $P < 0.00005$, **Indicates $P < 0.05$

**Table 1** Vertical air speed with and without the open-cell-suspended ceiling installed

| Airflow movement | Without suspended ceiling | With suspended ceiling | Reduction due to suspended ceiling |
|---|---|---|---|
| Average vertical airflow (±standard deviation) | 0.26 (±0.18) m/s | 0.18 (±0.14) m/s | 31% |

However, due to the high variability of the airflow rate at different points throughout the room, the overall difference in airflow rate due to the addition of the suspended ceiling was not statistically significant ($P = 0.23$).

### Irradiance in the lower-room

Horizontal irradiance at a height of 1.73 m (5′8″) was measured to estimate the exposure of the cornea to UV. As seen in Figure 5, one and two conventional louvered fixtures resulted in a median irradiance in the lower-room of 0.05 and 0.1 $\mu$W/cm$^2$, respectively. The eggcrate UV system allowed significantly more UV into the lower-room resulting in median horizontal irradiance of 0.22 and 0.27 $\mu$W/cm$^2$ for one and two-lamps, respectively. Individual 'hot spots' of horizontal irradiance higher than the 75th percentile of the overall measurements can be seen as whiskers in the one-lamp and two-lamp setups of conventional louvered and eggcrate UVGI. Maximum horizontal irradiance was equal to or <0.4 $\mu$W/cm$^2$ for both conventional louvered fixtures and eggcrate UVGI. The irradiances are only slightly higher for the whole ceiling UVGI fixtures.

Vertical irradiance measurements were taken to estimate the potential exposure to the skin on the top of a 6′0″ (1.83 m) tall person's head. The median irradiance for one conventional louvered fixture was 0.07 $\mu$W/cm$^2$. The use of two conventional louvered fixtures resulted in median vertical irradiance of 0.09 $\mu$W/cm$^2$. In contrast, median vertical irradiance was significantly higher for a one-lamp eggcrate UV setup, 0.34 $\mu$W/cm$^2$, and for two-lamp eggcrate UV configuration, 1.07 $\mu$W/cm$^2$. Maximum vertical irradiance was 0.14 and 0.17 $\mu$W/cm$^2$ for one and two conventional fixtures, respectively, while one- and two-lamp eggcrate UV systems resulted in 1.5 and 1.8 $\mu$W/cm$^2$ for all fixtures. Eggcrate UV fixtures also had a wider irradiance distribution, as noted by larger boxes and whiskers in Figure 5, than did the conventional fixtures.

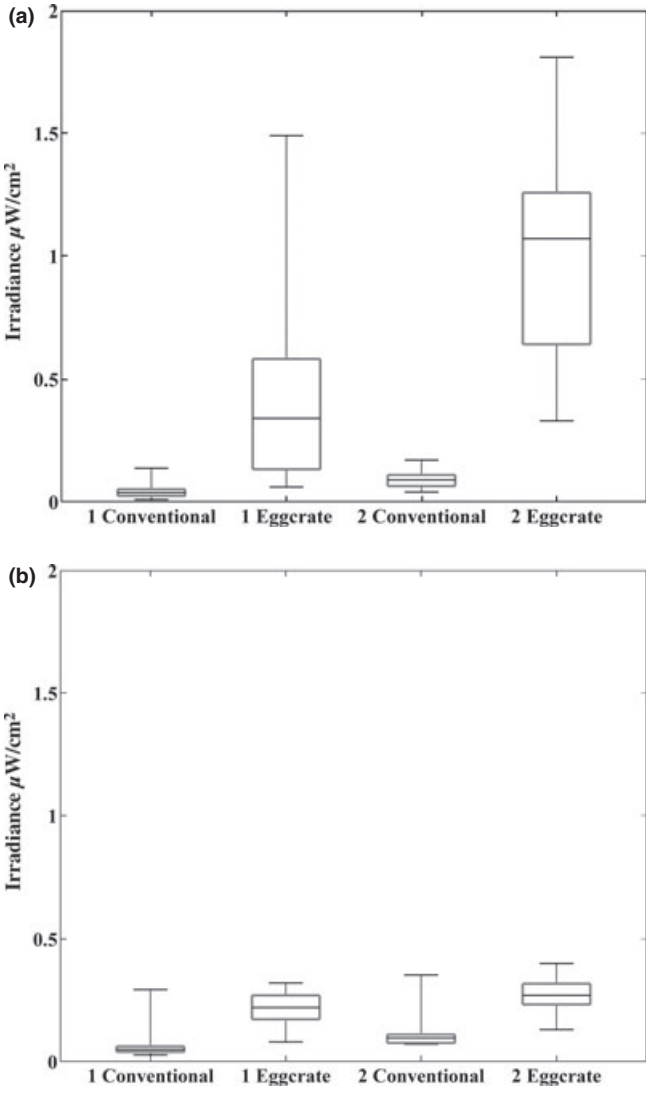


**Fig. 5** Lower room irradiance of conventional fixtures and of eggcrate UV for (a) vertical and (b) horizontal measurements. Boxplots show the 25th and 75th percentile as the box boundaries with the middle line indicating the median (50th percentile) measurement value. Minimum and maximum values are marked by the whiskers

## Discussion

Crowded conditions in hospitals, clinics, shelters, and prisons can strongly favor transmission of TB and other airborne infections, especially in lower- and middle-income countries with limited resources for infrastructure and infection control. UVGI fixtures can provide effective room air disinfection at low cost relative to ventilation and air filtration and can be an ideal technology for use in building renovations in resource-limited settings. This technology is also well-suited to complement natural ventilation, taking over when windows are closed or there is no wind. The eggcrate UV system has the advantage of greater efficacy per UV lamp than a conventional fixture while maintaining safety in the occupied portion of the room. Eggcrate UV has flexible installation requirements including strategic lamp placement, the ability to limit UV in the lower-room simply by adding multiple panels surrounding the fixture, and the availability of off-the-shelf components to build the system. Thus,

eggcrate UV enables adaptable, safe, and potentially more effective infection control in occupied rooms.

Using two-lamps in the eggcrate UV system, we demonstrated that this simple method of bacterial inactivation can achieve an 82% reduction in *B. atrophaeus* spores and 90% reduction in *M. parafortuitum* in our experimental chamber. In contrast, the two conventional UVGI fixtures were capable of reducing the percentage of *B. atrophaeus* spores and *M. parafortuitum* bacteria by only 37% and 63%, respectively. Previous steady-state experiments performed in the chamber using a total of six conventional UVGI fixtures resulted in a 67% reduction in *B. atrophaeus* (First et al., 2007). This is similar to the 62% efficacy of the one-lamp eggcrate UVGI system used herein. However, the current eggcrate UV setup required only 26 W of electrical energy input into the lamp while the study by First et al. required 216 W of electrical energy input into the lamps to achieve comparable reductions. While these experiments were performed in the same chamber, using the same fixture models, the current study included a larger fan (1.3 m vs. 1.2 m diameter) with rotation in the opposite direction (up vs. down used previously). Nonetheless, the present results show that one-lamp in the eggcrate UV system was nearly as effective against *B. atrophaeus* as using six conventional UVGI fixtures.

In this study, we used the components from identical conventional UVGI lamps to build the prototypes for the eggcrate UV system in both the one and two-lamp setups. By doing so, we were able to minimize experimental differences between tests using conventional upper-room UVGI fixtures and tests using eggcrate UVGI. The use of one-lamp in the eggcrate UV system provided an additional 9 and 27 ACH for *M. parafortuitum* and *B. atrophaeus,* respectively, compared with one conventional UVGI fixture. These improvements were entirely due to the change in setup rather than to any potential differences in lamp UV output caused by type or other variability between lamps and ballasts. The addition of a second lamp in the eggcrate UV system further improved the pathogen inactivation. We calculated that the eggcrate UV system with two UV lamps achieves efficiencies equivalent to an air exchange rate of 65 ACH provided by mechanical ventilation systems against *M. parafortuitum*. In contrast, with two conventional fixtures using the same UVGI lamps and ballasts, the equivalent of only 10 ACH were obtained in the corresponding *M. parafortuitum* tests. Even with the notoriously difficult to kill *B. atrophaeus* spores, the 27 $ACH_{UV}$ achieved with two UVGI lamps in the eggcrate UV system far exceeded recommended guidelines (12 ACH) for hospital wards and isolation rooms designed to prevent airborne disease transmission (Kowalski, 2009; Siegel et al., 2007). In contrast, natural and mechanical ventilation systems operating at these efficacies could cause extreme discomfort due to both excessive noise and airflow. *Mycobacterium parafortuitum* was chosen as a surrogate for *Mycobacterium tuberculosis* based on in their UV susceptibility (NIOSH, 2009). *Bacillus atrophaeus* (also known as *Bacillus subtilus* var. niger) spores were chosen for their stability in the environment and resistance to degradation in addition to being a common surrogate for *Bacillus anthracis* spores. Based on previously published UVGI susceptibility parameters, we would expect eggcrate UV to be similarly effective against other relevant airborne pathogens such as influenza (Brickner et al., 2003; Kowalski et al., 2000; McDevitt et al., 2012).

Because adequate vertical air circulation is crucial for upper-room UVGI, the overall reduction in air movement caused by the open-cell ceiling panels was determined by comparing vertical air speed with and without the suspended ceiling. While vertical air speed was reduced by the ceiling panels in the eggcrate UV system by 31%, the use of the ceiling fan provided sufficient air exchange as reflected by the air disinfection achieved. In our experimental chamber, both the supply and the exhaust air ducts are located in the lower-room, allowing for the potential for a 'short circuit' with air circumventing the UVGI in the upper-room if vertical airflow is not sufficient. However, as both the aerosol generation and the sampling locations were also in the lower-room, it is clear that the whole ceiling UVGI system adequately circulated air between the lower- and upper-rooms for substantial inactivation of the bacteria. It is probably more common for rooms to have supply air entering through the ceiling and contaminated air exhausted from wall or floor locations. It is unknown how these variations would affect UVGI efficacy.

Although the risks of upper-room UVGI are relatively minor compared with the risk of airborne infections such as multidrug resistant TB, the safety and comfort of room occupants are essential to the successful application of this intervention. Based on a previously published study monitoring exposure of room occupants, we made the very conservative assumption that eye exposure at peak irradiance is no more than 4 h in an 8-h period (First et al., 2007). This results in an eye-level irradiance limit of 0.4 $\mu W/cm^2$ for an 8-h period of proximate exposure; equivalent to the current South African guidelines for the application of upper-room UVGI (MRC, 1999). In some instances, the initial simulated corneal exposure was $>0.4$ $\mu W/cm^2$ (data not shown). To determine whether this irradiance could be reduced, an additional layer of eggcrate panels was placed at locations immediately surrounding the fixtures. The addition of these panels was sufficient to render the lower-room intensities equal to, or less than, the 0.4 $\mu W/cm^2$ target as shown in Figure 5a. Measurements taken in

the horizontal plane at 1.73 m height simulated the corneal exposure to UV irradiance of an occupant in the lower-room. However, the cornea's realistic exposure to UV is likely much less than the lower-room measurements taken by the UV sensor. A cornea receives exposure from light incident on the eye socket at an angle of only 80° or less (ACGIH, 2010), while light sensors collect irradiance measurements from all rays at angles <180°. Based on the conservative measurements made in this study, the horizontal UVGI emitted into the lower-room in the whole ceiling setup is not expected to cause corneal irritation to individuals who are not looking directly at the ceiling for extended periods.

We also took irradiance measurements vertically to estimate the skin's exposure to UV on the top of the head. The maximum UV during irradiance for 35 measurement locations within the room was between 0.1 and 1.8 $\mu W/cm^2$. The skin's UV exposure limits in a very lightly pigmented person is 21 $mJ/cm^2$, or 0.7 $\mu W/cm^2$ for a continuous 8-h period (Hawk and Parrish, 1982) suggesting that, in certain locations of the room in the whole ceiling setup, prolonged exposure of the skin could be a problem. However, these high irradiances can be reduced in future optimization of this approach, such as by angled eggcrate panels above the specific 'hot spots' in the lower-room. Another approach might be wall mounted louver-less UVGI fixtures with parabolic reflectors directing the UV in a more horizontal direction. Logically, the vertical irradiance in the whole ceiling setup is expected to be higher than a conventional UVGI lamp. The purpose of the whole ceiling system is to collimate light escaping the upper-room vertically to limit corneal exposure of standing or sitting individuals. In contrast, conventional fixtures use louvers to specifically collimate light in the horizontal direction and direct it into the upper-room. In hospital patient rooms and other locations where occupants might be expected to look up toward the ceiling for long periods of time, adaptations such as 45° angled eggcrate panels could be introduced above the patient beds to limit corneal exposure to UV. Further studies to determine ideal locations of UV lamps, effects of angled eggcrate panels, and consideration of potential occupant locations will need to be carried out to minimize the opportunity for overexposure.

In all upper-room UVGI applications, levels of UV in the lower-room are dependent on reflectivity of room surfaces. Thus, the lower-room UV irradiances measured in our experiments are, at best, a site-specific indication of safety. Covering the surfaces above the eggcrate panels with low-UV reflective paint would likely reduce lower-room irradiance. This would allow for an increase in the number and/or power of UV lamps that can be used above the open-cell panels without increasing lower-room UV, thereby increasing efficacy.

The eggcrate UV system presented herein yields highly effective bacterial inactivation using an easily adapted setup of off-the-shelf components. The system also allows for simple adjustments to lower-room irradiance by altering both the layout of the open-cell panels surrounding the UV lamp and the location of the UV lamp itself. In this study, two panels were stacked on top of one another and aligned using pressure sensitive adhesive. During commissioning, two or more open-cell tiles can be stacked on top of one another, either aligned or offset, to achieve the desired lower-room irradiance. This type of adjustment is not possible with conventional upper-room fixtures except through the use of a potentiometer that also drastically reduces the total upper-room UV fluence rate as well.

Although upper-room UVGI has been used for over 60 years, and conventional wall and suspended fixtures have incrementally improved over the years, this work is the first major advance in its application. Ease of installation and availability of such simple upper-room UVGI systems will be essential to airborne infection control in resource-limited settings. Eggcrate UV can provide more than the recommended air exchange rate for hospital settings and can augment both mechanical and natural ventilation systems. Further investigations will be required to ensure the appropriate use of this intervention in variable room and occupancy formats. These include the examination of efficacy at lower ceiling heights that reduce the volume of the upper-room irradiated by the UV lamps, the use of a greater number of lower-powered UVGI lamps (including, light-emitting diode, sources) to reach the same UV irradiance in the upper-room and the optimization of open-cell panels (deeper or wider openings, eggcrates angled at 45 degrees to redirect UV, etc.) to further reduce UV irradiance in the lower-room. Determining the optimal balance between efficacy and UV levels in the lower-room is necessary to allow for a system that has the greatest pathogen reduction while protecting occupants. The eggcrate UV system is a promising new method that has the potential to advance infection control of airborne disease by providing efficient, economical in-room air disinfection.

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