



# A design for a more efficient, upper room germicidal ultraviolet air disinfection luminaire

S Milonova MS<sup>a</sup>, HM Brandston Hon DFA<sup>b</sup>, S Rudnick DSc<sup>a</sup>, P Ngai MS<sup>c</sup>, K Simonson MS<sup>b</sup>, SF Rahman BS<sup>a</sup> and E Nardell MD<sup>a,d,e</sup>

<sup>a</sup>Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, MA, USA

<sup>b</sup>Independent Lighting Designer, Hollowville, NY, USA

<sup>c</sup>Acuity Brands Lighting, Atlanta, GE, USA

<sup>d</sup>Division of Global Health Equity, Brigham and Women's Hospital, Boston, MA, USA

<sup>e</sup>Department of Medicine, Harvard Medical School, Boston, MA, USA

Received 19 November 2016; Revised 1 April 2017; Accepted 1 May 2017

This paper describes a novel optical design principle for an upper room germicidal ultraviolet luminaire developed to limit the transmission of airborne diseases, particularly tuberculosis. A prototype was built to demonstrate the principle, and tests were conducted to determine its total ultraviolet (UV)-C output, biological effectiveness, and safety for lower room occupants. The prototype outperformed frequently used luminaires in total UV-C output, luminaire efficiency, and biological effectiveness against aerosolised *Mycobacterium*, while remaining safe for lower room occupants. The results presented here suggest that the design principle is ready for real-world application to mitigate the spread of airborne infectious diseases.

## 1. Introduction

Tuberculosis (TB) has recently surpassed the human immunodeficiency virus as the leading cause of death brought on by a single infectious agent. In 2015, approximately 10.4 million people developed TB, and an estimated 1.4 million people died as a result of the disease.<sup>1</sup> TB infection can occur when a susceptible person inhales respiratory droplet nuclei containing any of the *Mycobacterium* species in the *Mycobacterium tuberculosis* complex. These droplet nuclei, which result from the evaporation of water from

respiratory droplets exhaled by an infected individual, are so small that they are carried on air currents instead of settling out.<sup>2</sup>

Environmental controls to reduce the airborne concentration of infectious droplet nuclei in crowded areas are a critical part of TB infection control.<sup>3</sup> When combined with a ceiling fan to facilitate air mixing, upper room germicidal ultraviolet (GUV) irradiation is one of the simplest and most cost-effective method to reduce the risks of TB exposure in resource-limited countries, in part because it does not require structural changes to a room or building.<sup>4</sup> This paper describes a novel GUV luminaire design principle and tests a prototype luminaire for use as an environmental control to mitigate the spread of airborne infectious diseases.

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Address for correspondence: S Milonova, 73 Pembroke Woods Drive, Pembroke, MA 02359-4862, USA.  
E-mail: sonya.milonova@gmail.com

## 2. Background

### 2.1 History

It has been known since the mid-1800s that microorganisms respond to light.<sup>5</sup> In a revolutionary breakthrough in 1877, TP Blunt and Arthur Downes<sup>6</sup> proclaimed that '*light is inimical to the development of bacteria*' after discovering that sunlight could inactivate bacteria in test tubes and keep the tubes microbe-free for months at a time. About a decade later, microbiologist Robert Koch performed a series of experiments that showed that sunlight could inactivate tuberculosis-causing bacteria.<sup>5</sup> Then, in 1935, Wells and Fair<sup>7</sup> showed that 254 nm radiation could rapidly inactivate aerosolised *Bacillus coli*, which was the first time ultraviolet (UV) radiation was used to inactivate bacteria in air rather than liquid. These discoveries paved the way for today's use of GUV to reduce the spread of TB and other airborne diseases.

Currently, GUV is produced by mercury vapour arc lamps emitting predominantly 253.7 nm UV-C. Compared to other forms of UV radiation, which can cause skin cancer and permanent eye damage, GUV is minimally dangerous to humans. Because UV-C rays have shallow penetration depths, overexposure causes damage just to the outermost layer of the cornea and to the outer, dead layer of skin. GUV overexposure, therefore, causes only transitory side effects such as photokeratitis and erythema, which have no long-term consequences, and are rapidly repaired through normal cell turnover.<sup>8</sup>

### 2.2 Upper room GUV

Upper room GUV confines the germicidal radiation to the space above the room's occupants with specially designed luminaires. Upper room GUV is considered more effective than using GUV in ducts because microorganisms are inactivated in the occupied room soon after they are emitted by travelling upward with warm air currents.<sup>4</sup> These

systems depend on adequate air movement from the contaminated lower room into the irradiated zone, which can be accomplished with paddle fans or, less reliably, by natural convection.<sup>9</sup>

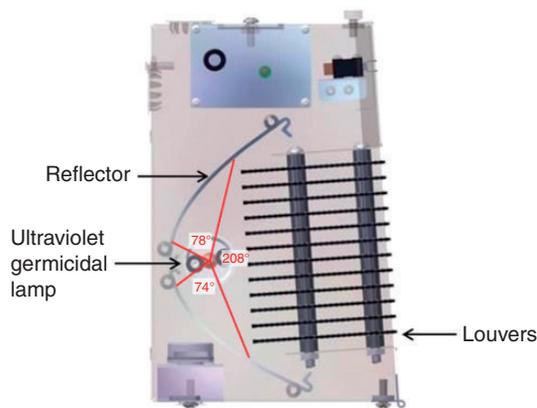
Upper room GUV luminaires are designed to accommodate a wide variety of room sizes, shapes, and ceiling heights. However, low ceilings present a challenge for the use of upper room GUV because of UV-C reflection into the lower room and because the smaller volume of the irradiated zone will result in a less effective system. A minimum ceiling height of 2.4 m (8 ft) is typically recommended for commercially available luminaires,<sup>10</sup> but in rooms with lower ceilings, customised luminaires can be installed to ensure occupant safety.

Multiple, nearly horizontal, tightly spaced, flat-black louvres are often used to limit reflection emanation into the lower room, thus protecting occupants from overexposure to UV-C. Louvres allow only predominantly horizontal rays to pass, which dramatically decreases the efficiency of upper room GUV systems by absorbing the majority of the total UV-C rays emitted by the lamps.<sup>11</sup> However, for all but the tallest rooms, louvres are considered necessary to protect occupants.

## 3. Design

The most common GUV luminaires available today are either ceiling- or wall-mounted enclosures, ideally including a parabolic reflector to redirect the UV-C radiation from the back of tubular germicidal lamps into the upper room, as shown in Figure 1.

The most important factor to consider when evaluating the performance of an upper room GUV luminaire is the total UV-C output, which will determine the luminaire's efficacy against airborne microorganisms.<sup>12</sup> The UV-C output from the luminaire is significantly less than the lamp output due to the design of the luminaire,



**Figure 1.** A side view drawing of a wall-mounted Atlantic Ultraviolet Hygeaire luminaire, Model LIND 24-EVO (Hauppauge, NY), with a parabolic reflector to direct UV rays out at a slightly upward angle, and louvers to block rays that are not parallel to the louvres. The lines indicate the estimated reflected component ( $152^\circ$  out of  $360^\circ$ ) and the direct component ( $208^\circ$  out of  $360^\circ$ ).

particularly the louvres, resulting in a lower luminaire efficiency. Luminaire efficiency is defined as the fraction of the lamp's UV emission emitted by the luminaire.<sup>13</sup> With a conventional wall-mounted design (Figure 1), a reflector wraps partially around the UV-C emitting tube and redirects a portion of the UV-C radiation from the back of the lamp through the louvres as a collimated beam. This is called the 'reflected component' (RC). The RC rays pass through the luminaire relatively unimpeded, because the parallel louvres are aligned to minimise their interference to the RC beam. The remaining, non-reflected portion of UV-C source radiation, called the 'direct component' (DC), radiates outward from the front of the lamp at diverging angles and is mostly not captured by the reflector; much of it is absorbed by the louvres and never exits the fixture. We can roughly estimate the RC and DC of the fixture pictured in Figure 1 by measuring the angles from the centre of the lamp to the edge of the reflectors in a side view drawing. This estimate is based on the assumptions that rays

are uniformly emitted from the surface of the lamp and exit perpendicular to the surface. In the Atlantic Ultraviolet Hygeaire wall luminaire pictured in Figure 1, the reflectors catch and redirect UV-C rays from less than half of the lamp ( $152^\circ$  out of  $360^\circ$ ). It is clear that the majority of DC rays, which make up 58% of the total coming out of the lamp ( $208^\circ$  out of  $360^\circ$ ), will not make it through the louvres, which are 78 mm wide, spaced 6.5 mm apart, and tilted  $4^\circ$  upward. The louver system intentionally obstructs most of the oblique DC rays to protect room occupants. The DC is not controlled by the reflector and is mostly wasted, diminishing the UV-C emission and the efficiency of the GUV luminaire.

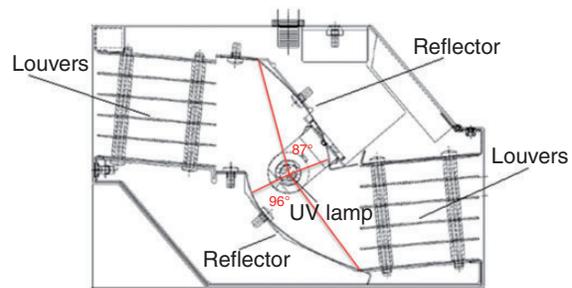
Because of these limitations, the wall-mounted design described above is not the most efficient way to irradiate the upper room. However, the luminaire illustrated in Figure 1 is a more efficient design than many other GUV luminaires that do not use reflectors at all. For example, some pendant mounted models, designed to emit UV-C uniformly in all directions in one plane, employ multiple compact UV-C lamps mounted vertically without reflectors. Although the folded-over lamps keep the luminaire's vertical profile to a minimum, the design means that all of the emitted UV-C radiation is uncontrolled DC, introducing greater UV-C absorption and reducing UV-C output. To our knowledge, there are no pendant luminaires that utilise reflectors, except the pendant luminaire produced by Atlantic, which actually consists of two wall fixtures back to back. The configuration may be advantageous for certain rooms, but because the optics are identical, it does not solve the problems inherent in the design.

A parabolic reflector on only one side of a UV-C lamp cannot capture all of the radiation emitted by the germicidal lamp, but it is the best current design for a wall luminaire. However, a luminaire suspended from the ceiling and located away from a wall can

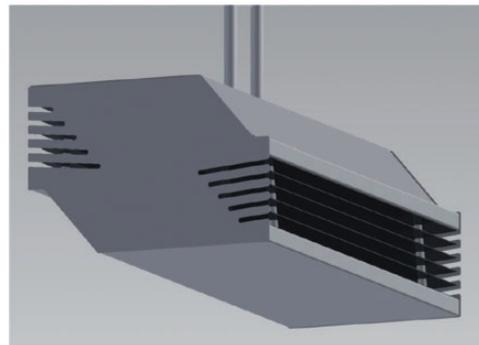
be a more effective design if the DC is limited with multiple well-positioned reflectors. To test this principle, Howard Brandston designed a novel fixture that wraps two half-parabolic reflectors around a linear UV-C source to capture approximately  $183^\circ$  of radiation, taking into consideration the part of the reflectors blocked by the lamp itself (Figure 2). The double-reflector redirects UV-C rays in opposing directions across a room or down a corridor. By increasing the RC, the new unit decreases oblique DC rays and, in theory, requires fewer louvres. Reducing the number of louvres decreases UV-C radiation obstruction and increases luminaire efficiency, as well as lowering manufacturing costs.

The prototype (Figures 2 and 3) is designed to be mounted in the centre of a corridor or rectangular room and aimed along the long axis of the space, so that the two opposite UV-C beams travel roughly half the room length to wall surfaces. The average ray length – the distance the UV-C ray travels before hitting the wall or ceiling – is therefore shorter than that of the single, long beam produced by a unidirectional fixture mounted on a wall at one side of a room. Since UV-C rays are mostly absorbed upon impacting a wall or ceiling (except for a small amount that is reflected), maximising the average ray length is ideal, but this is difficult to do without increasing the DC. By centrally mounting a luminaire that produces a higher UV-C output, the lethal effect of UV-C radiation upon airborne microorganisms may be increased even though the average ray length is decreased.

A prototype was built with sheet aluminium, a Philips TUV 25 W G25T8 tubular lamp, and an electronic ballast. The dimensions of the prototype are 46.0 cm long, 24.1 cm wide and 16.0 cm high (18.1" long, 9.5" wide and 6.3" high). A dielectric film stack was applied to the aluminium reflectors to improve their UV response; they are



**Figure 2.** Drawing of the novel prototype showing the lamp, reflectors, and louvres, with lines indicating the reflected component ( $183^\circ$  out of  $360^\circ$ ).



**Figure 3.** Rendering of the prototype showing one of the louvred faces, side slits, and the end view.

spectrally selective and non-absorbing in the UV-C band, relying on a combination of interference and absorption effects to suppress longer wavelengths. The louvres, which are 74.75 mm wide, were tilted  $5.5^\circ$  upward towards the ceiling and spaced 13 mm apart.

#### 4. Testing

A series of tests was conducted to compare the prototype luminaire to current designs. It was primarily compared with an Atlantic Ultraviolet Hygeaire luminaire, Model LIND 24-EVO, which is detailed in the

previous section. The Atlantic Hygeaire is one of the most efficient commercial GUV luminaires currently available for which luminaire output and lower room safety results have been published.<sup>14</sup>

#### 4.1 Total output

The total UV-C luminaire output of the prototype luminaire was measured and compared to other GUV luminaires with different designs. The protocol had been previously developed and validated to measure upper room louvred GUV luminaires.<sup>15</sup> A model P9710-1 optometer and a model UV-3718-2 UV-C detector were used to measure the UV-C output of the new luminaire. The prototype has two large louvred faces that each has an area of 259 cm<sup>2</sup>. To provide a grid for irradiance measurements, each face was divided into 11 mm<sup>2</sup> segments (the diameter of the sensing window) and these were marked as the measurement locations. The sensor was moved along the face of the luminaire, recording irradiance at each location. The average irradiance for each face was multiplied by its area in order to get the power in watts.

In addition to the two louvred faces, there are slits on either side of each face of the luminaire (Figure 3). The area of the slits is relatively small compared to the openings between louvres, and the UV-C radiation emitted from the side slits was negligible compared to the radiation emitted from the louvred faces.

The UV-C emission of the two faces was summed to obtain the total UV-C power of the luminaire. This measurement was repeated three times and averaged.

#### 4.2 Photometric tests

A photometric test was performed on the prototype using a 15 W T8 linear fluorescent lamp rated at 1000 lumens. The moving mirror photometer method that was used is detailed elsewhere<sup>16</sup> and is based on the

Illuminating Engineering Society of North America testing standards for industrial and commercial lighting applications. The output at various angle ranges was determined by measuring both apertures and averaging the results. A computer-simulated estimation of a photometric test was also done in a program called Photopia,<sup>17</sup> using both a T5 and a T8 linear fluorescent lamp.

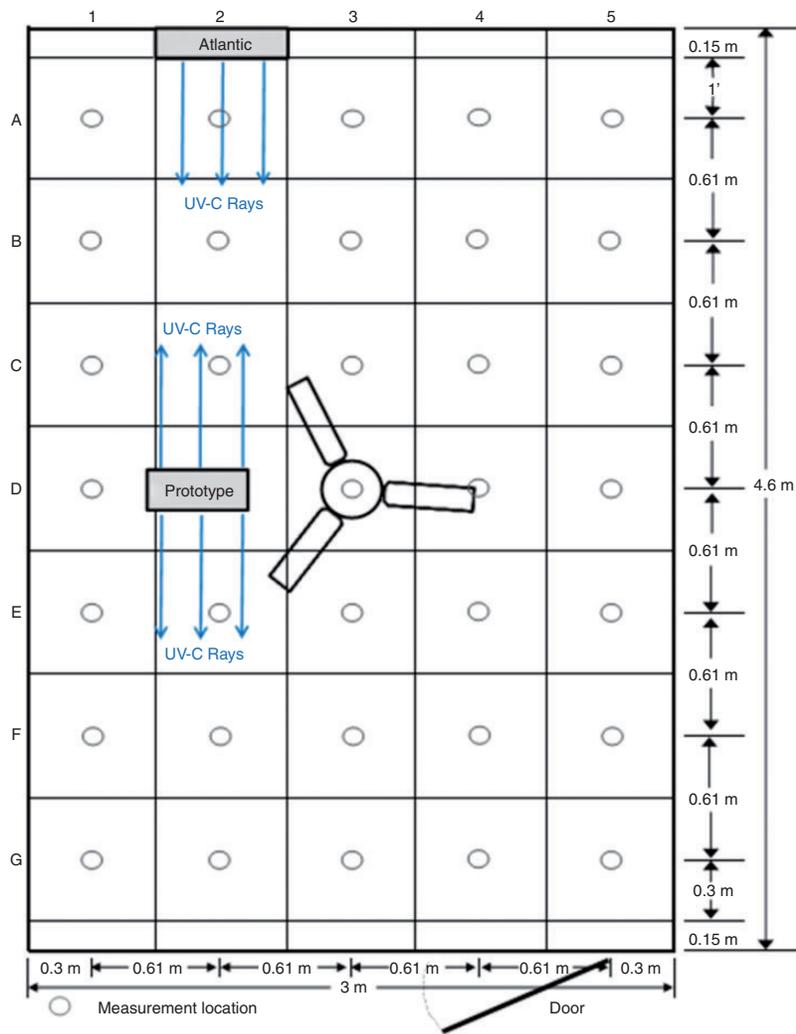
#### 4.3 Biological testing

In order to determine the germicidal efficacy of the prototype luminaire, biological tests were performed in an experimental chamber at the Harvard School of Public Health. In past years, this chamber has been used for extensive testing on common GUV luminaires.<sup>11,18,19</sup> The new fixture was compared to the Atlantic Hygeaire luminaire.

##### 4.3.1 Experimental chamber

Experimental tests were conducted in a room-size chamber that has a 3.0 m by 4.6 m floor and a 3.0 m high ceiling. All aerosolisation and sampling was done in a Class II biosafety cabinet located in an adjacent anteroom as described elsewhere.<sup>11</sup> The chamber is equipped with a heating, ventilation, and air conditioning system. The air exchange rate was maintained at six air changes per hour (ACH) for all tests.

The prototype luminaire was mounted between 1D and 2D (Figure 4), with the bottom of the luminaire at a height of 2.5 m (8.2 ft). The Atlantic luminaire was mounted on the wall of the experimental chamber at location 2 A with the bottom of the luminaire at a height of 2.4 m (8 ft). A ceiling fan with three 0.61 m (2 ft) blades (modified Haiku fan with shortened blades and a narrower chord, Big Ass Fans, Lexington, KY, USA) was mounted in the centre of the ceiling, with the tips of the blades at a height of approximately 2.8 m (9.2 ft). It was set to the highest speed of 231 r/min for all tests.



**Figure 4.** Tests were conducted in 3.0 m by 4.6 m chamber with 3.0 m high ceiling and a central ceiling fan. Circles indicate locations of lower room irradiance measurements.

Although it would be ideal to centre both luminaires, it was not possible to centre the prototype luminaire because of the location of the fan. Both luminaires were therefore offset slightly, as seen in Figure 4. The two luminaires were tested one at a time – the prototype was removed for testing of the Atlantic luminaire, and the Atlantic luminaire was covered during testing of the prototype.

#### 4.3.2 Bioaerosol tests

A liquid suspension of *Mycobacterium parafortuitum*, a *M. tuberculosis* surrogate, was aerosolised for all experiments. The suspension was diluted to a concentration of  $10^8$  colony-forming units (CFUs) per mL in phosphate-buffered saline solution (Lonza Group, Rockland, ME, USA), and was stored as 1 mL aliquots at  $-80^{\circ}\text{C}$  until used.

The procedure for aerosolising bacteria and collecting samples is detailed elsewhere.<sup>19</sup> For each trial, triplicate UV-C ‘on’ and UV-C ‘off’ samples were collected. Seven trials of the experiment were performed with the prototype, and four trials with the Atlantic Hygeaire fixture. The fraction of surviving bacteria was calculated as follows:

$$f = C_{UV} / C_{noUV} \quad (1)$$

where  $C_{UV}$  is the concentration of culturable bacteria in CFUs from samples with the UV-C lamps turned on, and  $C_{noUV}$  is the concentration of CFUs from the matched tests with UV-C lamps turned off.

#### 4.4 Lower room measurements

In order to assess the safety of room occupants, we measured the irradiance levels in the lower room while the prototype luminaire was operating. The American Conference of Governmental Industrial Hygienists<sup>20</sup> has established a threshold limit value (TLV) – the dose to which a worker can be exposed 8 hours a day, 40 hours per week for a working lifetime without adverse health effects – as a guideline for avoiding skin and eye injuries. For 254 nm, the primary wavelength that low-pressure mercury lamps emit, the dose limit is 6.0 mJ/cm<sup>2</sup>. Thus, a worker can be exposed to an irradiance of 60 mW/cm<sup>2</sup> for 0.1 second or to 0.2 μW/cm<sup>2</sup> for 8 hours, assuming continuous exposure. Using spot measurements to approximate exposure without knowing how occupants will move within the space is not accurate, as has been shown by a personal monitoring study where the 8-hour dose was a small fraction of the TLV even when areas contained higher irradiances than 0.2 μW/cm<sup>2</sup>.<sup>21</sup> However, using spot measurements is acceptable for the purpose of comparing the prototype to the Atlantic fixture, which has been safely used for years.<sup>22</sup>

Lower room irradiance measurements were done in the same chamber where the biological experiments were performed. Vinyl tiles cover the floor of the chamber, while a pebbled, hard-finish white plastic wallboard covers the four walls and the ceiling. The wallboard’s reflectivity was measured to be less than 10% at 254 nm.<sup>14</sup> A grid was created on the floor of the chamber, specified by five columns labelled 1–5 and seven rows labelled A–G (Figure 4).

Measurements were made using a GigaHertz-Optik model P-9710-1 optometer and a model UV 3718-2 flat UV-C sensor. The sensor was attached to a tripod so that the face of the sensor was vertical and the centre of the sensor was at a height of 1.73 m (5’8”), which simulated a standing person looking straight ahead. This height was used in adherence to previously published studies and corresponds to the 95th percentile for male eye height in the USA.<sup>19,21</sup> For each measurement, the sensor was rotated 360°, while always keeping the face vertical, in order to find the maximum irradiance at each point. Irradiance measurements were taken at 35 locations, indicated by circles in Figure 4. In order to calculate measurement error, the procedure was performed three times for each fixture. Each fixture was mounted in the same location as for the biological tests.

## 5. Results and discussion

### 5.1 Total output

The prototype GUV luminaire has a total UV-C output of 0.765 W (standard deviation of 0.0651 W). For comparison, Table 1 shows results of three other well-known luminaires that were measured using the same method, as detailed elsewhere.<sup>15</sup> The Atlantic Hygeaire, one of the best commercial GUV fixtures currently available,<sup>14</sup> is the easiest to compare because it also contains a 25 W lamp (05-1348-R Ster-L-Ray Germicidal lamp).

The total UV-C output allows us to calculate the efficiency of the fixture (Table 1). The luminaire UV-C efficiency is defined as the ratio of the fixture UV-C output to the lamp UV-C output.<sup>13</sup> Because of its higher UV-C output, the prototype has a fixture efficiency of 10.9%, almost double the efficiency of the Atlantic unit of 5.54%. The other two luminaires, a pendant and a corner luminaire, have even lower efficiencies than the Atlantic luminaire, with luminaire efficiencies of 2.38% and 1.22% for the pendant and corner luminaires, respectively.

Although there are many other GUV luminaires commercially available, manufacturers are not required to report the luminaire UV-C output, so it is difficult to make comparisons to all GUV luminaires. Lamp output is often reported, but as explained in the Design section, this does not help determine the luminaire efficiency.

Because more UV-C radiation is captured and reflected in the prototype luminaire than in the other luminaires, efficiency is almost two times higher than the second-most efficient luminaire. The reflectors control more of the radiation, which means fewer louvres are required to absorb the stray rays. However, with fewer louvres, the DC rays may increase lower room UV-C levels, and measurements must still be taken to ensure occupant safety.

### 5.2 Photometric tests

The results of the photometric tests are shown in Table 2. The number of lumens, as well as the percent of total output that the luminaire emits, is shown over various angle ranges, where 0° represents the vertical plumb-line from the bottom of the luminaire, and 90° runs parallel to the floor. The output below the luminaire, from 0–90°, should be minimised to ensure occupant safety, while the output from 90–110°, the range where the rays are designed to emit, should be maximised.

The output in the 0–90° range is high, but most of it occurs at higher angles (60–90°). The majority of the output (71.6%) is in the desirable range of 90–100°. Because UV-C rays from the prototype luminaire, which is designed to be mounted in the centre of the room, only need to travel half the distance,

**Table 2** The photometric results show the number of lumens as well as the percent of total output emitted over various angle ranges, where 0° represents the vertical plumb-line from the bottom of the luminaire, and 90° runs parallel to the floor.

	Prototype luminaire
Luminaire output normalised	1000 lumens
Luminaire efficiency	11.8%
Total light output	118 lumens
Output at 0–90°	20.3 lumens (17.2%)
Output at 60–90°	20.1 lumens (17.0%)
Output at 90–100°	84.5 lumens (71.6%)
Output at 100–110°	11.2 lumens (9.5%)
Output at 110–180° (by difference)	2.0 lumens (1.7%)

**Table 1** Luminaire efficiency of the prototype luminaire compared to other GUV luminaires.

Source type	Lamp UV-C output <sup>a</sup>	Luminaire UV-C output	Luminaire UV-C efficiency (luminaire output/lamp UV-C output)
Prototype luminaire	7 W	0.765 W	10.9%
Atlantic Hygeaire	8.5 W	0.471 W	5.54%
Lumalier pendant	22 W	0.523 W	2.38%
Lumalier corner	11 W	0.134 W	1.22%

UV: ultraviolet.

<sup>a</sup>as reported by manufacturer.

they do not have to be as tightly controlled as those of a wall-mounted luminaire, assuming both are in the same-sized room.

The photometric tests showed a slightly higher luminaire efficiency than the total output method described previously – 11.8% instead of 10.9%. However, the difference is small and suggests that photometric tests could be used to evaluate GUV luminaires. Further studies should be done to confirm this; because gonioradiometry is expensive and limited, the use of photometric tests to evaluate GUV luminaires would be extremely helpful.

The computer simulation with a T5 lamp estimated a higher efficiency of 14% for a T5 fluorescent lamp, compared to 11.9% for a T8 fluorescent lamp. A smaller diameter lamp would likely cause less blockage of UV-C rays and increase the RC.

### 5.3 Bioaerosol tests

On average, 45% of the *M. parafortuitum* bacteria were inactivated when using the Atlantic fixture, while 56% were inactivated when using the prototype (Table 3). An independent *t*-test revealed that the difference in the mean values of the inactivation rates for the two luminaires was statistically significant ( $p = 0.046$ ).

These results can also be expressed in equivalent air exchange rates (eqACH), which is the additional increase in air exchange rate needed to obtain the same concentration of viable microorganisms as GUV alone, assuming perfect mixing. Equivalent air exchange rate is used to compare the provision of additional mechanical ventilation to GUV luminaires. This result can be calculated from the equation:

$$\lambda_e = \frac{1-f}{f} \lambda \quad (2)$$

where  $f$  is the fraction surviving,  $\lambda$  is the air exchange rate provided by mechanical ventilation (maintained at 6 ACH in this study) and  $\lambda_e$  is the equivalent air exchange rate.<sup>11</sup> The

**Table 3** The percent inactivation of *Mycobacterium parafortuitum* and the equivalent air exchange rate of the prototype luminaire compared to the Atlantic Hygeaire.

Source type	Percent inactivation (95% confidence interval)	Equivalent air exchange rate (95% confidence interval)
Prototype luminaire	56% ( $\pm 5.07\%$ )	8.0 ( $\pm 1.75$ )
Atlantic Hygeaire	45% ( $\pm 9.58\%$ )	5.2 ( $\pm 2.35$ )

An additional 6 ACH was provided by mechanical ventilation.

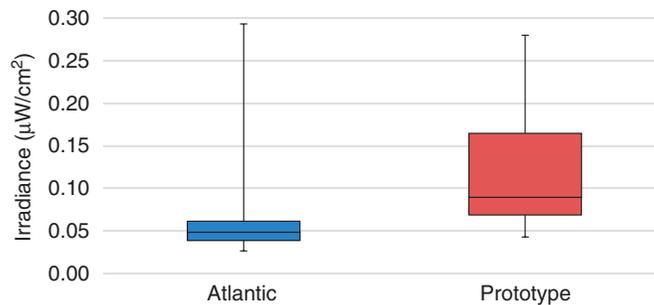
Atlantic fixture provided 5.2 eqACH, while the prototype provided 8.0 eqACH (Table 3).

The prototype luminaire inactivated a higher percentage of *M. parafortuitum* than the Atlantic luminaire, which is currently being used in many upper room GUV systems. The significantly higher germicidal efficacy of the prototype suggests that the design principle it employs may be ready for broader use in real-world applications.

### 5.4 Lower room measurements

The lower room irradiance measurements at 35 locations in the chamber are depicted in Figure 5. The average lower room irradiance measurement for the Atlantic was  $0.065 \mu\text{W}/\text{cm}^2$ , while the average measurement for the prototype was higher, at  $0.118 \mu\text{W}/\text{cm}^2$ . An independent *t*-test revealed that the differences in the mean values were statistically significant ( $p = 0.000692$ ). The maximum irradiance measurement for the two fixtures was similar; the maximum for the Atlantic was  $0.293 \mu\text{W}/\text{cm}^2$  (at location G3), while the maximum for the prototype fixture was  $0.280 \mu\text{W}/\text{cm}^2$  (at locations A1 and A2).

Although no alarmingly high irradiances were found in this small chamber for either luminaire, further lower room irradiance testing on the prototype should be done in a larger room. As with any GUV system installation, the best way to ensure safety for occupants is to use a personal monitor for



**Figure 5.** Lower room irradiance measurements with the prototype luminaire compared to the Atlantic luminaire showing minimum, maximum, median, and first and third quadrant irradiances.

several days. However, this comparison demonstrates that the luminaire is safe for lower room occupants in this space, and will not result in the negative side effects that can occur from overexposure to UV-C radiation.

## 6. Conclusions

The testing of a novel design principle discussed here was conducted using a prototype, with results surpassing those of GUV luminaires already in use. However, the prototype could be optimised before the design is finalised. For example, adding angled side reflectors near each electrode would help to capture and control more lamp radiation, further increasing efficiency. The cost–benefit of this improvement would require radiometric verification. In addition, the T8 lamp could be replaced with a T5; the computer simulation with a T5 lamp estimated a higher luminaire efficiency of 14% for a T5, compared to 11.9% for a T8. The increased efficiency makes sense because parabolic reflectors become more effective as the lamp diameter decreases; a line source would result in the highest effectiveness. In addition, the body of the lamp obstructs the light passage and absorbs some of the light – the larger the source, the greater is the absorption. Other refinements can be made by the product manufacturers prior to

the device being brought to market; there is guidance in the description and diagrams provided, and more diagrams are available upon request from the authors.

Even without modifications, the prototype showed excellent performance, inactivating airborne microbes more effectively than one of the most commonly used luminaires. The luminaire design is also efficient in its UV-C output and maintains safe irradiances in the occupied lower room, which means that fewer luminaires will be required to produce the same results, and installation costs kept to a minimum. The use of simple materials and fewer louvres made this prototype relatively inexpensive to fabricate, although its optics are identical.

This highly effective luminaire design can be utilised as an environmental control to mitigate the spread of tuberculosis and other airborne infectious diseases. It is our hope that this demonstration prototype will encourage a manufacturer to produce and bring a luminaire utilising this design principle to market.

## Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the Fogarty International Center of the National Institutes of Health (Award no. D43TW009379) and the National Institute for Occupational Safety and Health (Award no. 2R01OH009050). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

## Acknowledgements

The prototype was designed by Howard M Brandston. The prototype fixture was a contribution of Acuity Brands Lighting.

## References

- 1 World Health Organization. *Global Tuberculosis Report 2016*. Geneva: WHO, 2016.
- 2 Riley RL, O'Grady F. *Airborne Infection: Transmission and Control*. New York: The Macmillan Company, 1961.
- 3 Jensen PA., Lambert LA, Iademarco MF, Ridzon R. Guidelines for preventing the transmission of Mycobacterium tuberculosis in health-care settings. *Morbidity and Mortality Weekly Report: Recommendations and Reports* 2005; 54: 1–141.
- 4 First MW, Nardell EA, Chaisson W, Riley R. Guidelines for the application of upper-room ultraviolet germicidal irradiation for preventing transmission of airborne contagion - Part I: Basic Principles. *ASHRAE Transactions* 1999; pp.105.
- 5 Reed NG. The history of ultraviolet germicidal irradiation for air disinfection. *Public Health Reports* 2010; 125: 15–27.
- 6 Downes A, Blunt TP. The influence of light on the development of bacteria. *Nature* 1877; 16: 218.
- 7 Wells WF, Fair GM. Viability of B. Coli exposed to ultra-violet radiation in air. *American Association for the Advancement of Science* 1935; 82: 280–281.
- 8 Sliney D. Balancing the risk of eye irritation from UV-C with infection from bioaerosols. *Photochemical and Photobiological Sciences* 2013; 89: 770–776.
- 9 Brickner PW, Vincent RL, First M, Nardell E, Murray M, Kaufman W. The application of ultraviolet germicidal irradiation to control transmission of airborne disease: bioterrorism countermeasure. *Public Health Reports* 2003; 118: 99–114.
- 10 Coker I, Nardell E, Fourie B, Brickner P, Parsons S, Bhagwandin N, Onyebujoh P. *Guidelines for the utilisation of ultraviolet germicidal irradiation (UVGI) technology in controlling the transmission of tuberculosis in health care facilities in South Africa*. Johannesburg: South African Centre for Essential Community Services, 1999.
- 11 First M, Rudnick SN, Banahan KF, Vincent R, Brickner PW. Fundamental factors affecting upper-room ultraviolet germicidal irradiation - Part I. Experimental. *Journal of Occupational and Environmental Hygiene* 2007; 4: 321–331.
- 12 Rudnick SN, First MW. Fundamental factors affecting upper-room ultraviolet germicidal irradiation – Part II. Predicting effectiveness. *Journal of Occupational and Environmental Hygiene* 2007; 4: 352–362.
- 13 Dumyahn T, First M. Characterization of ultraviolet upper room air disinfection devices. *American Industrial Hygiene Association Journal* 1999; 60: 219–227.
- 14 Rudnick SN, First MW, Sears T, Vincent RL, Brickner PW, Ngai PY, Zhang J, Levin RL, Chin K, Rahn RO, Miller SL, Nardell EA. Spatial distribution of fluence rate from upper-room ultraviolet germicidal irradiation: experimental validation of a computer-aided design tool. *HVAC&R Research* 2012; 18: 774–794.
- 15 Rudnick SN, Nardell EA. A simple method for evaluating the performance of louvered fixtures designed for upper-room ultraviolet germicidal irradiation. *Leukos* 2016; 13: 91–105.
- 16 Illuminating Engineering Society of North America. *IESNA LM-75-01 Goniophotometer Types and Photometric Coordinates*. New York: IESNA, 2001.

- 17 Photopia. Optical Design Software Focused on Lighting. Retrieved 8 May 2016, from <http://www.ltioptics.com/en/photopia-standalone-base.html>
- 18 McDevitt JJ, Milton DK, Rudnick SN, First MW. Inactivation of poxviruses by upper-room UVC light in a simulated hospital room environment. *PLoS One* 2008; 3: e3186.
- 19 Linnes JC, Rudnick SN, Hunt GM, McDevitt JJ, Nardell EA. Eggcrate UV: a whole ceiling upper-room ultraviolet germicidal irradiation system for air disinfection in occupied rooms. *Indoor Air* 2014; 24: 116–124.
- 20 American Conference of Governmental Industrial Hygienists. *Threshold Limit Values and Biological Exposure Indices*. Cincinnati, OH: ACGIH, 2012.
- 21 First MW, Weker RA, Yasui S, Nardell E. Monitoring human exposures to upper-room germicidal ultraviolet irradiation. *Journal of Occupational and Environmental Hygiene* 2005; 2: 285–292.
- 22 Nardell EA, Bucher SJ, Brickner PW, Wang C, Vincent RL, Becan-McBride K, James MA, Michael M, Wright JD. Safety of upper-room ultraviolet germicidal air disinfection for room occupants: results from the tuberculosis ultraviolet shelter study. *Public Health Reports* 2008; 123: 52–60.