Special Issue Research Article

Critical Design Parameters in Design and Efficacy of Upper-Room UVC$_{254}$ Luminaire Systems: Part I: Overview of Major Parameters and Relationships[†]

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Received 1 January 2021, accepted 2 March 2021, DOI: 10.1111/php.13425

ABSTRACT

During the current SARS-CoV-2 and tuberculosis global pandemics, public health and infection prevention and control professionals wrestle with cost-effective means to control airborne transmission. One technology recommended by Centers for Disease Control and Prevention and the World Health Organization for lowering indoor concentration of these and other microorganisms and viruses is upper-room ultraviolet 254 nm (UVC$_{254}$) systems. Applying both a material balance as well as some nondimensional parameters developed by Rudnick and First, the impact of several critical parameters and their effect on the fraction of microorganisms surviving UVC$_{254}$ exposure was evaluated. Vertical airspeed showed a large impact at velocities <0.05 m s^{-1} but a lesser effect at velocities >0.05 m s^{-1}. In addition, the efficacy of any upper-room UVC system is influenced greatly by the mean room fluence rate as opposed to a simple volume- or area-based dosing criteria. An alternative UVC$_{254}$ dosing strategy was developed based on the fluence rate as a function of the UVC$_{254}$ luminaire output (W) and the square root of the product of the room volume and the ceiling height.

INTRODUCTION

During the current SARS-CoV-2 and tuberculosis pandemics, public health and infection prevention and control professionals wrestle with means to control the airborne transmission. This requires the implementation of airborne precautions (1–5):

Administrative controls: The first and potentially most effective level of airborne control is the use of administrative measures (policies and practices) to reduce the risk for exposure to persons who might have COVID-19, TB disease, measles, or some other airborne-transmitted disease. One often overlooked area includes the operation and maintenance of environmental controls as well as proper use of personal protective equipment.

Environmental controls: The second level of the hierarchy is the use of environmental controls to prevent the spread and reduce the concentration of small infectious droplets in ambient air.

Personal Protective Equipment (PPE): Respirators to protect the wearer and masks to protect the environment are the primary PPE measures when dealing with airborne transmission.

One technology that has been used globally for surface and air disinfection for over 100 years is Ultraviolet C Region (UVC). UVC, also known as germicidal ultraviolet (GUV) light and ultraviolet germicidal irradiation (UVGI), refers to short-wavelength ultraviolet "light" (radiant energy) that has been shown to inactivate bacteria, fungi and viruses (6). UVC wavelengths of 200–280 nanometers (nm) have been shown to be effective for disinfection; however, there is a dose dependency based on wavelength as well as the composition of materials surrounding the microdroplet. Two primary applications of UVGI air disinfection include upper-room UVC luminaires and in-duct UVC luminaires. This paper will not address in-duct UVC applications. Upper-room UVC may complement ventilation to effectively reduce the concentration of infectious microdroplets in the air.

The most common form of artificially generated UVC is by low-pressure mercury (Hg) discharge lamps at a predominant wavelength of 254 nm (UVC$_{254}$, subscript "254" denotes the wavelength in nm). While this technology is commonly used for water disinfection, it had been used as far back as the 1940s for air disinfection. A quick search on the Internet showed the rapid advancement of UVC LED technologies. UVC chips range in UVC output of 0.003–0.05 W and cost <\$30! While not quite powerful enough nor economical for current use, they will be soon (7,8). UVC LEDs are available in 260–270 nm and 270–280 nm ranges.

In the last quarter of the 20th century, UVC$_{254}$ became less and less popular in the United States due to the lower incidence of tuberculosis. With the SARS-CoV-1 pandemic in 2003 as well as increasing incidence of multidrug-resistant tuberculosis globally, there was a resurgence of UVC$_{254}$ usage in the United States. Now that we are fighting the SARS-CoV-2 pandemic, UVC$_{254}$ has made a strong comeback for both air and surface disinfection. Another wavelength that has been at the forefront of research in *recent* years is UVC$_{222}$. Other papers in this special issue of the *Journal of Photochemistry and Photobiology* address UVC$_{222}$ as well as other UVC-producing technologies.

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[†]This article is part of a Special Issue dedicated to the topics of Germicidal Photobiology and Infection Control.

This manuscript only pertains to upper-room UVC$_{254}$ applications.

Currently, there are no national (US) or international consensus standards on design of luminaires nor design of luminaire application/layout. Consensus standards exist for occupational exposure to UVC but not to nonoccupational persons (9). Underwriter's Laboratories published an ANSI/UL Standard 1598—Standard for Luminaires in 2018 (10) with the subsequent addition of Annex L—Additional Requirements For Germicidal Equipment, outside of the ANSI process (11). ANSI/UL 1598 addresses electrical safety of luminaires and Annex L attempts to classify germicidal equipment (luminaires) as "safe." Over the years, there have been "rules of thumb" and empirical recommendations. I will briefly summarize in Table 1.

In 1999, First *et al.* (12) stated that the use of germicidal irradiation for the disinfection of air is an old technology that, strangely, is not yet mature. Since that time, it has matured a bit. Except for the paper by Mphalele *et al.*, none of the recommendations helped designers with simple, generalizable dosing criteria that could be used as a starting point in the design cycle without the assistance of a CAD UVC lighting program (13,14). ASHRAE GPC 37 committee is working on publishing a document that details the commissioning cycle. Mphalele *et al.* (13) recommended starting with a volumetric dosing criterion of 0.017 W$_{UVC254}$ m^{-3} based on a study performed at the Airborne Infection Research Facility in eMalahleni (previously known as Witbank), South Africa. Patients with infectious tuberculosis were housed in one of three patient rooms. All the air from these three patient rooms was sent to one of two animal rooms which housed guinea pigs as air samplers. Each patient room had an operational ceiling fan to assist in air mixing. Upper-room UVC$_{254}$ luminaires were operated on alternating days. The air from the patient rooms was sent to alternate animal rooms, coinciding with the alternate use of the UVC$_{254}$ luminaires. The study was repeated with about 30% less UVC$_{254}$ output and showed a strikingly similar effect (unpublished). Environmental factors such as temperature, humidity (absolute and relative) and solar radiation are not within the scope of this manuscript.

The following parameters are deemed critical in providing effective disinfection of air:

- Room volume
- Room area
- Ceiling height
- Room geometry (L_{ROOM}/W_{ROOM}, H_{ROOM}/A_{ROOM}, H_{ROOM}/W_{ROOM}, C_{ROOM}/V_{ROOM}, etc.)
- Ray length
- Geometry (3D) of the UVC$_{254}$ "plume"
- Air exchange rate (λ_M, λ_{UVC}, λ_N)
- Volumetric airflow rate (Q_M, Q_{UVC}, Q_N)
- Air mixing (vertical airspeed, auxiliary fans, diffusers, etc.)
- Luminaire output of UVC$_{254,}$ W
- UVC$_{254}$ fluence rate (whole-room *vs* irradiated zone).
- Reflectance/absorbance of room surfaces
- Microbe sensitivity to UVC$_{254}$ (function of absorption of UVC$_{254}$ by microbe, solution around microbe and solute dissolved in the solution)
- Occupancy
- Other

Table 1. History of UVC$_{254}$ dosing criteria.

Citation(s)	Microorganism	Recommendation	Comments
Riley (25), Riley & Nardell (26), Macher (19), and First (12)	*M. tuberculosis* *M. bovis* *M. phlei*	30 W$_{NOMINAL}$/19 m^2 (30 W$_{NOMINAL}$/200 ft^2) or 1.5 W$_{NOMINAL}$ m^{-2} floor area	Does not account for UVC$_{254}$ lamp or luminaire efficiency
First (12) & Boehme (27)	*M. tuberculosis*	85% of irradiated zone area at least 0.5 W$_{UVC254}$ m^{-2} (50 µw cm^{-2}) with vertical speed of at least 0.025 m s^{-1} (1.0 in per s)	Easily predicted with CAD programOnce CAD programs are fully validated, is a useful guideline
First (12)	*Mycobacterium* spp.	0.1 W$_{UVC254}$ m^{-2} (10 µW cm^{-2}) average fluence rate in the upper-room irradiated zone	Easily predicted with CAD programOnce CAD programs are fully validated is a useful guideline
Miller (16), Xu (17)	*M. bovis* BCG *M. parafortuitum* *B. subtilis* spores	1.87 W$_{UVC254}$ per m^2 (room area) in the upper-room irradiated zone 6.3 W$_{UVC-254}$ per m^3 (room volume) in the upper-room irradiated zone	Unfortunately, these criteria are attributed to CDC/NIOSH 2009; however, it was stated as a "Rule of Thumb" and NOT a recommendation. These values are unique for the specific luminaires tested and reported by Miller & Xu
Miller (16)	*M. bovis* BCG *M. parafortuitum* *B. subtilis* spores	0.3–0.5 W$_{UVC254}$ m^{-2} (30–50 µW cm^{-2}) average fluence rate in the upper-room irradiated zone	Easily predicted with CAD programOnce CAD programs are fully validated is a useful guideline
CDC/NIOSH (28)	*M. tuberculosis*	0.3–0.5 W$_{UVC254}$ m^{-2} (30–50 µW cm^{-2}) average UVC$_{254}$ fluence rate in the upper-room irradiated zone	Easily predicted with CAD programOnce CAD programs are fully validated is a useful guideline
Mphalele (13,14)	*M. tuberculosis*	0.017 W$_{UVC254}$ total fixture output per m^3 room volume (patient rooms and corridor) NB: Unpublished data suggest similar inactivation rates with 0.012 W$_{UVC254}$ m^{-3}	Requires Total Fixture UV Output measurementMakes for an easier starting point for verification in CAD programs
Using data from Mphalele (13,14)	*M. tuberculosis*	0.019 W$_{UVC254}$ total fixture output per m^3 room volume (patient rooms only) NB: Unpublished data suggest similar inactivation rates with 0.012 W$_{UVC254}$ m^{-3} 0.049 W$_{UVC254}$ total fixture output per m^2 room area (patient rooms only) NB: Unpublished data suggest similar inactivation rates with 0.035 W$_{UVC254}$ m^{-2}	Requires Total Fixture UV Output measurementMakes for an easier starting point for verification in CAD programs

MATERIALS AND METHODS

Rudnick (15) developed a model based on experimental data generated in a large exposure chamber, 3.0 m × 4.6 m × 3.1 m (9.74 ft × 15.1 ft × 10 ft). Assuming perfect mixing of the air and equal fluence rate throughout the chamber, Rudnick derived two nondimensional numbers (Mixing Number [N_m] and Irradiance Number [N_i]) and a nondimensional index (Effectiveness Number [I]). An inverse relationship between the effectiveness index (I) and fraction surviving ($C_{UVC-ON}/C_{UVC-OFF}$) was derived. The data were fit to an exponential function. Below are the four major equations.

The vertical Mixing Number (N_m) is a dimensionless number to indicate airflow rate passing through the UVC_{254}-irradiated zone in the upper room is high relative to the mechanical air exchange rate (λ_M) and the ceiling height (H_{ROOM}). When N_m is large, a significant portion of the room air will be irradiated while if N_M is small, a small portion of the room air will be irradiated. AER_{UVC254} is the observed or expected air exchange rate (AER) based on the reduction in airborne microorganisms and viruses due to upper-room UVC_{254} systems. This is often called "equivalent AER," meaning that if a mechanical ventilation system had been used in lieu of an upper-room UVC_{254} system, one would observe equivalent or similar AER.

Following is equation 7 from Rudnick (15):

$$N_M = \frac{\overline{S}}{2H\lambda} \tag{1}$$

where S is the mean vertical speed (m s^{-1}), H_{ROOM} is the ceiling height (m) and λ_m is the air exchange rate due to mechanical ventilation (s^{-1}). The Irradiance Number (N_I) is related to UVC_{254} irradiation or mean fluence rate (E). When N_I is large, the more effective air disinfection should become. Note that the product of z and E is AER_{UVC254}.

Following are equations (4) and (16) from Rudnick (15):

$$N_I = \frac{zV_I\overline{E}_I}{\lambda V}$$
$$N_I = \frac{z\sum \overline{d}_i W_i}{V\lambda} \tag{2}$$

where z is the microbe susceptibility to UVC_{254} (m^2 J^{-1}), E is the mean fluence rate in the room (W m^{-2}), d_i is the mean UVC_{254} ray length (m), W_i is the UVC_{254} output of the luminaire, V_{ROOM} is the room volume and λ_M is the air exchange rate (s^{-1}). Dimensionless numbers N_I and N_M were combined into another dimensionless parameter, the Effectiveness Index (I), equation 17 from Rudnick (15). I is an Index of UVC_{254} effectiveness. When I is large, the larger the benefit from the upper-room UVC_{254} system. Note that the denominator of I is the sum of the inverse of the N_I and N_M; thus, one should understand the interrelations of all the parameters that went into this relative approximation of risk of disease transmission.

$$I = \frac{1}{\frac{1}{N_I} + \frac{1}{N_M}} \tag{3}$$

where N_I is the irradiance number (dimensionless) and N_M is the mixing number (dimensionless). Rudnick developed an empirical relationship of their data to estimate the fraction of microbes surviving the UVC_{254} treatment ($C_{UVC-ON}/C_{UVC-OFF}$) in their equation 18 (15). Miller and Xu also used a similar approach to present their results in terms of fraction of microbes surviving the UVC_{254} treatment (16–18).

$$\frac{C_{UVC-ON}}{C_{UVC-OFF}} = 0.83\,I^{-0.74} \tag{4}$$

where I is the effectiveness index. To ensure formulas from Rudnick et al. (15) were correctly entered in a Microsoft® Excel® for Microsoft 365 MSO (16.0.13426.20330) spreadsheet, data from table II were entered and compared with calculated parameters in table II. After verification that the spreadsheet calculations were correct, the following data, extracted from Mphalele (2015), were entered into the spreadsheet (13,14):
- Patient room dimensions ($L_{ROOM} \times W_{ROOM} \times H_{ROOM}$): 4.8 m × 3.0 m × 2.6 m (15.8 ft × 9.9 ft × 8.5 ft)
- Number of UVC_{254} luminaires: 2

- UVC_{254} output of each luminaire (W): 0.22 W and 0.49 W, respectively
- Air exchange rate (AER_M): 6 h^{-1}. Also tested model at AER = 1–25 h^{-1}.
- Mean vertical airspeed (S): Did not measure. Assumed 0.01–0.25 m s^{-1}.

To initially identify sensitivity of selected parameters, one input variable was changed at a time and its impact on other variables was evaluated.

The final step in this analysis paralleled much of the Rudnick modeling (15). Because much of Wells (19), Riley (20), Miller (16) and Rudnick (15) is based on a material balance, a closer look at the basis of these equations is necessary. General dilution ventilation is the term-of-art for the fundamental material balance (21):

Rate of Accumulation = Rate of Generation − Rate of Removal

$$V_{ROOM}\,dC_i = G\,dt - Q'\,C_i\,dt. \tag{5}$$

Where V_{ROOM} is the volume of the room (m^3), G is the rate of generation of microbes (microbes s^{-1}), Q' is the effective volumetric airflow rate (m^3 s^{-1}), C_i is the concentration at time t_i (microbes m^{-3}) and t is time (s).

At equilibrium or steady state, $dC_i = 0$; the dilution ventilation material balance becomes:

$$G\,dt = Q'\,C_i\,dt \tag{6}$$

To solve this equation, one would integrate from t_1 to t_2 as follows:

$$\int_{t_1}^{t_2} G\,dt = \int_{t_1}^{t_2} Q'C_i\,dt \tag{7}$$

where G is the rate of generation of microbes (microbes s^{-1}), Q' is the effective volumetric airflow rate (m^3 s^{-1}), C_i is the concentration at time t_i (microbes m^{-3}) and dt is delta time (s).

Note that the effective volumetric airflow rate is made up of three components (16,18,22):

$$Q' = Q_M + Q_{UVC254} + Q_N \tag{8}$$

where Q' is the effective total volumetric airflow rate (m^3 s^{-1}), Q_M is the volumetric airflow rate (i.e. clean air) of mechanical ventilation system, assuming C entering room is 0 (m^3 s^{-1}), Q_{UVC254} is the equivalent Q required to provide the same volumetric airflow rate as that observed by inactivation of airborne microbes due to UVC_{254} (m^3 s^{-1}) and Q_N is the equivalent Q required to provide the same volumetric airflow rate as that observed by natural decay of airborne microbes by various means (m^3 s^{-1}).

If the room is at equilibrium (i.e. C_i and G are constant), this material balance may be simplified and rearranged as follows:

$$G = Q'\,C_i$$
$$G = (Q_M + Q_{UVC254} + Q_N)C_i. \tag{9}$$

The air exchange rate (AER, λ) may be calculated as follows (21):

$$AER_M = Q_M/V_{ROOM}$$
$$AER_{UVC254} = Q_{UVC254}/V_{ROOM} \tag{10}$$
$$AER_N = Q_N/V_{ROOM}.$$

If we substitute AER for Q, we get the following:

$$G = (AER_M + AER_{UVC254} + AER_N)\,V_{room}C_i$$
$$C_i = G/(V_{ROOM} \times (AER_M + AER_{UVC254} + AER_N)) \tag{11}$$

If $AER_M = 0$ h^{-1} ($Q_M = 0$ m^3 s^{-1}) and $AER_N = 0$ h^{-1} (QN = 0 m^3 s^{-1}), then $C_i = G/Q_{UVC254}$.
If $AER_{UVC254} = 0$ h^{-1} and $AER_N = 0$ h^{-1}, then $C_i = G/Q_M$.

To demonstrate this, we will use the following data from Mphalele (13,14):

$$AER_M + AER_N = 6\,h^{-1}$$
$$AER_{UVC254} = 24\,h^{-1}.$$

EXAMPLE 1

Entering these criteria into the Eq. 11, and assuming both G & C_i = constant, the following relationships are established:

$$
\begin{aligned}
G &= C\,V_{ROOM1}(6+24)\\
&= C\,V_{ROOM1}30\\
C &= G/(30\,V_{ROOM1})
\end{aligned}
$$

EXAMPLE 2

Next, we will double the ceiling height (H_{ROOM}), keep the same luminaire power (W) and keep the same Q_M. As a result, volume of the room ($V_{ROOM2} = 2\,V_{ROOM1}$) will be doubled, the AER_M for Room 1 will be halved to $3\,h^{-1}$, the mean fluence rate in the room will be halved and the AER_{UVC254} will be halved. Entering these criteria, we get the following:

$$
\begin{aligned}
G &= C\,V_{ROOM2}(3+12)\\
&= C(2\,V_{ROOM1})(15)\\
&= C\,V_{ROOM1}30\\
C &= G/(30\,V_{ROOM1})
\end{aligned}
$$

Hence, the doubling of the room volume (V_{ROOM1}) resulted in the SAME equilibrium concentration of microbes in the room. Mathematically, this makes sense; however, it does not make sense logically as we are dealing with a biological response to mean fluence rate (E),

From Wells (23), Riley (20), Miller (16) and Rudnick (15), we further understand that:

$$AER_{UVC254} = z\,E \tag{12}$$

where: AER_{UVC254} is the air exchange rate (AER) due to UVC_{254} (s^{-1}), z is the microbe susceptibility to UVC_{254} ($m^2\,J^{-1}$) and E is the mean Fluence Rate in Room (W m^{-2}).

The main premise of the Rudnick equations is that the room is at equilibrium, the generation rate (G, microbes s^{-1}) equals the removal and inactivation rates (15). When the generation rate equals 0 microbes s^{-1}, the material balance may be rearranged as follows (15):

$$C_{UVC_{254}-ON}(t) = C_0 e^{-(ACH_M + ACH_{UVC254} + ACH_N)t} \tag{13}$$

There have been many evaluations of this material balance in the industrial environment for vapors, gases and particulates; however, there have been limited studies with bioaerosols. From the standpoint of AER_N and AER_M, there should be no difference in modeled results because bioaerosols are simply particles. From the standpoint of AER_{UVC} (254 nm or other wavelengths), the data are far more limited, partly because of the cost of conducting such experiments and because we are dealing with a biological response to UVC. This biological response is related to the sensitivity of the microbe(s) to UVC and other environmental factors (temperature, relative humidity, solar radiation, etc.), the composition of the liquid coating surrounding the microbe (absorbing of UVC and/or shielding microbe from UVC), dose of UVC, etc.

RESULTS AND DISCUSSION

To evaluate the significance of vertical airspeed (S), estimated fraction surviving ($C_{UVC-ON}/C_{UVC-OFF}$) is plotted against vertical airspeed (S) in Fig. 1. In this case, the room dimensions, luminaire output (W) and mean fluence rate in room (E, W m^{-2}) were held constant. Three lines were developed for AERs of 2, 6 and 12 h^{-1}. See Fig. 1. This family of lines appears to approach that of an inverse power function. With an AER of 2 h^{-1}, increasing the vertical airspeed (S) beyond 0.05 m s^{-1} results in a very small decrease in estimated fraction surviving ($C_{UVC-ON}/C_{UVC-OFF}$). As the AER increases, the vertical airspeed (S) beyond which a benefit is noted also increases. For example, with an AER of 6 h^{-1}, vertical airspeed (S) more than 0.10 m s^{-1} yields small benefit while with an AER of 12 h^{-1}, vertical airspeed (S) more than 0.015 m s^{-1} yields similarly small improvements.
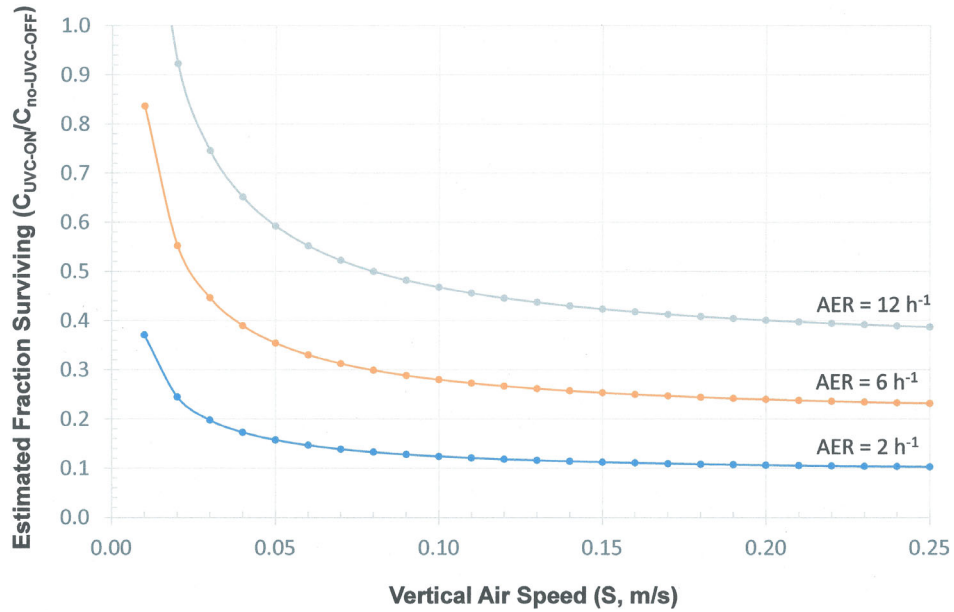
Another plot of estimated fraction surviving ($C_{UVC-ON}/C_{UVC-OFF}$) *vs* vertical airspeed (S) was developed to understand the relationship of mean fluence rate (E) with vertical airspeed (S) in Fig. 2. In this case, the room dimensions and air exchange rate (λ_M) of 6 h^{-1} were held constant. The luminaire UVC_{254} outputs (W) of 0.35, 0.71, 1.06 and 1.41 W resulted in mean fluence rates (E) in the room of 0.025, 0.050, 0.075 and 0.100 W m^{-2}, respectively. This plot shows similar relationships of the decreasing influence of the estimated fraction surviving ($C_{UVC-ON}/C_{UVC-OFF}$) with increasing vertical airspeed (S). Another finding is that a mean fluence rate (E) of 0.025 W m^{-2} is significantly less bactericidal that a mean fluence rate (E) of 0.050 W m^{-2} or higher. In addition, there is a relatively small increase in inactivation when increasing the mean fluence rate from 0.050 to 0.075 W m^{-2} and an even smaller increase in inactivation when increasing mean fluence rate (E) from 0.075 to 0.100 W m^{-2}.

To further evaluate the significance of vertical airspeed (S), estimated fraction surviving is plotted against air exchange rate (λ_M), ranging 1–25 h^{-1} in Fig. 3. In this case, the room dimensions, luminaire output (W) and mean fluence rate (E) in room (W m^{-2}) were held constant. Five lines were developed for vertical airspeeds (S) of 0.05, 0.10, 0.15, 0.20 and 0.25 m s^{-1}. See Fig. 3. Like Fig. 1, this family of lines appears to approach that of an inverse power function. In addition to showing the poorer performance with the lower vertical airspeed (S) of 0.05 m s^{-1}, there is not much difference shown with higher vertical airspeeds other than their importance when increasing the air exchange rate (λ_M). Miller (16) demonstrated that up to an AER of 6 h^{-1} with mechanical ventilation, the total benefit was the additive effects of only mechanical ventilation and only upper-room UVC_{254}. Beyond an air exchange rate (λ_M) of 5–6 h^{-1}, the lines appear to diverge.

To evaluate the effect of increasing ceiling height (H_{ROOM}) and room volume (V_{ROOM}), we evaluated two conditions:
● Luminaire output (W, 0.71 W) constant which resulted in decreasing mean fluence rate in the room (E, 0.050–0.025 W m^{-2} [5.0 to 2.5 µW cm^{-2}]), and
● Luminaire output increased (W, 0.71–1.42 W) which resulted in constant mean fluence rate (E, 0.050 W m^{-2} [5.0 µW cm^{-2}]). See Figs. 4 and 5.

If one keeps the same luminaires (*i.e.* holding luminaire output as a constant and increases the room volume) the mean fluence rate would decrease as the room volume increases. The converse is true as well. If one wants to keep the same mean fluence rate in the room, one must proportionally increase the luminaire output (E) as the room volume (V_{ROOM}) increases. Note that the constant mean fluence rate (E) in the room shows an

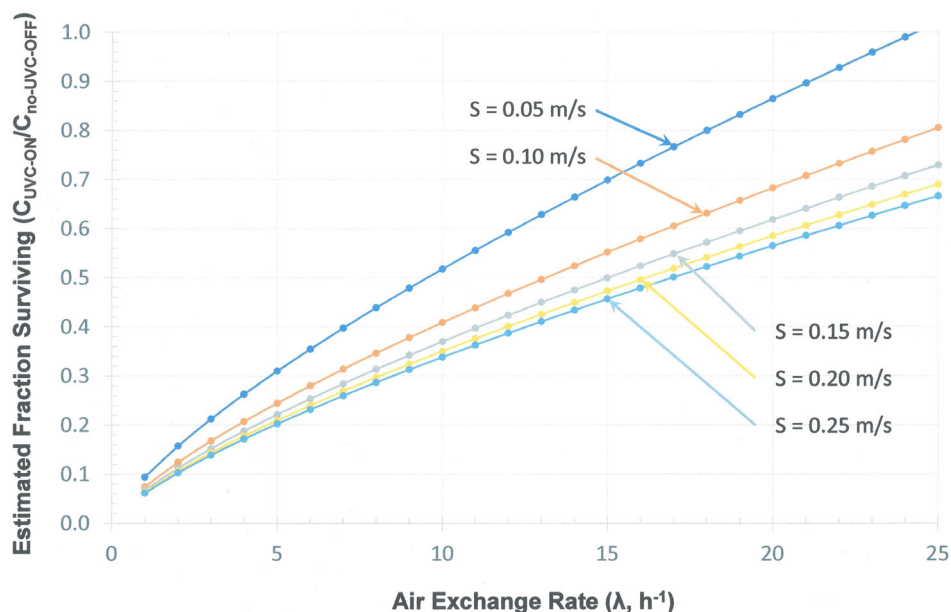**Figure 1.** Estimated fraction surviving ($C_{UVC-ON}/C_{UVC-OFF}$) *vs* vertical airspeed (S, 0.01–0.25 m s^{-1}). Room area (A_{ROOM}, 14.4 m^2; ceiling height (H_{ROOM}, 2.6 m); room volume (V_{ROOM}, 37 m^3); mean fluence rate (E, 0.050 W m^{-2} [5.0 µW cm^{-2}]); luminaire UVC$_{254}$ power (W, 0.71 W; air exchange rate (λ_M, 2, 6 and 12 h^{-1}).
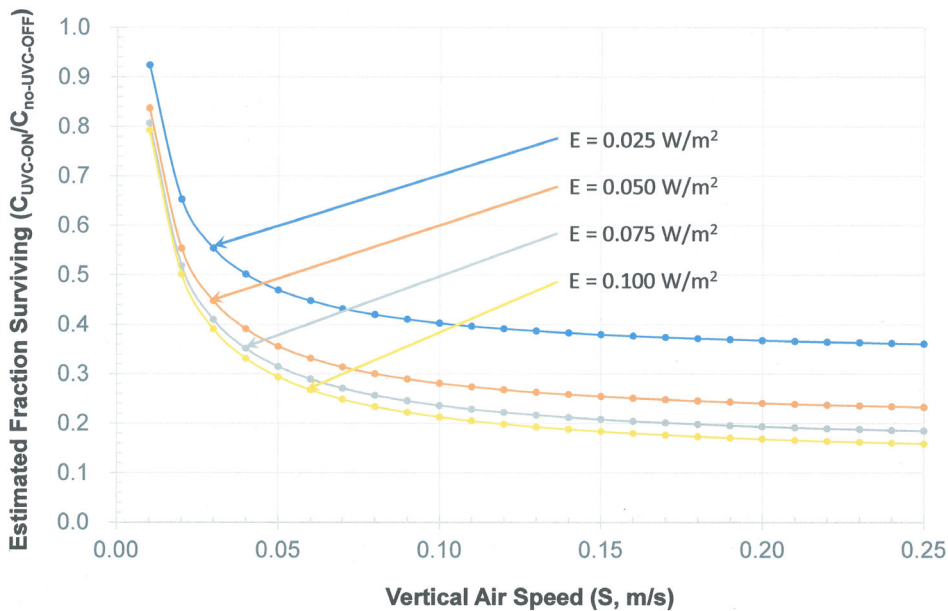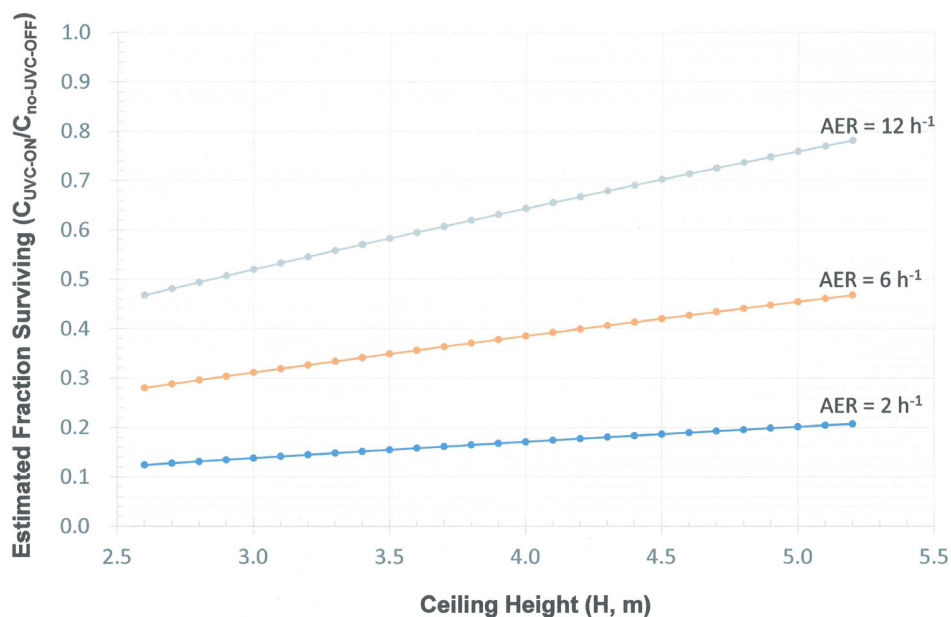

Figure 2. Estimated fraction surviving ($C_{UVC-ON}/C_{UVC-OFF}$) *vs* vertical airspeed (S, 0.01–0.25 m s^{-1}). Room area (A_{ROOM}, 14.4 m^2); ceiling height (H_{ROOM}, 5.2 m); room volume (V_{ROOM}, 74 m^3); mean fluence rate (E, 0.025, 0.050, 0.075, 0.100 W m^{-2} [2.5, 5.0, 7.5, 10.0 µW cm^{-2}]); Luminaire UVC$_{254}$ Power (W, 0.35, 0.71, 1.06 and 1.41 W); air exchange rate (λ_M, 6 h^{-1}).

increase in surviving fraction ($C_{UVC-ON}/C_{UVC-OFF}$) for all three air exchange rates (λ_M) as the ceiling height (H_{ROOM}) increases. However, when the mean fluence rate (E) was kept constant, the increase in surviving fraction was less dramatic. This might seem counterintuitive. The increase in surviving fraction may be due to the decrease in benefit provided by the upper-room UVC$_{254}$ luminaire systems or may be that the model developed by Rudnick is not generalizable (15). Note the linear relationship between the luminaire output (W) and the mean fluence rate (E) when the room volume (V_{ROOM}) increases due to an increase in ceiling height (H_{ROOM}).

Figures 6 and 7 are similar to the previous two figures except the room volume (V_{ROOM}) was increased due to an increase in room area (A_{ROOM}) with a constant ceiling height (H_{ROOM}). In Fig. 6, the luminaire output (W) remained constant (0.71 W) and the mean fluence rate (E) decreased from 0.050 to 0.036 W m^{-2}. At the three air exchange rates (λ_M) of 2, 6 and 12 h^{-1}, the three lines are relatively flat. In Fig. 7, the luminaire output (W) increased 0.71 to 1.0 W and the mean fluence rate (E) remained constant (0.050 W m^{-2}). At the three air exchange rates (2, 6 and 12 h^{-1}), the lines have a slightly shallower slope. Because the mean fluence rate (E) is a function of the ray length (d) and

Figure 3. Estimated fraction surviving ($C_{\text{UVC-ON}}/C_{\text{UVC-OFF}}$) *vs* air exchange rate (λ_M, 1–25 h^{-1}). Room area (A_{ROOM}, 14.4 m^2); ceiling height (H_{ROOM}, 2.6 m); room volume (V_{ROOM}, 37 m^3); vertical airspeed (S, 0.05, 0.10, 0.15, 0.20, 0.25 m s^{-1}; mean fluence rate (E, 0.050 W m^{-2} [5.0 µW cm^{-2}]); luminaire UVC$_{254}$ power (W, 0.71 W); volumetric airflow rate (Q_m, 0.0104–0.156 m^3 s^{-1}).

Figure 4. Estimated fraction surviving ($C_{\text{UVC-ON}}/C_{\text{UVC-OFF}}$) *vs* ceiling height ($H_{\text{ROOM}}$, 2.6–5.2 m). Room area (A_{ROOM}, 14.4 m^2); room volume (V_{ROOM}, 37–75 m^3); mean fluence rate (E, 0.050–0.025 W m^{-2} [5.0–2.5 µW cm^{-2}]); vertical airspeed (S, 0.10 m s^{-1}); luminaire UVC$_{254}$ power (W, 0.71 W); air exchange rate (λ_M, 2, 6 and 12 h^{-1}).

the ray length (d) is a function of the square root of the room area (A_{ROOM}), there is a nonlinear relationship between luminaire output (W) and mean fluence rate (E).

Based on Miller (16) & Rudnick (15) laboratory studies and the evaluation above, the mean room fluence rate (E) may be a better predictor than a simple volumetric-based or area-based UVC$_{254}$ dosing criterion. As shown in Examples 1 and 2, there is a limit to the validity of applying a simple material balance to solve the UVC$_{254}$ dosing conundrum, and specifically, a volumetric-based UVC$_{254}$ dosing criterion. Because the mean fluence rate (E) in the room is proportional to the square root of the

room area (A_{ROOM}) and inversely proportional to the volume of the room (V_{ROOM}), we must consider the following derivation of mean fluence rate as well as ray length. Rudnick estimated ray length as follows (15):

$$\bar{d} \cong \sqrt{A} \quad \text{Corner} - \text{type fixtures}$$
$$\bar{d} \cong 0.7\sqrt{A} \quad \text{Wall} - \text{type fixtures} \qquad (14)$$
$$\bar{d} \cong 0.5\sqrt{A} \quad \text{Pendant} - \text{type fixtures}$$

where d is the mean UVC$_{254}$ ray length (m) and A_{ROOM} is the area of the room (m^2).
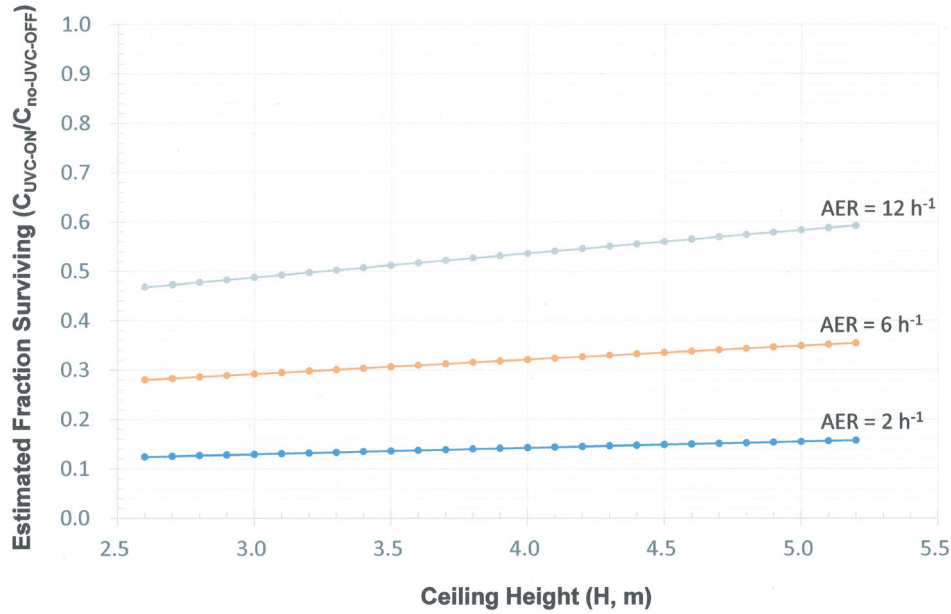
Figure 5. Estimated fraction surviving ($C_{\text{UVC-ON}}/C_{\text{UVC-OFF}}$) *vs* ceiling height ($H_{\text{ROOM}}$, 2.6–5.2 m). Room area (A_{ROOM}, 14.4 m^2); room volume (V_{ROOM}, 37–75 m^3); vertical airspeed (S, 0.10 m s^{-1}); mean fluence rate (E, 0.050 W m^{-2} [5.0 μW cm^{-2}]); luminaire UVC$_{254}$ power (W, 0.71–1.42 W); air exchange rate (λ_{M}, 2, 6 and 12 h^{-1})

As Rudnick stated that this simplified method of calculation of ray length is based on a length-to-width ratio of 3 or less (15). These equations only deal with the "plume" of UVC$_{254}$ in a horizontal plane. Based on measurements taken in the field, there is also a vertical component that is not accounted for by Rudnick (15). Some luminaires have more vertical spread of UVC$_{254}$ than others due to increased spacing between baffles as well as the removal of some or all the baffles. As the ceiling height (H_{ROOM}) increases, the vertical dimensions of the plume increase. Beggs and Sleigh (24) performed some modeling of upper-room UVC$_{254}$ and concluded that if the size of the irradiated zone is doubled, the length of time the microdroplet is exposed to UVC$_{254}$ doubles, hence, the fluence rate could also be reduced by 50%. They hypothesize that the microdroplet will still receive the same dose. Hence, an alternative to the 2D plume should be investigated.

Now, let us take a closer look at ray length (d). As shown in Fig. 2, the mean fluence rate (E) is a function of ray length (d) (15):

Ray length (d) is a function of the square root of area (A_{ROOM}) and the inverse of room volume (V_{ROOM}). We can substitute the product of room area (A_{ROOM}) and ceiling height (H_{ROOM}) for room volume (V_{ROOM}), and we develop the following the relationship with mean fluence rate (E) being proportional to room area (A_{ROOM}) and ceiling height (H_{ROOM}) through the following series of substitutions:

$$
\begin{aligned}
E \ &\alpha & W A_{\text{ROOM}}^{0.5}/V_{\text{ROOM}} \\
&\alpha & W A_{\text{ROOM}}^{0.5}/(A_{\text{ROOM}} H_{ROOM}) \\
&\alpha & W A_{\text{ROOM}}^{-0.5} H_{\text{ROOM}}^{-1} \\
&\alpha & W A_{\text{ROOM}}^{-0.5} H_{\text{ROOM}}^{-0.5} H_{\text{ROOM}}^{-0.5} \\
&\alpha & W V_{\text{ROOM}}^{-0.5} H_{\text{ROOM}}^{-0.5} \\
&\alpha & W (V_{\text{ROOM}} H_{\text{ROOM}})^{-0.5}
\end{aligned}
\qquad (15)
$$

Assuming a mean fluence rate (E) of 0.05 W m^{-2} (5 μW cm^{-2}), we can estimate the constant and solve Eq. 15 to some up with the following:

$$W = \beta E (V_{\text{ROOM}} H_{\text{ROOM}})^{0.5} \qquad (16)$$

where W is the required UVC$_{254}$ output of the luminaire (W), E is the desired mean fluence rate (W m^{-2}), V_{ROOM} is the volume of the room (m^3), H_{ROOM} is the ceiling height (m) and β is the proposed dosing criterion (dimensionless).

Applying this relationship to data from Mphalele (13,14), the following new dosing criterion was developed:

$$W = 1.44 E (V_{\text{ROOM}} H_{\text{ROOM}})^{0.5} \qquad (17)$$

A volume-based UVC$_{254}$ dosing criterion would provide mean fluence rate (E) equal to or greater than the result of equation 17 while the area-based UVC$_{254}$ criterion would provide mean fluence rate (E) equal to or less than the result of equation 17. Equation 17 assures mean fluence rate (E) in a room like that found in Mphalele (13,14). Equation 17, with all the previous assumptions noted, may be used as the starting point for luminaire selection in the design cycle to implement an upper-room UVC$_{254}$ system.

CONCLUSION

Assumptions of steady-state conditions and perfect mixing are not realistic assumptions for real-world applications. People may not be generating infectious aerosols at the same rate at all times nor do many facilities have perfect air mixing. Near perfect air mixing can be achieved using auxiliary room fans and/or ventilation supply diffusers. In addition, poor implementation room mixing fans and poor diffuser designs may adversely affect the containment or protective attributes of a room. In addition, room mixing fans may adversely impact infection prevention and control practices in traditional and nontraditional healthcare settings. These parameters will be discussed in a companion paper.

Figures 1–4 demonstrate that there is a limit beyond which additional vertical airspeed (S) provides minimal additional benefit. "Fast" fan speeds may cause discomfort due to drafts.
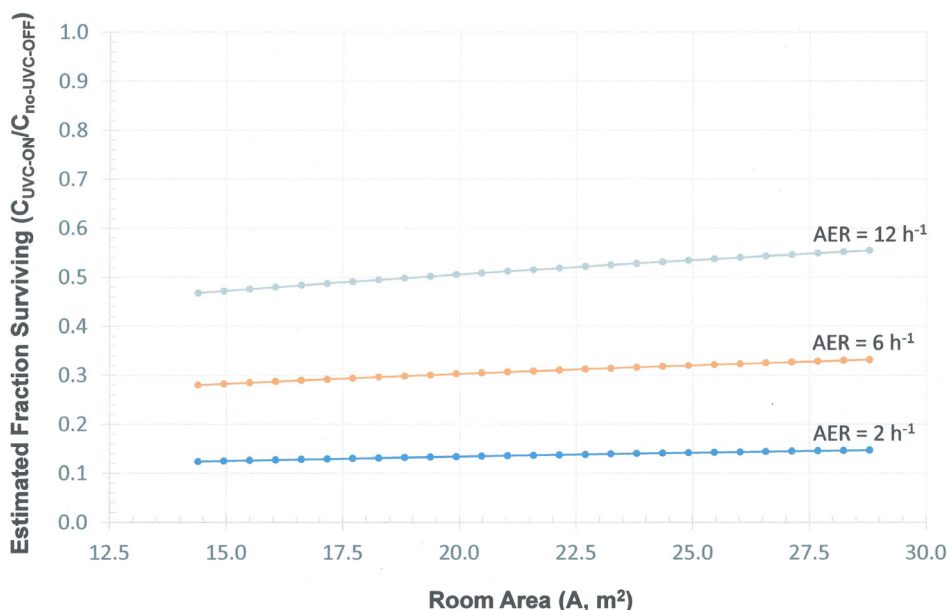
Figure 6. Estimated fraction surviving ($C_{\text{UVC-ON}}/C_{\text{UVC-OFF}}$) *vs* room area ($A_{\text{ROOM}}$) = 14.4–28 m^2). Ceiling height (H_{ROOM}, 2.6 m); room volume (V_{ROOM}, 37–75 m^3); vertical airspeed (S, 0.10 m s^{-1}); mean fluence rate (E, 0.050–0.036 W m^{-2} [5.0–3.6 µW cm^{-2}]); luminaire UVC$_{254}$ power (W, 0.71 W); air exchange rate (λ_{M}, 2, 6 and 12 h^{-1}).
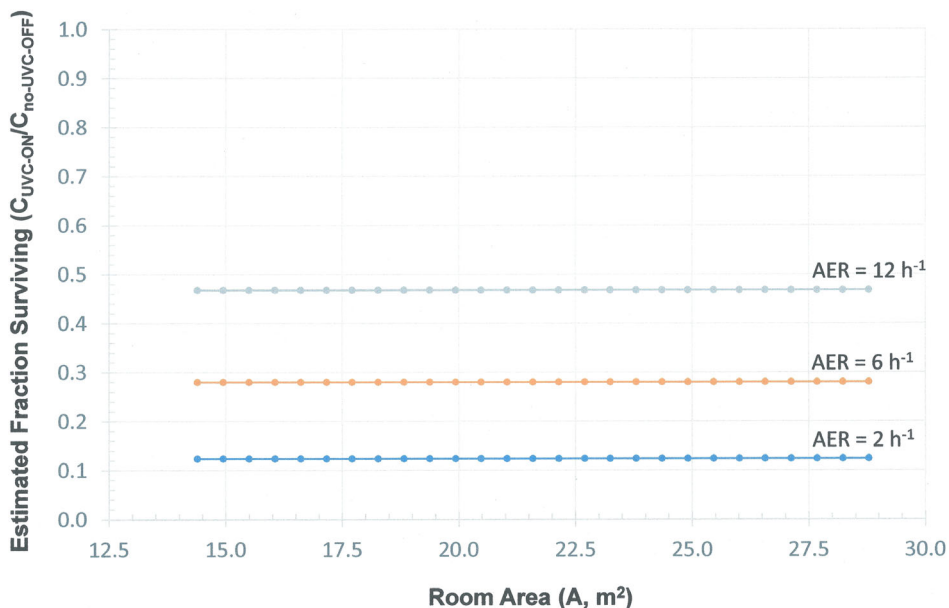
Figure 7. Estimated fraction surviving ($C_{\text{UVC-ON}}/C_{\text{UVC-OFF}}$) *vs* room area ($A_{\text{ROOM}}$) = 14.4–28 m^2). Ceiling height (H_{ROOM}, 2.6 m); room volume (V_{ROOM}, 37–75 m^3); vertical airspeed (S, 0.10 m s^{-1}); mean fluence rate (E, 0.050 W m^{-2} [5.0 µW cm^{-2}]); luminaire UVC$_{254}$ power (W, 0.71–1.00 W); air exchange rate (λ_{M}, 2, 6 and 12 h^{-1}).

Figures 5 and 7 demonstrate that when the mean fluence rate (E) is constant, estimated fraction surviving ($C_{\text{UVC-ON}}/C_{\text{UVC-OFF}}$) decreases with increasing ceiling height (H_{ROOM}); however, effectiveness is constant as room area (A_{ROOM}) increases. Thus, effectiveness is not linearly proportional to mean fluence rate (E) and room volume (V_{ROOM}).

Both the volumetric dosing criterion (W/V_{ROOM}) and the area dosing criterion (W/A_{ROOM}) may be adequate starting points to enumerate the make, model and number of UVC$_{254}$ luminaires for a room. However, a more accurate method would be to select a desired mean fluence rate (E) and allow a CAD program to iteratively quantitate the number and location of UVC$_{254}$ luminaires.

Additionally, the mean fluence rate is not the simple relationship of luminaire output (W) and room volume (V_{ROOM}) or room area (A_{ROOM}); rather, it is a function of the luminaire output (W) divided by the product of the square root of the room area (A_{ROOM}) and the ceiling height (H_{ROOM}) or the luminaire output (W) divided by the square root of the product of the room volume (V_{ROOM}) and ceiling height (H_{ROOM}). Again, the dosing

criterion is not simply based on one-dimensional criterion of a room; rather, it is the fluence rate (E).

In summary, average fluence rate (E) and the mean vertical airspeed (S) are critical design parameters when dosing a room with UVC_{254}. Use of a UVC CAD program is necessary to fine-tune the design and final performance testing is necessary to ensure a safe environment for the room occupants and sufficient UVC_{254} in the upper room to inactivate microorganisms and viruses at the desired rate.

Further evaluation of the effectiveness index (E) is needed, particularly in other rooms with other geometries and sizes. A simple and affordable method to assess the vertical airspeed (S) must be identified and evaluated. The accuracy of volume-based and area-based UVC_{254} dosing criteria needs to also be evaluated in other rooms with other geometries, dimensions, volumetric air-flow rates (λ_M) and mixing conditions.

Some engineers have raised the issue of alternative dosing criteria for "high" ceilings. None of the proposed dosing criteria consider other factors within the room that might positively or negatively affect the actual mean fluence rate. For example, what is the actual reflectance of various surfaces? How will various objects (TVs, room furnishings, illumination fixtures, etc.) influence the actual mean fluence rate? These questions are critical as the next step in the design cycle is to evaluate the preliminary make, model and quantity of luminaires using a UVC_{254} CAD program. As with any CAD or non-CAD modeling, the "proof" is in the details and assumptions.

Part 2 of this series will include more detail on ceiling height, ray length, air mixing and CAD programming.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article:

Appendix S1. Nomenclature.

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