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Bare-bulb Upper-Room Germicidal Ultraviolet-C (GUV) Indoor Air Disinfection for COVID-19[†]

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ABSTRACT

Reliable indoor air disinfection could make clinical and other necessary indoor spaces safer during epidemics with airborne transmission like COVID-19. Low-dose upper-room germicidal ultraviolet-C (GUV 254 nm) is well suited for this because of the SARS-CoV-2 virus' sensitivity to GUV inactivation and GUV's relatively easy adaptability to many types of indoor spaces without respect to outside weather conditions. However, most existing upper-room GUV fixtures are relatively expensive and inefficient at creating an upper-room disinfection zone due to loss of disinfecting UV-C photons caused by the casing and louvers designed to protect persons in the occupied space. Presented herein are two moderate-size restaurant spaces, 900 ft^2 (83.6 m^2) and 630 ft^2 (58.5 m^2), respectively, in which low-cost bare-bulb GUV fixtures, without exterior casing, were installed with upward-pulling ceiling fans to provide upper-room disinfection and lower-room safety. Proper safety-tested installations like these are adaptable to hospital emergency department waiting rooms, clinics, nursing home and prison common areas, public libraries, schools and restaurants.

INTRODUCTION

Indoor air photo-disinfection with low-dose upper-room germicidal ultraviolet-C (GUV 254 nm) of susceptible coronaviruses, for example, SARS-CoV-19 (1,2), and Mycobacterium tuberculosis (3,4), is a fundamental tactic, a part of environmental strategies for source control during outbreaks and epidemics with airborne components. Like most single tactics, it is insufficient by itself to achieve the strategic objective and should be understood as part of a multitiered approach. Further, it has up-front and ongoing requirements to be safe and effective that are not auto-fulfilling and its resource requirements must be weighed against those of other tactics.

There are substantial concerns and knowledge gaps among public health practitioners and managers of indoor public space regarding using GUV, for example, that it is unsafe to use with persons in a room because it causes cataracts and skin cancer (5). They weigh other tactics such as outdoor air ventilation and high-efficiency particulate air (HEPA) filtration for desired goals of speed of air disinfection, microbe-inactivation efficiency and cost-effectiveness. If aspects of GUV appear onerous or relatively ineffective, they may dismiss it entirely. This is the situation at present, with closing of societally important institutions like schools and public libraries and persisting dangerous conditions in common areas of many nursing homes and prisons, as well as emergency department waiting rooms and outpatient hemodialysis centers, for example.

This report describes two types of simple inexpensive GUV installations, each with two substantial advantages over typical installations: higher disinfection efficiency and lower cost. Previous typical installations feature one or more GUV shielded fixtures with low-pressure mercury tubes (bulbs) and supporting ballast encased within a structure designed for mounting high in the room and protecting persons in the occupied space below by louvers. Despite parabolic reflective mirrors and optimized polishing, efficiency, defined as total UV-C wattage output divided by input wattage (wall-plug efficiency), is typically between < 1 and 6% (4) . However, the bare bulb(s) with ballast within such fixtures have approximately 20% efficiency and cost one-fifth, about $200. This report describes how these much more efficient and far less expensive bare-bulb approaches can be safely and effectively installed by knowledgeable persons where conditions permit.

MATERIALS AND METHODS

Bare-bulb GUV with upward-pulling ceiling fans was installed in different ways in two restaurant spaces. In the first restaurant, the space measured 50 × 18 ft (15 × 5.5 m) with a suspended ceiling at 8.5 ft (2.6 m; volume 7650 ft^3, 214 m^3), with a 14 to 24-inch (36–60 cm) attic above that. The attic ceiling was covered with nonreflective black fabric, the suspended ceiling tiles replaced with black perforated (83% air space per tile) eggcrate tiles (Intersource Co, Plymouth WI), and four 8 W 254 nm UV-C bare bulbs with ballast (output 1.6 W each, Atlantic Ultraviolet, Hauppauge NY) were installed on the walls at mid-height in the attic height space at intervals around the perimeter, with aluminum foil-on-cardboard reflectors above and below each. Black fabric was laid 2 × 2 ft (0.6 × 0.6 m) on the tiles underneath the UV fixtures to prevent direct radiation below. Four ceiling fans were installed, switched to pull air up (Fig. 1). With the fixtures on for 20 min, a calibrated ILT 2400-UVGI radiometer (ILT, Peabody MA) was used to measure UV-C dose above the tiles 4 ft orthogonal from the bulbs in the horizontal plane. Safety measurements were obtained below the eggcrate, 6 ft

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Figure 1. Low-dose upper-room germicidal ultraviolet with eggcrate ceiling. Perforated ceiling tiles are removed to show two of the four 1.6-W output UV-C fixtures. Faint blue light emitted in the visible range from germicidal UV fixtures is seen near-left and far-right and ceiling fan blades are evident. Red arrows point to the bare GUV bulbs above the eggcrate.

(1.8 m) above the floor and 4 ft (1.2 m) orthogonal to each fixture and at the room approximate center. These horizontal- and vertical-plane measurements 6 ft (1.8 m) above the floor were recorded but without hooding typically used to mimic eyelids, using the highest measurement obtained in 360-degree turns.

In the second restaurant space of 35 × 18 ft (10.7 × 5.5 m), there was a 14 ft (4.3 m) nonreflective black painted ceiling and no suspended ceiling. An 8-W bare-bulb fixture was placed horizontally on each of three walls approximately 9 ft above the floor (2.7 m; volume 5670 ft^3, 159 m^3) with aluminum foil-covered cardboard above. Under each was centered a "lower lip" 2 ft wide and 1 ft deep, with reflective aluminum upper surface, extending into the room upwards at approximately a 25-degree angle, such that the upper edge of the bulb was not visible to a person standing anywhere in the room. The inside angles where the up-sloping lower lip met the wall under the UV-C fixture were covered with small pieces of black felt. Three upward-pulling ceiling fans were installed approximately midline and evenly spaced down the 35 ft length (Fig. 2). Measurements were made as described in the first space above.

RESULTS

In the first described space with the eggcrate perforated suspended ceiling, averaged calculated dosing rate from the four 1.6-W bulbs for the entire space (6.4 W for 7650 ft^3) was 837 μW ft^{-3}, 24 μW m^{-3}, in the range recommended for tuberculosis air disinfection by a South African governmental-World Health Organization-Centers for Disease Control and Prevention consortium (4). Measurements above the eggcrate ranged from 28 to 80 μW cm^{-2}, similar to the 37 μW cm^{-2} irradiance shown to reduce an airborne coronavirus (murine hepatitis virus) by 88% in 16 sec (1). However, in the occupied area below, dose rates were 2–30 nW cm^{-2}, well below the 200 nW cm^{-2} time-weighted average irradiance limit recommended for 254 nm radiation during an 8-h work day (6,7).

In the second restaurant space without eggcrate, 4.8W total UV-C output from three fixtures in 5670 ft^3, 159 m^3, resulted in an average dose rate of 847 μW cm^{-2}. Fluence rate measurements 9 ft (2.7 m) from the floor and 4 ft (1.2 m) orthogonal to the fixture centers ranged from 74 to 100 μW cm^{-2}. Safety measurements 6 ft (1.8 m) above the floor 4 ft (1.2 m) orthogonal to the plane of the fixtures were 24–59 nW cm^{-2} in the vertical and 20–24 nW cm^{-2} in the horizontal planes. As in the first restaurant, these irradiances were below the 200 nW cm^{-2} time-weighted average irradiance limit.

Figure 2. Bare-bulb germicidal ultraviolet lower-lip installation. Ballast with bare bulb affixed to wall with reflecting up-sloping lower-lip underneath to shield occupied space from direct UV-C photons. Limited blue light in the visible spectrum emitted from the fixtures is seen above and a ceiling fan in the foreground. A red arrow points to the location of the hidden bulb behind the up-sloping lower lip.

DISCUSSION

Upper-room bare-bulb GUV fixtures produced dose rates in the inactivating range for coronavirus (and tubercule bacilli) above the inexpensive suspended eggcrate ceiling setting (8,9), as well as when installed with a reflective lower lip below to obscure bulb view from the occupied space. In each setting, although exposure of sufficient duration to the fluence rates in the upper space could cause temporary human skin and eye injury, quite safe UV-C fluence rates were measured in the occupied space below. The four UV-C fixtures in the first setting cost $748 while in the second setting, three fixtures plus lower lips cost $620, both costs before tax and shipping. In each restaurant, the bare-bulb fixture costs provided more upper-room GUV irradiance at lower cost than the cost of a single far less efficient louvered fixture, $900–$1600. Ceiling fans (both installations) and eggcrate tiles (the first) are inexpensive but there is one-time installation cost also. Altogether, the GUV disinfection lamps, ceiling fans and switches for these moderate-sized indoor spaces were easily installed at low cost in a few hours.

With the recent report of an unmasked Korean restaurant patron becoming SARS-CoV-2-infected with just a 5-min exposure at 20 feet distance (10), indoor space managers and public health practitioners are seeking not merely inactivating pathogenic microbes indoors, but speediest possible inactivation. Completeness of UV-C microbe inactivation over time is affected by fluence rate intensity, which can depend on distance from the UV-C source, and duration of exposure. Modeling coronavirus' very high susceptibility to airborne inactivation (11) with different outdoor air room ventilation rates resulted in estimating 90% inactivation with 4 air changes per hour in just 2.4 min by just 4 μW cm^{-2}. In contrast, lower intensity dosing such as 1 μW cm^{-2} from a less efficient fixture would result in just 50% inactivation in that time interval. Providing regions of higher UV-C dose (fluence rates) in more regions of the upper-room disinfection zone is predicted to inactivate more infectious virus faster than lower doses whatever a room's air changes per hour. Moreover, since UV-C photons diffuse and dissipate as they hit molecules, a moderate-size room with a single low-efficiency high-cost louvered fixture in one location will have a smaller zone of high-dose rapid microbe inactivation than multiple inexpensive fixtures separated by spatial intervals, where their emitted photons can inactivate microbes over a greater upper-room surface area, for a great deal less cost.

Other than the certainty that moving air in the room is important to increase the probability of a pathogenic microbe encountering sufficient UV-C to inactivate it, how this is best accomplished can vary. While a microbial source beneath an upward-pulling fan produces the best efficacy (9), central ceiling fans or conditioned air blowing down might be superior where possible pathogen sources sit along the room's far walls where air would be expected to rise. Each setting will differ somewhat depending upon if and where outside air is intermittently or continually introduced, how air is moved in the room and the pathogen burden introduced. Exhaled air, warmed to body temperature and humidified, will tend to rise even in a partially conditioned indoor space, favoring exposure to upper-room GUV that can be enhanced or hindered by existing or introduced fan-driven ventilation.

The practical applicability of installing such inexpensive bare-bulb fixtures with inexpensive upward-pulling ceiling fans is appealing. Suppressing COVID-19 transmission by disinfecting indoor public spaces with upper-room low-dose germicidal UV-C is a safe, easy and inexpensive retrofit applicable to a variety of community settings. However, the protective armor surrounding the bare bulbs in typical "extra-safe" GUV fixtures impairs disinfection efficiency and adds expense. The fundamentals of safe and optimized upper-room GUV are easily learned; trained installers of less armored cheaper fixtures could easily help spread this technology. Hospital and other clinical setting infection control specialists, as well as public health practitioners, can generalize this information in hospitals to emergency departments, ICUs, outpatient hemodialysis centers, clinics, common spaces in nursing rehabilitation facilities, as well as houses of worship, prisons, classrooms and restaurants, adding public space indoor air disinfection to existing COVID-19 control measures.

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REFERENCES

1. Walker, C. M. and G. Ko (2007) Effect of ultraviolet germicidal irradiation on viral aerosols. *Environ. Sci. Technol.* **41**, 5460–5465.
2. Bianco, A., M. Biasin, G. Pareschi, A. Cavalieri, C. Cavatorta, C. Fenizia, P. Galli, L. Lessio, M. Lualdi, E. Redaelli, I. Saulle, D. Trabattoni, A. Zanutta and M. Clerici (2020). UV-C irradiation is highly effective in inactivating and inhibiting SARS-CoV-2 replication. medRxiv doi: https://doi.org/10.1101/2020.06.05.20123463
3. Nardell, E. A., S. J. Bucher, P. W. Brickner, C. Wang, R. L. Vincent, K. Becan-McBride, M. A. James, M. Michael and J. D. Wright (2008) Safety of upper-room ultraviolet germicidal air disinfection for room occupants: Results from the Tuberculosis Ultraviolet Shelter Study. *Public Health Rep.* **123**, 52–60.
4. Mphaphlele, M., A. S. Dharmadhikari, P. A. Jensen, S. N. Rudnick, T. H. Van Reenen, M. A. Pagano, W. Leuschner, T. A. Sears, S. P. Milonova, M. van der Walt, A. C. Stoltz, K. Weyer and E. A. Nardell (2015) Institutional tuberculosis transmission. Controlled trial of upper room ultraviolet air disinfection. *Am. J. Respir. Crit. Care Med.* **192**, 477–484.
5. Brenner, D., TED (2017) A new weapon in the fight against superbugs. https://www.ted.com/talks/david_brenner_a_new_weapon_in_the_fight_against_superbugs?language=en, 4:00 to 6:00. Accessed 26 December 2020.
6. Sliney, D. (2013) Invited review: Balancing the risk of eye irritation from UV-C with infection from bioaerosols. *Photochem. Photobiol.* **89**, 770–776.
7. International Commission on Illumination technical report: UV-C photocarcinogenesis risk from germicidal lamps, 2010. http://files.cie.co.at/cie187-2010%20(free%20copy%20March%202020).pdf. Accessed 15 September 2020.
8. Linnes, J. C., S. N. Rudnick, G. M. Hunt, J. J. McDevitt and E. A. Nardell (2014) Eggcrate UV: A whole ceiling upper-room ultraviolet germicidal irradiation system for air disinfection in occupied rooms. *Indoor Air* **24**, 116–124.
9. Rahman, S. F., S. N. Rudnick, S. P. Milonova, J. J. McDevitt and E. A. Nardell (2014) Influence of bioaerosol source location and ceiling fan direction on eggcrate upper-room ultraviolet germicidal irradiation. *Br. J. Appl. Sci. Technol.* **4**, 3856–3861.
10. Kwon, K.-S., J.-I. Park, Y. J. Park, D.-M. Jung, K.-W. Ryu and J.-H. Lee (2020) Evidence of long-distance droplet transmission of SARS-CoV-2 by direct air flow in a restaurant in Korea. *J. Korean Med. Sci.* **35**, e415.
11. Beggs, C. B. and E. J. Avital (2020) Upper-room ultraviolet air disinfection might help to reduce COVID-19 transmission in buildings: a feasibility study. *PeerJ* **8**, e10196.