**Special Issue Research Article**

**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's 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-cost bare-bulb GUV 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.

**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.

**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 ft³, 214 m³), 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 above the tiles.
The three walls are approximately 9 ft above the ceiling. An 8-W bare-bulb fixture is shown to reduce an airborne coronavirus (murine hepatitis virus) by 28 to 80 µW m\(^{-2}\), 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 above, dose rates were easily installed at low cost in a few hours. Altogether, the GUV disinfection lamps, plus lower lips 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 lowered 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 $\mu W \, \text{cm}^{-2}$. In contrast, lower intensity dosing such as 1 $\mu W \, \text{cm}^{-2}$ 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 retrofittable 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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