Far-UVC: Technology Update with an Untapped Potential to Mitigate Airborne Infections

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Clinicians and patients spent the fall and winter of 2022 grappling with the triple surge of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), influenza, and respiratory syncytial virus. Meanwhile, a host of zoonotic diseases await the inevitable mutations that could fuel human-to-human transmission and the next pandemic. Because respiratory infections are transmitted through shared indoor air, strategies for prevention should embrace effective modalities for cleaning indoor air. As an analogy, we don't rely on vaccines to prevent waterborne illness, even though there is a vaccine against cholera: We rely on effective water treatment to provide safe drinking water that is free of the spectrum of disease-causing microbial agents. We should take a similar engineering approach to shared indoor air spaces.

Existing technologies include air filtration, ventilation, and application of ultraviolet (UV) germicidal irradiation, now called germicidal UV light (GUV). These modalities have a proven track record for safely reducing airborne pathogen exposure, with benefits that complement and are of similar magnitude as masking and vaccination (1, 2). An air change (AC) occurs when the volume of outdoor, infection-free air enters and leaves a room. A common measure of ventilation is ACs per hour (ACHs). Because new and old air mix, one AC removes ~63% of room air contaminants. An equivalent AC because of GUV or filtration represents the inactivation or removal of 63% of pathogens from a room, and equivalent air changes per hour (eACH) standardize the rate of air cleaning by ventilation, filtration, or GUV. GUV can reduce pathogens as measured by eACH more effectively than ventilation and filtration, because these depend on dilution with outside air.

Since its inception nearly a century ago, UVC at a wavelength of 254 nm has been used and is recommended by the CDC to reduce airborne pathogen transmission in hospitals, schools, and homeless shelters (3–5). Newer LED GUV (currently 265–270 nm) will eventually replace 254-nm mercury light sources. However, sources of 254 and 265–270 nm GUV must be kept overhead to avoid direct overexposure resulting in short-term keratoconjunctivitis and erythema (6). Although UVA and UVB in sunlight are recognized causes of cataracts and skin cancer, UVC, with shorter wavelengths and higher energy is so biologically active that it is mostly absorbed before reaching the lens or the deep basal layer of skin (where skin cancers originate). The technological breakthrough of even shorter wavelength, or ultraviolet-C light with germicidal effect, with wavelengths typically ranging 200–230 (far-UVC) (222 nm), is yet more biologically active and absorbed in the tear layer of the eye or the stratum corneum of the skin, theoretically eliminating even short-term adverse effects. This allows the use of far-UVC directly in occupied spaces, offering more efficient air disinfection where people breathe, speak, and cough (Figure 1).

In the laboratory, 222 nm UVC is as effective a germicide as 254 nm GUV—including against *Mycobacterium tuberculosis*, SARS-CoV-2, and influenza (7). A single, upper-room GUV fixture delivered the equivalent of 18–110 eACH, depending on the susceptibility of the test microbe and relative humidity (3), whereas a single far-UVC fixture delivered 33–66 eACH (8). Even the lower range of effectiveness with more robust pathogens corresponds to more efficient air cleaning than is feasible with ventilation and filtration.

Compared with 254 nm, 222 nm far-UVC inactivates viral aerosols through a dual mechanism that damages protein and nucleic acid structures, suggesting the potential for the improved disinfection effectiveness of 222 nm far-UVC over both 254- and 265- to 270-nm systems. Far-UVC can be applied across a broader range of indoor settings and closer to

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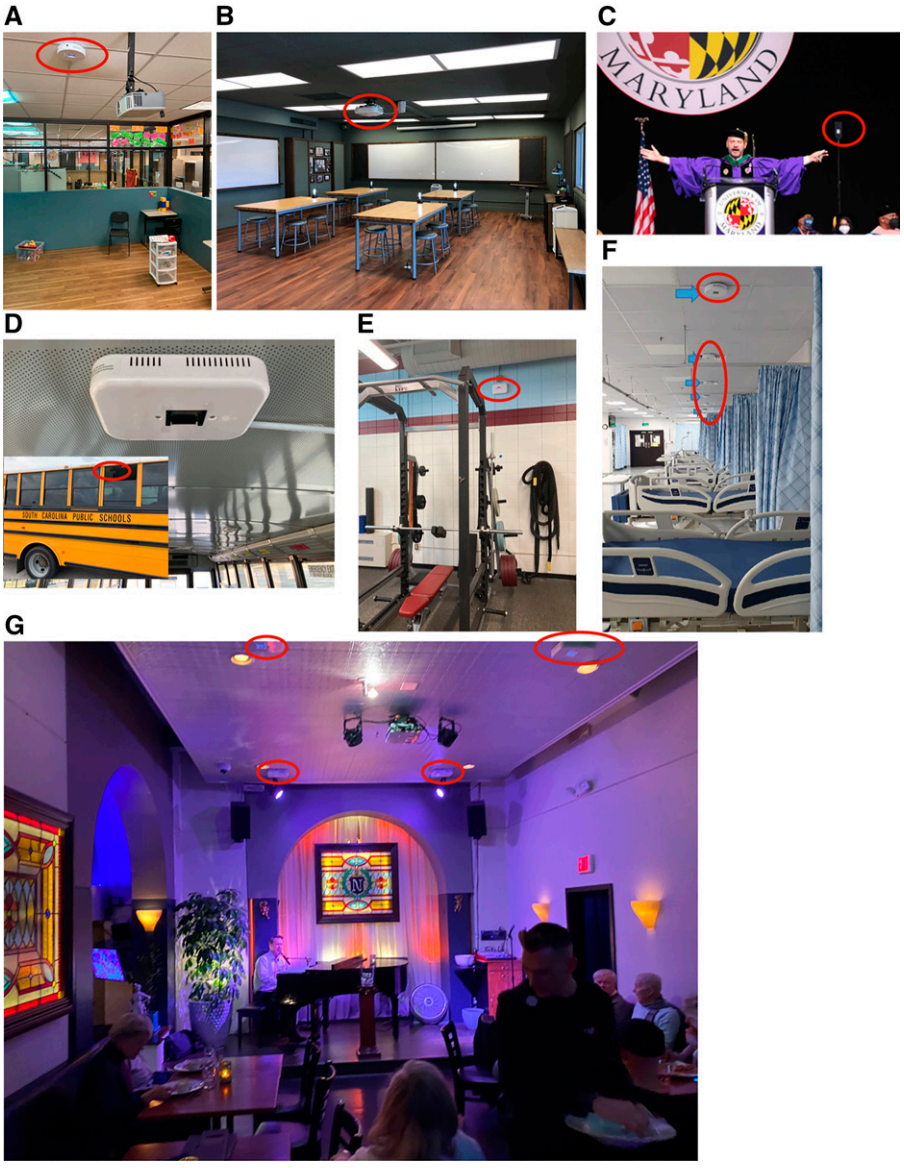

Figure 1. Images of 222 nm germicidal ultraviolet radiation deployed in indoor settings. Red circles indicate fixtures. (*A*) Child care setting. (*B*) Classroom. (*C*) University commencement ceremony. (*D*) School bus. (*E*) Workout room. (*F*) Healthcare setting. (*G*) Nightclub. Images (*A*)-(*F*) used with permission by PJ Piper.

breathing zones, making them potentially useful in public transportation and other settings while offering better protection from infectious transmission from nearby room occupants.

Effective, energy-efficient air disinfection is a critical public health need. The three available technologies—ventilation, filtration, and GUV—vary greatly in their practical capacity to interrupt the airborne transmission of pathogens. Ventilation and filtration improve air quality and offer some protection against infection but, in many scenarios, may not produce sufficient levels of equivalent ventilation to reduce transmission (9, 10). GUV (whether upper room 254 nm or far-UVC 222 nm) provides the high eACH range needed to address airborne pathogens that are shed at high quanta emission rates (e.g., 5,000 quanta per hour for measles or 1,000 quanta per hour for SARS-CoV-2) (9). Increased air disinfection with GUV reduces inhalation exposure to infectious aerosols; the risk of infection; and, potentially, the severity of infections that do occur (11). Although well-functioning heating, ventilation, and air conditioning systems are essential, GUV provides enhanced protection at a sustainable cost (12, 13).

Laboratory toxicology studies have consistently demonstrated the safety of properly filtered 222 nm GUV. Highly susceptible hairless mice that were exposed to far-UVC for 8 h/d, 5 d/wk, for 66 weeks (which is considered long-term exposure for mouse studies) did not develop skin abnormalities any more frequently than unexposed mice or those that were exposed to lower doses (14). After repetitive high-dose exposure to 222 nm UVC, hairless mice that were susceptible to skin cancer because of xeroderma pigmentosum knockout developed few DNA dimers in the upper epidermis, no elevation in the chemokine CXCL1 involved in carcinogenesis, no ear swelling, no corneal damage, and no tumor formation, whereas mice that were exposed to lower doses of 254 nm UVC or UVB developed elevated markers of inflammation and carcinogenesis and tumors (15). Studies that exposed human skin models or human volunteer skin showed similarly low cytotoxicity (16, 17). Studies examining skin and eye effects across age groups and among those with sensitive skin or dry eyes found no significant difference in susceptibility to any potential adverse health effects from far-UVC exposure (18).

Other health and environmental concerns have been raised with regard to 222 nm GUV, including the potential generation of ozone or other inhalational toxicants. Investigation of photochemistry found that using 222 nm GUV could lead to the formation of ozone, radicals, volatile organic compounds, and secondary organic particulates, emphasizing the importance of maintaining ventilation standards to remove typical levels of indoor and outdoor air contaminants (19). Thus far, secondary chemistry studies are limited to highly controlled chamber studies. Real-world measurements under different use scenarios coupled with the assessment of health outcomes would provide useful information to confirm the findings of the controlled studies and determine the magnitude of ozone and secondary toxicant generation.

Concerns have been raised about eliminating inhalational infections in young children, potentially making them more immunologically susceptible to later infections and asthma. Research can be performed to test this variant of the hygiene hypothesis, but the close contact among young children in day care, school, and other settings makes

elimination of viral transmission unlikely. Reducing exposure to rhinovirus in early life may help prevent viral infection–associated asthma exacerbations in school-age children (20). Concerns have also been raised about altering the skin microbiome by using far-UVC. However, only a fraction of skin is exposed to GUV when used in indoor environments, and the microbial disruption is likely far less than the impact of bathing.

The safety profile of properly filtered 222-nm doses of GUV is encouraging, and widespread application in indoor spaces would reduce infection risk. Priority spaces for application include congregate settings such as health care, schools, grocery stores, public transportation, restaurants, bars, and occupational settings that place workers in proximity with each other or the public. Guidelines on the application of upper room GUV exist, and new guidelines are expected soon from the American Society of Heating, Refrigerating and Air-Conditioning Engineers. Although the use of 222 nm GUV is widespread, formal application guidelines are not yet available.

The following research and development points should be prioritized:

1. Engineering and manufacturing research to improve availability and reduce costs.
2. Postinstallation dynamic dose monitoring with UV-sensitive film badges.
3. Field-condition active surveys for skin and eye complaints.
4. In-use room chemistry studies.
5. Ongoing clinical studies to address intervention effectiveness, as well as any associated adverse outcomes.
6. Public communication and engagement research to better promote correct, widespread adoption.

The emergence of far-UVC offers a game-changing approach to controlling community transmission of airborne infections in shared indoor settings. Environmental control of airborne pathogens provides widespread population benefit against a variety of respiratory infections that are responsible for millions of deaths per year. We advocate for a greater level of investment in GUV—far-UVC, in particular—and a sense of urgency. Although coronavirus disease (COVID-19) is no longer a World Health Organization global health emergency of public concern as of May 2023, the infection and other airborne viruses continue to spread, and other pandemics will follow. ■

Author disclosures are available with the text of this article at www.atsjournals.org.

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