Photochemistry and Photobiology, 2021, 97: 464–465

Editorial

Air Disinfection with Germicidal Ultraviolet: For this Pandemic and the Next

Germicidal ultraviolet (GUV) air disinfection (also referred to as Ultraviolet Germicidal Irradiation or "UVGI"), as a control method for the transmission of airborne pathogens, has been used for more than 80 years. In 1942, upper-room GUV (disinfecting the room air by irradiating the air space above head height with air mixing) with 254 nm low-pressure mercury lamps was used very effectively to reduce the transmission of measles (the most infectious virus known) in two Philadelphia suburban schools (1–4). More recently, in the 1980s, it was also common to find UV luminaires in hospital emergency rooms, clinics, waiting rooms and operating theaters, primarily due to a global resurgence of drug-resistant tuberculosis (5). Unfortunately, interest in UV air disinfection waned primarily because drugs and vaccines became available for airborne bacterial and viral diseases such as tuberculosis, measles, mumps and chicken pox (6). However, research continued, leading to significant advances; confirmation of the efficacy and safety of upper-room GUV, new studies with ultraviolet radiation in the wavelength region 200 to 230 nm (dubbed "far-UVC") and development of ultraviolet-C (UVC) light-emitting diodes (LEDs).

It is clear that aerosols are an important, if not dominant, route for SARS-CoV-2 transmission (7–11). Therefore, it is time once again to implement GUV air disinfection, with upper-room GUV still the most cost-effective way to disinfect large volumes of room air as an effective and safe control measure when installed properly and people are properly trained regarding its use (12–15). Furthermore, whole room GUV with UVC wavelengths less than 230 nm shows great promise. GUV is a "behavior independent" control measure, meaning it does not rely upon the behavior of people, for example, social distancing, cough hygiene or mask wearing.

Due to its mode of action, damaging ubiquitous nucleic acids, GUV can inactivate not just SARS-CoV-2 but also its mutated variants and a wide-range of pathogens including drug-resistant bacteria (16,17). For that reason, it is also likely to be effective against the next pandemic, whatever the pathogen. As UV inactivates pathogens by causing genetic mutations, concerns periodically arise that UV exposure could contribute to more infectious, more pathogenic or more drug-resistant pathogens. However, it is unchecked replication of virus in human populations, something which GUV is specifically designed to limit, that results in far more mutations than external exposure to GUV.

However, appropriate deployment of GUV is critical. Whilst upper-room GUV radiation is highly effective for air disinfection, in contrast, walk-through UV portals and UV wands are subject to much greater challenges for surface disinfection and are also less likely to be effective. Marketing of such devices is often exaggerated, supported with scant unpublished data on safety and efficacy and, of course, they are not designed for tackling airborne transmission, an important mode of Covid-19 spread. Much larger UV exposures are required and the realities of the real world, such as macro and micro-shadows in materials and absorption by dirt and oils, are barriers to GUV being the primary surface disinfection technique. This has been known in the healthcare community for some time, where UVC surface decontamination is successfully deployed as an adjunct to manual cleaning (18).

Implementation barriers for GUV include concern about the adverse health effects from exposure, but this is only an issue when the technology is misapplied. Upper-room GUV has been shown to be safe when fixtures are well-designed, properly installed, checked for safe exposure levels before being activated and properly maintained. A major attraction of UVC wavelengths below 230 nm is its frequently equivalent efficacy compare with 254 nm UVC but it is characterized by limited penetration in tissue due to its shorter wavelength (19–21). This suggests that such sources, exemplified by krypton chloride (KrCl) lamps, particularly if modified to remove energy above 230 nm, can be used to inactivate airborne microbes throughout occupied spaces while not posing a health hazard to workers in the lower room (14,22–24). Similarly, the limited penetration depth by 254 nm radiation from low-pressure mercury GUV lamps will not pose a health hazard if the in-room exposures are kept within safe levels (25).

Whilst it is undeniable that improved ventilation should be a first-line measure, in a significant proportion of buildings or transport vehicles, increasing ventilation effectiveness is not possible or is prohibitively expensive. Moreover, increasing ventilation produces declining increments in protection at escalating costs (26). In contrast, upper-room GUV systems are cost-effective and applicable to most settings with an effective ceiling height of at least 2.3 meters. In rooms with low ceilings of less than 2.3 meters, UVC wavelengths below 230 nm can be introduced as one alternative. Whilst UVC systems emitting below 230 nm are currently expensive and have limited lamp life, both these factors are likely to improve in the coming months and new technologies, emitting at the relevant wavelengths, will emerge.

From our past extensive experience in GUV applications, we support specific goals to resolve current safety concerns and expedite implementation of available and appropriate technology for GUV disinfection. They include:

1 Exploration and potential revision of exposure limits based upon recent studies including those in this Symposium in Print.

DOI: 10.1111/php.13424

2 Establishing guidelines and standards for the safe and effective installation, deployment and maintenance of GUV.
3 Effective training of installers along with independent certification of competent and compliant installation and maintenance of GUV.

GUV is an important and underused infection control measure. The potential benefit to health and the economy from a reduction in Covid-19 cases far outweighs risks of potential adverse health effects. Within well-established exposure limits, the risk of skin cancer and eye cataracts are vanishingly small, a tiny fraction of the risk from everyday exposure to the more penetrating ultraviolet-A and ultraviolet-B in sunlight (25). Overexposure to UVC is avoidable, but when it does occur, typically results in mild skin redness or eye irritation. Research on upper-room GUV and far-UVC will of course continue, but with the unprecedented severity of COVID-19 on health and global economy, we already know more than enough about the safety and efficacy of GUV to conclude that the benefit-risk balance is dramatically on the side of benefit.

REFERENCES

1. Wells, W. F., M. W. Wells and T. S. Wilder (1942) The environmental control of epidemic contagion. I. An epidemiological study of radiant disinfection of air in day schools. *Amer. J. Epi.* **35**, 97–121.
2. Wells, W. F. and M. W. Wells (1943) Dynamics of air-borne infection. *Amer. J. Med. Sci.* **206**, 11–17.
3. Wells, W. F. (1943) Air disinfection in day schools. *Am. J. Public Health Nations Health.* **33**, 1436–1443.
4. Wells, M. W. (1945) Ventilation in the spread of chickenpox and measles within school rooms. *J. Am. Med. Assoc.* **129**, 197–200.
5. 2013 Special Issue: Symposium in Print on Upper-Room Ultraviolet Germicidal Irradiation for Air Disinfection. *Photochem. Photobiol.* **89**, 763–1007.
6. Reed, N. G. (2010) The history of ultraviolet germicidal irradiation for air disinfection. *Public Health Rep.* **125**, 15–27.
7. Morawska, L. and D. K. Milton (2020) It is time to address airborne transmission of coronavirus disease 2019 (COVID-19). *Clin. Infect. Dis.* **71**, 2311–2313.
8. The Lancet Respiratory Medicine (2020) COVID-19 transmission—up in the air. *Lancet Resp. Med.* **8**, 1159.
9. World Health Organization (2020) Coronavirus disease (COVID-19): How is it transmitted? Available at: https://www.who.int/news-room/q-a-detail/coronavirus-disease-covid-19-how-is-it-transmitted. Accessed on 26 February 2021.
10. Centers for Disease Control and Prevention (2020) Scientific Brief: SARS-CoV-2 and Potential. Available at: https://www.cdc.gov/coronavirus/2019-ncov/more/scientific-brief-sars-cov-2.html. Accessed 26 February 2021.
11. National Academies of Sciences, Engineering, and Medicine (2020) *Airborne Transmission of SARS-CoV-2: Proceedings of a Workshop in Brief*. The National Academies Press, Washington, DC.
12. 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: a basis for new dosing guidelines. *Am. J. of Respir. Crit. Care Med.* **192**, 477–484.
13. Escombe, A. R., D. A. J. Moore, R. H. Gilman, M. Navincopa, E. Ticona, B. Mitchell, C. Noakes, C. Martinez, P. Sheen, R. Ramirez, W. Quino, A. Gonzalez, J. Friedland and C. Evans (2009) Upper-room ultraviolet light and negative air ionization to prevent tuberculosis transmission. *PLoS Medicine* **6**, e1000043.
14. Buonanno, M., D. Welch, I. Shuryak and D. Brenner (2020) Far-UVC light (222 nm) efficiently and safely inactivates airborne human coronaviruses. *Sci. Rep.* **10**, 1–8.
15. Illuminating Engineering Society (2020) IES Committee Report: Germicidal Ultraviolet (GUV) – Frequently Asked Questions. IES CR-2-2—V1.
16. Kowalski, W. (2009) *Ultraviolet Germicidal Irradiation Handbook: UVGI for Air and Surface Disinfection*. Springer, Berlin Heidelberg.
17. Ponnaiya, B., M. Buonanno, D. Welch, I. Shuryak, G. Randers-Pehrson and D. Brenner (2018) Far-UVC light prevents MRSA infection of superficial wounds in vivo. *PLoS One* **13**, e0192053.
18. Ramos, C., J. Roque, D. B. Sarmiento, L. Suarez, J. Sunio, K. Tabungar, G. Tengco, P. C. Rio and A. L. Hilario (2020) Use of ultraviolet-C in environmental sterilization in hospitals: A systematic review on efficacy and safety. *Int. J. Health Sci.* **14**, 52–65.
19. Buonanno, M., B. Ponnaiya, D. Welch, M. Stanislauskas, G. Randers-Pehrson, L. Smilenov, D. F. Lowy, D. M. Owens and D. J. Brenner (2017) Germicidal efficacy and mammalian skin safety of 222-nm UV light. *Radiat. Res.* **187**, 493–501.
20. Barnard, I. R. M., E. Eadie and K. Wood (2020) Further evidence that far-UVC for disinfection is unlikely to cause erythema or premutagenic DNA lesions in skin. *Photodermatol. Photoimmunol. Photomed.* **36**, 476–477.
21. Beck, S. E., R. A. Rodriguez, M. A. Hawkins, T. M. Hargy, T. C. Larason and K. G. Linden (2016) Comparison of UV-induced inactivation and RNA damage in MS2 phage across the germicidal UV spectrum. *Appl. Environ. Microb.* **82**, 1468–1474.
22. American Conference of Governmental Industrial Hygienists (2020) *TLVs and BEIs: Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices*. ACGIH Worldwide, Cincinnati, OH.
23. International Commission on Non-Ionizing Radiation Protection (2004) ICNIRP Guidelines on Limits of Exposure to Ultraviolet Radiation of Wavelengths between 180 nm and 400 nm (Incoherent Optical Radiation). *Health Phys.* **87**, 171–186.
24. Woods, J. A., A. Evans, P. D. Forbes, P. J. Coates, J. Gardner, R. M. Valentine, S. H. Ibbotson, J. Ferguson, C. Fricker and H. Moseley (2015) The effect of 222-nm UVC phototesting on healthy volunteer skin: A pilot study. *Photodermatol. Photoimmunol. Photomed.* **31**, 159–166.
25. International Commission on Illumination (2010) UV-C Photocarcinogenesis Risks from Germicidal Lamps. CIE Document 187.
26. Nardell, E. A., J. Keegan, S. A. Cheney and S. C. Etkind (1991) Airborne infection: theoretical limits of protection achievable by building ventilation. *Am. Rev. Respir. Dis.* **144**, 302–306.

Rolf Bergman[1], David Brenner[2], Manuela Buonanno[2], Ewan Eadie[3], Paul Donald Forbes[4], Paul Jensen[5], Edward A. Nardell[6], David Sliney[7], Richard Vincent[8], David Welch[2] and Kenneth Wood[9]*

[1]Rolf Bergman Consulting, Cleveland, OH
[2]Center for Radiological Research, Columbia University Medical Center, New York, NY
[3]Photobiology Unit, NHS Tayside, Ninewells Hospital and Medical School, Dundee, UK
[4]Toxarus, Inc., Malvern, PA
[5]Final Approach Inc., Port Orange, FL
[6]Harvard Medical School, Harvard School of Public Health, Boston, MA
[7]Department of Environmental Health Sciences, Johns Hopkins Bloomberg School of Public Health, Baltimore, MD
[8]General Internal Medicine, Icahn School of Medicine at Mount Sinai, New York, NY
[9]SUPA, School of Physics & Astronomy, University of St Andrews, St Andrews, UK