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Alexander Linder , Alexander Zhu , Richard Bruns , Paula Olsiewski , Gigi Gronvall *

Posted Date: 7 October 2024

doi: 10.20944/preprints202410.0392.v1

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FAR-UV Technology and Germicidal Ultraviolet (GUV) Energy: A Policy and Research Review for Indoor Air Quality and Disease Transmission Control

Linder AG, Zhu AW, Bruns R, Olsiewski P and Gronvall G *

Johns Hopkins Center for Health Security
* Correspondence: ggronvall@jhu.edu

Abstract: COVID-19 highlighted the challenges of public acceptance of public health measures, including mask-wearing and vaccination. which has spurred interest in engineered approaches to reduce infections. Germicidal Ultraviolet (GUV) Energy has been used for decades in hospital rooms to limit TB transmission, but it is expensive to install in the upper part of rooms where it may be used safely. In contrast, FAR-UV energy is a relatively new, flexible technology that can be set up in rooms for moderate costs, and studies thus far indicate it is efficacious and not damaging to eyes or skin. To examine the state of the field, experts in aerosol biology, infection control, and building engineering from academia, government, and industry were convened to inform policy recommendations for future investments, identify research required, and examine policy options for using these technologies. Despite its high efficacy for deactivating several types of microorganisms and pathogens of concern, before FAR-UV technologies may be widely deployed, additional studies are needed to understand potential adverse effects, as well as the best approaches to use, standardize, and regulate the technology. In some environments, the use of FAR-UV can generate ozone, which can react with volatile organic compounds that may be hazardous to human health, such as respiratory tract irritation. Even with these concerns, the demonstrated effectiveness in disease control of both FAR-UV and longer wavelengths of GUV deserve increased policy attention to reduce risks of indoor disease transmission. While potentially useful to counter disease in high-risk indoor environments, further standardization and regulatory measures, as well as research into the production of oxidative compounds is necessary before broad adoption of FAR-UV.

Keywords: indoor air qualtiy (IAQ); indoor environmental quality (IEQ); FAR-UV; GUV

Introduction

The COVID-19 pandemic highlighted the role of poor indoor air quality (IAQ) in furthering disease transmission and has led to calls to improve IAQ and indoor environmental quality (IEQ) to prepare for future pandemic preparedness. Reducing disease transmission indoors limits disease transmission and could provide time to develop effective countermeasures to a novel pathogen [1]. Increased awareness of the role IAQ has on health and disease transmission has resulted in a series of policy actions and recommendations to promote healthy indoor air and limit the spread of respiratory pathogens indoors [2]. The Biden-Harris Administration responded to the need for improved air quality by allocating $350 billion to the Coronavirus State and Local Fiscal Recovery Funds (SLFRF) program, as well as an additional $120 billion earmarked to improve air quality in schools. In tandem, the Centers for Disease Control and Prevention (CDC) developed recommendations that organizations, including employers and business owners, aim for 5 air-changes-per-hour (ACH) in their buildings to improve indoor air quality and prevent the spread of COVID-19 and other respiratory pathogens [3]. However, funding alone does not implement effective responses to disease transmission indoors. To successfully and sustainably implement

 doi:10.20944/preprints202410.0392.v1

measures to clean the air of respiratory byproducts and disinfect it from respiratory pathogens, policy coupled with engineered solutions are necessary.

Engineered solutions may prevent the spread of pathogens that transmit through the air, reducing disease transmission. Behavioral interventions - such as mask-wearing, social distancing, limiting time indoors, or vaccination - continue to receive pushback from the public, despite continued evidence supporting their effectiveness [4]. Engineering controls provide a proven, powerful, and unobtrusive means to increase public health. Engineered controls complement public health responses providing scalable and sustainable means to implement public health without needing to rely on individual compliance. Improving IAQ and reducing disease, engineering controls provide a continuous, resilient solution to create healthier indoor environments.

One engineering control proven effective to both clean indoor air and reduce the spread of respiratory pathogens is germicidal ultraviolet (GUV) energy, previously called ultraviolet germicidal irradiation. Producing a wavelength of 254 nm, GUV effectively kills pathogens and disinfects indoor environments [5], and has been successfully deployed in the upper room in a series of high-risk environments, such as hospital operating rooms, to reduce disease transmission, with particular success at countering TB [6]. Despite its effectiveness, GUV has not been broadly implemented in mass due the harm it can have on human tissues when they are over-exposed, causing sunburn (skin erythema) and external eye inflammation (photokeratitis and photoconjunctivitis) [7]. GUV fixtures require expert installation and maintenance to ensure inadvertent over-exposure does not occur; they may face regulatory standards adding to the costs of installation; and is difficult to retrofit the fixtures into older buildings. GUV at 254nm is usually deployed in the upper parts of rooms or in unoccupied spaces of specific buildings such as hospitals. While these concerns have limited the adoption of GUV as an engineering control, there is renewed interest in using fixtures that enclose GUV 254nm, drawing air through them to inactivate pathogens, reducing the risks of inadvertent exposure.

A new technology, FAR-UV, has the potential to expand the use of UV irradiation as a tool to counter respiratory pathogens transmission indoors and enhance indoor air quality. FAR-UV is a germicidal ultraviolet energy without the drawbacks of 254 nm GUV. Producing light between 200-235 nm [8], available evidence demonstrates how FAR-UV effectively kills respiratory pathogens with minimal or no nucleic acid or protein damage to human epithelial cells and eyes. [8–17]. Unlike GUV, FAR-UV energy fixtures do not require expert installation or maintenance, raising the possibility of mass adoption. FAR-UV is a potentially exciting new engineered solution to reduce indoor disease transmission, providing the benefits of GUV of improved IAQ and reduced disease transmission in more and novel spaces, at potentially lower costs and with less risk to human tissues.

Though initial studies of FAR-UV are promising, there are safety and efficacy questions that require additional research, particularly related to long-term exposure of human tissue to FAR-UV and the interactions of this higher-frequency energy with the indoor environment. To address these research gaps, with the support of Effective Giving, the OSLUV Project, and Blueprint Biosecurity, the Johns Hopkins Center for Health Security hosted a 1-day not-for-attribution meeting on February 27, 2024, in Washington, DC, convening 54 experts from academia, government, and industry to discuss current research about the effectiveness and use of FAR-UV; how FAR-UV compares to other technologies including GUV at 254nm; and any outstanding questions about safety efficacy, and feasibility for implementation. Experts presented on a range of topics, including, efficacy, the role of engineering controls, indoor chemistry considerations, energy efficiency, impacts on eyes, skin, and respiration, environmental effects, ozone and oxidation products, regulatory issues, and standards development. These plenaries were followed by moderated discussion. In this work, we explore the research areas discussed in the workshop, summarize the findings, and provide a commentary and recommendations for the implementation of FAR-UV and the regulatory frameworks surrounding this new technology.

 doi:10.20944/preprints202410.0392.v1

Findings

Topics included an overview of FAR-UV technology and remaining knowledge gaps; the impact of FAR-UV on human tissues; the environmental effects and indoor chemistry of FAR-UV; and the current regulatory environment for FAR-UV technologies. T

FAR-UV Reduces Concentrations of Bacteria and Viruses in Indoor Spaces with High Efficacy

FAR-UV, like GUV, has been shown to inactivate infectious aerosols indoors, though most of the FAR-UV studies to date have been performed in artificial settings (chambers) or simulated settings, not in field settings. FAR-UV use reduces the viability of SARS-CoV-2 by up 88.5% and up to 99.7% at 1 and 3 mJ/cm^2, respectively, demonstrating that the increased intensity of UV energy may produce more pathogen inactivation [18]. Further, FAR-UV inactivates 99.9% of a series of aerosolized human coronaviruses even at low levels of exposure on surfaces and in aerosols [8]. FAR-UV is not only effective against viral pathogens, but against bacterial agents as well; studies demonstrate the successful inactivation of 98% of *Staphylococcus aureus* within 5 minutes using posted guidelines by the American Conference of Governmental Industrial Hygienists in 2022. [9]. Further, 222 nm FAR-UV systems reduce pathogens on surfaces by 99.9% following only 5 seconds of exposure for many different types of microscopic organisms and pathogens including SARS-CoV-2 (virus) *E. coli* (bacteria), *P. aeruginosa* (bacteria), *A. niger* (mold), *and R. mucilaginosa* (yeast) [19]. These findings demonstrate that even at low levels of exposure, FAR-UV can serve as a highly effective means of reducing the disease burden of infectious agents on both surfaces and infectious aerosols, as well as deactivation of a common bacteria, molds, and yeasts. While there is a need for more studies with human bioaerosols emitted with mucoproteins and secretions, the effectiveness of FAR-UV technologies as a disinfectant explains the growing interest in the technology, as a potentially exciting new engineered solution to combat disease transmission indoors.

Using FAR-UV May Save Energy Compared to Other Disinfection Methods

Despite the demonstrated efficacy of FAR-UV as an effective means of disinfection of indoor environments, some have raised concerns about increased energy usage and thus potential negative environmental impacts of improving indoor air quality [20,21]. Modeling studies conducted at the Pacific Northwest National Laboratory compared the effectiveness and energy use of different air cleaning solutions (HVAC with MERV 13 filters, increased outdoor air, portable cleaners, UV systems in air duct, upper room GUV, and whole room FAR-UV systems) to meet CDC clean air targets in office buildings. Findings from this study demonstrated, that, along with portable air cleaners (PACs), FAR-UV and GUV were the most energy-efficient options [22]. to achieve the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 241 for indoor air quality measures aimed at controlling the spread of infectious aerosols, as well as the CDC clean air targets. Meanwhile, HVAC systems, even with upgraded MERV 13 filtration alone were unable to meet the CDC targets and led to significant energy increases. These findings suggest that GUV and the newer FAR-UV disinfection methods, in conjunction with air purifiers, may greatly reduce disease transmission indoors.

Available FAR-UV Data Show Negligible Adverse Events to Date on Eyes, Skin, and the Respiratory System in Research Environments

FAR-UV Appears to Be Safe for Eyes

Studies thus far on FAR-UV at 222 nm have demonstrated negligible adverse events to date on eye tissues. Whereas 254 nm UV-C penetrates to the corneal endothelium and can cause corneal damage even from small exposures [23], 222 nm UV energy is absorbed in the outermost layer of corneal epithelium, [24,25]. a layer which typically peels off within 24-48 hours and protects the underlying corneal epithelial cells, lowering potential concerns about long term impacts [26]. Other studies support these results, finding that mice with mutations that increase susceptibility to ultraviolet energy were found to develop no tumors or other abnormalities of the eyes and skin following extended, repetitive exposure to FAR-UV [14]. This is further supported by an assessment from ophthalmologists who worked for 6.7 hours per week on average over a 12 month period in a room with two FAR-UV Kr-Cl germicidal lamps installed. Researchers observed no changes nor abnormalities caused by irradiation for levels efficacious in deactivating microorganisms. These studies suggest that long-term exposure to FAR-UV fixtures may have minimal impact on human eyes, possibly allowing for its implementation in more spaces as an engineered control for combatting disease transmission indoors [27].

Studies to Date Demonstrate That FAR-UV Appears Safe for Skin Exposure

FAR-UV energy sources fail to penetrate past the outermost stratum corneum of the epidermis [28–30]. At this level, cells are fully differentiated, do not divide, and are shed from the skin within 20 days [31], reducing concerns skin cancer concerns. Further, there is little evidence of double-strand breaks from FAR-UV in the skin [14,32], and no erythema (skin reddening) was observed, even at exposure levels in excess of those expected during routine daily activities [33]. Thus far, published data suggest that FAR-UV has minimal or negligible adverse effects on human skin, further supporting its potential use to improve IAQ and reduce disease transmission in indoor environments.

The Environmental Impacts of FAR-UV and Interactions with the Indoor Chemistry

FAR-UV irradiation reacts with oxygen to produce ozone and hydroxyl radicals (OH) as byproducts of the interactions of this higher energy with compounds in room air and with components of human skin oils [34–39]. This is particularly noteworthy as ozone is a regulated pollutant [40], and dangerous to human health. These disinfection byproducts, if not properly ventilated out of indoor spaces, may have unintentional interactions with indoor surfaces, and other compounds found present in the indoor environment, including reactive, volatile organic molecules in indoor air that can further react with ozone or OH to create secondary aerosol particulate matter (PM2.5 or ultrafine PM) [41]. The negative health effects of inhaling this particulate matter are well studied [42]. However, there is a knowledge gap that needs to be closed about how consistent exposure to elevated levels of oxidative byproducts produced by FAR-UV will affect human health. From modeling studies performed to assess its application in indoor environments, at levels of irradiation which provides effective virus-removal, there is a small, if noteworthy, production of ozone through FAR-UV use, This production and its health impacts could be mitigated by proper ventilation rates or air purification measures; this needs further study [43]. Ozone/byproduct studies are also needed in which FAR-UV is used in the presence of humans to understand how much human skin contributes to air contaminants.

Regulatory Gaps Remain Which Hamper the Widespread Distribution and Use of FAR-UV

Fixture

Recommendations

FAR-UV technology has considerable promise as an engineered solution to reduce respiratory disease transmission indoors and improve IAQ. From the information presented at our workshop, we identified three major recommendations for implementing FAR-UV and next steps for expanding knowledge and understanding of this new technology.

Implementation of UV Disinfection Solutions 254 (Older GUV Technology) and 222nm (Newer FAR-UV Technology) Should Be Considered for Locations That Have High Infection Potential

FAR-UV should be considered as a potentially efficacious engineered control to counter the spread of disease and improve air quality indoors, used in tandem with effective ventilations systems and air purifications systems, and it deserves more study in a variety of settings. With its high energy efficiency, high efficacy for neutralizing both viruses and bacteria, reduced concerns for human tissues, and low installation costs, FAR-UV has the capacity to be a valuable tool to in the pandemic toolbox to counter novel and highly infectious pathogens. Despite these merits, findings of the

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production of oxidation byproducts are a concern. Our recommendation would be for the use of FAR-UV technologies in tandem with air purifiers and traditional ventilations systems in high-risk areas until more research is published on the production of oxidative compounds. For example, in indoor spaces with higher respiratory disease risk, FAR-UV could be used with ventilation or air purifiers to balance the reduction of airborne pathogens with the production of indoor air pollutants. Since it is unlikely that ventilation and filtration improvements can reduce the risk of infectious disease transmission to zero [46], adoption of FAR-UV could make a demonstrable impact in locations with high infection potential such as hospitals and nursing homes, as well as busy areas such as airports, older office buildings and schools, sporting venues, and public transportation, combining ventilation and purification with the proven efficacy of UV disinfection. With the implementation of improved ventilation or purification devices in buildings, concerns surrounding FAR-UV and interactions with the indoor environment could be tempered, particularly in these gathering spaces and in arenas where there is a high risk of transmission.

Additionally, exploring FAR-UV further underscored the importance, overall, of GUV air disinfection as a means to reduce respiratory disease transmission. GUV has a proven record of reducing disease transmission indoor environments, which allows for building to achieve the highest standards as set by ASHRAE 241, and further studies based on contemporary study designs could be illuminating. While incurring initial costs, long-term savings from improved health outcomes and reduced chemical disinfectant use may support the investment in GUV systems [47]. Indeed, GUV systems could run at night and FAR-UV systems could run during working hours. UV disinfection is a generally safe and effective measure to clean indoor environments of pollutants and infectious aerosols and should be implemented more widely with existing measures to ensure safe use.

The US Government (USG) Should Support a Human Health Risk Assessment of FAR-UV Technology and Develop Guidance for Its Use

With low to no impacts on identified human tissues of concern, high energy efficiency, and ease of installation, FAR-UV may provide a safe, and cost-effective measure to mitigate indoor transmission of respiratory pathogens in a variety of spaces with proven UV irradiation disinfection, without requiring the need of expert installation and maintenance. FAR-UV is a new technology, however, and to ensure public support for this technology, actions need to be taken to demonstrate the efficacy and safety of FAR-UV technologies to the public. If FAR-UV technology is to be adopted widely, the USG should fund a human health risk assessment of FAR-UV devices and develop guidance for use. Findings from a human health risk assessment would demonstrate to the public the safety of a new technology; indeed, such studies could also be used to compare the ozone production associated with FAR-UV with other ozone-producing cleaning devices to ascertain how FAR-UV compares to other devices already on the market [48]. While this intervention may appear costly, it could yield significant returns in diminishing the burden of infectious disease.

In addition to more real-world studies, guidance for use of FAR-UV is also needed. Without these measures, consumers and industry are left in a vacuum on the safety of various FAR-UV devices, and how and where they should best be used to produce the maximum benefit. Developing guidance for FAR-UV would not be a novel action; NIOSH developed the guidance for GUV for TB in 2009 and could expand this work for FAR-UV. Another possibility to build trust in this new technology is to require device producers to register their products and submit safety and efficacy data prior to distribution or sale for all products which fall under FIFRA; this would include FAR-UV devices. Doing so would ensure that consumers do not bear the burden of determining which devices work and under what conditions. Another possibility would be the creation of a health registry to track safety and effectiveness.

There has been a push in some states to ban devices that produce ozone [49]. However, lawmakers should use caution to avoid including promising, potentially transformational technology that could facilitate a paradigm shift in engineering infection control measures. FAR-UV is a promising means to reduce respiratory disease transmission and improve IAQ, yet, despite its promise and efficacy, the technology is still novel; banning FAR-UV when concerns regarding

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oxidation byproducts could be rectified with engineered controls such as improved ventilation or other means or new research would be premature and hamper the ability of the public to combat infectious disease threats.

Continued Research Is Needed on FAR-UV and Interactions with the Indoor Environment

While the benefits of FAR-UV in areas of high traffic and in venues where highly transmissible pathogens are present, evidence of the interactions of FAR-UV with indoor chemistry to produce ozone and other oxidative byproducts is needed. Further studies to ensure the safe use of FAR-UV are necessary to determine the chemical interactions in real-world indoor environments between FAR-UV light, ozone, and other oxidants. Further, research is needed to develop best practices to mitigate secondary organic aerosols generated by FAR-UV use. We also recommend studies be conducted to determine under what conditions FAR-UV is most effective (including light levels, time and placement of fixtures, ventilation levels) which should also consider ventilation rate, indoor air chemistry, and a focus on maximizing infectious disease mitigation while minimizing ozone production. Development of and research testing of FAR-UV fixtures should consider the applicability of automatic safety that shut off the lights when they detect levels of chemicals that could have adverse effects on human health. These questions should be answered prior to mass adoption of FAR-UV, but do not preclude the use of FAR-UV in areas of high movement or in areas of where highly infectious aerosols are present.

Conclusions

FAR-UV has great promise to be an engineered tool which can counter highly transmissible and virulent aerosols indoors. With high efficacy, and low energy requirements FAR-UV could be a promising tool to combat disease transmission in high-risk indoor environments and improve IAQ, particularly when coupled with ventilation systems. It is prudent to better understand the indoor chemistry and the chemical interactions which occur prior to mass adoption of FAR-UV, and to develop safety and use standards for the technology. FAR-UV has great potential and should be used in spaces at high risk of disease transmission indoors.

References

1. Lewis AC, Jenkins D, Whitty CJM. Hidden harms of indoor air pollution — five steps to expose them. *Nature*. 2023;614(7947):220-223. doi:10.1038/d41586-023-00287-8
2. FACT SHEET: DEPARTMENTS AND AGENCIES COMMIT TO CLEANER INDOOR AIR ACROSS THE NATION | OSTP. The White House. December 8, 2022. Accessed September 12, 2024. https://www.whitehouse.gov/ostp/news-updates/2022/12/08/fact-sheet-departments-and-agencies-commit-to-cleaner-indoor-air-across-the-nation/
3. CDC. Improving Ventilation In Buildings. Centers for Disease Control and Prevention. February 11, 2020. Accessed April 12, 2024. https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/improving-ventilation-in-buildings.html
4. Schismenos S, Smith AA, Stevens GJ, Emmanouloudis D. Failure to lead on COVID-19: what went wrong with the United States? *Int J Public Leadersh*. 2020;17(1):39-53. doi:10.1108/IJPL-08-2020-0079
5. *Environmental Control for Tuberculosis: Basic Upper-Room Ultraviolet Germicidal Irradiation Guidelines for Healthcare Settings.* U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health; 2009. doi:10.26616/NIOSHPUB2009105
6. Sarkar M. Tuberculosis infection prevention and control. *Indian J Tuberc*. Published online August 23, 2024. doi:10.1016/j.ijtb.2024.08.011
7. Zaffina S, Camisa V, Lembo M, et al. Accidental Exposure to UV Radiation Produced by Germicidal Lamp: Case Report and Risk Assessment. *Photochem Photobiol*. 2012;88(4):1001-1004. doi:10.1111/j.1751-1097.2012.01151.x
8. Buonanno M, Welch D, Shuryak I, Brenner DJ. FAR-UVC light (222 nm) efficiently and safely inactivates airborne human coronaviruses. *Sci Rep*. 2020;10(1):10285. doi:10.1038/s41598-020-67211-2
9. Eadie E, Hiwar W, Fletcher L, et al. FAR-UVC (222 nm) efficiently inactivates an airborne pathogen in a room-sized chamber. *Sci Rep*. 2022;12(1):4373. doi:10.1038/s41598-022-08462-z

10. Kousha O, O'Mahoney P, Hammond R, Wood K, Eadie E. 222 nm FAR-UVC from filtered Krypton-Chloride excimer lamps does not cause eye irritation when deployed in a simulated office environment. *Photochem Photobiol*. 2024;100(1):137-145. doi:10.1111/php.13805
11. Ivanova I, Svilenska T, Kurz B, et al. Improved Spectral Purity of 222-nm Irradiation Eliminates Detectable Cyclobutylpyrimidine Dimers Formation in Skin Reconstructs even at High and Repetitive Disinfecting Doses. *Photochem Photobiol*. 2022;98(5):1149-1156. doi:10.1111/php.13594
12. Welch D, Buonanno M, Buchan AG, et al. Inactivation Rates for Airborne Human Coronavirus by Low Doses of 222 nm FAR-UVC Radiation. *Viruses*. 2022;14(4):684. doi:10.3390/v14040684
13. Fukui T, Niikura T, Oda T, et al. Exploratory clinical trial on the safety and bactericidal effect of 222-nm ultraviolet C irradiation in healthy humans. *PLOS ONE*. 2020;15(8):e0235948. doi:10.1371/journal.pone.0235948
14. Yamano N, Kunisada M, Kaidzu S, et al. Long-term Effects of 222-nm ultraviolet radiation C Sterilizing Lamps on Mice Susceptible to Ultraviolet Radiation. *Photochem Photobiol*. 2020;96(4):853-862. doi:10.1111/php.13269
15. Buonanno M, Ponnaiya B, Welch D, et al. Germicidal Efficacy and Mammalian Skin Safety of 222-nm UV Light. *Radiat Res*. 2017;187(4):483-491. doi:10.1667/RR0010CC.1
16. Buonanno M, Stanislauskas M, Ponnaiya B, et al. 207-nm UV Light-A Promising Tool for Safe Low-Cost Reduction of Surgical Site Infections. II: In-Vivo Safety Studies. *PloS One*. 2016;11(6):e0138418. doi:10.1371/journal.pone.0138418
17. Görlitz M, Justen L, Rochette PJ, et al. Assessing the safety of new germicidal FAR-UVC technologies. *Photochem Photobiol*. n/a(n/a). doi:10.1111/php.13866
18. Kitagawa H, Nomura T, Nazmul T, et al. Effectiveness of 222-nm ultraviolet light on disinfecting SARS-CoV-2 surface contamination. *Am J Infect Control*. 2021;49(3):299-301. doi:10.1016/j.ajic.2020.08.022
19. Childress J, Roberts J, King T. Disinfection with FAR-UV (222 nm Ultraviolet light).
20. Franco A, Bartoli C, Conti P, Miserocchi L, Testi D. Multi-Objective Optimization of HVAC Operation for Balancing Energy Use and Occupant Comfort in Educational Buildings. *Energies*. 2021;14(10):2847. doi:10.3390/en14102847
21. Moghadam TT, Ochoa Morales CE, Lopez Zambrano MJ, Bruton K, O'Sullivan DTJ. Energy efficient ventilation and indoor air quality in the context of COVID-19 - A systematic review. *Renew Sustain Energy Rev*. 2023;182:113356. doi:10.1016/j.rser.2023.113356
22. Faulkner CA, Salsbury TI, Abboushi B, et al. Comparison of effectiveness and energy use of airborne pathogen mitigation measures to meet clean air targets in a prototypical office building. *Build Environ*. Published online April 2, 2024:111466. doi:10.1016/j.buildenv.2024.111466
23. Kaidzu S, Sugihara K, Sasaki M, Nishiaki A, Igarashi T, Tanito M. Evaluation of acute corneal damage induced by 222-nm and 254-nm ultraviolet light in Sprague–Dawley rats. *Free Radic Res*. 2019;53(6):611-617. doi:10.1080/10715762.2019.1603378
24. Kaidzu S, Sugihara K, Sasaki M, et al. Re-Evaluation of Rat Corneal Damage by Short-Wavelength UV Revealed Extremely Less Hazardous Property of FAR-UV-C†. *Photochem Photobiol*. 2021;97(3):505-516. doi:10.1111/php.13419
25. Kaidzu S, Sugihara K, Sasaki M, et al. Safety Evaluation of FAR-UV-C Irradiation to Epithelial Basal Cells in the Corneal Limbus. *Photochem Photobiol*. 2023;99(4):1142-1148. doi:10.1111/php.13750
26. Sliney DH, Stuck BE. A Need to Revise Human Exposure Limits for Ultraviolet UV-C Radiation†. *Photochem Photobiol*. 2021;97(3):485-492. doi:10.1111/php.13402
27. Sugihara K, Kaidzu S, Sasaki M, et al. One-year Ocular Safety Observation of Workers and Estimations of Microorganism Inactivation Efficacy in the Room Irradiated with 222-nm Far Ultraviolet-C Lamps. *Photochem Photobiol*. 2023;99(3):967-974. doi:10.1111/php.13710
28. Pfeifer GP, Besaratinia A. UV wavelength-dependent DNA damage and human non-melanoma and melanoma skin cancer. *Photochem Photobiol Sci*. 2012;11(1):90-97. doi:10.1039/c1pp05144j
29. Zamudio Díaz DF, Klein AL, Guttmann M, et al. Skin optical properties from 200 to 300 nm support far UV-C skin-safety in vivo. *J Photochem Photobiol B*. 2023;247:112784. doi:10.1016/j.jphotobiol.2023.112784
30. Finlayson L, Barnard IRM, McMillan L, et al. Depth Penetration of Light into Skin as a Function of Wavelength from 200 to 1000 nm. *Photochem Photobiol*. 2022;98(4):974-981. doi:10.1111/php.13550
31. Grove GL, Kligman AM. Age-associated Changes in Human Epidermal Cell Renewal1. *J Gerontol*. 1983;38(2):137-142. doi:10.1093/geronj/38.2.137
32. Eadie E, O'Mahoney P, Finlayson L, Barnard IRM, Ibbotson SH, Wood K. Computer Modeling Indicates Dramatically Less DNA Damage from FAR-UVC Krypton Chloride Lamps (222 nm) than from Sunlight Exposure. *Photochem Photobiol*. 2021;97(5):1150-1154. doi:10.1111/php.13477
33. Eadie E, Barnard IMR, Ibbotson SH, Wood K. Extreme Exposure to Filtered FAR-UVC: A Case Study†. *Photochem Photobiol*. 2021;97(3):527-531. doi:10.1111/php.13385
34. Link MF, Shore A, Hamadani BH, Poppendieck D. Ozone Generation from a Germicidal Ultraviolet Lamp with Peak Emission at 222 nm. *Environ Sci Technol Lett*. 2023;10(8):675-679. doi:10.1021/acs.estlett.3c00318

35. Graeffe F, Luo Y, Guo Y, Ehn M. Unwanted Indoor Air Quality Effects from Using Ultraviolet C Lamps for Disinfection. *Environ Sci Technol Lett*. 2023;10(2):172-178. doi:10.1021/acs.estlett.2c00807
36. Barber VP, Goss MB, Franco Deloya LJ, et al. Indoor Air Quality Implications of Germicidal 222 nm Light. *Environ Sci Technol*. 2023;57(42):15990-15998. doi:10.1021/acs.est.3c05680
37. Zannoni N, Lakey PSJ, Won Y, et al. The human oxidation field. *Science*. 2022;377(6610):1071-1077. doi:10.1126/science.abn0340
38. Weschler CJ, Nazaroff WW. Human skin oil: a major ozone reactant indoors. *Environ Sci Atmospheres*. 2023;3(4):640-661. doi:10.1039/D3EA00008G
39. Weschler CJ, Nazaroff WW. Ozone Loss: A Surrogate for the Indoor Concentration of Ozone-Derived Products. *Environ Sci Technol*. 2023;57(36):13569-13578. doi:10.1021/acs.est.3c03968
40. US EPA O. Ozone (O3) Air Quality Standards. September 16, 2016. Accessed May 17, 2024. https://www.epa.gov/naaqs/ozone-o3-air-quality-standards
41. Mattila JM, Arata C, Abeleira A, et al. Contrasting Chemical Complexity and the Reactive Organic Carbon Budget of Indoor and Outdoor Air. *Environ Sci Technol*. 2022;56(1):109-118. doi:10.1021/acs.est.1c03915
42. *Why Indoor Chemistry Matters*. National Academies Press; 2022. doi:10.17226/26228
43. Peng Z, Miller SL, Jimenez JL. Model Evaluation of Secondary Chemistry due to Disinfection of Indoor Air with Germicidal Ultraviolet Lamps. *Environ Sci Technol Lett*. 2023;10(1):6-13. doi:10.1021/acs.estlett.2c00599
44. US EPA O. Pesticide Devices: A Guide for Consumers. October 14, 2015. Accessed April 12, 2024. https://www.epa.gov/pesticides/pesticide-devices-guide-consumers
45. EPA Regulations About UV Lights that Claim to Kill or Be Effective Against Viruses and Bacteria. Accessed April 12, 2024. https://www.epa.gov/sites/default/files/2020-10/documents/uvlight-complianceadvisory.pdf
46. Rockey NC, Sage VL, Shephard M, et al. Ventilation does not affect influenza virus transmission efficiency in a ferret playpen setup. Published online December 26, 2023:2023.12.26.573248. doi:10.1101/2023.12.26.573248
47. Operator TP. UV vs. Chlorine for Wastewater Disinfection. Treatment Plant Operator. September 17, 2018. Accessed September 12, 2024. https://www.tpomag.com/blog/2018/09/uv-vs-chlorine-for-wastewater-disinfection_sc_0039e
48. US EPA O. What are ionizers and other ozone generating air cleaners? February 19, 2019. Accessed September 23, 2024. https://www.epa.gov/indoor-air-quality-iaq/what-are-ionizers-and-other-ozone-generating-air-cleaners
49. California's Regulation to Limit Ozone Emissions from Indoor Air Cleaning Devices | California Air Resources Board. Accessed September 12, 2024. https://ww2.arb.ca.gov/resources/fact-sheets/californias-regulation-limit-ozone-emissions-indoor-air-cleaning-devices