Radiation Protection Dosimetry, 2026, ncaf186
https://doi.org/10.1093/rpd/ncaf186
Paper

Ultraviolet radiation dosimetry using radiochromic film for extended dose range applications and estimating eye exposure

Raabia Hashmi[1], Samantha Meeker[2], Mike Rockwood[2], Kenneth Rockwood[2,3], Camryn Petersen[1], David J. Brenner[1], David Welch[1,*]

[1]Center for Radiological Research, Columbia University Irving Medical Center, New York, NY 10032, United States
[2]Nova Scotia Health, Division of Geriatric Medicine, Halifax, NS B3H 2E1, Canada
[3]Division of Geriatric Medicine, Dalhousie University, Halifax, NS B3H 2E1, Canada

*Corresponding author. Center for Radiological Research, Columbia University Irving Medical Center, 630 West 168th St., New York, NY 10032, United States. E-mail: dw2600@cumc.columbia.edu

Abstract

Radiochromic films are a reliable tool for quantifying ultraviolet exposure dose. When used without modification, these films enable a simple, low-cost measurement of accumulated dose over time which is amenable to personal exposure monitoring. This study presents two methods to expand the utility of these films for dosimetry applications. One approach utilized an ultraviolet radiation attenuator to effectively extend the usable dose range of radiochromic films. The attenuators have the added advantage of obscuring the film from view so the color change of the film due to increasing exposure dose is not visible. The practical use of these films with attenuators over prolonged exposure periods is highlighted as a case study in this manuscript. A second modification is the addition of a structure to limit the dose received by the film to an 80° field of view. Limiting the field of view of the film dosemeter provides for an estimate of the dose received by the eyes, accounting for protection provided by the ocular cavity, and the use of a dosemeter with a restricted field of view is included in recommendations for commissioning of ultraviolet lighting installations. Radiochromic films, when used in conjunction with these tools, offer an effective solution for extended dose ranges and eye-specific ultraviolet dose measurement in indoor spaces utilizing germicidal ultraviolet technologies.

Introduction

Airborne-mediated microbial diseases continue to be a major public health concern. One promising approach to limit their spread is to inactivate airborne pathogens using ultraviolet (UV) radiation. Two popular approaches for deploying UV radiation are upper-room installations with conventional 254 nm ultraviolet C (UVC) and whole-room installations using far-UVC wavelengths, most commonly 222 nm [1–7].

UV radiation functions as an engineering control, and proper installation and commissioning of a UV system are essential for safe and effective operation. The American Conference of Governmental Industrial Hygienists (ACGIH) and the International Commission on Non-Ionizing Radiation Protection provide recommendations for daily exposure limits for UV radiation [8, 9]. These limits were established to prevent acute or chronic health effects in occupants, so ensuring they are not exceeded is critical. Typically, measurements to determine compliance with ACGIH limits are performed in accordance with Recommended Practices from the Illuminating Engineering Society, such as RP-27.1 and RP-44, which describe safety precautions and testing for an UV installations [10, 11].

Orthochromic-1 (OC-1) films are a reliable tool for measuring the radiant exposure, or dose, from 222 or 254 nm radiation [12]. Importantly, individual exposure monitoring using films attached to occupants allows for an estimate of the time-weighted average dose which accounts for movements of occupants within an area with non-uniform exposure. These

Received: October 16, 2025. **Revised:** December 4, 2025. **Accepted:** December 8, 2025

OC-1 films can also be used to determine the average irradiance and the extrapolated 8-h dose to the film, two critical components when implementing UV into any environment, when the total exposure time for a film is known [13]. It should be noted that these films are responsive to UV exposure from sunlight or any other UV source; however, the peak wavelength for spectral effectiveness is approximately 250 nm and the response to wavelengths above 300 nm is more than three orders of magnitude less. A previous study confirmed that fluorescent lighting does not have any significant effect on film color change when exposing for 8 h [13]. When measuring 222 nm exposure, the films can measure doses as low as 5 mJ cm^{-2} and have an accuracy of ±10 per cent. Films can be cut to very small sizes for measurements since film data is obtained using a high-resolution optical scanner. Overall, UVC dosimetry using films is cost-effective and straightforward to implement.

Although using the films for dosimetry on the shoulders or on the top of the head provides a good representation of the overall dose received to the skin at those locations, there is a need to create an effective method of monitoring the dose received by the eyes. The 80° field of view (FOV) provides a more accurate representation of the dose actually received by the eye, which is significantly reduced due to the anatomical properties of the eye such as the ocular cavity, browbone, and eyelashes [14–20]. For example, a previous study using films placed across a manikin head within a far-UVC lamp installation estimated the dose received by the eye to only be about 6 per cent of the maximum dose on the received by the head [16]. Using the 80° FOV allows for a more accurate safety assessment for participants in a space, particularly since these doses may be compared against published exposure limits [8].

Polytetrafluoroethylene, or PTFE (trademarked as Teflon), is a useful material to attenuate radiation. When paired with a radiochromic film the dose measurement range is effectively extended proportional to the attenuation. Importantly, the optical properties of PTFE allow some UVC radiation to transmit through while also attenuating visible light. The reduced transmission in the visible range causes the PTFE to conceal color changes to radiochromic film beneath the PTFE. PTFE has been studied extensively for its reliable attenuation and transmission properties across a wide range of UV wavelengths and has been effectively implemented as part of a UVC film dosimetry system [21].

After a revision in 2022, the ACGIH updated Threshold Limit Values (TLVs) suggest daily safe exposure doses as high as 160 mJ cm^{-2} for the eyes and 479 mJ cm^{-2} for the skin for exposure with 222 nm radiation [8, 22]. While the increased limits reflect the reduced health hazard for far-UVC exposure compared to conventional UVC wavelengths, it is still a necessity to ensure occupant exposure remains within these daily limits. Additionally, the lower TLVs at far-UVC wavelengths for the eyes compared to the skin suggests that a method to estimate how much dose the eyes are receiving is important to ensure compliance with these recommendations and therefore avoid adverse effects to the eyes such as photokeratitis [23–26].

We have previously demonstrated the use of radiochromic films as a reliable sensitive dosemeter for individual exposure monitoring within a far-UVC installation [12, 13, 16]. This manuscript presents an extension of the functionality of radiochromic films for UV dosimetry by expanding the dose range through the addition of an attenuator and by adding a shield to create an 80° FOV.

Materials and methods

Film exposure

Photosensitive OC-1 films (Orthochrome Inc., Hillsborough, NJ) were employed to measure the dose of UV radiation at wavelengths of 222 or 254 nm. Measurements of 222 nm exposure from an Ushio B1 module (Ushio America, Cypress, CA) used the films without modification. Measurements of 254 nm exposure from a Philips TUV PL-L 36 W/4P Germicidal Light Bulb (Philips lighting Company, Somerset, NJ, USA) used the films with a PTFE attenuator placed against the active layer of the film. The PTFE attenuator used with the films was 1/16-in. thick (Chemical-Resistant Slippery Teflon PTFE Sheet, McMaster-Carr, Elmhurst, IL). Tests for the angular response of the film when using the PTFE attenuator were performed with the 254 nm source because of the higher sensitivity of the film to that wavelength [12].

The transmission properties of the PTFE attenuator were evaluated using a Gigahertz Optik X1 Optometer with a UV-3727 detector (Gigahertz-Optik Inc, Amesbury, MA). This detector is calibrated for responsivity at 222 nm, 254 nm, and UV LED wavelengths (220–300) nm in 5 nm steps. The spectral responsivity of the detector is from 200 to 310 nm. Transmission percentage was tested by placing the meter perpendicular to the UV source at 1 m distance and recording the irradiance both with and without the PTFE covering the sensor.

80° FOV tool

To construct the 80° FOV tool, a 1/4-in. (6.35 mm) thick transparent acrylic sheet was drilled to create exposure apertures measuring 9.6 and 10.7 mm in diameter. While the acrylic is transparent to visible light it does not transmit UVC radiation. When testing the 80° FOV tool concurrently with a PTFE attenuator, the

PTFE was positioned between the film and the acrylic sheet, such that the final configuration consisted of the film at the bottom, the PTFE in the middle, and the acrylic sheet on top. During exposures, the UV source was directed onto the acrylic side, passing through the aperture (and PTFE, when present) before reaching the film. Preliminary tests were conducted with other aperture diameters, but they did not produce a field of view close to 80° and thus were not used in subsequent tests (data not shown). To test angular performance, films were mounted on a precision rotating stage (Thorlabs Inc., Newton, NJ) located 1 m away from the UV source. The angular response of the films with the 80° FOV tool attached was tested normal to the lamp (0 degrees) and at ±15°, ±30°, ±35°, ±40°, and ±45°.

Real-world case study

OC-1 films were prepared for use in the real-world case study by adhering each film to a 1 cm diameter carrier badge and then attaching a PTFE cover on top of the film. These films were secured to the clothing of staff members with a magnetic backing to hold the badge in a fixed position at the top of the shoulder. This positioning allowed the films to face upright and in line with the direction of exposure from the downward facing lamps. The magnetic attachment permitted simple attachment and release of the badge from the clothing. Badges were distributed to three participating long-term care homes where filtered 222 nm far-UVC KrCl lamps (UVX Inc., Vancouver, BC, Canada) or identical placebo lamps were installed [27]. One or two staff members in each area wore the badges daily for 2 wks, and all staff members were unaware of which locations had far-UVC or placebo lamps installed. Staff members did not move between different research areas to maintain consistency in location-based dosimetry. Film badges were never worn outside of the test location. A log was maintained for recording the duration of time each badge was worn throughout the study period. The films were then mailed for analysis at the end of the exposure trials.

Color response analysis

All films were scanned using an Epson Perfection V850 Pro photo flatbed scanner (Epson, Suwa, NGN, Japan) and analyzed for color change response by calculating the net color density (netCD) based on their RGB values. Dose was determined by using a color change calibration curve from known doses and netCD values, as done previously in Welch et al. [13]. For analysis of films exposed using the acrylic 80 FOV tool, the pixel at the center of the exposure aperture, with an area of 84 μm × 84 μm when scanned at 300 dpi, was used to determine the dose. All analysis was done using MATLAB R2022b software code.

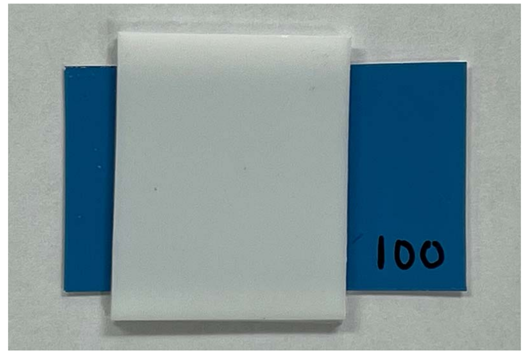

Figure 1. 1/16-in. PTFE covering a film exposed to 100 mJ cm^{-2} of 222 nm radiation depicting the effectiveness of PTFE obscuring the color change.

Results

PTFE transmission characterization

The incorporation of PTFE as an attenuator significantly extended the measurement range of the films. A 1/16-in. (1.6 mm) sheet of PTFE was shown to transmit only 6.88 per cent ± 0.25 per cent of incident 222 nm radiation and 12.04 per cent ± 0.24 per cent of 254 nm radiation to the meter placed directly behind the film. This substantial attenuation enabled the film to record higher exposure levels without color change saturation. Additionally, the PTFE effectively obscured visible color changes in the film, making it a viable approach for extended dose ranges or in scenarios where dose readings must be concealed. The color blocking property is exhibited in Fig. 1 with PTFE placed partially over a film that has been exposed to 100 mJ cm^{-2} of 222 nm UVC radiation.

80° FOV angular response

Figure 2 presents data for the angular response of the setup using the 9.6 mm acrylic hole with the PTFE attenuator on top of the film. Figure 3 shows the angular response of the configuration using only the 10.7 mm acrylic hole over the film. The normalized dose curves exhibit strong agreement with the expected cosine response at angles close to normal. The slight skew observed in the 9.6 mm hole, favoring the left side, is most likely attributable to a minor off-center alignment in the exposure setup. However, the results confirm that the 50 per cent reduction in color response consistently occurs within the expected 80° angular window for both aperture sizes. Exact film response and 80° window was calculated using a linear fit model between ±30 to 50 degrees. Results for each aperture size are listed in Table 1.

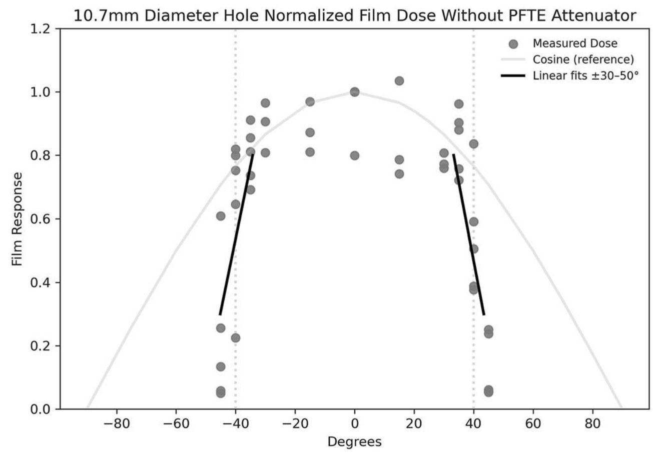

Figure 2. 80° FOV normalized film dose without a PTFE attenuator plotted against typical cosine response using a 10.7 mm diameter hole in a 1/4-in. thick acrylic sheet.

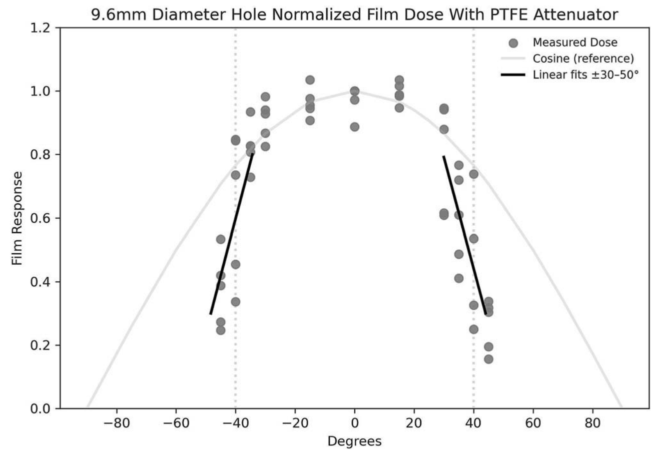

Figure 3. 80° FOV normalized film dose with a PTFE attenuator plotted against typical cosine response using a 9.6 mm diameter hole in a 1/4-in. thick acrylic sheet.

Table 1. Results for calculating the FOV using the acrylic shields with and without the presence of a PTFE attenuator. Linear fit lines from ±30° to 50° were used to calculate the 50 per cent film response point for comparison to the ideal 80° FOV response. The 95 per cent confidence interval is indicated in brackets.

	50% Cross-point degree (−50° to −30°)	**50% Cross-point degree (30° to 50°)**
9.6 mm Diameter hole (with PTFE attenuator)	−42.7 [−45.3, −40.2]	38.3 [36.2, 40.4]
10.7 mm Diameter hole (without PTFE attenuator)	−40.8 [−43.2, −38.4]	39.4 [37.6, 41.1]

Real-world case study

One of the key advantages of employing PTFE attenuators for extended dose ranges is their ability to conceal color change in the underlying films. This feature proved particularly valuable in a blinded study conducted in Nova Scotia, where both 222 nm far-UVC lamps and placebo lamps are deployed as part of a clinical trial of far-UVC technology [27]. Since the PTFE attenuator masked visible color changes, occupants remained unaware of exposure status, thereby

Table 2. Data obtained from real world use-case in Nova Scotia, Canada of users who wore PTFE covered film badges for extended exposures across multiple days.

Badge number	Dose on film (mJ cm^{-2})	Actual dose received (mJ cm^{-2})	Total time (h)	Calculated average irradiance (μW cm^{-2})	Calculated 8-h dose (mJ cm^{-2})
1	1.9	27.9	47.3	0.16	4.7
2	6.6	96.2	85.2	0.31	9.0
3	11.0	160.1	145.1	0.31	8.8
4	8.9	129.6	194.3	0.19	5.3
5	7.5	109.3	214.0	0.14	4.1
6	9.2	134.0	214.2	0.17	5.0
7	10.0	145.6	214.4	0.19	5.4
8	10.2	148.5	214.6	0.19	5.5
9	7.4	107.8	214.9	0.14	4.0
10	24.9	362.2	220.5	0.46	13.1
11	24.9	362.2	221.5	0.45	13.1
12	8.1	118.0	232.9	0.14	4.1
13	11.4	165.9	236.2	0.20	5.6
14	11.7	170.3	249.9	0.19	5.5
15	15.2	221.2	251.7	0.24	7.0
16	9.8	142.7	251.8	0.16	4.5
17	9.4	136.9	257.5	0.15	4.3

preserving the study design while still actively monitored for far-UVC dose.

The results summarized in Table 2 demonstrate the applicability of PTFE-covered film badges for extended monitoring periods. The badges were easy to attach and remove multiple times due to the magnet backer, and rugged enough to be functional for more than 250 h. The exposure dose results are reliable because unwanted exposure was avoided when not in use by storage in a light-proof container. Attentive logging of the exposure duration for each film permitted calculation of the average irradiance upon each film. Notably, the calculated values for actual dose received, which factors in the attenuation of the PTFE, are sometimes over 200 mJ cm^{-2}—a dose which would exceed the saturation threshold of the films when no attenuator is used. Thus, the use of PTFE attenuators in conjunction with film dosemeters significantly extends the practical monitoring window and enables reliable assessment of extended far-UVC exposure doses.

Discussion

The acrylic attachments tested here were able to effectively create an 80° FOV cone for film dosimetry with and without the addition of a PTFE attenuator. The field of view was confirmed by applying a linear fit to film dosimetry measurements performed across a range of exposure angles, as shown in Figs. 2 and 3. The aperture size needed when using the film with the PTFE attenuator was smaller than the size when only the film was present. While this difference in aperture size may seem counterintuitive, since the addition of the PTFE extends the FOV tool height above the film by the thickness of the PTFE (1/16 in), a modification which would theoretically decrease the FOV, this adjustment to a smaller diameter hole is likely necessary to account for the diffusing properties of the PTFE. In this study, the PTFE likely diffuses the incident radiation that would otherwise not reach the center of the film area, which was used for dosimetry, so the FOV is effectively increased through the use of PTFE. This result highlights the need to experimentally confirm the operational characteristics of an 80° FOV tool.

The real-world case study of far-UVC film dosimetry illustrates both the applicability and the limitations of PTFE-attenuated film badges. While the data were successfully collected, the process demands diligent administrative controls. Careful logging and consistent film dosemeter handling procedures were necessary for extended monitoring. Nevertheless, the film badges proved useful and practical, which was the primary conclusion intended from this case study.

Conclusions

OC-1 films offer a practical and reliable method for monitoring UV exposure in indoor environments. Using a 1/4-in. thick acrylic attachment with exposure holes of 9.6 mm (with PTFE) or 10.7 mm (without PTFE) produced an 80° FOV window that aligned well with the expected cosine response curve with the target cutoff angle, enabling accurate eye-dose assessments. The PTFE attenuator extends the effective exposure dose measurement range of the film and provides color masking, an advantage for studies requiring occupants to not be aware of their exposure status. Film dosimetry remains a valuable tool for UV exposure monitoring, and its applications can be further expanded by integrating accessories that increase the dose measurement range and accurately estimate the dose received to occupants' eyes.

Conflict of interest: None declared.

Funding

This work was supported by Open Philanthropy Foundation; Empire State Biodefense Commercialization Fund; Centers for Disease Control and Prevention (CDC) National Institute for Occupational Safety and Health (NIOSH) [R01OH012312]; a Columbia University Urban Tech Award; and Research Nova Scotia.

References

1. Buonanno M, Kleiman NJ, Welch D. *et al.* 222 nm Far-UVC light markedly reduces the level of infectious airborne virus in an occupied room. *Sci Rep* 2024;**14**:6722. https://doi.org/10.1038/s41598-024-57441-z
2. Buonanno M, Welch D, Shuryak I. *et al.* Far-UVC light (222 nm) efficiently and safely inactivates airborne human coronaviruses. *Sci Rep* 2020;**10**:10285. https://doi.org/10.1038/s41598-020-67211-2
3. Ponnaiya B, Buonanno M, Welch D. *et al.* Far-UVC light prevents MRSA infection of superficial wounds in vivo. *PLoS One* 2018;**13**:e0192053. https://doi.org/10.1371/journal.pone.0192053
4. Jensen PA. Critical design parameters in design and efficacy of upper-room UVC(254) luminaire systems: part I: overview of major parameters and relationships(†). *Photochem Photobiol* 2021;**97**:532–41. https://doi.org/10.1111/php.13425
5. Liu H, Liu Z, He J. *et al.* Reducing airborne transmission of SARS-CoV-2 by an upper-room ultraviolet germicidal irradiation system in a hospital isolation environment. *Environ Res* 2023;**237**:116952. https://doi.org/10.1016/j.envres.2023.116952
6. Nardell EA, Bucher SJ, Brickner PW. *et al.* Safety of upper-room ultraviolet germicidal air disinfection for room occupants: results from the tuberculosis ultraviolet shelter study. *Public Health Rep* 2008;**123**:52–60. https://doi.org/10.1177/003335490812300108
7. Park S, Mistrick R, Sitzabee W. *et al.* Effect of ventilation strategy on performance of upper-room ultraviolet germicidal irradiation (UVGI) system in a learning environment. *Sci Total Environ* 2023;**899**:165454. https://doi.org/10.1016/j.scitotenv.2023.165454
8. American Conference of Governmental Industrial Hygienists. *Threshold Limit Values and Biological Exposure Indices*. American Conference of Governmental Industrial Hygienists: Cincinnati, OH, 2022.
9. Guidelines on limits of exposure to ultraviolet radiation of wavelengths between 180 nm and 400 nm (incoherent optical radiation). *Health Phys* 2004;**87**:171–86. https://doi.org/10.1097/00004032-200408000-00006
10. Illuminating Engineering Society. ANSI/IES RP-44-21, Recommended Practice: Ultraviolet Germicidal Irradiation (UVGI). New York: IES; 2021.
11. Illuminating Engineering Society. ANSI/IES RP-27.1-22, Recommended Practice: Risk Group Classification and Minimization of Photobiological Hazards From Ultraviolet Lamps and Lamp Systems. New York: IES; 2022.
12. Welch D, Brenner DJ. Improved ultraviolet radiation film dosimetry using OrthoChromic OC-1 film. *Photochem Photobiol* 2021;**97**:498–504. https://doi.org/10.1111/php.13364
13. Welch D, Hashmi R, Petersen C. *et al.* Film dosimetry for occupant exposure monitoring within far-UVC installations. *Photochem Photobiol* 2025;**101**:157–66. https://doi.org/10.1111/php.13960
14. Milonova S, Rudnick S, McDevitt J. *et al.* Occupant UV exposure measurements for upper-room ultraviolet germicidal irradiation. *J Photochem Photobiol B* 2016;**159**:88–92. https://doi.org/10.1016/j.jphotobiol.2016.03.009
15. Abboushi B, Rodriguez-Feo Bermudez E, Tuenge J. *et al.* GUV installations demonstrate effectiveness and exposure safety in field settings. *Environ Sci Technol* 2025;**59**:8640–50. https://doi.org/10.1021/acs.est.4c10774
16. Duncan MA, Welch D, Shuryak I. *et al.* Ocular and facial far-UVC doses from ceiling-mounted 222 nm far-UVC fixtures. *Photochem Photobiol* 2023;**99**:160–7. https://doi.org/10.1111/php.13671
17. Marro M, Moccozet L, Vernez D. Assessing human eye exposure to UV light: a narrative review. *Front Public Health* 2022;**10**:900979. https://doi.org/10.3389/fpubh.2022.900979
18. Marro M, Moccozet L, Vernez D. Modeling the protective role of human eyelashes against ultraviolet light exposure. *Comput Biol Med* 2022;**141**:105135. https://doi.org/10.1016/j.compbiomed.2021.105135
19. Sliney DH. UV radiation ocular exposure dosimetry. *J Photochem Photobiol B Biol* 1995;**31**:69–77. https://doi.org/10.1016/1011-1344(95)07171-5
20. Sliney DH. Geometrical assessment of ocular exposure to Envirmmental UV radiation—implications for ophthalmic epidemiology. *J Epidemiol* 1999;**9**:22–32. https://doi.org/10.2188/jea.9.6sup_22
21. Su A, Geldert A, Grist SM. *et al.* Optical attenuators extend dynamic range but alter angular response of planar ultraviolet-C dosimeters. *Photochem Photobiol* 2022;**98**:864–73. https://doi.org/10.1111/php.13532
22. Sliney DH, Stuck BE. A need to revise human exposure limits for ultraviolet UV-C radiation. *Photochem Photobiol* 2021;**97**:485–92. https://doi.org/10.1111/php.13402
23. Sliney D. Balancing the risk of eye irritation from UV-C with infection from bioaerosols. *Photochem Photobiol* 2013;**89**:770–6. https://doi.org/10.1111/php.12093
24. Das S, Panigrahi PK, Pareek D. Photokeratitis following exposure to germicidal ultraviolet lamps during the

COVID pandemic. *Indian J Health Sci Biomed Res KLEU* 2021;**14**:279. https://doi.org/10.4103/kleuhsj.kleuhsj_31_21
25. Delic NC, Lyons JG, di Girolamo N. *et al.* Damaging effects of ultraviolet radiation on the cornea. *Photochem Photobiol* 2017;**93**:920–9. https://doi.org/10.1111/php.12686
26. Moore LA, Hussey M, Ferreira JT. *et al.* Review of photokeratitis: Corneal response to ultraviolet radiation (UVR) exposure. *African Vision and Eye Health*. 2010;**69**:123–31. https://doi.org/10.4102/aveh.v69i3.137
27. Nix HP, Meeker S, King CE. *et al.* Preventing respiratory viral illness invisibly (PRiVII): protocol for a pragmatic cluster randomized trial evaluating far-UVC light devices in long-term care facilities to reduce infections. *Trials* 2024;**25**:88. https://doi.org/10.1186/s13063-024-07909-0

Radiation Protection Dosimetry, 2026, 1–7
https://doi.org/10.1093/rpd/ncaf186
Paper