Appendix 4. Ultraviolet (UV) Inactivation Doses and Information about UV Germicidal Irradiation (UVGI) Applications and Safety

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A. Estimates and measurements of inactivation UV doses

Table 1. Predicted average upper-room UV irradiance fluxes required to achieve 50%, 70%, and 90% inactivation for SARS-CoV-2 assuming a range of Z_{ur} values and ventilation rates (assuming Z_{ur} = 0.3770 or 0.0377 m²/J)[a,b] (Beggs and Avital 2020)

Ventilation rate (air changes/ hour)	Average particle residence time in UV field (min)	UV susceptibility constant, Z_{ur} (m^2/J)	Average irradiance (μW/cm^2) required for 50% inactivation	Average irradiance (μW/cm^2) required for 70% inactivation	Average irradiance (μW/cm^2) required for 90% inactivation
1	9.6	0.3770	0.319	0.554	1.060
2	4.8	0.3770	0.638	1.109	2.121
4	2.4	0.3770	1.277	2.218	4.241
6	1.6	0.3770	1.915	3.327	6.362
8	1.2	0.3770	2.554	4.436	8.482
1	9.6	0.0337	3.192	5.544	10.604
2	4.8	0.0337	6.384	11.088	21.207
4	2.4	0.0337	12.768	22.177	42.414
6	1.6	0.0337	19.152	33.266	63.621
8	1.2	0.0337	25.536	44.355	84.829

[a] Z is the assumed UV susceptibility constant for SARS-CoV-2 in units of m^2/J, where J = joule; UV dose is the product of irradiance (W/cm^2) and exposure time (s), where W = watt

[b] Z_{ur} is the effective upper-room Z value (m^2/J)

(continued)

Table 2. Summary of ultraviolet studies on coronaviruses (Kowalski, Walsh, and Petraitis 2020), see reference for estimate sources

Microbe	**D_{90} dose[a] (J/m^2)**	**UV *k*[b] (m^2/J)**
Coronavirus[c]	6.6	0.35120
Berne virus (Coronaviridae)[e]	7.2	0.32100
SARS-CoV-2 (Italy-INMI1)	12.3	0.18670
Murine Coronavirus (MHV)	15.0	0.15351
SARS Coronavirus (Frankfurt 1)	16.4	0.14040
Canine Coronavirus (CCV)	28.5	0.08079
Murine Coronavirus (MHV)	28.5	0.08079
SARS Coronavirus (CoV-P9)	40.0	0.05750
SARS-CoV-2 (SARS-CoV-2/Hu/DP/Kng/19-027)	41.7	0.05524
Murine Coronavirus (MHV)	103.0	0.02240
SARS Coronavirus (Hanoi)	133.9	0.01720
SARS Coronavirus (Urbani)[e]	2410	0.00096
Average	237	0.00972
Average excluding outliers	47	0.04943
Average for SARS-CoV-2	**27**	**0.08528**

[a] UV dose for 90% inactivation

[b] Microorganism-specific standard rate constant that defines the sensitivity of a microorganism to UV exposure

[c] Outliers

(continued)

Table 3. Summary of references reporting the effect of UV radiation on SARS-CoV-2 and similar viral agents

Agent	Effect	Dose (mJ/cm^2)	Wavelength (nm)[a]	Notes	Reference
SARS-CoV-2	3-log inactivation	3.7	254	Cell culture, MOI[b] = 0.05	(Bianco et al. 2020)
SARS-CoV-2	Complete inhibition	16.9	254	Cell culture, MOI = 5	(Bianco et al. 2020)
SARS-CoV-2	Complete inactivation	1048	254	Viral stock, 5×10^6 $TCID_{50}$/mL[c]	(Heilingloh et al. 2020)
SARS-CoV-2	87.4% reduction	3.74–225	280[d]	Viral suspension, cell culture & plaque assay	(Inagaki et al. 2020)
SARS-CoV-2	99.9% reduction	3.74–225	280[i]	Viral suspension, cell culture & plaque assay	(Inagaki et al. 2020)
Coronaviruses	99.9% reduction	1200–1700, ~3 mJ/cm^2/h	222[e]	Aerosolized virus ~8 min	(Buonanno et al. 2020)
Coronaviruses	~90%	1200–1700, ~3 mJ/cm^2/h	222[j]	Aerosolized virus ~11 min	(Buonanno et al. 2020)
Coronaviruses	~95%	1200–1700, ~3 mJ/cm^2/h	222[j]	Aerosolized virus ~16 min	(Buonanno et al. 2020)
Coronaviruses	~99%	1200–1700, ~3 mJ/cm^2/h	222[j]	Aerosolized virus ~25 min	(Buonanno et al. 2020) (continued)

[a] UV-C (short-wave: 100–280 nm): the most effective wavelengths for germicidal control (ASHRAE 2020), peak nucleic acid UV radiation absorption: 260–265 nm; peak RNA virus absorption: 250 nm

[b] Multiplicity of infection: the ratio of the numbers of virus particles to the number of host cells in a given infection medium

[c] $TCID_{50}$/mL: 50% tissue culture infective dose

[d] Deep ultraviolet light-emitting diode (DUV-LED)

[e] New lamps emitting at 222 nm have been advertised that claim far greater safety, but may still exceed the Threshold Limit Value (ACGIH 2020b)

Agent	Effect	Dose (mJ/cm²)	Wavelength (nm)[a]	Notes	Reference
Coronaviruses	90% reduction	10.6	254	Upper limit (low-absorbance media)	(Heßling et al. 2020) Review (aerosol, surface, liquid)
Coronaviruses	90% reduction	3.7		More precise estimation (see above)	(Heßling et al. 2020)
Viruses similar to SARS-CoV-2	Inactivated	≥1	254	N95 respirator, Radiation may not reach inner layers, Shadows can block radiation	(N95Decon 2020)
Viruses similar to SARS-CoV-2	≥3-log reduction	≥1	254	N95 respirator, Radiation may not reach inner layers, Shadows can block radiation	(N95Decon 2020)

(continued)

Table 4. Summary of reported effective Z values for single-pass UV irradiation experiments performed on aerosolized viruses (Beggs and Avital 2020), see reference for estimate sources

Virus	Effective Z value (m^2/J)
Adenovirus	0.0546
Coxsackie B-1	0.1108
Influenza A	0.1187
Sindbis virus	0.104
Vaccinia virus	0.1528
Adenovirus	0.039
Murine hepatitis virus (coronavirus)	0.377
Influenza A	0.27
Vaccinia virus	2.54

Table 5. Ultraviolet germicidal irradiation susceptibility (Z value) of the MS2 bacteriophage, respiratory adenovirus serotype 2, and murine hepatitis virus coronavirus, at 50% relative humidity (Walker and Ko 2007)

Microorganism	UV dose (μW s/cm^2)	Percent survival[k]	Z value ($\times 10^4$) [l]
MS2 (*N* = 5)	2608	31.1 ± 2.9	3.8 ± 0.3
Adenovirus (*N* = 4)	2608	32.9 ± 2.3	3.9 ± 0.3
Coronavirus (*N* = 3)	599	12.2 ± 7.2	37.7 ± 11.9

[k] Percent survival) = 100 × (number of plaques in the presence of UV exposure)/ (number of plaques in the absence of UV exposure).

[l] Z values ($\times 10^4$) were calculated as $-10^4 \times \log$ (% survival)/UV dose (μWs/cm^2).

Table 6. Comparison of the UV susceptibility (Z value [× 10^4]) of the MS2 bacteriophage, adenovirus, and coronavirus in aerosol at 50% relative humidity and in liquid suspension (Walker and Ko 2007)

Microorganism	Viral aerosol (Z value [× 10^4])	Liquid suspension (Z value [× 10^4])	Z value ratio, (aerosol)/(liquid)
MS2	3.8 ± 0.3	0.55	6.9
MS2	3.8 ± 0.3	0.24	16.3
Adenovirus	3.9 ± 0.3	0.18	21.7
Coronavirus	37.7 ± 11.9	0.44	85.7

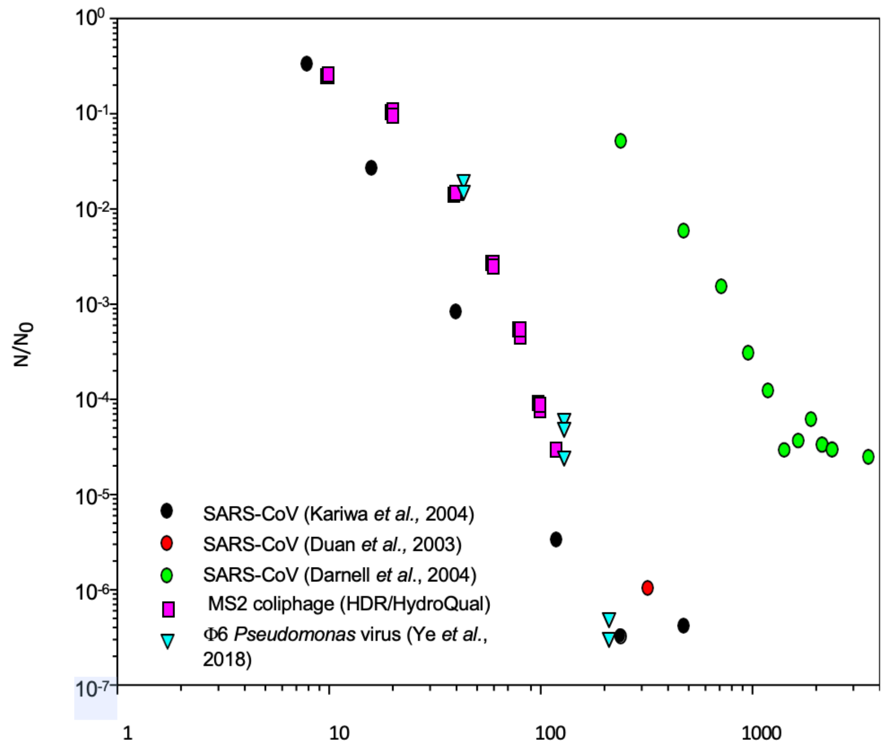

Figure 1. Reported 254-nm-UV dose–response data for SARS-CoV in aqueous suspension. Note that the single data point provided by Duan et al. (2003) was based on radiation at 260 nm (Blatchley, Petri, and Sunc 2020).

B. Additional, recent publication

Improper use of germicidal range ultraviolet lamp for household disinfection leading to phototoxicity in COVID-19 suspects (Leung and Ko 2020)

Purpose
To report germicidal range ultraviolet (UV) irradiation-induced phototoxicity due to unprotected exposure to UV lamps for presumed household disinfection of SARS-CoV-2 in a domestic setting.

Methods
We report on a family of three adults who experienced photophobia, intense eye pain, epiphora, blurred vision, and burning sensation over the face and neck area after a short period of unprotected exposure to UV germicidal lamps.

Results
Initial examination revealed erythema and tenderness over the face and neck area, reduced visual acuity of 6/12, and conjunctival injections bilaterally in all three patients. Further assessment at the ophthalmology department three days later revealed gradual improvement of visual acuity to 6/6 bilaterally. Slit-lamp examinations revealed few punctate epithelial erosions. Fundal examinations were normal without evidence of solar retinopathy. The patients were diagnosed with germicidal-range UV irradiation-induced photokeratitis and epidermal phototoxicity. Lubricants and emollients were prescribed for symptom relief, and the patients were warned against using a UV germicidal lamp for disinfection purposes without appropriate protection.

Conclusions
Although SARS-CoV-2 is structurally akin to SARS-CoV-1 and MERS-CoV, and previous studies demonstrated high levels of inactivation of beta-coronavirus with germicidal-range UV, evidence for its efficacy to inactivate SARS-CoV-2 is lacking. This case report serves to emphasize the potential consequences of phototoxicity from improper use of UV germicidal lamps for household disinfection as well as to highlight the fact that UV germicidal lamps currently have no established role in household disinfection of SARS-CoV-2.

C. Governmental workplace regulations

OSHA Interim Enforcement Plan for COVID-19
The Occupational Safety and Health Administration (OSHA) recommends using ultraviolet germicidal irradiation (UVGI) devices only in addition to high efficiency particulate air (HEPA) filtration when air from Airborne Infection Isolation Rooms (AIIRs) cannot be exhausted directly outside and must be recirculated (OSHA 2020), similar to the Centers for Disease Control and Prevention's recommendations for *Mycobacterium tuberculosis* (Jensen et al. 2005).

To function properly and minimize potential hazards to room occupants, upper air UVGI systems should be properly installed, maintained, and labeled (Jensen et al. 2005). These authors further advise:

- that someone with experience in the use of UV radiometers or actinometers should monitor UV irradiance levels to ensure that exposures in the work area are within safe exposure levels;
- that UV irradiance levels in the upper air, where the air disinfection occurs, should also be monitored to determine that irradiance levels are within the desired effectiveness range
- that UVGI tubes be changed and cleaned according to manufacturer instructions or when irradiance measurements indicate that output has fallen below effective levels.

Because classrooms are also occupational settings, potentially exposed workers should be taught:

- the basic principles of UVGI systems (mechanism and limitations;
- the potential hazardous effects of UVGI if overexposure occurs;
- the potential for photosensitivity associated with certain medical conditions or use of certain medications; and
- the importance of maintenance procedures and record-keeping. In settings that use UVGI, occupants should be informed of the purpose of the system and be warned about the potential hazards and safety precautions (Jensen et al. 2005), i.e., warning labels must be posted on all upper air UV fixtures.

D. Professional associations

American Conference of Governmental Industrial Hygienists (ACGIH)
Ultraviolet radiation in: *TLVs and BEIs* (ACGIH 2020a)
The exposure dose limit during a workday is 3 mJ/cm^2 for actinic UV radiation (200 nm–315 nm).

The irradiation efficacy in occupied spaces can exceed the ACGIH® TLV® for Ultraviolet C at the traditional mercury-lamp wavelength of 254 nm. New lamps emitting at 222 nm have been advertised that claim far greater safety, but may still exceed the TLV® (ACGIH 2020b).

American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASHRAE. Ultraviolet Lamp Systems, 2020 *ASHRAE Handbook* (ASHRAE 2020)

UV energy is electromagnetic radiation with a wavelength shorter than that of visible light, but longer than soft x-rays. All UV ranges and bands are invisible to the human eye. The UV spectrum can be subdivided into following bands:

- UV-A (long-wave; 400 to 315 nm): the most abundant in sunlight, responsible for skin tanning and wrinkles
- UV-B (medium-wave; 315 to 280 nm): primarily responsible for skin reddening and skin cancer
- UV-C (short-wave; 280 to 200 nm): the most effective wavelengths for germicidal control
- Radiation below 200 nm is also called vacuum UV and can produce zone (O_3) in air.

Ultraviolet germicidal irradiation (UVGI) in the UV-C band has been used in air ducts and air-handling units for some time, and its use is becoming increasingly frequent as concern about energy, maintenance, and indoor air quality increases. UV-C energy is used as an engineering control to interrupt the transmission of pathogenic organisms, such as *Mycobacterium tuberculosis* (TB), influenza viruses, mold, and possible bioterrorism agents. In addition, it has been used extensively to irradiate air-conditioning cooling coils to maintain cleanliness and provide energy savings.

Concerns

- Effect of air temperature and movement as well as lamp age on UV output
- UV-C photodegradation of materials
- Lamp maintenance (inspection, cleaning, and testing) and disposal, especially mercury vapor lamps
- Safety: eyes and skin

Table 6. Permissible Exposure Times for Given Effective Irradiance Levels of UV-C Energy at 253.7 nm

Permissible Exposure Time[m] [a]	Effective Irradiance, µW/cm^2
24 h	0.07
18 h	0.09
12 h	0.14
10 h	0.17
8 h	0.2
4 h	0.4
2 h	0.8
1 h	1.7
30 min	3.3
15 min	6.7
10 min	10
5 min	20
1 min	100
30 s	200
15 s	400
5 s	1200
1 s	6000

[m] Calculated time period that humans, with unprotected eyes and skin, can be exposed to a given level of UV irradiance without exceeding the National Institute for Occupational Safety and Health recommended exposure limit (REL) (CDC/NIOSH 1972) or the ACGIH Threshold Limit Value® (TLV®) for UV radiation (ACGIH 2020a).

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