UV Inactivation of SARS-CoV-2 across the UVC spectrum: KrCl* excimer, mercury-vapor, and LED sources

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- **ABSTRACT**

Effective disinfection technology to combat severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) can help reduce viral transmissions during the on-going COVID-19 global pandemic and in the future. Ultraviolet (UV) devices emitting UVC irradiation (200-280 nm) have proven to be effective for virus disinfection, but limited information is available for SARS-CoV-2 due to the safety requirements of testing, which is limited to biosafety level (BSL) 3 laboratories. In this study, inactivation of SARS-CoV-2 in thin-film buffered aqueous solution (pH 7.4) was determined across UVC irradiation wavelengths (222 nm to 282 nm) from krypton chloride (KrCl*) excimers, a low-pressure mercury-vapor lamp, and two UVC light emitting diodes. Our results show that all tested UVC devices can effectively inactivate SARS-CoV-2, among which the KrCl* excimer had the best disinfection performance (i.e., highest inactivation rate). The inactivation rate constants of SARS-CoV-2 across wavelengths are similar to those for murine hepatitis virus (MHV) from our previous investigation, suggesting that MHV can serve as a reliable surrogate of SARS-CoV-2 with a lower BSL requirement (BSL-2) during UV disinfection tests. This study provides fundamental information for UVC action on SARS-CoV-2 and guidance for achieving reliable disinfection performance of UVC devices.

IMPORTANCE

UV light is an effective tool to help stem the spread of respiratory viruses and protect public health in commercial, transportation and healthcare settings. For effective use of UV, there is a need to determine the efficiency of different UV wavelengths in killing pathogens, specifically SARS-CoV-2, to support efforts to control the on-going COVID-19 global pandemic and future coronavirus-caused respiratory virus pandemics. We found that SARS-CoV-2 can be inactivated

effectively using a broad range of UVC wavelengths, and 222nm provided the best disinfection performance. Interestingly, 222 nm irradiation has been found to be safe for human exposure up to thresholds that are beyond effective for inactivating viruses. Therefore, applying UV light from KrCl* excimers in public spaces can effectively help reduce viral aerosol or surface transmissions.

Keywords: UV disinfection, far UVC, COVID-19, surrogate, human coronavirus 229E, murine hepatitis virus (MHV), bacteriophage Phi6

• INTRODUCTION

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is an enveloped, non-segmented positive-sense RNA virus (1), which is causing the on-going COVID-19 global pandemic. It is transmitted primarily via respiratory droplets produced while talking, coughing, and sneezing (2). Indirect routes, such as airborne and surface-mediated transmission, are also possible, especially considering SARS-CoV-2 can stay viable in aerosols and on surfaces up to 72 hours (3). Effective disinfection procedures can help reduce viral transmission, especially in high-risk places, such as hospitals, other healthcare facilities, and public transportation systems.

Ultraviolet (UV) devices emitting UVC irradiation (200-280 nm) such as low-pressure (LP) UV lamp and UV light emitting diodes (LEDs) have been widely used for virus disinfection of water, air, and surfaces since the early 20th century (4–8). Compared to other disinfection methods (e.g., heating and using chemical oxidants), UVC disinfection has several advantages, including rapid effectiveness, no chemical residual, and limited to no material degradation (6). One limitation of conventional UVC devices is that they are not safe for human exposures due to adverse effects on human skin and eyes (9, 10). Emerging far UVC devices (emitting UVC irradiation in the wavelength range of 200-225 nm) like the krypton chloride (KrCl*) excimer, however, have been proposed to disinfect occupied public spaces as recent studies reported that far UVC light exposure results in no adverse effects to skin or eyes in mouse studies due to its very limited penetration into biological materials (11–14).

There are only a few studies that document inactivation efficiencies of SARS-CoV-2 using UVC devices. An average UV fluence of 1.2 mJ/cm^2 to over 60 mJ/cm^2 were required for 1-log inactivation (90%) of SARS-CoV-2 in aqueous solutions using LP UV lamps, reported in previous investigations (15–18), whereas 1.6 mJ/cm^2 of UVC irradiation from a KrCl* excimer

with a 222 nm bandpass filter was needed to achieve the same virus reduction (19). A few other studies also investigated UV inactivation effectiveness against SARS-CoV-2 in virus droplets and on surfaces using LP UV lamps and KrCl* excimers (17, 20, 21). Despite these prior works, information on UVC inactivation of SARS-CoV-2 is still limited across UV wavelengths and in comparison to surrogate enveloped viruses, primarily due to the safety requirement of testing, which is limited to biosafety level (BSL) 3 laboratories. Thus, comparative studies including reliable and accessible surrogates of SARS-CoV-2 with a lower BSL requirement are needed for extensive assessment of UVC device, source, and wavelength performance.

In this study, UVC inactivation of SARS-CoV-2 in thin-film aqueous solution was determined using five UVC devices with different emission spectra in a bench-scale collimated beam apparatus. The UV sensitivities of SARS-CoV-2 and its potential testing surrogates classified as BSL-1 and BSL-2 viruses, including human coronavirus (HCoV) 229E, murine hepatitis virus (MHV), and bacteriophage Phi6 (22), were compared and recommendations for reliable UV testing surrogates of SARS-CoV-2 are made.

• MATERIALS AND METHODS

Virus preparation and enumeration. SARS-CoV-2 (Isolate USA WA1 2020), an enveloped respiratory virus, was propagated and assayed in the monkey kidney VeroE6 cell line (ATCC CRL-1586). VeroE6 cells were grown in Dulbecco's Modified Eagle Medium (DMEM) with 10% fetal bovine serum (FBS), 100µg/mL kanamycin sulfate, 200U/mL penicillin, 200µg/mL streptomycin, and 0.5µg/mL amphotericin B and incubated for 3 days at 37 ^{o}C in a 5% CO_2 atmosphere. The viral stock was then added into VeroE6 cells with fresh medium and incubated for 2 days at the same conditions, when cytopathogenic effects (CPE) were observed in the

monolayer. Infected cells were subjected to three freeze-thaw cycles to release the viruses, and the cell lysates were centrifuged at 1,000×g for 20 minutes to pellet the cell debris for removal and discard. The viruses in the supernatant then underwent a polyethylene glycol (12% w/v, MW 8000) precipitation with 0.5 M sodium chloride, and slow mixing overnight at 4°C. After centrifugation at 10,000 ×g for 60 minutes at 4°C, the pelleted virus was resuspended in 0.01M phosphate buffered saline (PBS; pH 7.4) to approximately a 10 mL volume. The SARS-CoV-2 stocks were then aliquoted and stored at -80 °C.

The viral stocks were enumerated on VeroE6 cells seeded into 96-well cell culture trays using the $TCID_{50}$ (tissue culture infectious dose at the 50% endpoint) technique as described by Payment and Trudel (23). This technique determines the dilution at which 50% of the wells show CPE. Serial 10-fold dilutions of SARS-CoV-2 samples were prepared in DMEM without FBS, followed by plating onto VeroE6 monolayers prepared in 96-well trays in replicates of six per dilution with 50 µL per well. DMEM containing 2% FBS was then added to bring the volume in each well up to 180µl. After the plates were further incubated for 7 days at 37 ^{o}C in a 5% CO_2 atmosphere, $TCID_{50}$ values were then calculated using the Spearman and Kärber algorithm (detection limit=6 $TCID_{50}$/mL) (24).

UV exposure experiments. The UV lamps were set up in a bench-scale collimated beam apparatus (Fig. 1-A) as described by Bolton and Linden (25). Normalized emission spectra for these UV lamps as used in the experiments (Fig. 1-B) were measured using a calibrated Maya 2000 Pro spectrometer (Ocean Insight, Dunedin, FL). Five UV sources were used in this investigation: an unfiltered KrCl* excimer lamp emitting primarily at 222 nm with a small peak at 258 nm (USHIO, Cypress, CA, USA), a filtered KrCl* excimer lamp with a 220 nm bandpass filter pre-installed (USHIO, Cypress, CA, USA), a conventional LP mercury lamp emitting at

254 nm, and two benchtop UV LED systems with peak emission wavelengths of 270 nm and 282 nm (AquiSense Technologies, Earlanger, KY, USA).

Figure 1. Schematic diagram of bench-scale collimated beam apparatus (A) and relative lamp emission (RLE) for the UV devices used in this investigation, absorbance of samples used in UV exposure tests, and normalized absorbance (normalized to maximum value at 200 nm) of nucleic acid (DNA/RNA) and protein (B). The nucleic acid and protein absorbance data were reproduced from Ma et al. (22).

UV exposure experiments were performed according to a standard protocol by Bolton and Linden (25). Virus samples (5 mL each) were made by diluting virus stocks 100-fold into sterile PBS (pH 7.4) and placed in 50 mm × 35 mm (diameter × height) sterile glass dishes (0.38 cm in depth) with a customized quartz lid (Corning 7980, Corning, NY, USA; Fig 1-A) with UV transmittance (UVT) greater than 90% at 200-400 nm, according to the information provided by the manufacturer and confirmed by measuring the UV absorbance of the lid using a UV-Vis spectrophotometer (DR-6000, Hach Company, Loveland, CO, USA). Absorbance for the samples was measured using a UV-Vis spectrophotometer. The UV incident irradiance at the center of sample surface was measured using a calibrated radiometer (ILT-2400, International Light Technologies, Inc., Peabody, MA, USA) set at the respective peak emission wavelength for a UVC device (222 nm was used for unfiltered KrCl* excimer). The radiometer detector was placed directly under the quartz lid during irradiance measurements at the liquid surface to include any effects from absorption and reflection of the quartz plate. UV exposure time for each sample was calculated using the target UV fluences for unweighted emissions between 200 nm to 300 nm according to a protocol by Linden and Darby (26) and Bolton and Linden (25), where average UV fluence calculation included corrections for radiometer detector sensitivity correction across lamp emission spectra (i.e., lamp correction factor), sample absorbance from 200 nm to 300 nm and path length (i.e., Beers law), divergence of light through the sample,

147 reflection factor, and non-uniformity of incident irradiance across the sample surface (i.e., petri
148 factor). Duplicate control samples (no UV exposure) were collected at the beginning and the end
149 of UV exposure tests for each UVC device. Eight virus samples were exposed with five different
150 UV fluences for each UVC device, in which three fluences were tested with duplicate samples
151 and the other two fluences were tested with one sample. All virus samples after UV exposures
152 were collected sacrificially so no subsampling was performed in the UV exposure tests. The
153 infectivity of virus samples without and after UV exposure was measured as described above,
154 and the infectivity reduction in $\log_{10}$ scale was determined.

155 **Statistical analysis.** The UV dose-responses using different UVC devices were evaluated based
156 on a pseudo-first-order inactivation kinetics model in $\log_{10}$-scale:

$$log_{10}I = log_{10}(\frac{N_0}{N}) = k \times D$$

157 where $log_{10}\ I$ is infectivity reduction in $\log_{10}$ scale, N_0 and N are the virus sample infectivity
158 before and after UV exposure, D is UV fluence in mJ/cm^2, and k is the pseudo-first-order
159 inactivation rate constant in cm^2/mJ computed from a $\log_{10}$-scale kinetic model. The $\log_{10}$-scale
160 inactivation rate constant was used, which made it easy to calculate the log inactivation from the
161 rate constant.

162 The mean and standard error (SE) of inactivation rate constants were calculated using 'linear
163 regression' function in OriginPro 2021 (intercept was fixed at zero). Samples with infectivity
164 equal to or less than the detection limits were excluded from the regression analyses. Analysis of
165 covariance (ANCOVA) was used to determine if there was a statistically significant difference in
166 the inactivation rate constants.

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170 • **RESULTS AND DISCUSSION**

171 All UVC devices tested in this study were very effective in inactivating SARS-CoV-2 in aqueous
172 solution (Fig. 2). Among all tested UVC devices, unfiltered and filtered KrCl* excimer exhibited
173 the greatest performance with inactivation rate constants (±S.E.) of 1.52±0.17 cm^2/mJ and
174 1.42±0.40 cm^2/mJ, respectively. These values are much higher than the value reported by
175 Robinson et al. (19) (0.64 cm^2/mJ). One possible explanation for such difference is that sample
176 absorbance at 222 nm was much higher in the Robinson study (>30 cm^{-1}) than this study (0.05
177 cm^{-1}; Fig. 1-B), and UV absorption by constituents in the sample matrix (i.e., proteins and other
178 constituents from the cell culture extracts) may affect the virus sensitivity toward UV irradiation.
179 Greater performance of KrCl* excimers compared to other UVC devices were also observed for
180 non-enveloped viruses (e.g., MS2 coliphage and adenovirus (4, 5, 27), enveloped bacteriophage
181 Phi6 (22), and coronaviruses (22) in previous studies, suggesting such superior performance may
182 be universal across virus types. This is likely because KrCl* excimers were capable of inflicting
183 greater viral protein and nucleic acid damage compared to other UVC devices due to the higher
184 protein absorbance at far UVC wavelengths around the 222 nm wavelength emitted by these
185 devices (Fig. 1-B). The superior performance of KrCl* excimer is particularly promising because
186 far UVC device are safe to be applied in occupied public spaces, up to the allowable threshold
187 limit value of 25 mJ/cm^2 at 220 nm, ACGIH 2021 (28) or perhaps beyond, to disinfect viruses in
188 respiratory secretions and airborne droplets as well as on contaminated surfaces, to limit the
189 presence and transmission of SARS-CoV-2 or other respiratory viruses. Previous studies on
190 aerosol and surface UV disinfection (29, 30) suggested that viruses in airborne droplets and on
191 surfaces tend to be more susceptible to UVC irradiation. Recent work with UV 222 nm

192 inactivation of SARS-CoV-2 on surfaces (17, 20, 21) and of other coronaviruses in air (12),
193 however, show very similar inactivation compared to this study, suggesting data for inactivation
194 generated using thin-film aqueous suspensions can represent inactivation of coronaviruses across
195 various media.
196 An average UV dose of 1.3 mJ/cm^2 was required for 1-log inactivation of SARS-CoV-2 using
197 the LP UV lamp, which is similar to the results from several previous studies (1.2-5.0 mJ/cm^2 for
198 1 log inactivation (15–17)). Another study by Heilingloh et al. (18), however, suggested 1-log
199 inactivation would require above 60 mJ/cm^2 using a LP UV source. This divergence from the
200 UV doses reported in numerous other studies is likely due to the significant difference in the
201 experimental setup for UV exposures and calculation for UV fluences. The inactivation tests
202 reported in Heilingloh were performed in cell culture media in 24-well plates with the UV source
203 placed only 3 cm above the bottom of the plate, which could lead to differences in UV intensity
204 between each well. Also no information is given on how the UV irradiance was measured, there
205 is no report of the absorbance of the suspending media, and standardized procedures for UV
206 fluence calculation (e.g., corrections for sample UV absorbance, depth of sample, UV beam
207 reflection and divergence, and petri factor) were not followed. Based on the data presented
208 herein, no statistically significant difference in UV inactivation performance was observed
209 between the LP UV lamp and the UV LED 270 (P=0.16; Fig. 2). Viral genome damage is likely
210 to be the primary inactivation mechanism for these UVC devices (27), and SARS-CoV-2 should
211 have similar sensitivities to UV irradiation from these devices due to similar nucleic acid
212 absorbance at their peak emission wavelengths (i.e., 254 nm and 270 nm, respectively; Fig. 1-B).
213 UV LED 282 provided the lowest inactivation rate constant among all tested UVC devices. Viral
214 genomes tends to absorb less UV irradiation in the wavelength range emitted from UV LED 282

(4, 31) (Fig. 1-B), which leads to less genome damage. While viral proteins, should be slightly more sensitive to UV irradiation from around 282 nm wavelength (32), this previous observation did not appear to enhance the effectiveness for the 282 nm LED in this current study.

Figure 2. Dose-response of SARS-CoV-2 to UV irradiation from all tested UVC devices. Dashed lines represent linear regression results computed from experimental data. The *k* values (mean ± standard error; in cm^2/mJ) and adjusted R^2 values are listed. Open symbols represent samples with infectivity equal to or less than the detection limits. Solid symbols with black edge represent two samples overlapping in the plot with the same UV dose response. Primary emission wavelengths for UVC devices are listed in each sub-figure legend.

The inactivation rate constants of SARS-CoV-2 were compared with the values of potential enveloped virus surrogates: HCoV 229E, MHV, and bacteriophage Phi6 (Fig. 3). These three viruses were selected as candidates of SARS-CoV-2 surrogates for UV inactivation tests due to their molecular similarities (i.e., all are enveloped RNA viruses) and lower biosafety requirements (BSL-1 for Phi6, and BSL-2 for HCoV 229E and MHV). All virus surrogates were previously tested in the identical collimated beam apparatus except that the quartz lid was not applied for non-BSL3 organisms. The inactivation rate constants were also calculated following the same data analysis method (22). Among the three candidates, MHV exhibited the greatest similarities in inactivation rate constants across UVC devices compared to SARS-CoV-2. No statistically significant difference in the rate constant values ($P>0.05$) were observed for all tested UVC devices except for unfiltered KrCl* excimer ($P=0.008$), for which the inactivation rate of MHV was only 26% lower than the value for SARS-CoV-2 (Fig. 3). These results suggest that MHV can serve as a reliable UV surrogate of SARS-CoV-2 testing across UVC wavelengths when a lower biosafety requirement is needed. HCoV 229E could also serve as a viable surrogate of SARS-CoV-2, especially for testing unfiltered KrCl* excimer (Fig. 3). Considering SARS-

CoV-2, MHV, and HCoV 229E are all coronaviruses, evidence suggests that coronaviruses in general have similar sensitivities to UVC irradiation across wavelengths due to their similar molecular structures. This is further supported by comparing the UV inactivation rate constants of other coronaviruses, such as HCoV-OC43. UV inactivation rate constants of 0.77, 0.64, and 0.43 cm^2/mJ were reported by Gerchman et al. (33) using UV LEDs with peak emission at 267, 279, and 286 nm, respectively, which are similar to the values we observed using UV LED 270 and UV LED 282 (0.93 and 0.53 cm^2/mJ; Fig. 2). Although significantly lower inactivation rate constants were observed for bacteriophage Phi6 ($P<0.05$; Fig. 3), it can still serve as a conservative virus surrogate where use of coronaviruses is not feasible (e.g., lack of mammalian cell culture facilities). Compared to non-enveloped viruses, use of enveloped viruses like bacteriophage Phi6 is particularly desirable in surface and aerosol disinfection tests to best represent any interactions between the viral envelope and its surrounding environment that may affect viral sensitivity to UVC irradiation (34–36). Other bacteriophage, such as T1 and T7, although non-enveloped double stranded DNA phages, exhibit similar sensitivities to SARS-CoV-2 across UVC wavelengths (31) and could also serve as UV disinfection surrogates.

Figure 3. UV inactivation rate constants of SARS-CoV-2, two coronaviruses (HCoV 229E and MHV), and enveloped bacteriophage Phi6 for all tested UVC devices. The mean inactivation rate values are labeled. The values for Phi6, HCoV 229E and MHV were published by Ma et al. (22). Asterisk brackets represent two inactivation rate values that were not statistically significantly different at 95% confidence level ($P>0.05$).

This research defines the fundamental inactivation rate constants of SARS-CoV-2 for UVC devices with peak emission wavelengths of 222 nm to 282 nm. These devices can be used to effectively inactivate SARS-CoV-2, among which far UVC devices like KrCl* excimer provided the best disinfection performance, with the added benefit of limited safety requirements when applied in occupied spaces. MHV is recommended as a reliable UV testing surrogate of SARS-

CoV-2 due to its similar UV sensitivities across UVC wavelengths, but other T-phages could also serve as surrogates. While these inactivation data align well with previous studies of UV disinfection of coronaviruses in aerosols and dried on surfaces, future work should continue to evaluate UV inactivation of SARS-CoV-2 in aqueous and other media relative to surrogates such as MHV or bacteriophage, and expand these comparisons to other disinfectants important to minimizing the transmission of respiratory viruses.

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- **DISCLOSURES**

The authors declare no competing interest.

References

1. World Health Organization. 2020. Transmission of SARS-CoV-2: Implications for Infection Prevention Precautions.
2. Pitol AK, Julian TR. 2020. Community Transmission of SARS-CoV-2 by Fomites: Risks and Risk Reduction Strategies. Environ Sci Technol Lett 8:263–269.
3. Doremalen N van, Bushmaker T, Morris DH, Holbrook MG, Gamble A, Williamson BN, Tamin A, Harcourt JL, Thornburg NJ, Geber SI, Lloyd-Smith JO, Wit E de, Munster VJ. 2020. Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1. N Engl J Med 382:1564–1567.
4. Beck SE, Rodriguez RA, Linden KG, Hargy TM, Larason TC, Wright HB. 2014. Wavelength dependent UV inactivation and DNA damage of adenovirus as measured by cell culture infectivity and long range quantitative PCR. Environ Sci Technol 48:591–598.
5. Hull NM, Linden KG. 2018. Synergy of MS2 disinfection by sequential exposure to tailored UV wavelengths. Water Res 143:292–300.
6. Linden KG, Hull N, Speight V. 2019. Thinking Outside the Treatment Plant: UV for Water Distribution System Disinfection. Acc Chem Res 52:1226–1233.
7. Beck SE, Ryu H, Boczek LA, Cashdollar JL, Jeanis KM, Rosenblum JS, Lawal OR, Linden KG. 2017. Evaluating UV-C LED disinfection performance and investigating potential dual-wavelength synergy. Water Res 109:207–216.
8. Kowalski W, Bahnfleth W, Hernandez M. 2009. A genomic model for predicting the ultraviolet susceptibility of viruses. IUVA News.
9. Tenkate TD. 1998. Ultraviolet radiation: human exposure and health risks. J Environ Health 61:9+.
10. Zaffina S, Camisa V, Lembo M, Vinci MR, Tucci MG, Borra M, Napolitano A, Cannatã V. 2012. Accidental exposure to UV radiation produced by germicidal lamp: Case report and risk assessment. Photochem Photobiol 88:1001–1004.
11. Buonannoa M, Ponnaiyaa B, Welcha D, Stanislauskasb M, Randers-Pehrsona G, Smilenova L, Lowyc FD, Owensb DM, Brennera DJ. 2017. Germicidal Efficacy and Mammalian Skin Safety of 222-nm UV Light. Radiat Res 187:483–481.
12. Buonanno M, Welch D, Shuryak I, Brenner DJ. 2020. Far-UVC light (222 nm) efficiently and safely inactivates airborne human coronaviruses. Sci Rep 10:1–8.
13. Narita K, Asano K, Morimoto Y, Igarashi T, Nakane A. 2018. Chronic irradiation with 222-nm UVC light induces neither DNA damage nor epidermal lesions in mouse skin, even at high doses. PLoS One 13:1–9.
14. Kaidzu S, Sugihara K, Sasaki M, Nishiaki A, Ohashi H, Igarashi T, Tanito M. 2021. Re-Evaluation of Rat Corneal Damage by Short-Wavelength UV Revealed Extremely Less Hazardous Property of Far-UV-C†. Photochem Photobiol 97:505–516.
15. Biasin M, Bianco A, Pareschi G, Cavalleri A, Cavatorta C, Fenizia C, Galli P, Lessio L, Lualdi M, Tombetti E, Ambrosi A, Redaelli EMA, Saulle I, Trabattoni D, Zanutta A, Clerici M. 2021. UV-C irradiation is highly effective in inactivating SARS-CoV-2 replication. Sci Rep 11:1–7.
16. Patterson EI, Prince T, Anderson ER, Casas-Sanchez A, Smith SL, Cansado-Utrilla C, Solomon T, Griffiths MJ, Acosta-Serrano Á, Turtle L, Hughes GL. 2020. Methods of Inactivation of SARS-CoV-2 for Downstream Biological Assays. J Infect Dis 222:1462–1467.

17. Storm N, McKay LGA, Downs SN, Johnson RI, Birru D, de Samber M, Willaert W, Cennini G, Griffiths A. 2020. Rapid and complete inactivation of SARS-CoV-2 by ultraviolet-C irradiation. Sci Rep 10:1–5.
18. Heilingloh CS, Aufderhorst UW, Schipper L, Dittmer U, Witzke O, Yang D, Zheng X, Sutter K, Trilling M, Alt M, Steinmann E, Krawczyk A. 2020. Susceptibility of SARS-CoV-2 to UV irradiation. Am J Infect Control 48:1273–1275.
19. Robinson RT, Mahfooz N, Rosas-Mejia O, Liu Y, Hull NM. 2021. SARS-CoV-2 disinfection in aqueous solution by UV 222 from a krypton chlorine excilamp. medRxiv 2021.02.19.21252101.
20. Kitagawa H, Nomura T, Nazmul T, Omori K, Shigemoto N, Sakaguchi T, Ohge H. 2020. Effectiveness of 222-nm ultraviolet light on disinfecting SARS-CoV-2 surface contamination. Am J Infect Control 49:299–301.
21. Kitagawa H, Nomura T, Nazmul T, Kawano R, Omori K, Shigemoto N, Sakaguchi T, Ohge H. 2021. Effect of intermittent irradiation and fluence-response of 222 nm ultraviolet light on SARS-CoV-2 contamination. Photodiagnosis Photodyn Ther 33:102184.
22. Ma B, Linden YS, Gundy PM, Gerba CP, Sobsey MD, Linden KG. 2021. Inactivation of Coronaviruses and Phage Phi6 from Irradiation across UVC Wavelengths. Environ Sci Technol Lett 8:425–430.
23. Payment P, Trudel M. 1994. Methods and techniques in virology.
24. Ramakrishnan MA. 2016. Determination of 50% endpoint titer using a simple formula. World J Virol 5:85–86.
25. Bolton JR, Linden KG. 2003. Standardization of Methods for Fluence (UV Dose) Determination in Bench-Scale UV Experiments. J Environ Eng 129:209–215.
26. Linden KG, Darby JL. 1997. Estimating Effective Germicidal Dose from Medium Pressure UV Lamps. J Environ Eng 123:1142–1149.
27. Beck SE, Rodriguez RA, Hawkins MA, Hargy TM, Larason TC, Linden KG. 2016. Comparison of UV-induced inactivation and RNA damage in MS2 phage across the germicidal UV spectrum. Appl Environ Microbiol 82:1468–1474.
28. 2021. Threshold Limit Values (TLVs ®) and Biological Exposure Indices (BEIs ®), 2021. The American Conference of Governmental Industrial Hygienists (ACGIH).
29. Chun-Chieh T, Li C-S. 2007. Inactivation of Viruses on Surfaces by Ultraviolet Inactivation of Viruses on Surfaces by Ultraviolet. J Occup Environmenal Hyg 9624.
30. Walker CM, Ko G. 2007. Effect of ultraviolet germicidal irradiation on viral aerosols. Environ Sci Technol 41:5460–5465.
31. Beck SE, Wright HB, Hargy TM, Larason TC, Linden KG. 2015. Action spectra for validation of pathogen disinfection in medium-pressure ultraviolet (UV) systems. Water Res 70:27–37.
32. Beck SE, Hull NM, Poepping C, Linden KG. 2018. Wavelength-Dependent Damage to Adenoviral Proteins Across the Germicidal UV Spectrum. Environ Sci Technol 52:223–229.
33. Gerchman Y, Mamane H, Friedman N, Mandelboim M. 2020. UV-LED disinfection of Coronavirus: Wavelength effect. J Photochem Photobiol B Biol 212.
34. Kim K, Jothikumar N, Sen A, Murphy JL, Chellam S. 2021. Removal and Inactivation of an Enveloped Virus Surrogate by Iron Conventional Coagulation and Electrocoagulation. Environ Sci Technol 55:2674–2683.

35. Silverman AI, Boehm AB. 2020. Systematic Review and Meta-Analysis of the Persistence and Disinfection of Human Coronaviruses and Their Viral Surrogates in Water and Wastewater. Environ Sci Technol Lett 7:544–553.
36. Aquino De Carvalho N, Stachler EN, Cimabue N, Bibby K. 2017. Evaluation of Phi6 Persistence and Suitability as an Enveloped Virus Surrogate. Environ Sci Technol 51:8692–8700.