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Spectrum of virucidal activity from ultraviolet to infrared radiation

Luke Horton,[a] Angeli Eloise Torres,[b] Shanthi Narla,[b] Alexis B. Lyons,[b] Indermeet Kohli,[b,c] Joel M. Gelfand,[d] David M. Ozog,[b] Iltefat H. Hamzavi[b] and Henry W. Lim[b]

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The COVID-19 pandemic has sparked a demand for safe and highly effective decontamination techniques for both personal protective equipment (PPE) and hospital and operating rooms. The gradual lifting of lockdown restrictions warrants the expansion of these measures into the outpatient arena. Ultraviolet C (UVC) radiation has well-known germicidal properties and is among the most frequently reported decontamination techniques used today. However, there is evidence that wavelengths beyond the traditional 254 nm UVC – namely far UVC (222 nm), ultraviolet B, ultraviolet A, visible light, and infrared radiation – have germicidal properties as well. This review will cover current literature regarding the germicidal effects of wavelengths ranging from UVC through the infrared waveband with an emphasis on their activity against viruses, and their potential applicability in the healthcare setting for general decontamination during an infectious outbreak.

Introduction

The COVID-19 pandemic has provoked society to implement strict precautions for contagion containment. In addition to social distancing, effective decontamination techniques are needed for personal protective equipment (PPE), rooms, and surfaces in the hospital and ambulatory setting.

While COVID-19 transmission occurs primarily *via* person-to-person contact through respiratory droplets and fecal-oral route, there remains a significant risk of transmission *via* fomites in the environment.[1–4] This is true for many viral and bacterial pathogens significant to public health.[5–11] Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the causative agent of COVID-19, remains viable for 3 hours in aerosols, up to 72 hours on plastic and stainless steel, 24 hours on cardboard, and 4 hours on copper.[12] Presently, there are several methods of environmental decontamination utilized in the healthcare setting, including chlorinated disinfectants, alcohol-based disinfectants, hydrogen peroxide disinfectants, and light-based methods.[13–15] Ultraviolet C (UVC) radiation is the light-based methodology most commonly utilized for decontamination, but evidence shows that ultraviolet B (UVB), ultraviolet A (UVA), visible light (VL) and infrared radiation (IR) have germicidal properties as well; however, their use in surface decontamination is uncommon.[15–19]

The extensive spread of the virus has resulted in worldwide shortages of PPE necessary to protect frontline workers.[15] As such, innovative techniques for PPE conservation and surface decontamination are essential to reduce transmission and save lives. The United States Centers for Disease Control and Prevention (CDC) defines decontamination as any method that rids objects of pathogenic microorganisms rendering them safe for use, handling, or disposal.[20] There are different types of decontamination depending on the amount of microorganisms that a specific method is able to eliminate (Table 1). For

Table 1 Types of decontamination as defined by CDC[20]

Term	Definition
Sterilization	A process that eliminates all forms of microbial life, usually through physical or mechanical means (*e.g.* dry heat, steam under pressure, hydrogen peroxide gas plasma).
Disinfection	A process that eliminates many or all pathogenic organisms except bacterial spores.
High level disinfection	A process that will eliminate all microorganisms except a large number of bacterial spores in a reasonable amount of time.
Low level disinfection	A process that will eliminate most vegetative bacteria, some fungi, and some viruses in a practical period of time (≤10 minutes).
Cleaning	Removal of visible residue from objects or surfaces.
Virucidal	Refers to any agent that can kill or inactivate viruses.

[a]*Wayne State University School of Medicine, Detroit, MI, USA*
[b]*Photomedicine and Photobiology Unit, Department of Dermatology, Henry Ford Health System, Detroit, MI, USA. E-mail: hlim1@hfhs.org; Fax: +1(313) 916-2093; Tel: +1 313-916-4060*
[c]*Department of Physics and Astronomy, Wayne State University, Detroit, MI, USA*
[d]*Department of Dermatology, University of Pennsylvania Perelman School of Medicine, Philadelphia, PA, USA*

Table 2 Ultraviolet, visible, and infrared radiation with corresponding wavelengths[88]

Spectrum	Wavelength[a]
Ultraviolet C (UVC)	200–290 nm
Ultraviolet B (UVB)	290–320 nm
Ultraviolet A (UVA)	320–400 nm
UVA2	320–340 nm
UVA1	340–400 nm
Visible light	400–700 nm
Infrared (IR)	700–1 mm
IR-A	700–1400 nm
IR-B	1400–3000 nm
IR-C	3000 nm–1 mm

[a] Of note, wavelength ranges are arbitrary and may vary depending on the source or discipline. The above values represent the most widely used ranges in photodermatology.[88]

the purposes of this review, decontamination will refer to low-level disinfection, which is defined by the CDC as those that eliminate most bacteria, fungi, and viruses in ≤10 minutes. Low-level disinfection is used for surfaces that come in contact with intact skin (bed rails, blood pressure cuffs, and table tops).[20] This review covers wavelengths ranging from UVC to infrared (Table 2) and their potential as low-level decontamination methods, with an emphasis on viral inactivation.[20]

Discussion

Ultraviolet radiation

Ultraviolet (UV) radiation (UVR) has known virucidal properties. It damages the viral genome or structure through the formation of pyrimidine dimers and generation of reactive oxygen species (ROS),[17,21] which leads to microorganism inactivation and inhibits replication.[15,22] UV absorbance by deoxyribonucleic acid (DNA) peaks within the UVC range, making it the most effective UV wavelength for viral inactivation; however, UVA and UVB are also potentially damaging to viruses.[17,23,24]

The virucidal efficacy of UVR is influenced by the target pathogen, the environment, and the surface being decontaminated. Viruses with single-stranded (SS) genomes are inactivated at lower irradiation doses compared to their double-stranded (DS) counterparts.[23] DNA viruses are more susceptible to UV damage compared to ribonucleic acid (RNA) viruses due to the presence of thymine in DNA, which yields a more damaging photoproduct compared to uracil in RNA.[17] Viruses with larger genomes have more target bases, which increases their likelihood of incurring UV damage following exposure.[17,21] Viral packaging and morphology also play a role, as an icosahedral-shaped virus is inactivated more quickly than a rod-shaped virus.[23] Additionally, high humidity enhances viral resistance to UVR secondary to water adsorption onto viral surfaces.[25] Finally, viral inactivation is influenced by the characteristics of the surface or substrate being decontaminated.[15,26] For example, reflective material may improve the decontamination of pathogens through UVC, while organic matter such as dirt or sebum absorb UVC and limit its efficacy.[27] Together, these factors lead to significant variance in the UV exposure needed for viral inactivation, specifically, the dosage required for SARS-CoV-2 inactivation will depend upon the object being decontaminated.

Ultraviolet C (200 nm–290 nm)

UVC has been utilized for the decontamination of air, water, and various surfaces in hospitals and laboratories.[14,15,28–30] This method – termed ultraviolet germicidal irradiation (UVGI) – generates UVC from either a low-pressure mercury or light-emitting diode (LED) lamp source, emitting a peak wavelength of 254 nm.[15,17]

Whole room decontamination with UVGI has demonstrated efficacy in achieving a 4-log reduction in a variety of viruses and common nosocomial pathogens.[27,31–34] Of note, previous studies have considered ≥3 to 4-log reductions significant (*i.e.* an adequate level of reduction in viral load to report in the literature). However, these values are arbitrarily assigned based on academic exercises and may not be readily generalized into real-life practice since depending on the initial inoculation dose and the pathogen in question, there could be enough viral particles remaining despite a 3–4 log reduction to induce infection in an exposed individual.[35,36] For the purposes of this review, the word "significant" as it refers to level of decontamination will be used in accordance with the previous vernacular reported in literature (3 to 4-log reduction). Similar to all UVR, UVC intensity – and accordingly, the biocidal efficacy – decreases with increasing distance between the substrate and the light source. Furthermore, UVC travels in a straight line and can be blocked by objects in its path (*e.g.* shadowing, organic materials); hence, only exposed surfaces will benefit, and visibly soiled surfaces should be cleaned beforehand.[27,37,38]

UVGI is a frequently described method for the decontamination of N95 respirators, known as filtering facepiece-2 (FFP2) in the European Union.[15] A dose of ~1 J cm^{-2} is required to achieve a minimum of 3-log reduction.[22,26] Viral pathogens which have been successfully inactivated at this dose include H1N1 influenza, avian influenza A (H5N1), influenza A (H7N9), severe acute respiratory syndrome coronavirus 1 (SARS-CoV-1), and Middle East respiratory syndrome coronavirus (MERS-CoV).[22,26,35,36,39,40] There is currently no peer-reviewed published data regarding the dose required to effectively eliminate SARS-CoV-2. However, since UVC has evidence of virucidal activity against MERS-CoV and SARS-CoV-1, these could serve as potential surrogates. Importantly, UVC degrades polymers over time – an important consideration when used to decontaminate N95 respirators for reuse.[15,41]

Although the effects of UVGI on human health are not fully established, it can potentially damage human cells.[42,43] In mice, exposure to UVC has been shown to cause sunburn, desquamation, and hyperkeratosis. These changes reflect cell damage and are secondary to the formation of cyclobutane pyrimidine dimers (CPDs) in the DNA, which is associated

with the development of skin cancer.[42,44,45] Further, UVC can cause cataracts, photokeratitis, and/or conjunctivitis.[46–48]

Compared to 254 nm UVC, far UVC (222 nm) is thought to be less harmful to mammalian cells. Far UVC has limited penetration beyond the stratum corneum of the skin or outer tear film of the eye, and is absorbed by peptide bonds in proteins and other biomolecules in the cell wall and cytoplasm before it reaches the nuclei.[42,46,49–51] A study on the effects of far UVC in a xeroderma pigmentosum mouse model showed that CPDs were formed only in the uppermost layer of the epidermis. This was observed at high doses (100 kJ m^{-2} or 100 000 J cm^{-2}) suggesting a low risk of carcinogenesis.[52] Further research is needed to verify safety in humans.[2,50–52]

Far UVC has been shown to have germicidal effects in solution, comparable to that of 254 nm UVC, at doses of 6 to 96 mJ cm^{-2} depending on the organism.[49] Non-detectable levels of influenza A virus in media have been achieved at 6 mJ cm^{-2}, while 95% of aerosolized H1N1 influenza can be inactivated at 1.6 mJ cm^{-2}.[49,50,53] In one study, loss of adenovirus infectivity was found to be almost 16 times greater at 210 nm, and more than 10 times greater at 220 nm than at 254 nm UVC. This enhanced efficacy was attributed to the additive effect of UV-induced damage to viral proteins, which occurs at wavelengths below 240 nm.[54] To date, the efficacy of far UVC against coronaviruses has not been studied.

Far UVC's poor penetration into organic tissue, while reducing its capacity to harm humans, raises concern about its ability to penetrate and decontaminate inorganic material such as woven N95 respirators sufficiently for reuse.[42] More studies are needed before far UVC can be used for PPE and surface decontamination. However, far UVC provides an opportunity to safely reduce viral transmission through aerosols, especially in places with high levels of human traffic.[50] Other potential uses of far UVC include prevention or reduction of surgical site infections, promotion of wound healing, and hand sanitation.[53,55–57] Both far UVC and 254 nm UVC can be used as low-level decontamination methods as defined by the CDC.[20]

Ultraviolet B (290 nm–320 nm)

UVA and UVB radiation are used in phototherapy in dermatology. This presents an opportunity to repurpose phototherapy equipment for decontamination.[58,59] However, the utility of UVA and UVB as environmental decontaminants in the healthcare setting has not been sufficiently studied.

Generally, both UVA and UVB are capable of microbial inactivation, but require higher doses to achieve comparable levels of reduction to UVC.[21] It has been estimated that compared to 260 nm, doses at 400 nm, 340 nm, and 300 nm need to be 10^4, 10^3, and 10^1 times higher, respectively, to achieve equivalent efficacy.[60,61] Similarly, a dose–response analysis showed an inverse relationship between wavelength and log reductions in MS2 and T4 bacteriophage *in vitro*.[61] Based on a composite UVA/UVB action spectrum by Lytle *et al.*,[17] our group calculated that to achieve a 1/*e* (67%) reduction in viral load, a dose of 2500 J cm^{-2} would be needed at 310 nm, compared to only 1 J cm^{-2} of UVC (254 nm). Relative dosing for other wavelengths were also extrapolated (Fig. 1). Notably, 1/*e* reduction doses at 254 nm are expected to be less than 1 J cm^{-2}, and corresponding doses at other wavelengths can be scaled accordingly. However, UVB has better penetration than UVC which could result in a lower required decontamination doses for materials (*e.g.* N95 respirators). Systematic studies comparing virucidal efficacy of UVB to UVC are warranted in the future.

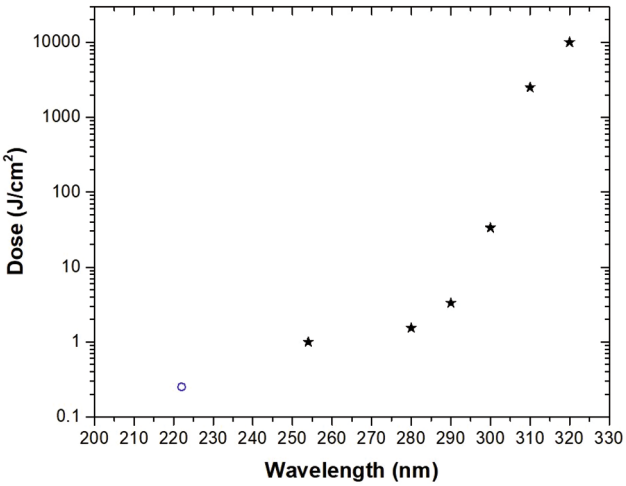

Fig. 1 Virus inactivation doses extrapolated from the relative sensitivities of viruses. The doses are normalized against that at 254 nm and represent the respective efficacy to achieve 1/*e* (63%) reduction in the viral load. In other words, if it takes 1 J cm^{-2} of 254 nm UVC for 1/*e* reduction of a given pathogen at a given substrate, then it will take approximately 1.5 J cm^{-2} at 280 nm, 3.3 J cm^{-2} at 290 nm, 33.3 J cm^{-2} at 300 nm, and so on and so forth. Graph created with sensitivities reported in Lytle *et al.*[17] (★) and Beck *et al.*[54] (○). Of note, doses for 1/*e* reduction at 254 nm will be much lower than 1 J cm^{-2} and doses at other wavelengths can be scaled down accordingly.

Data focusing on the virucidal activity of UVB is limited. One study found that UVB exposure resulted in a 4-log reduction in MS2 bacteriophage and murine norovirus (MNV) in suspension following irradiation at 909 mJ cm^{-2} and 367 mJ cm^{-2}, respectively.[16] UVB at 310 nm has also demonstrated ability to inactivate H1N1 (3-log reduction at 1.32 J cm^{-2}) and H1N5 (5-log reduction at 1.32 J cm^{-2}) influenza viruses in suspension. This was less effective than UVC, which achieved a 3-log and 5-log reduction of H1N1 and H1N5, respectively at 0.055 J cm^{-2}.[39] A study of the elimination of viruses in plasma showed that UVB was less effective than UVC. Nearly all viruses studied were reduced to the detection limit at 1 J cm^{-2} UVC while only the most sensitive viruses reached this point with 2.5 J cm^{-2} UVB. The inactivation factors of the other viruses were approximately 1.9-log.[62] No study on the virucidal activity of narrowband UVB (311–313 nm) has been published. Clearly, further studies are needed on this topic.

Similar to UVC, UVB radiation can deteriorate plastics, rubber, and wood. The rate of degradation depends on the

chemical nature of the material as well as any light stabilizers applied to it (*e.g.* protective coating). Individual studies are needed to determine the efficacy and functionality of PPE decontaminated by UVB, although degradation is likely with more frequent exposures and higher dosages.[63–65] In order for UVB to meet the criteria of a low-level decontamination method as defined by the CDC, the virucidal doses required need to be determined, and the irradiance of the device would need to be high enough that such doses could be delivered in ≤10 minutes.[20]

Ultraviolet A (320 nm–400 nm)

While UVA is the most penetrating wavelength in UVR, it is the least effective for decontamination.[16,21,66] Compared to UVC and UVB, UVA is not as efficient in modifying nucleic acid bases and forming CPDs. Its germicidal effect stems from the generation of ROS.[67] In a study comparing the efficacy of UVA (365 nm) to UVB (310 nm) and UVC (280 nm) against H1N1 influenza A virus in suspension, UVA at 63 J cm^{-2} caused a 2-log reduction, while UVB and UVC attained 3-log reductions at 1.32 J cm^{-2} and 0.055 J cm^{-2}, respectively.[39]

Most studies evaluating UVA effects on viruses involve water sterilization.[67] Bacteriophage F2 and bovine rotavirus in water have shown a 3-log reduction after 3.3 and 2.5 hours of UVA exposure (corresponding to 900 J cm^{-2} and 680 J cm^{-2}), respectively.[68] Another study showed that exposure to 365 nm LED-UVA at 65 J cm^{-2} lead to a 3-log reduction of MS2 phage in water, while *Salmonella enteritidis* required over 500 J cm^{-2} to achieve a 3-log reduction. The authors noted that while LED-UVA is an inexpensive, energy-efficient water sterilization modality, it requires a high dose of radiation to achieve pathogen log inactivation that is comparable to UVC.[69]

A study compared the efficacy of UVA, bleach, UVC, autoclave, and steam in eliminating *Bacillus subtilis* spores on an N95 respirator. It found that *Bacillus subtilis* survival remained above 20% after 20 minutes of irradiation with 365 nm at 31.2 mW cm^{-2} (*i.e.*, 37.4 J cm^{-2}), while the other four methods achieved 99–100% biocidal efficacy.[70] Another study reported a 3-log reduction in *E. coli* from the surface of vegetables following a 90-minute exposure to 365 nm UVA at 125 mW cm^{-2} (*i.e.*, 675 J cm^{-2}).[71] However, studies utilizing UVA for decontamination of rooms, surfaces, or PPE are limited.

The sensitivity of plastics decreases exponentially with wavelength; hence, UVA degrades materials less effectively than UVC or UVB.[63] While this, together with superior penetration of UVA, would be beneficial for decontamination of PPE for reuse, the lack of proven virucidal efficacy, the need for extremely high doses, and long duration of irradiation do not make UVA an ideal option for low-level decontamination at this time.

Visible light (400 nm–700 nm)

VL is an emerging technique used to decontaminate air, rooms, and surfaces.[14] The wavelength utilized is within the violet-blue range (400–420 nm), with a peak at 405 nm.[72] Inactivation of microorganisms by VL was traditionally carried out using a photodynamic technique which entails the use of an exogenous photosensitizer such as methylene blue, rose bengal, or cationic porphyrins. The photosensitizer acts as the chromophore, which upon exposure to VL generates ROS that destroy microbial proteins, lipids, and nucleic acids leading to inactivation. It was later discovered that the addition of exogenous photosensitizers is not always required since endongenous molecules such as porphyrins and flavins that are naturally present within microbial cells can act as the chromophore that facilitates the decontamination process.[72–75] The source of VL is typically an LED, which delivers low-irradiance violet-blue light at 405 nm. Because of the low irradiance, microbial inactivation by VL occurs more slowly compared to UVR, and a longer exposure time is needed.[14,19]

VL has well-documented biocidal activity against an array of bacteria and fungi including *Methicillin-resistant Staphylococcus aureus* (5-log reduction with 36 J cm^{-2}),[76] *Acinetobacter baumanii* (4.2-log reduction with 108 J cm^{-2}),[76] *Helicobacter pylori* (5-log reduction with 30 J cm^{-2}),[77] *Propionibacterium acnes* (4-log reduction with 150 J cm^{-2}),[78] and *Candida albicans* (6-log reduction with 70 J cm^{-2}).[79] However, data on its virucidal effects are lacking. One review noted that viruses are among the least sensitive to VL, while Gram-negative and Gram-positive vegetative bacteria are the most susceptible.[73] This may be due to the absence of endogenous porphyrins in virions, which, in contrast, are abundantly present in bacteria.[77] One study showed that feline calicivirus, a surrogate for norovirus, required a dose of 2800 J cm^{-2} of 405 nm light to achieve a 4-log reduction on minimal media. However, a reduction by as much as 5-log was demonstrated on artificial saliva, blood plasma, and artificial feces following exposure to doses of 421 J cm^{-2}, 561 J cm^{-2}, and 1400 J cm^{-2}, respectively.[80] In another study, streptomyces phage φC31, a surrogate for non-enveloped double-stranded DNA viruses, was reduced by only 0.3-log on minimal media after exposure to 306 J cm^{-2} of 405 nm light. Higher log reductions were achieved on nutrient-rich (2.7-log reduction) and porphyrin-supplemented media (>2.5-log reduction) using the same dose. This observation supports the role of endogenous porphyrins in the biocidal activity of VL.[72]

VL decontamination is a safer alternative to UV-based systems. At 405 nm, VL is considered safe for human exposure, allowing decontamination to be delivered continuously without disrupting clinic flow.[19] However, known photobiologic effects of VL, including skin hyperpigmentation (415 ± 5 nm), photoretinis (440 nm), and alterations in mood and circadian rhythm (480 nm), should be noted.[19] Induction of lesions of solar urticaria, chronic actinic dermatitis and cutaneous porphyrias by VL could also occur.[81,82]

Unlike UVR, VL does not degrade materials. Its lower energy requirement entails less frequent bulb replacement and maintenance. Of note, light-sensitive liquid solutions can undergo photochemical changes when exposed to VL, which may be mitigated through storage of these solutions in shadowed areas. Violet-blue light can potentially interfere with

color perception and pose difficulties during physical examination or surgery.[19] Furthermore, since VL surface decontamination is a relatively new technology, few companies manufacture these devices and none are approved by the United States Food and Drug Administration (US FDA). These devices are typically ceiling-mounted, and in some cases, a white LED light is incorporated, allowing the device to serve as both luminescent lighting and decontaminant.[19]

Infrared radiation (700 nm–1 mm)

IR is divided into near IR (NIR) (IR-A; 700–1400 nm), mid IR (IR-B; 1400–3000 nm), and far IR (IR-C; 3000 nm–1 mm).[83,84] Decontamination *via* IR is achieved through wavelengths within the NIR range.[84] The exposure causes vibration of water molecules within the substrate, producing heat that destroys microbial nucleic acids, proteins, and cell walls. This technique is widely used in the food processing industry to inhibit bacteria, spores, yeast, and mold. Traditional sources of IR are electric and gas-fired heaters.[85]

In the healthcare setting, IR has been used to decontaminate non-heat sensitive instruments and high efficiency particulate air (HEPA) filters.[84,86] One study demonstrated inactivation of *Bacillus subtilis* spores from stainless steel instruments using a prototype IR chamber. A 6-log reduction was achieved after 8 minutes and 40 seconds of exposure with a maximum temperature of 180 °C within the IR chamber.[84] Damit *et al.* applied flash IR heating to HEPA filters loaded with bioaerosols. Within 5 seconds of exposure to >200 °C, a log reduction of 3.77, 4.38, and 5.32 were observed for *Bacillus subtilis* spores, *E. coli*, and MS2 bacteriophage, respectively.

Table 3 Inactivation doses of selected viruses and virus surrogates at various wavelengths and surfaces

Organism	Wavelength (nm)	Dose (J cm^{-2})	Log reduction[a]	Surface/Substrate	Ref.
Adenovirus	210	0.010	4	Suspension	54
	254	0.174	4	Suspension	54
Ebola virus	254	0.0004	1	Glass cover slips	34
Feline calicivirus[b]	222	0.036	3	Suspension	49
	405	421	5	Artificial saliva	80
		561	5	Plasma	80
		1400	5	Artificial feces	80
		2800	4	Minimal media	80
H1N1 influenza virus	222	0.006	5	Suspension	49
	254	1.1	4	N95 respirators	35
	280	0.055	3	Suspension	39
	310	1.32	3	Suspension	39
	365	63.6	2	Suspension	39
H5N1 influenza virus	280	0.055	5	Suspension	39
	310	1.32	5	Suspension	39
	365	31.8	<1	Suspension	39
HIV	Unspecified UVC	1.0	0.63 ± 0.21	Plasma	62
MERS-CoV	Unspecified UVC	1.0	5.91	Glass cover slips	40
MS2 bacteriophage	254	0.060	3	Suspension	61
		1.0	3	N95 respirators	36
	282	0.080	2	Suspension	61
	297	0.220	0.5	Suspension	61
	310	0.120	1.5	Suspension	61
	320	0.060	0.35	Suspension	61
	365	65	3	Water	69
	1000	40	5.32	HEPA filter	86
	Unspecified UVB	0.909	4	Suspension	16
	Unspecified UVA	1.0	1	Suspension	16
Murine norovirus	Unspecified UVB	0.367	4	Suspension	16
	Unspecified UVA	1.0	0.5	Suspension	16
SARS-CoV-1	Unspecified UVC	1.0	6.11	Glass cover slips	40
Streptomyces phage φC31[c]	405	306	0.3	Minimal media	72
			2.7	Nutrient rich media	72
			>2.5	Porphyrin supplemented media	72
T4 bacteriophage[d]	297	0.190	3	Suspension	61
	310	0.100	3.5	Suspension	61
	320	0.045	0.05	Suspension	61
Vaccinia virus[e]	254	0.0006	1	Glass cover slips	34

[a] Previous studies have considered ≥3 to 4-log reductions significant; however, these are based on academic exercises and may not be readily generalized into real-life practice.[35,36] [b] Surrogate for norovirus. [c] Surrogate for non-enveloped double-stranded DNA viruses. [d] Surrogate for DNA viruses. [e] Surrogate for norovirus.

Degradation of polymer fibers was not seen and filtration efficacy of the HEPA filter was preserved.[86]

The advantages of IR decontamination include uniform heating, low energy consumption, and short cycle time. Its efficacy can be influenced by the material type, temperature, and moisture content within the substrate.[85] Certain substrate configurations such as holes or hinges in medical instruments can potentially shield pathogens from being inactivated.[84] Of note, temperatures above 100 °C have been found to reduce the filtration efficacy of N95 respirators; thus, direct supervision is warranted.[15] Moreover, the depth of penetration of IR in solid objects has not been fully elucidated.[86] In humans, 30% of NIR is absorbed in the skin, of which 65% penetrates deep into the dermis. Hence, NIR can cause inflammation, photoaging, and potentially photocarcinogenesis.[87] Despite the commercial availability of IR sources, there are currently no US FDA approved IR decontamination systems.

Table 3 provides a summary of selected viruses and viral surrogates mentioned in this article along with their inactivation doses at various wavelengths and surfaces.

Conclusion

Resumption of healthcare services amidst the COVID-19 pandemic requires stringent measures to minimize the risk of viral transmission. UV, VL, and IR systems have promising roles in this respect, and with approriate dosing, these measures are effective against a variety of viruses. However, further studies are needed to determine the surface-specific dosing that is adequate to inactivate SARS-CoV-2 in addition to common nosocomial pathogens. Data on UVC decontamination are the most robust, although its depth of penetration is the lowest of all the wavelengths reviewed. UVC delivers adequate virucidal doses in a reasonable amount of time in contrast to other wavebands, which require higher dosages and longer administration times. Finally, given the possibilty of long-term use, the effects of UV, VL, and IR radiation on human health and degradation of materials are important considerations.

Conflicts of interest

Luke Horton, Angeli Torres, and Indermeet Kohli have no relevant disclosures. Shanthi Narla and Alexis Lyons are sub-investigators for Biofrontera. Joel Gelfand is the principal investigator for the LITE study, which is funded by PCORI with home phototherapy units provided by Daavlin. David Ozog is an investigator for Biofrontera. Iltefat Hamzavi is an investigator for LITE study, which is funded by PCORI with home phototherapy units provided by Daavlin. Henry W. Lim is an investigator for LITE study, which is funded by PCORI with home phototherapy units provided by Daavlin and has participated as a speaker in general educational session for Ra Medical System.

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