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REVIEW ARTICLE

The value of photomedicine in a global health crisis: Utilizing ultraviolet C to decontaminate N95 respirators during the COVID-19 pandemic

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Abstract

One early problem during the height of the COVID-19 global pandemic, caused by severe acute respiratory syndrome 2 (SARS-CoV-2), was the shortage of personal protective equipment donned by healthcare workers, particularly N95 respirators. Given the known virucidal, bactericidal, and fungicidal properties of ultraviolet irradiation, in particular ultraviolet C (UVC) radiation, our photomedicine and photobiology unit explored the role of ultraviolet germicidal irradiation (UVGI) using UVC in effectively decontaminating N95 respirators. The review highlights the important role of photobiology and photomedicine in this pandemic. Namely, the goals of this review were to highlight: UVGI as a method of respirator disinfection—specifically against SARS-CoV-2, adverse reactions to UVC and precautions to protect against exposure, other methods of decontamination of respirators, and the importance of respirator fit testing.

KEYWORDS

COVID-19, disinfection, personal protective equipment, ultraviolet radiation

1 | INTRODUCTION

The severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) COVID-19 global pandemic has driven the healthcare system worldwide into a state of crisis. An early problem during the height of the pandemic was the shortage of personal protective equipment (PPE), particularly N95 filtering facepiece respirators (FFRs). N95 FFRs are meant to be disposed after each use; however, with widespread PPE shortages, the US Center for Disease Control and Prevention (CDC) developed contingency and crisis strategies to help healthcare facilities conserve and reuse their supplies, including exploring various decontamination methods.[1] The CDC has stated that ultraviolet germicidal irradiation (UVGI) using ultraviolet C (UVC), vaporous hydrogen peroxide, and moist heat have shown the most promise as potential methods to decontaminate FFRs.[1] In a recent study conducted by Sickbert-Bennett et al,[2] the authors found that 11-year expired N95 respirators and used respirators sterilized with ethylene oxide and vaporized hydrogen peroxide all had unchanged fitted filtration efficiencies (FFEs) of more than 95%. Other authors endorse and encourage the healthcare community's innovative solutions in the way of alternatives to single-use N95 masks, such as decontamination of respirators for their reuse.[3]

UV radiation, especially UVC, has known virucidal, bactericidal, and fungicidal properties. UV radiation damages the genomes of these pathogens through the formation of pyrimidine dimers and the generation of reactive oxygen species, inactivating these microorganisms.[4] UVC has been utilized in the decontamination of air, water, and various surfaces in hospitals and laboratories.[5-7] UVGI utilizes the germicidal properties of UVC and is produced from a low-pressure mercury or light-emitting diode (LED) lamp source, which emits a peak wavelength of 254 nm. This peak wavelength is near the maximum absorption of nucleic acids at 265 nm, making it an effective UV wavelength for microbial inactivation.[8,9]

The efficacy of decontamination by UVGI depends on several factors, namely, the UVC dose, the pathogen to be inactivated, and the surface or substrate to be decontaminated such that the same pathogen on two different surfaces will require different doses in order to achieve the same level of decontamination. Most studies on UVGI would consider a 3- to 4-log reduction as an adequate level of decontamination.[10] Prior to the COVID-19 pandemic caused by SARS-CoV-2, UVGI had been shown to effectively inactivate coronaviruses, including SARS-CoV, which causes severe acute respiratory syndrome (SARS), and Middle East respiratory syndrome coronavirus (MERS-CoV), with a >5-log reduction on glass cover slips.[11] Another study found that H1N1 influenza A-infected N95 FFRs found a 3-log reduction in viable influenza virus after a UVGI dose of 1 J/cm^2 administered over 60-70 seconds.[12] Knowing these properties of ultraviolet radiation through advances in photobiology coupled with the demand of decontamination methods for the reuse of PPE, specifically N95 FFRs, our photomedicine and photobiology unit explored the role of UVGI in effectively decontaminating N95 FFRs. Safely reusing PPE through surface decontamination methods is vital and even necessary in emergency situations such as the COVID-19 pandemic. However, it should be emphasized that there are significant limitations and potential adverse effects of UVC decontamination methods, and thus, this process of decontamination of respirators should only be implemented during severe shortages of PPE. This perspective paper outlines one center's experience in applying the fundamental concepts of photomedicine directly to the global crisis at hand, providing timely solutions to critical problems including shortages of PPE during this pandemic.

2 | UVGI AS A METHOD OF RESPIRATOR DISINFECTION

During the height of the pandemic, the photomedicine and photobiology unit at Henry Ford Health System proposed a potential method for respirator decontamination with UVGI. Working closely with The Daavlin Company, a major manufacturer of phototherapy devices, our group repurposed a UVGI unit (referred to as the Daavlin 1 series unit in this manuscript)[13] for decontamination and emphasized that the minimum dose of UVC for proper decontamination should be at least 1 J/cm^2 to each side. This was corroborated by N95Decon, an international volunteer collective of scientists, engineers, clinicians, and students focused on gathering and disseminating information on the protection of respirators during COVID-19.[14,15] Subsequently, our group performed a study that assessed the minimum dose received by various parts of the N95 respirator after one complete decontamination cycle with the Daavlin 1 series unit. One complete decontamination cycle consisted of administering a UVC dose of 1.5 J/cm^2 each to the outside-facing and wearer-facing surfaces of the respirator, amounting to a total dose of 3 J/cm^2 to the respirator. This study found that all parts of the respirator surface received a dose of at least 1 J/cm^2. More globally, this study provides a model by which UVC dose received by different areas of FFRs can be accurately assessed, given differences in UVGI devices and different types of FFRs.[16] Importantly, these decontamination doses are unlikely to be sufficient for all known pathogens but were meant for coverage of the causative agent of the pandemic, SARS-CoV-2.

3 | PUTTING IT TO THE TEST

A study by Fischer et al[17] demonstrated that UVC (260-285 nm) effectively decontaminated N95 respirators inoculated with SARS-CoV-2, but long exposure time (approximately 1 hour for 3-log reduction) was needed. This was because the low irradiance of the UVC LED source utilized to irradiate the inoculated N95 discs, which was a limitation of their study. UVC devices with high irradiances, >10 mW/cm^2, can administer sufficient doses in less than 5 minutes. As such, a subsequent study was conducted as a collaboration between Henry Ford Health System (HFHS) and the University of Michigan to determine the effect of UVC, with the Daavlin 1 series unit, on SARS-CoV-2 inoculated N95 respirators using a variety of FFRs available to healthcare employees at HFHS in Detroit, MI. Four different locations (three on the facepiece and one on the strap) on five different N95 FFR models (3M 1860, 8210, 8511, 9211; Moldex 1511) were inoculated with 10 µl of SARS-CoV-2 viral stock (8×10^7 $TCID_{50}$/mL), or a total of 8×10^5 viral copies. The outside-facing and wearer-facing surfaces of the respirators were each irradiated with a dose of 1.5 J/cm^2 UVC (254 nm). Viable SARS-CoV-2 was quantified by a median tissue culture infectious dose assay ($TCID_{50}$) and was measured prior to and following UVC. The results of this study showed that UVC delivered using a dose of 1.5 J/cm^2 to each side of the FFR was an effective method of decontamination for the 3M 1860 and Moldex 1511 facepieces and for the straps of 3M 8210 and the Moldex 1511 models—viral concentrations on these models were significantly decreased after UVC. This suggests that this dose of UVC applied to both sides of N95 FFRs effectively decontaminates SARS-CoV-2 on some but not all models of N95 FFRs.[18] We noted that materials with hydrophilic characteristics such as the straps of 3M 1860 and facepieces of 3M 8210 showed reduced decontamination results, whereas hydrophobic materials such as the 3M 1860 facepiece showed adequate decontamination. Thus, we proposed a secondary disinfection step for the straps and showed that straps inoculated with SARS-CoV-2 were adequately decontaminated by wiping the straps with 70% isopropyl alcohol three times, regardless of UVC irradiation.[18]

Although no studies evaluating the actual viral load of SARS-CoV-2 on respirators in a real-life healthcare setting have been performed to date, Wang et al[19] developed a theoretical model to quantify the number of viral copies that may be present in particles (both aerosols and droplets). The authors concluded that from a single cough, a person with a high viral load in respiratory fluid (2.35×10^9 copies per mL) may generate as many as 1.23×10^5 viral copies that remain airborne after 10 seconds, and only 386 viral copies remain airborne after 10 seconds in a patient with a normal viral load (7.00×10^6 copies per mL). Thus, the inoculum used in our study (8×10^5 viral copies)[18] is higher than the number of SARS-CoV-2 viral copies estimated to be airborne from a cough in this theoretical model.[19]

4 | UVC-INDUCED SKIN REACTION AND PROTECTION AGAINST IT

As UVGI becomes increasingly incorporated in health systems throughout the country for the disinfection of N95 FFRs, one must be aware of the adverse effects of UVC exposure on the operator. Overexposure to UVC radiation can cause damage to the cornea and various skin reactions. Lyons et al reported a case of a 50-year-old man with repeated exposure to UVC from a UVGI device who developed erythema and peeling after 4 days. The exposure was unintentional; dose of UVGI was 1.5 J/cm^2, and the patient was exposed to approximately 30 rounds of radiation.[20] Another case report describes a 90-minute accidental exposure to UVC radiation in 26 medical school students; all of whom reported ocular symptoms, diagnosed as photokeratitis, and varying skin symptoms (erythema, burning sensation, irritation, and pain) followed by desquamation.[21] Since UVC is filtered out by the atmosphere, the effects from long-term exposure to UVC are largely unknown.

Given that UVC may lead to adverse cutaneous and ocular adverse reactions, our group also conducted a study to determine whether sunscreens, UV goggles, and surgical mask face shields minimize UVC exposure from UVGI devices. The study measured the irradiance of a UVGI unit with a UVC light radiometer, with different sunscreens, UV goggles, and a surgical mask face shield. The study showed that the three tested sunscreens, UV goggles, and surgical mask face shields all protected against UVC irradiation, which would consequently protect against the side effects.[22] Thus, it is recommended that those operating UVC devices wear a broad-spectrum SPF 30 or above sunscreen and wear eye protection in the form of UV goggles or a surgical mask face shield to protect against UVC-induced skin and eye damage.

5 | OTHER DECONTAMINATION METHODS

Our group explored other wavelengths of electromagnetic radiation ranging from other types of ultraviolet radiation to infrared radiation for their decontamination potential. In a review by Horton et al,[10] our group extrapolated the dose of radiation needed at each wavelength to achieve a (1/*e*) 67% reduction in viral load, based on a composite UVA/UVB action spectrum by Lytle and Sagripanti[23] We reported that if it takes 1 J/cm^2 of 254 nm UVC for 1/*e* reduction in 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—meaning higher doses are needed at higher wavelengths, in order to attain the same level of decontamination. Of note, actual doses required for 1/e reduction will be much lower than 1 J/cm^2 at 254 nm and corresponding doses at other wavelengths can be scaled down accordingly. This review indicated that while UVB, UVA, visible light, and infrared irradiation could decrease viral load, the doses needed would require an impractically long duration of irradiation based on currently available light sources.[10] Another review by our group explored various decontamination methods of filtering facepiece N95 respirators, which included UVGI, hydrogen peroxide vaporization, microwave-generated steaming, and dry heating. The review compared the advantages and limitations of each method and concluded that all of these methods have demonstrated microbicidal activity against many viruses including influenza, SARS-CoV, and MERS-CoV. Again, additional studies must be conducted to establish their efficacy against the novel coronavirus SARS-CoV-2 and other pathogens.[7]

6 | SOME PRECAUTIONS TO NOTE

Through our group's experience with using UVC as a decontamination method for N95 respirators during the COVID-19 pandemic, we noted an important factor to consider with this treatment. We conducted a study to establish the number of irradiation cycles that the respirator can endure before failing fit testing. Our results suggested that fit testing must be done after decontamination as UVGI treatment may degrade polymers in the respirators themselves and impact the elasticity of the bands.[24] In addition, the appropriate minimum dosage can be different for each respirator type, and therefore, the appropriate dose must be determined for each model of N95 FFR.[17] In addition, studies are needed on the different SARS-CoV-2 variants to determine whether there are varying responses to UVGI treatment.

7 | CONCLUSIONS

The experience of our single center clearly demonstrates the important contribution of photobiology and photomedicine to all specialties of medicine during this pandemic. The unprecedented global pandemic of the novel coronavirus SARS-CoV-2 quickly led to dire shortages of essential PPE for healthcare personnel around the world. Thus, our group initiated an effort to utilize the known germicidal properties of UV irradiation, more specifically UVC in the form of UVGI to decontaminate respirators within Henry Ford Health System. As outlined above, we extrapolated UVC dosing from prior virology work, developed models for dosing UVC irradiation specifically as it relates to decontaminating N95 respirators, tested the effect of the proposed treatment on SARS-CoV-2 inoculated respirators, and explored the side effects of UVC and precautions to take with its use. With such advances, three hospitals decontaminated almost 10 000 respirators from April 7, 2020 to July 2, 2020, which were then returned for reuse to their original frontline healthcare workers. The current global health crisis has created a need for creative solutions for unprecedented problems, and our group used the abundance of knowledge and research in photobiology and photomedicine to construct one.

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CONFLICT OF INTEREST

None declared.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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