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Ultraviolet-C and other methods of decontamination of filtering facepiece N-95 respirators during the COVID-19 pandemic

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During global health emergencies such as the current COVID-19 pandemic, the decontamination of single-use personal protective equipment (PPE) becomes a necessary means to keep up with the growing demand from healthcare workers and patients alike. Many unverified methods are being considered, which can pose the risk of incomplete decontamination and lead to catastrophic results. Several factors come into play when determining the suitability of such methods including the quality of the decontamination technique, the targeted pathogen, cost, ease of installation and use, rate of sterilization, and the surface or material to be sterilized. The germicidal properties of ultraviolet-C are well known. This review will cover the most commonly described methods for the sterilization of N95 respirators, namely, ultraviolet germicidal irradiation, hydrogen peroxide vaporization, microwave-generated steaming, and dry heating. These techniques have been tested previously and have demonstrated efficacy in reducing or inactivating viral and bacterial pathogens, although testing against SARS-CoV-2 specifically has not been done. Moreover, it must be emphasized that proper disposal after a single use is still ideal under normal circumstances.

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Introduction

The unprecedented global pandemic of the novel 2019 coronavirus (COVID-19) opened humanity to the vulnerability of our healthcare systems, particularly, our readiness to face a contagion of this magnitude. The shortage of personal protective equipment (PPE), specifically N95 or filtering facepiece respirators (FFRs), is a universal problem amidst the increasing demand from healthcare workers and patients alike. FFRs are designed to fit snugly over the wearer's nose and mouth. They are capable of filtering airborne pathogens, as opposed to a regular surgical mask that protects against large droplets or splashes only. The terms FFR and N95 respirators will be used interchangeably throughout this review.

As stockpiles around the world are rapidly depleting, healthcare workers are resorting to repeated use of single-use, disposable FFRs. In these circumstances, decontamination of FFRs could be an option to minimize the risk of viral transmission while facilitating the conservation of scarce resources, provided that the FFRs are not visibly soiled or worn out. At the time of this writing, three hydrogen peroxide decontamination systems – namely, STERRAD Sterilization System (Advanced Sterilization Products, Inc., California), STERIS Sterilization System (STERIS Corporation, Ohio), and Battelle Decontamination System (Battelle Memorial Institute, Ohio) – have been granted Emergency Usage Authorization (EUA) by the United States Food and Drug Administration (US FDA) for the decontamination of N95 respirators.[1] The EUA approval for ultraviolet germicidal irradiation (Daavlin Desktop UVC Germicidal Lamp, Daavlin, Ohio) is underway.

According to the Institute of Medicine (IOM), simple decontamination techniques must be evaluated based on several factors. These include efficacy in removing or inactivating pathogens, potential hazards to the wearer from chemical residues or noxious fumes (off-gassing), cost, and ease of implementation in the workplace.[2] In many cases, the efficacy of decontamination does not depend solely on the utilized method alone, but also on the surface or material being sterilized. In addition, the ability of the target pathogen to survive on surfaces is an important factor taken into consideration. SARS-CoV-2, the causative agent of COVID-19, has been found to remain viable on stainless steel and plastic surfaces for up to 72 hours, on copper for up to 4 hours, and on cardboard for up to 24 hours.[3]

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Another important element to consider is the effect of the decontamination procedure on the integrity of the FFRs. Certain sterilization techniques may degrade the polymers in the FFRs, thereby decreasing their ability to filter out aerosols.[4] However, others may maintain the filtration capacity intact but cause loosening of the elastic bands. This is nonetheless significant as proper fit is key in FFRs.

This article will review available recent evidence on different methods of FFR decontamination that may potentially be applied during this pandemic or future emergencies.

Discussion

Ultraviolet germicidal irradiation

Ultraviolet germicidal irradiation (UVGI) is a method to disinfect disposable N95 FFRs for reuse. This technique employs the germicidal properties of ultraviolet-C (UVC), which have been utilized in the decontamination of water, air, and various surfaces.[5] In the hospital setting, UVC systems are often used to disinfect objects which cannot be immersed in liquid biocides as well as for disinfecting high-touch surfaces.[6–8] The mechanism underlying UVGI is the absorption of photons by microbial nucleic acids, causing the formation of pyrimidine photoproducts,[5] which subsequently damage the deoxyribonucleic acid (DNA),[9] prevent replication, and inactivate microorganisms.[10,11]

UVGI is commonly produced from a low-pressure mercury lamp source which emits short-wave UVC (100–290 nm), mostly at 254 nm. This is close to the peak emission for bacterial killing, which is 265 nm.[5] Mercury lamps produce ozone as a byproduct, which itself is a reactive oxygen species that can further inactivate bacteria.[10] These lamps are often used for water and air purification systems. Ozone and free radicals can diffuse into places which are shielded from direct exposure of UV radiation to further inhibit microorganisms.[10] Studies have found that the disinfection time required to inactivate bacteriophage MS2 is much lower with light sources emitting UVC and ozone combined than with UVC alone.[12] These systems are limited due to the restrictions related to ozone emission and the toxic effects of ozone on human health. In addition, due to the concerns of mercury pollution, the United Nations Environment Programme (UNEP) convened in 2013 to propose a ban on the export and import of mercury-containing lamps and have them be replaced by UV light emitting diode (UV-LED) light sources;[13] however, countries can still manufacture mercury-based products for their own use. UV-LED sources have a more diverse wavelength capability compared to the traditional mercury-based UV devices.[14–16] Studies comparing UVC mercury light sources *versus* UVC-LED have demonstrated comparable results for killing microorganisms.[17] However, UVC-LED light sources have lower irradiance levels compared to mercury lamps. Although this can be compensated by adding an appropriate number of LEDs arranged in a desired pattern, it can significantly impact the cost of the unit. Currently, most UVGI systems still utilize mercury-based sources.

Several studies have been performed examining the use of UVGI for disinfecting N95 FFRs. This is recommended for used but not visibly soiled FFRs in order to achieve the sufficient 3-log reduction for disinfection reported in the literature.[11] A study comparing the survival of bacteria on an N95 FFR after decontamination with UVC, UVA, ethanol, bleach, and autoclave found that UVC, bleach, and autoclave provided better germicidal efficacy than ethanol and UVA.[18] A study of H1N1 influenza A-infected N95 FFRs found a $\geq$3-log reduction after a UVGI dose of 1 J cm^{-2} administered over 60–70 seconds.[19] This dose has been supported by additional studies, and higher doses (>1 J cm^{-2}) provided diminished benefits.[20,21] UVGI has also been shown to effectively inactivate coronaviruses including severe acute respiratory syndrome coronavirus (SARS-CoV) and Middle East respiratory syndrome coronavirus (MERS-CoV).[22] Of note, although categorized as $\geq$3- log, 3.5- to 9-log reductions have been reported in the literature which can be relevant in higher initial viral load situations.[8,19–21] This can be one potential explanation for the variation in the UVC dosing reported in the literature. Other potential explanations for variations in the reported UVC dosing can be the pathogen itself, the substrate or the surface being irradiated, and the distance from, and the uniformity of the UVC radiation source.

In general, all viruses and almost all bacteria are vulnerable to UVGI; however, the degree of susceptibility is highly species-specific.[23] Larger microorganisms such as spores tend to be more resistant to UVGI, though are easier to filter out, while the opposite is true for smaller microbes such as viruses.[23] According to a study by Tseng *et al.*, double-stranded (ds) DNA and dsRNA viruses required twice the UVGI dose compared to those of single-stranded (ss) DNA and ssRNA viruses in order to achieve 90% inactivation. Moreover, conditions of high relative humidity (85%) rendered viruses more resistant to UVGI-induced DNA damage due to water adsorption onto the viral surface.[24]

The configuration of the surface being treated is also an important factor that influences the UVC dosage. Since UVC is primarily a surface decontaminant, shadowed areas may not be adequately reached by the light source, thereby receiving suboptimal doses of UVC.[19] For FFRs, this corresponds to the curved edges, angulated areas, and ridges in certain models, as well as areas soiled with make-up. Accordingly, any obstruction between the radiation source and the target can absorb UVC and decrease the effective dose received by the target. The dose received by the target also decreases with increasing distance from the source.[25]

Because UVC radiation degrades polymers, there exists the possibility for UVGI to decrease the efficacy of FFRs and therefore the afforded protection.[11] A study in which four different N95 FFRs underwent UVGI doses of 120–950 J cm^{-2} revealed a small increase in particle penetration (up to 1.25%) with little effect on flow resistance.[4] In addition, at higher doses, the strength of the respirator material was significantly reduced

(sometimes >90%), but this varied greatly between the different models. At a dose of 2360 J cm^{-2}, 100–1000× higher than the dose known to disinfect H1N1, the breaking strength of the straps was reduced by 20–51%.[4]

The ongoing COVID-19 pandemic and imminent threat to FFR supplies have triggered a rapid emergence of many different UVGI devices and manufacturers. Some involve hanging of the N95 FFRs in an enclosed UVC unit (Orbitform Mask Sanitizer, Orbitform Medical, Michigan), while others utilize a tray to irradiate FFRs under a desktop UVC unit and require flipping of the FFRs in order to expose both the exterior and interior surfaces (Daavlin Desktop UVC Germicidal Lamp, Daavlin, Ohio).[11] It is important to emphasize that only UVC units with validated dosimetry should be used. As not all devices are built the same, incorrect dosing may confer the risk of inadequately killing the viral pathogens and pose serious hazards to healthcare workers.[26] The effects of UVC on human health must also be considered. Unlike UVA and UVB, UVC does not penetrate deep into the tissues, hence, adverse effects are confined to the superficial layers of the skin and eyes. These include erythema, photokeratitis, and conjunctivitis.[5,23] Although the long-term effects of excessive UVC exposure have not been fully established, the possibility of UV-induced carcinogenesis, cataract formation, and photoaging should be emphasized.[23]

Hydrogen peroxide vaporization

Hydrogen peroxide (H_2O_2) has long been proven to be highly effective against bacteria, viruses, fungi, and spores.[27–29] Decontamination using H_2O_2 is typically carried out aerially either through a vapor or an aerosolized system. The former involves the generation of gas from 30 to 35% H_2O_2 through heat, while the latter utilizes ultrasonic nebulization or pressure to produce aerosols from 5 to 6% H_2O_2.[30] In the hospital setting, this provides an effective "hands-free" method of decontaminating hospital rooms, while leaving as little as 0–5% of pathogenic residua. However, it must be noted that H_2O_2 is deactivated by organic debris (*i.e.* dirt); hence, prior to disinfection, all dirt and visible residues must be removed.[30,31]

In a head-to-head comparison of the two systems, H_2O_2 vapor (HPV) was found to be more effective at deactivating microbial particles (6-log reduction) of methicillin-resistant *Staphylococcus aureus* (MRSA), *Clostridium difficile*, and *Acinetobacter baumannii* as compared to aerosolized H_2O_2 (aHP) (less than 4-log reduction). HPV was likewise noted to have a more uniform delivery of germicidal activity throughout the room, whereas aHP exhibited greater microbial inactivation in areas near to the machine.[32]

HPV has been shown to effectively reduce or inactivate enteric and respiratory viruses on various surfaces. In a study by Tuladhar *et al.*, the utilization of HPV of 127 parts per million (ppm) for 1 hour at room temperature resulted in a >4-log reduction of poliovirus, rotavirus, adenovirus and murine norovirus from stainless steel and wood panel, while a reduction of 3.5-log and 3.1-log was observed on stainless steel and wood panel, respectively, for influenza A. A >2-log reduction was shown for all of the above viruses on gauze.[33]

A proposed protocol for the HPV system sterilization of N95 respirators was recently reported by Schwartz *et al.* (Table 1). The process allows sterilization of one hundred 3 M brand 1860 N95 respirators that are hung from stainless steel racks in an HPV room. Utilizing 35% of H_2O_2 solution, each decontamination cycle would last 45 minutes. Efficacy was evaluated based on a 6-log reduction of biological indicators (*Geobacillus stearothermophilus* spores). Although N95 respirators were found to maintain their functional integrity after 50 cycles, some degradation of their elastic material has been reported; hence, a reuse cycle of 30 times has been recommended.[34] Similar efficacy was demonstrated by the Battelle Decontamination System (Battelle Memorial Institute, Ohio) utilizing a gassing time of 20 minutes, a dwell time of 150 minutes, and a decontamination cycle of 50 times with no FFR degradation.[35]

Microwave-generated steaming

Microwave ovens are user-friendly and often readily available in the home or hospital setting, making them an attractive option for FFR sterilization. An important caveat is the requirement of the presence of moisture.[36]

Microwave-generated steaming (MGS) decontamination involves the placement of FFRs over a water reservoir, allowing microwave radiation to generate heat from water and subsequently releasing steam. The steam is made to pass through the FFRs, allowing the heat from the vapor to denature enzymes and other microbial components.[37] In a study by Heimbuch *et al.*, MGS decontamination of FFRs inoculated with H1N1 influenza virus at 1250 watts for 2 minutes resulted in a viable influenza reduction by as much as 5-log. No gross signs of mask degradation were noted post-MGS, except for a

Table 1 Methods of N95 FFR decontamination

Decontamination method	No. of FFRs[a]	Intensity/dose/concentration	Treatment time
Ultraviolet germicidal irradiation (UVGI)	Variable	1 J cm^{-2}	60–70 seconds
Hydrogen peroxide vaporization (HPV)	100	35% H_2O_2 solution Required HPV level: 480+ ppm[b]	Gassing time: 25 minutes Gassing dwell: 20 minutes
Microwave-generated steaming (MGS)	1	1250 W	2 minutes
Dry heating	Variable	FFR[a] surface temperature: 60–75 °C	30 minutes

[a] FFR – filtering facepiece respirator. [b] ppm – parts per million.

Table 2 Advantages and limitations of decontamination methods

Decontamination method	Advantages	Limitations
Ultraviolet germicidal irradiation (UVGI)	- Good germicidal activity - Short treatment duration - Has activity against coronaviruses	- Not readily available - Degrades polymers - May decrease the tensile strength of FFR[a] straps
Hydrogen peroxide vaporization (HPV)	- Proven effective sterilization method - Allows sterilization of large quantities at once - Uniform delivery - Intact FFR[a] integrity (30 cycles)	- Not readily available - Requires an enclosed space - Possible off-gassing - Possible degradation of elastic bands after 50 cycles
Microwave-generated steaming (MGS)	- Readily available - Fast (2 minutes) - No chemical residues or off-gassing - No FFR[a] degradation (3 cycles)	- Non-uniform delivery may affect efficacy - One FFR[a] at a time only - Reduced filtration capacity after 5 cycles or more
Dry heating	- Readily available - No chemical residues or off-gassing - Maintains filtration capacity even after 20 cycles	- Insufficient efficacy data with regard to FFR[a] decontamination - May degrade FFR[a] ("dry microwaving") - Requires direct supervision

[a] FFR – filtering facepiece respirator.

minor separation of the foam nose cushion in one N95 surgical FFR out of the six that were tested.[28,36] Similarly, Lore *et al.* noted undetectable levels of influenza A/H5N1 on viral culture of FFRs following MGS decontamination, although trace amounts of viral elements were detected on polymerase chain reaction (PCR) in some. MGS decontamination did not affect the filtration capacity of the FFRs. Of note, the viral load applied to the FFRs in this trial was well above what is expected in actual encounters.[37] A modified set-up was utilized in one study where FFRs were placed in microwave steam bags typically used for cleaning infant feeding accessories. In this experiment, heating for 90 seconds at 1100 W (steam bag package instructions) resulted in a >3-log reduction of bacteriophage MS2, with no adverse effects on FFR filtration performance after 3 cycles.[2] One study revealed that the filtration capacity of propylene fibers from N95 respirators was maintained above 95% when steamed for 10 minutes for 3 cycles, but dropped by 15% and 20% after 5 and 10 cycles, respectively (Y. Cui *et al.*, unpublished data, March 2020).

The disadvantage of this method is the non-uniformity of steam, which may not evenly penetrate the FFR material, thereby altering the efficacy of decontamination. Exposure times needed to generate the steam may also differ depending on the surface area of the liquid (smaller area will require longer exposure), volume of the liquid (more volume will require longer exposure), and power of the microwave (less than 1250 W will require longer exposure).[37] In addition, the dimensions of most microwave oven units may only accommodate one FFR at a time, making this less than ideal in situations where a rapid turnover of PPE is warranted.

Dry heating

The efficacy of decontamination *via* dry heat may be extrapolated based on the knowledge that many viruses are sensitive to high temperatures. For instance, SARS-CoV titers have been found to fall below detectable levels when exposed to 56 °C for 30 minutes, and have been found to be completely eliminated at 60 °C maintained over the same amount of time.[38] One recent review recommended dry heating of respirators in a laboratory oven at 60 °C for 30 minutes, but reported a slight reduction in the filtration capacity after heating. Of note, the temperature refers to that of the respirator and not of the oven.[28] Since temperatures above 100 °C have been shown to destroy the FFR performance,[36] this method entails the need for direct supervision to facilitate the accurate measurement of FFR surface temperature.

Microwave oven irradiation ("dry microwaving") has been shown to partially melt FFRs, rendering them unwearable.[39] However, in one study comparing the effect of dry heat (rice cooker without water), moist heat (autoclave), and liquid submersion methods (ethanol, isopropanol, and bleach) on FFR integrity, it was noted that dry heat and moist heat had little effect on the overall filter quality, while chemical methods tended to reduce them.[40] Moreover, dry heating at 75 °C for 30 minutes has been shown in one study to maintain the N95 filtration fiber capacity above 95% even after 20 cycles (Y. Cui *et al.*, unpublished data, March 2020). Further studies are needed to corroborate these results.

Tables 1 and 2 summarize the different decontamination protocols discussed above, as well as their advantages and limitations.

Conclusion

Given the current COVID-19 pandemic, extreme measures are needed to keep those on the front line protected. UVC, hydrogen peroxide, microwave, and dry heat systems are all viable options to kill microorganisms on N95 FFRs to enable their reuse. These options are cost-effective, quick to employ, and have the potential to save many lives and valuable resources.

These methods have demonstrated good biocidal activity against many viruses including influenza, SARS-CoV, and MERS-CoV; however, their efficacy against the novel coronavirus SARS-CoV-2 specifically has not been tested. Given their novel use and development, further studies on these methods are needed. Additionally, many unverified variations of these techniques are being considered by healthcare institutions and individual providers, which can yield catastrophic results if incomplete decontamination is rendered to the contaminated FFRs. Lastly, it must be emphasized that such measures should be employed only when absolutely necessary, and that proper discarding of disposable PPEs after a single use is still ideal.

Conflicts of interest

Angeli Torres, Indermeet Kohli, and Angela Parks-Miller have no relevant disclosures. Alexis Lyons and Shanthi Narla are sub-investigators of Biofrontera. David Ozog is an investigator of Biofrontera. Iltefat Hamzavi is an investigator of the LITE study, which is funded by PCORI with phototherapy units provided by Daavlin. Henry Lim is an investigator of the LITE study, which is funded by PCORI with phototherapy units provided by Daavlin, and has participated as a speaker in the general educational session of Ra Medical Systems.

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