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REVIEWS

Decontamination of respirators amid shortages due to SARS-CoV-2

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Abstract
The pandemic created by SARS-CoV-2 has caused a shortage in the supplies of N95 filtering facepiece respirators (FFRs), disposable respirators with at least 95% efficiency to remove non-oily airborne particles, due to increasing cases all over the world. The current article reviewed various possible decontamination methods for FFR reuse including ultraviolet germicidal irradiation (UVGI), hydrogen peroxide vapor (HPV), microwave-generated steam (MGS), hydrogen peroxide gas plasma (HPGP), and 70% or higher ethanol solution. HPV decontamination was effective against bacterial spores (6 $\log_{10}$ reduction of *Geobacillus stearothermophilus spores*) on FFRs and viruses (> 4 $\log_{10}$ reduction of various types of viruses) on inanimate surfaces, and no degradation of respirator materials and fit has been reported. 70% or higher ethanol decontamination showed high efficacy in inactivation of coronaviruses on inanimate surfaces (> 3.9 $\log_{10}$ reduction) but it was lower on FFRs which filtration efficiency was also decreased. UVGI method had good biocidal efficacy on FFRs (> 3 $\log_{10}$ reduction of H1N1 virus) combined with inexpensive, readily available equipment; however, it was more time-consuming to ensure sufficient reduction in SARS-CoV-2. MGS treatment also provided good viral decontamination on FFRs (> 4 $\log_{10}$ reduction of H1N1 virus) along with less time-intensive process and readily available equipment while inconsistent disinfection on the treated surfaces and deterioration of nose cushion of FFRs were observed. HPGP was a good virucidal system (> 6 $\log_{10}$ reduction of *Vesicular stomatitis virus*) but filtration efficiency after decontamination was inconsistent. Overall, HPV appeared to be one of the most promising methods based on the high biocidal efficacy on FFRs, preservation of respirator performance after multiple cycles, and no residual chemical toxicity. Nonetheless, equipment cost and time of the HPV process and a suitable operating room need to be considered.

Keywords Decontamination · Hydrogen peroxide vapor (HPV) · Filtering facepiece respirator (FFR) · N95 · COVID-19

1 Introduction

SARS-CoV-2 (Severe Acute Respiratory Syndrome-Coronavirus-2) or COVID-19 (Coronavirus Disease 2019) is an infectious disease caused by a virus in the family of coronaviruses which usually causes respiratory illness in humans [1, 2]. The novel coronavirus spreads rapidly from person to person, and its basic reproductive number (R_0) was estimated to be 5.7 in Wuhan, China [3]. SARS-CoV-2 originated in Wuhan, Hubei province, China in November of 2019, and has quickly spread around the world to become a pandemic as defined by the World Health Organization (WHO). The virus is primarily transmitted through the inhalation of respiratory aerosols/droplets that are exhaled by an infected person while in close contact. Infection may occur due to contact with a contaminated surface and subsequently touching one's face, eyes, or mouth [4]. The major symptoms of illness caused by SARS-CoV-2 are sore throat, cough, fever, chills, difficulty breathing or shortness of breath, repeated shaking with chills, muscle pain, and loss of taste or smell [5, 6]. On January 20, 2020, the first case of SARS-CoV-2 in the United States was confirmed in Snohomish County, in the state of Washington from a 35-year-old man who traveled to Wuhan, China [7]. SARS-CoV-2 has a case fatality rate (CFR referring to the number of deaths due to the virus divided by confirmed cases recorded by world governments) of 1.70% in the United States of America, and CFR numbers range anywhere from 1.0% (Turkey) to 8.7% (Mexico) as of

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January 15, 2021 [8]. It is likely to have an infection fatality rate (IFR referring to the number of deaths due to the virus divided by total infections) between 0.08 and 1.26% depending on the country and age distribution of their population, as per data from the Johns Hopkins Coronavirus Resource Center [8].

A respirator is personal protective equipment (PPE) which covers the nose and mouth or the entire face or head to protect the wearer from inhaling harmful atmospheric contaminants [9]. Air-purifying respirator (APR) is a type of respirators which use filters or cartridges to remove contaminants from the air-breathed, filters for protection against particulates and cartridges for protection against gases/vapors. Two main types of APRs are particulate respirators and chemical cartridge respirators. Filtering facepiece respirator (FFR) is the type of particulate respirators with a filter as an integral part of the facepiece or with the entire facepiece composed of the filtering medium [10, 11]. The National Institute for Occupational Safety and Health (NIOSH) tests, approves, and certifies respirators. There are three series of resistance to filter efficiency degradation, N-, R-, and P-series, and three levels of filtration efficiency, 95, 99, and 99.97% [12]. N-, R-, and P-series filters are designed to protect against free of oil aerosols, oil-based liquid aerosols for limited time, and oil-based liquid aerosols, respectively [12]. N-series filters are tested with sodium chloride (NaCl) with a count median diameter (CMD) of 0.075 ± 0.02 µm and a geometric standard deviation (GSD) not exceeding 1.86 [13]. Thus, N95 FFRs are at least 95% efficient to remove non-oily aerosols under the NIOSH test conditions stated in the 42 Code of Federal Regulations (CFR) Part 84. N95 FFRs are considered as tight-fitting respirators which make a tight seal between the respirator and user's face. The Occupational Safety and Health Administration (OSHA) mandates employers to ensure that employees who use tight-fitting facepiece respirators under respiratory protection program pass fit testing unless they are under voluntary use conditions, and even in those cases it is recommended to be fit tested [14].

Surgical masks are devices which cover the wearer's nose and mouth and provide a physical barrier to fluids and particulates [15]. Manufacturers of surgical masks test their product to obtain clearance by the Food and Drug Administration (FDA) [15] and the masks are tested using a biological organism aerosol (i.e., *Staphylococcus aureus*) and a 0.1 µm latex sphere aerosol in accordance with American Society for Testing and Materials (ASTM) standards F2101 and F2299 [16]. Surgical masks have lower filtration efficiency for small particles mainly due to the lower filtration requirements. Further, loose-fitting facepieces including surgical masks lower the degree of protection due to leakage around the edges. In the context of an influenza pandemic, health care workers (HCWs) are recommended to wear surgical N95 FFRs for protection against bodily fluids, with the added benefits of high filtration efficiency and tight fit from NIOSH certified N95 FFRs [16]. Additional face shields may provide extra protection from droplets/aerosols directly expelled at the HCW but are not required.

At present, FFRs are considered one-time use products (i.e. disposable) and there is no manufacturer authorized method for decontamination before reuse [17]. The CDC estimated that HCWs may require 90 million N95 respirators in the U.S. if a pandemic last for 42 days [16]. During the 2009 H1N1 influenza pandemic, the CDC Influenza Interim Guidance document acknowledged N95 supply shortages [18]. Under the current SARS-CoV-2 pandemic, many American hospitals have experienced widespread PPE shortages, including respirators [19]. Therefore, reuse of FFRs during a pandemic could be a viable solution to the respirator shortage. Various decontamination techniques have been examined, however, there are few review articles which outline different types of decontamination methods for reuse of disposable respirators. Rubio-Romero et al. performed a literature review on several decontamination methods of FFRs, but a systematic review on respirator performance, such as filtration efficiency and fit testing is lacking, along with practical factors, such as time and cost [20]. NIOSH addressed that vaporous hydrogen peroxide, ultraviolet germicidal irradiation, and moist heat are shown the most promising methods of FFR decontamination but no details are available on the webpage [17]. In this article, we outlined various decontamination methods for the application of disposable N95 type FFRs based on the literature available with two purposes: first, to identify/summarize common decontamination methods, and second, to determine more efficient method(s) based on the determinant factors for overall performance including decontamination efficacy, respirator function, and feasibility.

2 Methods

Literature review was conducted on peer-reviewed publications to identify different types of decontamination methods in which antimicrobial efficiency had been tested primarily with N95 type FFRs, using key words "decontamination", "filtering facepiece respirator (FFR)", and "respirator," as well as variants of "COVID-19" and "SARS-CoV-2." There were two main classifications of decontamination methods, chemical and physical. The chemical methods found were soapy water, bleach, liquid hydrogen peroxide, isopropyl alcohol, ethylene oxide, hydrogen peroxide vapor (HPV), vaporized hydrogen peroxide (VHP) or hydrogen peroxide gas plasma (HPGP), ozone solution, and disinfectant wipes. The physical methods were autoclave, dry heat, ultraviolet germicidal irradiation (UVGI), microwave radiation,

microwave-generated steam (MGS), and moist heat. The first step was to choose common decontamination methods. Different types of decontamination methods were examined for their biocidal efficacy in at least two studies. The second step of the study was to review the performance of decontamination methods in terms of antimicrobial efficacy, residual chemical hazards, post-decontamination filtration efficiency, post-decontamination physical integrity, availability of equipment and time for decontamination, and, if available, the cost of decontamination equipment.

3 Results and discussion

Table 1 summarizes decontamination methods on biocidal efficacy identified in the present review and Table 2 summarizes the effects of various decontamination methods on filtration efficiency, physical integrity, and residual chemical hazards. Five most common decontamination methods selected were ethanol, ultraviolet irradiation (UVGI), microwave-generated steam (MGS), hydrogen peroxide vapor (HPV), and hydrogen peroxide gas plasma (HPGP) and each method is discussed in detail below.

3.1 Ethanol

Severe acute respiratory syndrome coronavirus (SARS-CoV) and Middle East respiratory syndrome coronavirus (MERS-CoV) have been effectively inactivated by 70%, 78%, 80%, 85%, and 95% ethanol solutions (i.e., suspension tests) and all concentrations resulted in a $\log_{10}$ reduction of viral infectivity of 3.9 or above [32–36]. Lin et al. performed a study examining filtration efficiency of electret masks including N95 FFRs after multiple different decontamination methods [42]. The authors observed that treatment of electret masks with ethanol or with isopropanol increased the penetration of particles which was probably because the electrostatic charge on the filters was eliminated; fiber diameter, packing density, and charge density ultimately determine the effect on filtration [42, 43]. Lin et al. found that 70% ethanol decontamination increased the penetration of both 75 nm and 300 nm particles through the masks and the most penetrating particle size (MPS) of N95 FFRs increased upon decontamination with ethanol, indicating reduced filtration efficiency [42]. Lin et al. also found that pressure dropped in all examined electret masks after ethanol decontamination. In another study, they examined the relative survival (RS) of *Bacillus subtilis* spores on N95 FFRs under worst-case temperature and relative humidity conditions and 70% ethanol resulted in 22% of RS in 24 h which was decayed from the initial RS of 73% [23]. The conclusion that may be drawn from the results of the studies above is that ethanol decontamination can effectively inactivate coronavirus on inanimate surfaces, but when applied to FFRs, it may lower biocidal efficacy and degrade the filter quality. Ethanol decontamination requires more studies to confirm effectiveness in decontaminating respirators as well as impact on FFR materials.

3.2 Ultraviolet germicidal irradiation (UVGI)

UVGI involves the use of 254 nm UV light, using a readily available 55-W source [44]. The main benefit of using UVGI is that a portable chamber can be created to disinfect respirators of HCWs at the hospital or care center, rather than shipping contaminated PPE to a central location for decontamination. The materials for the chamber, according to Donat [44], cost approximately $ 400 for the bulbs and lamps and approximately $420 for the Reflectix aluminized insulation. These easy to find components may be purchased at many generic hardware stores. The UVGI treatment of influenza virus on FFRs has shown ≥ 3 $\log_{10}$ reduction and 4 $\log_{10}$ reduction for H1N1 and H5N1, respectively [21, 22, 24]. In a Fischer et al.'s study, the UVC decontamination procedure inactivated SARS-CoV-2 more slowly on N95 fabric than on steel due to the nature of the material's weave; the material was too porous to be quickly decontaminated [45]. Although UVC decontamination may be less expensive and easy to set up, it may not be the best method of decontamination due to the time it would take to remove all possible contamination from the PPE. Studies have found that certain decontamination methods and procedures degraded respirators to the point of it being ineffective after even one or two rounds of decontamination, but UV-treated N95 FFRs, along with vaporous hydrogen peroxide (VHP) treated FFRs, maintained acceptable filtration efficiency after three rounds of decontamination [45].

3.3 Microwave-generated steam (MGS)

This process involves the use of microwave radiation to generate heat for the decontamination process. MGS is one of the least time-intensive methods and readily available [22]. It has been found that this process provides > 3 $\log_{10}$ reduction and > 4 $\log_{10}$ reduction in inactivation of bacteriophage MS2 and H1N1 influenza virus on FFRs, respectively [22, 26]. Furthermore, minimal degradation in filtration efficiency was found after disinfection of FFRs using microwave steam bags, and performance of the FFRs after MGS decontamination was maintained at 42 CFR 84 requirements when fit tested [26, 46]. However, in the Heimbuch et al.'s study, sporadic viable viruses were detected on FFRs after MGS treatment as well as after UVGI treatment [22]. FFR samples showed partial separation of the inner foam nose cushion after MGS treatment [46]. In addition, studies address the

Table 1 Summary of decontamination methods on test conditions, parameters, and results

References	Decontamination Method	FFRs	Microbe tested	Dose	Duration	Antimicrobial efficacy
Ultraviolet Germicidal Irradiation (UVGI)						
[21]	Ultraviolet germicidal irradiation	✓	*H1N1 influenza A/PR/8/34 (VR-1469)*	1 J/cm^2	60–70 s	≥3 log reduction
[22]	Ultraviolet germicidal irradiation	✓	*H1N1 influenza virus*	1.6–2.0 mW/cm^2	15 min	>4 log reduction
[23]	Ultraviolet irradiation (A & C)	✓	*Bacillus subtilis*	UVA 365 nm (31.2 mW/cm^2) UVC 254 nm (18.9 mW/cm^2)	5 min (UVA) 20 min (UVC)	Relative survival remained above 20% (UVA) No Colony found (UVC)
[24]	Ultraviolet germicidal irradiation (UVGI)	✓	*H5N1*	18 kJ/ m^2	15 min	>4 log reduction
[25]	Ultraviolet-C (UVC) light	✓	*Methicillin-resistant Staphylococcus aureus (MRSA) and bacteriophages MS2 and Phi6*	One lamp below and 1 above N95 respirator	1 min	NA (Contamination was reduced however decontamination from all sites on the N95 respirator criteria was not met)
Microwave-Generated Steam (MGS)						
[22]	Microwave-generated steam	✓	*H1N1 influenza virus*	1250 W	2 min	>4 log reduction
[24]	Microwave-generated steam	✓	*H5N1*	1250 W	2 min	>4 log reduction
[26]	Microwave Steam Bags	✓	*Bacteriophage MS2*	1100-Watt (microwave experimentally functioned at 750 Watt)	90 s	NA (99.9% effective)
Heat						
[22]	Warm moist heat	✓	*H1N1 influenza virus*	65 °C ± 5 °C/85% ± 5% RH	30 min	>4 log reduction
[23]	Dry Heat (Traditional electric rice cooker-TERC)	✓	*Bacillus subtilis*	149–164 °C without added water	3 min	99 – 100% biocidal efficacy
[23]	Autoclave	✓	*Bacillus subtilis*	121 °C and 103 kPa	15 min	99 – 100% biocidal efficacy
[24]	Moist heat	✓	*H5N1*	65 ± 5 °C	20 min	>4 log reduction
[25]	Dry heat	✓	*Methicillin-resistant Staphylococcus aureus (MRSA) and bacteriophages MS2 and Phi6*	70 °C	30 min	NA (Limited effectiveness against bacteriophages MS2 and Phi6 versus MRSA)
Hydrogen peroxide vapor (HPV)						

Table 1 (continued)

References	Decontamination Method	FFRs	Microbe tested	Dose	Duration	Antimicrobial efficacy
[47]	Hydrogen peroxide vapor	✓	*Geobacillus stearothermophilus* spores	±480 ppm	25 min gassing phase and 20 min dwell phase	6 log reduction
[27]		✖	*Human adenovirus (type 1), Feline calicivirus (strain 255), TGEV (Purdue, type 1), Avian influenza virus (H9N9) and Swine influenza virus (H3N2)*	25, 27 and 33 mL	2 mL/min for 1, 2 or 5 min followed by 1.5 mL/min for 15 min	1. > 4 log reduction (FCV, adenovirus, TGEV and AIV at lowest vaporized volume tested (25 mL)) 2. > 3.8 log reduction (SwIV for 25 mL vaporized volume) and > 4 log reduction (SwIV for 27 mL and 33 mL vaporized volumes)
[28]		✖	*Poliovirus, human norovirus genogroup II.4 (GII.4), murine norovirus 1, rotavirus, adenovirus and influenza A (H1N1)*	127 ppm	1 h	> 4 log reduction (Poliovirus, rotavirus, adenovirus and murine norovirus on stainless steel and framing panel carriers) > 2 log reduction (Influenza A virus on stainless steel and framing panel carriers, and for all viruses on gauze carriers)
[29]		✖	*Norovirus Surrogate Feline Calicivirus*	30%	20 min	> 4 log reduction on stainless steel, glass, vinyl flooring, ceramic tile and PVC plastic cornering
[30]		✖	*Murine Norovirus and Feline Calicivirus*	7%	90 s	≥ 4.84 log reduction on glass cover (MNV) ≥ 4.85 log reduction on glass cover (for FCV) ≥ 3.90 log reduction on stainless steel disks (MNV) ≥ 5.30 log reduction on stainless steel disks (FCV)
[31]		✖	*MS2 bacteriophage*	10^7 plaque-forming units (PFU)/carrier (at lowest viral concentration) 10^9 PFU/carrier (at highest viral concentration)	10 min (lowest concentration) 45 min (highest concentration)	6 log reduction

Table 1 (continued)

References	Decontamination Method	FFRs	Microbe tested	Dose	Duration	Antimicrobial efficacy
[25]	Aerosolized peracetic acid and hydrogen peroxide	✓	*Methicillin-resistant Staphylococcus aureus (MRSA) and bacteriophages MS2 and Phi6*	15 min dwell time	31 min	> 6 log reduction
Hydrogen peroxide gas plasma (HPGP)						
[51]	Hydrogen peroxide gas plasma	✓	*SARS-CoV-2 and two ESKAPE bacteria (Acinetobacter baumannii and Staphylococcus aureus)*	NA	47 min	SARS-CoV-2 was not detected and A baumannii and S aureus were not cultivable (100% bacterial death)
[52]		✓	*Vesicular stomatitis virus*	(59% H_2O_2)	47 min	> 6 log reduction
Ethanol						
[23]	Ethanol	✓	*Bacillus subtilis*	0.4 mL with 50% concentration	24 h	Relative Survival = 33 ± 8%
				0.4 mL with 70% concentration		Relative Survival = 22 ± 8%
				0.4 mL with 80% concentration		Relative Survival = 20 ± 2%
				0.4 mL with 95% concentration		Relative Survival = 26 ± 7%
[32]		✖	*SARS-CoV, Middle East Respiratory Syndrome (MERS) coronavirus or endemic human coronaviruses (HCoV)*	62–71%	1 min	≥ 4 log reduction
[33]		✖	*SARS-CoV*	95%	30 s	≥ 5.5 log reduction
[33]		✖	*SARS-CoV*	85%	30 s	≥ 5.5 log reduction
[33]		✖	*SARS-CoV*	80%	30 s	≥ 4.3 log reduction
[34]		✖	*MERS-CoV*	80%	30 s	≥ 4.0 log reduction
[35]		✖	*SARS-CoV*	78%	30 s	≥ 5.0 log reduction
[36]		✖	*MHV-Mouse hepatitis virus*	70%	10 min	> 3.9 log reduction
Other decontamination methods						
[23]	Bleach	✓	*Bacillus subtilis*	5.4%, 2.7% and 0.54% concentrations	10 min	99 – 100% biocidal efficacy
[37]	1. Hypochlorite, benzalkonium chloride wipes 2. Inert wipes-nonantimicrobial wipes	✓	*Mucin and Staphylococcus aureus*	1. 0.9% hypochlorite (OCL) 2. Inert-no active antimicrobial ingredients	30 s	1. < 1 log reduction (Mucin) 2. ~1log reduction (S aureus)

Table 1 (continued)

References	Decontamination Method	FFRs	Microbe tested	Dose	Duration	Antimicrobial efficacy
[38]	1. Quaternary Ammonium /isopropyl alcohol wipes 2. Bleach detergent wipes	✖	*A/H1N1 Influenza Virus*	1. 70% isopropyl alcohol (Webcol; Kendall) 2. 0.28% 2–2-diisobutylphenoxyethoxyethyldimethyl ammonium chloride (a quaternary ammonium chloride [QAC]) plus 17.2% isopropyl alcohol (Caviwipe; Metrex Research Corporation) 3. 1: 10 bleach dilution plus detergent (Dispatch; Caltech Industries)	15 min	Complete removal of influenza virus treated with a quaternary ammonium chloride/isopropyl alcohol or bleach

✓ tested on FFR materials, ✖ not tested on FFR materials, *NA* not available from the reference, *s* seconds, *mins* minutes, J/cm^2 joule per square centimeter, mW/cm^2 milliwatt per square centimeter, *nm* nanometer, kJ/m^2 kilojoule per square meter, *W* watt, *°C* Celsius, *RH* relative humidity, *kPa* kilopascal, *mL* milliliter, *ppm* parts per million

concern that the metallic noseband of FFRs would generate combustion when using dry microwave irradiation [24, 40].

3.4 Hydrogen peroxide vapor (HPV)

Two technologies using H_2O_2 vapor are condensing and non-condensing; condensing technology is called hydrogen peroxide vapor (HPV) and non-condensing technology is termed vaporized hydrogen peroxide vapor (VHP) [27]. HPV decontamination is conducted by saturating a disinfection chamber. This process has achieved biocidal efficacy of 6 $\log_{10}$ reduction for the decontamination of N95 FFRs using *Geobacillus stearothermophilus spores* [47]. The four major steps in the process are chamber conditioning, gassing, dwell (i.e., contact phase), and H_2O_2 aeration [48]. These four steps can take up to several hours depending on the procedure employed and other researchers have tested this process for a duration ranging from a few minutes to an hour on various inanimate surfaces. On inanimate surfaces commonly found in a hospital setting, such as stainless steel, glass, and ceramic tile, > 4 $\log_{10}$ reduction of *feline calicivirus (FCV), human adenovirus type 1, transmissible gastroenteritis coronavirus (TGEV), avian influenza virus (AIV), poliovirus, rotavirus, and murine norovirus 1* was reported [27–29]. H_2O_2 off-gassing testing and fit testing of N95 FFRs were conducted by Schwartz et al. and neither off-gassing nor loss of fit was found after the HPV decontamination process [47]. The authors reported that N95 respirators can still meet performance requirements after 50 times of decontamination with HPV. In another study by Kenney et al., a single HPV cycle completely eradicated the phage used as a proxy for SARS-CoV-2 from N95 respirators, with a limit of detection lower than the infectious dose of the majority of respiratory viruses [49]. FDA has granted several decontamination systems using HVP an emergency use authorization (EUA) for FFRs. While the VHP is a no-touch automated technology in which operator errors are minimized [27], considerations regarding equipment cost, entire process time, and locating a suitable operating room need to be made.

3.5 Hydrogen peroxide gas plasma (HPGP)

Sufficient energy can ionize a gas that becomes the fourth state of matter, called plasma. Many studies using the VHP method have used a plasma added (no-touch automated) system called hydrogen peroxide gas plasma (HPGP) to aid in the removal of H_2O_2 residues. HPGP sterilization system was the most used sterilizers in U.S. hospitals according to the Boiano and Steege's survey and it was noted that HPGP is not environmentally damaging (i.e., hydrogen peroxide vapor breaks down to water and oxygen after disinfection which is also applied to the HPV method), and it is time

Table 2 Effects of various decontamination methods on filtration efficiency, physical integrity, and residual chemical hazards

References	Method	Equipment	Dose	Time	Post-decontamination filtration efficiency	Post-decontamination physical integrity	Residual chemical hazards
[39]	Ozone	"A2Z" brand "bubbler" ozone generator	10–20 ppm	10–30 min	100%	✓	NA
[40]	Ultraviolet germicidal irradiation (UVGI)	UV Bench Lamp (UVC, 254 nm, 40 W), Model XX-40S (UVP, LLC, Upland, CA)	1.8 mW/cm^2	45 min	Mean penetration levels < 5%	✓	NA
[41]		Sterilgard III laminar flow cabinet (The Baker Company, Sanford, ME)	1.8 mW/cm^2	30 min	NA	Significant reduction in fit, increase in discomfort, or increased difficulty in donning	Median odor
[40]	Ethylene oxide	Amsco® Eagle® 3017 100% EtO Sterilizer/ Aerator (STERIS Corp., Mentor, OH)	736.4 mg/L	1 h	Mean penetration levels < 5%	✓	NA
[40]	Hydrogen peroxide gas plasma (HPGP)	STERRAD® 100S H_2O_2 Gas Plasma Sterilizer (Advanced Sterilization Products, Irvine, CA),	(59% H_2O_2)	55 min	Mean penetration levels > 5%	✓	NA
[40]	Hydrogen Peroxide Vapor (HPV)	RBDS™, (BIOQUELL UK Ltd, Andover, UK)	59%	15 min dwell (125 min total cycle time)	Mean penetration levels < 5%	✓	NA
[47]		BIOQUELL Clarus C (Bioquell Inc., Horsham, PA)	35%	20 min dwell (total cycle time NA)	NA	✓	Not detected
[41]	Microwave-generated steam (MGS)	2,450-MHz, Sharp Model R-305KS (Sharp Electronics, Mahwah, NJ	750 W/ft^3 (at maximum power setting of 10)	2 min	Mean penetration levels < 5%	Partial	NA
[40]		2450 MHz, Sharp Model R-305KS (Sharp Electronics, Mahwah, NJ)	750 W/ft^3 (at maximum power setting of 10)	2 min	NA	Significant reduction in fit, increase in discomfort, or increased difficulty in donning	Median odor
[40]	Bleach	6.00 ± 0.06% (w/w) available chlorine; Cat No. 7495.7–1, CAS No. 7732–18-5 (Ricca Chemical Company, Pequannock, NJ)	0.6%	30 min	Mean penetration levels < 5%	Tarnished metallic nosebands, oxidized staples, yellow inner nose pads	Bleach odor

Table 2 (continued)

References	Method	Equipment	Dose	Time	Post-decontamination filtration efficiency	Post-decontamination physical integrity	Residual chemical hazards
[40]	Liquid hydrogen peroxide	30% hydrogen peroxide; Cat No. H325-500, CAS Nos. 7722–84-1, 7732–18-5, 12,058–66-1 (Fisher Scientific, Fair Lawn, NJ)	6%	30 min	Mean penetration levels < 5%	✓	NA
[40]	Moist heat	Caron model 6010 laboratory incubator (Marietta, OH)	60 ^{0}C 80% Relative Humidity	30 min	Mean penetration levels < 5%	Partial Damage	None
[41]		Caron Model 6010 laboratory incubator (Marietta, Ohio)	60 ^{0}C 80% Relative Humidity	30 min	NA	Significant reduction in fit, increase in discomfort, or increased difficulty in donning	Median odor

✓ kept physical integrity, *NA* not available from the reference, *mins* minutes, *ppm* parts per million, mW/cm^2 milliwatt per square centimeter, *mg/L* milligrams per liter, W/ft^3 watt per cubic feet

efficient [50]. No SARS-CoV-2 was detected and *Acinetobacter baumannii* and *Staphylococcus aureus* were not cultivable after the decontamination of N95 FFRs with the HPGP [51]. Kumar et al., also confirmed > 6 $\log_{10}$ reduction in inactivation of *Vesicular stomatitis* on N95 FFRs after the HPGP process and no deterioration of respirator structure and function was not observed [52]. Viscusi et al. examined the particle penetration of FFRs treated with HPGP and the least effect on the filtration efficiency was observed among other chemical and physical methods examined [53]. However, Bergman et al. found that in a three cycle HPGP decontamination of N95 respirators, it caused aerosol penetration of > 5% in the samples tested [40]. FDA also has issued an EUA for FFR decontamination using VHP (with and without laser).

Although the N95 FFR is one of the most commonly used respiratory form of PPE by healthcare workers, powered air purifying respirators (PAPRs) such as positive pressure respiratory protective hoods (PPRPHs) may be used as well, especially during the high-risk procedures such as intubating a sick patient. It is important to state that "UVC, autoclave, and dry heating sterilization are not suitable for PPRPHs" [54]. This is due to the difference in materials between N95 respirators and the thermoplastic urethane or polyvinyl chloride material in PPRPHs. However, similarly to N95 FFR decontamination, VHP may be used. When the injection time was > 15 min, and the consumption of hydrogen peroxide was > 60 g, complete sterilization of *Geobacillus stearothermophilus ATCC7953* on PPRPHs could be achieved [54]. Either 15 min injection time with 4 g/min injection rate, or a 60 min injection time with a 1 g/min injection rate were effective at decontaminating PPRPHs using VHP. VHP would be one of the most promising options with regards to PPRPHs, as it is as effective as other decontamination methods, yet far less damaging to the equipment in this specific case.

4 Conclusion

Evidence suggests that disinfecting N95 FFRs using UVGI, MGS, HPV, HPGP, and 70% or higher ethanol decontamination methods for reuse can be effective. While all of the decontamination methods appear to provide an acceptable degree of biocidal efficacy, the HPV treatment would be the main suggestion of this paper, due to its combination of high decontamination efficacy even after 50 cycles and no reported degradation of filtration efficiency and respirator fit. Some limiting factors include equipment cost (higher than UVGI and MGS), operation time (longer than the others in general), and a need for locating a suitable operating room.

The FDA EUA was granted to the three decontamination treatments for FFRs including HPV, HPGP, and VHP.

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Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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