

Review Article

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Factors affecting decontamination of N95 masks for reuse: Feasibility & practicality of various methods

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The SARS-CoV-2 pandemic has led to an enormous increase in cases worldwide in a short time. The potential shortage might call for the reuse of personal protective equipment especially N95 masks. In this review, the methods available for decontamination of N95 masks have been compared to highlight the advantages and efficacies of different methods. Studies conducted to evaluate the biocidal efficacy, effect on filtration efficacy of the decontamination method, and maintenance of structural integrity of masks, were reviewed. Ultraviolet germicidal irradiation (UVGI) and hydrogen peroxide (H₂O₂) vapour were the most commonly evaluated interventions and showed good germicidal activity without significant deleterious effects on mask performance. Vapourous H₂O₂ was the best method as it maintained NIOSH (The National Institute for Occupational Safety and Health) recommendations of the mask on re-use and additionally, one mask could be decontaminated and reused 30 times. Ethylene oxide (EtO) preserved the maximum filtration efficacy and flow resistance. Chemical and heat-based methods had the advantages of being cost-effective and feasible but affected the structural integrity and fit of the masks. For the decontamination of N95 masks, among the heat-based methods steam was found to be the best for low middle-income countries setting. H₂O₂-based methods, UVGI, and EtO all exhibited both adequate biocidal efficacies and functionality (fit testing and structural integrity). Further studies on logistics, healthcare worker acceptability of reuse, and actual efficacy of protection against SARS-CoV-2 infection should be carried out to validate the use of decontamination in the real-life settings.

Key words Biocidal efficacy - COVID-19 - decontamination - heat - N95 mask - personal protective equipment - SARS-CoV-2

The current pandemic of SARS-CoV-2 has led to an enormous increase in cases worldwide in a short period. This rapid increase has led to a high demand for personal protective equipment (PPE), particularly masks. The Infectious Diseases Society of America recommended the use of reprocessed N95 masks based on laboratory evidence¹. The panic buying of N95 masks by the general population has also contributed to the depletion of the stocks worldwide. The potential shortage led to the reuse of PPE especially N95 masks.

Many studies have reported methods for reprocessing the used masks^{2,3}. Physical methods included heat-based methods like dry and moist heat, autoclave and microwave generated heat (MGH), and ultraviolet germicidal irradiation (UVGI). Chemical methods included the application of the alcohol and chlorine-based solution (Bleach), ethylene oxide (EtO), hydrogen peroxide (H₂O₂) sterilization (ionized, gas plasma, and vaporized form). However, which method is the best for disinfection of masks remains to be determined.

In this review, we discuss the various methods of decontamination of the N95 masks along with the advantages and disadvantages of the methods.

Physical methods

Heat-based methods

N95 masks are made of multiple layers of polypropylene non-woven fabrics and the most critical part among these layers is the one that is produced through the melt-blown process. Since the maximum operating temperature for polypropylenes is 80-100°C and the melting point is 165°C, temperatures >80°C can soften and melt the filter, hence compromising its performance⁴.

Heat is the most basic, easy, and cheapest method of decontamination. The main concern with heat-based methods is the loss of structural integrity and fit due to overheating, which could render the mask non-wearable or could impact fit. The identification of a temperature that provides the user a good fit along with maintenance of structural integrity while fulfilling other NIOSH (The National Institute for Occupational Safety and Health) criteria is required⁵⁻⁷.

Heat-based methods (Table I) included dry heat (3 studies)^{5,13,14}, moist heat (3 studies)^{7,9,10}, steam (2 studies)^{11,14}, autoclave (2 studies)^{5,8} and MGH (6 studies)^{5-7,9,10,12}.

(i) Structural integrity: Viscusi *et al*^{5,6} assessed the filtration performance and structural integrity following decontamination by the method of dry heat at two temperatures (80°C and 160°C). At 160°C the N95 masks melted and were unfit for use but tolerated the heat up to the 80°C. Bergman *et al*⁷ demonstrated that moist heat at 60°C was able to maintain structural integrity up to one cycle. Beyond three cycles, slight melting of the head straps with partial separation of the inner foam nose cushion was observed. Ma *et al*¹¹ studied the efficacy of steam (100°C) at four different durations of 0, 20, 60, and 120 min. The masks were able to tolerate steam at 100°C up to one cycle in contrast to autoclave and MGH where the masks were deformed, shrunken, stiff, and mottled. Also, there was a loss of elasticity of the rubber straps of the masks with each autoclave treatment⁸. The use of MGH/irradiation (MGH/MGI) resulted in loss of structural integrity of the mask and caused sparking due to the metallic noseband⁵. A study by Lore *et al*⁹ also concluded that rather than the structural make of the mask, the type of heat based method along with the

time of exposure was a critical factor affecting the end result of decontamination.

(ii) Biocidal efficacy (BE): is critical for assessing the efficacy of a decontamination procedure in controlling the microbial burden. The BE has been assessed by using bacteriophages and the H1N1 virus as a surrogate. Cadnum *et al*¹³ demonstrated a good BE for surrogate phage Phi 6 and MS2 by the dry heating method. Liao *et al*¹⁴ and Heimbuch *et al*¹⁰, demonstrated a reduction of 8-5.5 log₁₀ TCID₅₀/ml of H1N1 by moist heat and microwave generated irradiation (MGI). All methods of heating provided a good BE.

(iii) Filtration efficacy and reduction in pressure drop: Filtration efficiency was best maintained by heat and steam compared to autoclaving and MSH/MGI^{5,8}. Liao *et al*¹⁴ loaded three models of N95 masks into a preheated 5-sided heating chamber with dry heat (≤85°C) under various relative humidity (≤100% RH) conditions. They found this as the most promising, non-destructive method for the preservation of filtration properties in N95-grade respirators. Heating could be applied up to 50 cycles (85°C, 30% RH) without observation in the degradation of the filtration efficacy¹⁴.

Thus, among the various methods of decontamination by heat, steam at 100°C best maintains the structural integrity, along with a good fit and filtration efficacy. Heat is effective in providing BE provided the temperature and contact time are sufficient. Installation of heat-based decontamination methods in a small setting is a feasible option. This method is cost-effective and does not require a large infrastructure. The disadvantage is that heat-based methods allow the decontamination for a single decontamination cycle only.

Ultraviolet germicidal irradiation (UVGI) based decontamination of N95 masks

UVGI is a highly energetic short-wave (254 nm) ultraviolet light shown to be a useful sterilization technique in a variety of applications. The virucidal mechanism of UVGI is derived from the energy contained within the electromagnetic wave and its effect on the viral genome. Single-stranded RNA viruses are especially susceptible to this type of radiation. This method was evaluated for its efficacy as a decontamination method in 10 studies (Table II)^{5-10,13-16}.

(i) Structural integrity: A major disadvantage of UV radiation is that it tends to degrade polymers, which

Table I. Heat based methods for decontamination of N95 masks

Study	Place of study	Temperature (°C)	Time of exposure (min)	Biocidal efficacy	Filtration performance (%)	Pressure drop (mm H ₂ O)	Fit testing	Residual toxicity	Structural integrity	Performance cycles
Dry heat										
Viscusi <i>et al</i> , 2007 ⁵	USA	80	60	ND	0.84	ND	ND	ND	Maintained	1
		160	60	ND	Could not be tested as mask melted	ND	ND	ND	Largely melted and unusable after twenty two minutes	1
Cadnum <i>et al</i> , 2020 ¹³	USA	70	30	Phi 6	ND	ND	ND	ND	NM	1
				MS2						
Liao <i>et al</i> , 2020 ¹⁴	USA	75	30	ND	>96	0.7 mm H ₂ O	ND	ND	NM	1
Moist heat										
Bergman <i>et al</i> , 2010 ⁷	USA	60	30	ND	<4	<17.6.	ND	ND	Slight melting of the head straps, partial separation of the inner foam nose cushion	3
Lore <i>et al</i> , 2012 ⁹	USA	65±5	180	H1N1-5.5 log ₁₀ TCID ₅₀ /ml	ND	ND	ND	ND	NM	1
Heimbuch <i>et al</i> , 2011 ¹⁰	Panama city	65±5	30	H1N1 - ~8 log ₁₀ TCID ₅₀ /ml	ND	ND	ND	ND	NM	1
Steam										
Liao <i>et al</i> , 2020 ¹⁴	USA	100	10	ND	<6	0.8	ND	ND	NM	1
Ma <i>et al</i> , 2020 ¹¹	China	100	0	Avian infectious bronchitis virus H120	<2	ND	Passed	ND	Maintained	1
			20	Avian infectious bronchitis virus H120	<2	ND	Passed	ND	Maintained	1
			60	Avian infectious bronchitis virus H120	<2	ND	Passed	ND	Maintained	1
			120	Avian infectious bronchitis virus H120	<2	ND	Passed	ND	Maintained	1
Autoclave										
Viscusi <i>et al</i> , 2007 ⁵	USA	121 (15 psi)	15	ND	>18.7	ND	ND	ND	N95 FFRs were deformed, shrunken, stiff and mottled	1
		121 (15 psi)	30	ND	>34.4	ND	ND	ND	N95 FFRs were deformed, shrunken, stiff and mottled	1

Contd...

Study	Place of study	Temperature (°C)	Time of exposure (min)	Biocidal efficacy	Filtration performance (%)	Pressure drop (mm H ₂ O)	Fit testing	Residual toxicity	Structural integrity	Performance cycles
Bopp <i>et al</i> , 2020 ²³	USA	115	60	ND	>8	ND	Pass/fail	Slight loss of elasticity in the rubber straps of the FFRs with each autoclave treatment	Slight loss of elasticity in the rubber straps of the FFRs with each autoclave treatment	1
							Pass/fail			
							Pass/fail			
							Pass/fail			
							Pass/fail			
							Pass/fail			
							Pass/fail			
							Pass/fail			
							Pass/fail			
Viscusi <i>et al</i> , 2007 ⁵	USA	750	2	ND	1.13	NA	NA	NA	No visible changes were observed	1
							NA			
							NA			
							NA			
							NA			
							NA			
							NA			
							NA			
							NA			
Viscusi <i>et al</i> , 2009 ⁶	USA	750	2	ND	Melted - Could not be assessed	<15.8 mm H ₂ O, melted	NA	NA	Considered unwearable	4
							NA			
Bergman <i>et al.</i> , 2010 ⁷	USA	750	2	ND	<4	<17.6 mm H ₂ O.	NA	NA	Slight melting of the head straps, partial separation of the inner foam nose cushion	3
Lore <i>et al</i> , 2012 ⁹	USA	1250	2	H1N1-5.5 log ₁₀ TCID ₅₀ /ml	0	NA	NA	NA	Moisture retention, metal noseband of FFRs generated combustion	1

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Study	Place of study	Temperature (°C)	Time of exposure (min)	Biocidal efficacy	Filtration performance (%)	Pressure drop (mm H ₂ O)	Fit testing	Residual toxicity	Structural integrity	Performance cycles
Heimbuch <i>et al</i> , 2011 ¹⁰	Panama city	1250	2	H1N1 - ~8 log ₁₀ TCID ₅₀ /ml	NT	NA	NA	NA	Slight separation of the foam nose cushion	1
Fisher <i>et al</i> , 2011 ¹²	USA	1100	1.5	3 log or 99.9% reduction in MS2	<4	NA	NA	NA	NM	3

ND, not done; NM, not mentioned; MGS/MGI, microwave generated heat/irradiation; TCID, tissue culture infective dose; NA, not available; FFRs, filtering facepiece respirators; MRSA, methicillin resistant *Staphylococcus aureus*

presents the possibility that UVGI exposure while decontaminating, may also reduce the efficacy of the mask and decrease the level of protection. Therefore, the energy of exposure needs to be standardized for the UVGI exposure. Varying amounts of energy ranging from 1 to 1000 J/cm² were administered in different studies. Lindsley *et al*¹⁵ gauged the energy and noticed that the structural integrity was lost when the masks were exposed to energy >500 J/cm². Liao *et al*¹⁴ evaluated the performance of the masks after 10 cycles, and even after multiple exposures the structural integrity was maintained if exposed to energy <500 J/cm². The time exposure varied in all studies ranging from 1 to 30 min. Lindsley *et al*¹⁵ exposed both sides of material coupons and mask straps from four models of N95 masks to UVGI doses ranging from 120-950 J/cm². They found that at the higher UVGI doses, the strength of the layers of mask material was substantially reduced (in some cases, by >90%).

(ii) BE: Mills *et al*¹⁶ evaluated the decontamination efficacy by UVGI on N95 masks contaminated with influenza virus after soiling them with artificial saliva or artificial skin oil. Significant reductions in influenza virus viability (≥3 logs) were observed for both soiling conditions (artificial saliva and artificial skin oil) on UVGI-treated face pieces from 12 of 15 filtering facepiece respirator (FFR) models and UVGI-treated straps from 7 of 15 FFR models. Lore *et al*⁹ examined all FFRs post decontamination by viral culture. UVGI was successful in reducing the viral load by >4 logs median tissue culture infective dose (TCID₅₀).

(iii) Filtration efficiency: Viscusi *et al*⁵ evaluated the filtration performance of the N95 and N100 masks after using UVGI through the poly-dispersed sodium chloride aerosol method. UVGI did not significantly affect the average penetration results. Lore *et al*⁹ found that there was practically no reduction (<5%) in the penetration of 300 nm particles of sodium chloride (1%) after UV decontamination

(iv) Bergman *et al*⁷: found that the filter aerosol penetration and filter airflow resistance were maintained for three consecutive UVGI decontamination cycles. Thus, in all the above-mentioned studies, UVGI provided a good method for the maintenance of filtration efficacy and pressure resistance.

Even though there are many advantages of UVGI as a decontamination method, the logistical issues such as the need for the installation of the specific equipment, and their availability at the different levels of healthcare delivery in many low- and

Table II. Ultraviolet germicidal irradiation for decontamination of N95 masks

Study	Place of study	Energy	Time of exposure (min)	Biocidal efficacy	Filtration performance (%)	Pressure drop (mm H ₂ O)	Fit testing	Residual toxicity	Structural integrity	Performance cycles
Viscusi <i>et al</i> , 2007 ⁵	USA	2.4 J/cm ²	30	ND	0.57	ND	ND	ND	Maintained	1
Viscusi <i>et al</i> , 2009 ⁶	USA	1.8-2.0 J/cm ²	480	ND	0.79	ND	ND	ND	Maintained	1
Bergman <i>et al</i> , 2010 ⁷	USA	18 J/cm ²	15	ND	<2	<16.5	ND	ND	Maintained	1
Fisher and Shaffer, 2010 ¹⁷	USA	0.03-4.7 J/cm ²	45	ND	<4	<17.6	ND	ND	NM	3
Loe <i>et al</i> , 2012 ⁹	USA	18 kJ/m ²	2-266	(MS2) coliphage* 3 LR	12-1	2-8	ND	ND	NM	1
Heimbuch <i>et al</i> , 2015 ¹⁵	Panama City	1.6-2.0 mW/cm ²	15	Influenza A/H5N1 >4 log ₁₀ TCID ₅₀ /ml	<5	ND	ND	ND	NM	1
Lindsley <i>et al</i> , 2015 ¹¹	USA	0 J/cm ²	1	H1N1 >4 log ₁₀ TCID ₅₀ /ml	ND	ND	ND	ND	Maintained	1
		120 J/cm ²	2	ND	<5	Unchanged	ND	ND	Maintained	1
		240 J/cm ²	3	ND	<5	Unchanged	ND	ND	Maintained	1
		470 J/cm ²	4	ND	<5	Unchanged	ND	ND	Maintained	1
		710 J/cm ²	5	ND	<5	Unchanged	ND	ND	Strap breaks at >500 J/cm ²	1
		950 J/cm ²	6	ND	NM	Unchanged	ND	ND	Strap breaks at >500 J/cm ²	1
Mills <i>et al</i> , 2018 ¹⁶	Panama	1 J/cm ²	1	H1N1 influenza 3 LR TCID ₅₀	ND	ND	ND	ND	NM	1
Cadnum <i>et al</i> , 2020 ¹³	USA	Room (RDD)	30	+(Phi 6, MS2, MRSA)	ND	ND	ND	ND	NM	1
		UVC box	1	+	ND	NT	ND	ND	NM	1
Liao <i>et al</i> , 2020 ¹⁴	USA	254 nm, 8 W 3.6 J/cm ²	30	ND	<5	0.72	ND	ND	NM	20
					>7	0.72	ND	ND	NM	30

*It was dependent on IFM specific to the particular model. ND, not done; NM, not mentioned; IFM, inner filter membrane; TCID, tissue culture infective dose; MRSA, methicillin resistant *Staphylococcus aureus*; RDD, room decontamination device; NT, ND, not done

middle-income countries (LMICs) may be an issue to be considered when considering implementation. Also, any factor that contributes to the non-uniform distribution of UV irradiation across the face of the mask can alter its effectiveness. UVGI can only be effective if the radiation reaches the surfaces. The efficacy varies with different mask types and in different locations on the mask. In N95 masks the edge can receive less UV, thus can lead to decreased efficacy of the method. The upper limit for the UVGI exposure during repeated disinfection cycles would be set by the physical degradation of the respirator material and not by the loss of infiltration capacity¹⁴. UVGI is not associated with any residual toxicity. Thus, this method can be considered as a potential method of decontamination.

Chemical-based methods of decontamination of N95 masks

H₂O₂-based methods

H₂O₂ can be used in various forms for mask decontamination; vaporized, ionized, liquid, and gas plasma. Many commercial platforms are available for decontamination including STERRAD, SteraMist, and Bioquell. The H₂O₂ concentration and the time of exposure vary with each form of H₂O₂ application used (Table IIIA)^{2,18-23}.

(i) Structural integrity: H₂O₂ causes the elastic straps to degrade and also causes tarnishing of the aluminium nosebands^{5,6}. Schwartz *et al*¹⁹ found the method satisfactory in both the structural integrity and fit for up to 30 cycles. Cramer *et al*³ found that the fit was retained for five cycles in all conditions. Similarly, Saini *et al*²², showed maintenance of N95 fabric for up to 10 cycles.

(ii) BE: H₂O₂ treatment provided good BE on various surrogate viruses such as H1N1, and phage such as Phi 6 and T1, T7^{18,21}.

(ii) Filtration efficiency: Bergman *et al*⁷ compared three forms of H₂O₂ treatment along with other methods. When H₂O₂ was applied in plasma form, after three cycles it led to a decrease in filtration efficacy beyond recommended levels of >5 per cent. Vaporous H₂O₂ could be provided safely up to 30 cycles¹⁹. N95 masks still met performance requirements after decontamination with vaporous H₂O₂ in the laboratory setting for over 50 cycles²². Others reported that filtration efficacy and pressure resistance were within recommended limits^{18,21}.

Ethylene oxide (EtO)-based methods

(i) Structural integrity: Two studies by Viscusi *et al*^{5,6} and one by Bergman *et al*⁷ noted that masks were able to preserve their structural integrity after EtO reprocessing (Table IIIB).

(ii) BE: The three studies⁵⁻⁷ did not evaluate the ability of the ETO based decontamination to inactivate infectious biological organisms from the contaminated N 95 masks.

(iii) Filtration efficiency: The three studies⁵⁻⁷ found that after EtO reprocessing the filter aerosol penetration, as well as the appearance and filter airflow resistance, were unaffected. Furthermore, changes in filter penetration following three cycles of treatment were <5 per cent. EtO was able to maintain filtration efficacy below four per cent and pressure resistance <17.6 mm H₂O. These criteria are acceptable for mask reuse according to the NIOSH guidelines⁵⁻⁷.

The limiting factor with the EtO method is that it requires a long duration in comparison to the other decontamination methods. There are always concerns regarding the carcinogenic potential of EtO, which hampers its usage for any application. There was a minor cosmetic effect of darkening of the straps. If a longer duration is given for aeration (4-5 h), the EtO evaporates making masks safe for usage⁶.

Decontamination using other methods

Alcohols, in concentrations between 70-75 per cent have been used in a few studies^{5,6,14} (Table IIIC). It was found that small molecules such as solvents can permeate into the fabric and liberate the charge traps or frozen charges of the electret, thereby decreasing the filtration efficiency²⁴. Bleach is another method of decontamination^{5-7,14}. Bleach was shown to oxidize the aluminium nose-bands and staples and to create a peculiar smell persisting even after drying (Table IIID). Though lesser than alcohol-based methods, the use of chlorine-based solutions may also degrade the efficiency of the N95 masks due to their higher water content. As the material of the mask (*i.e.* the polypropylene) is hydrophobic, the chlorine-based solutions may have more difficulty penetrating the fabric, and the static charge of fibres deeper within the melt-blown may be less affected. Chlorine-based solutions, or soaps used to clean the mask, lead to degradation in the static charge that is necessary for the mask to meet the N95 standard²⁵. These chemical methods are not recommended to use for decontamination of N95 masks.

Table III. Chemical based methods for decontamination of N95 masks
Hydrogen peroxide

Study	Place of study	Platform	Energy	Time of exposure (min)	Biocidal efficacy	Filtration performance (%)	Pressure drop (mm H ₂ O)	Fit	Residual toxicity	Structural integrity	Performance cycles
VHP											
Viscusi <i>et al</i> , 2007 ⁵	USA	STERRAD® NX	58% H ₂ O ₂	28	ND	0.5	15.2	ND	ND	Aluminum nosebands were slightly tarnished and visibly not as shiny	1
		STERRAD® 100S	58% H ₂ O ₂	28	ND	0.75	14.1	ND	ND	Aluminum nosebands were slightly tarnished and visibly not as shiny	2
Viscusi <i>et al</i> , 2009 ⁶	USA	STERRAD® 100S	58% H ₂ O ₂	55	ND	<2	<16.2	NA	NA/all hydrophobicity test positive	Metallic nosebands were slightly tarnished	3
Bergman <i>et al</i> , 2010 ⁷	Pennsylvania, USA	BIOQUELL Clarus® R	30% H ₂ O ₂	125	ND	<4	<17.6	NA	NA	No change	3
Battelle, 2016 ²³	Ohio	Bioquell ClarusTM C	30% H ₂ O ₂	150	ND	<0.2%	8-11	NA	NA	Straps degrade when stretched	30-50
Schwartz <i>et al</i> , 2020 ¹⁹	Duke	Bioquell ClarusTM C	35% H ₂ O ₂	45	ND	ND	ND	Maintained	Smell and ppm levels*	No change	30
Grossman <i>et al</i> , 2020 ²	St. Louis	Bioquell Z-2	10 g per unit volume H ₂ O ₂	270	ND	ND	ND	ND	ppm levels checked^	No change	1
Perkins <i>et al</i> , 2020 ²⁰	USA	Bioquell ClarusTM C	30% H ₂ O ₂	129	ND	ND	ND	ND	ppm levels checked*	No change	20

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Study	Place of study	Platform	Energy	Time of exposure (min)	Biocidal efficacy	Filtration performance (%)	Pressure drop (mm H ₂ O)	Fit	Residual toxicity	Structural integrity	Performance cycles					
Kenney <i>et al.</i> , 2020 ²¹	USA	Bioquell ClarusTM C	30% H ₂ O ₂	65-70	T1, T7, and	ND	ND	ND	NA	No change	5					
					<i>Pseudomonas</i> phage phi-6											
Saini <i>et al.</i> , 2020 ²²	India	In-house	7-8% H ₂ O ₂	120-130	<i>Escherichia coli</i> , <i>Mycobacterium smegmatis</i> and spores of <i>Bacillus stearothermophilus</i>	ND	ND	ND	NA	No change	10					
iHP																
Cramer <i>et al.</i> , 2020 ³	USA	Steramist HPV ionized	7.8% aqueous H ₂ O ₂	15	ND	4	15.2	Passed ^s	ND	ND	1					
					100							4	14.1	Passed ^s	ND	2
					100							2	NM	Passed ^s	ND	3
					100							2	NM	Passed ^s	ND	4
					100							2	14.33	Passed ^s	ND	5
Cheng <i>et al.</i> , 2020 ¹⁸	Hong Kong	Steramist HPV ionized	7.8% aqueous H ₂ O ₂ aerosolized	6 s	H1N1	NA	NA	ND	ppm levels (<1)	No change	NA					
Liquid hydrogen peroxide																
Viscusi <i>et al.</i> , 2007 ⁵	USA	NM	3%	30	ND	0.75	ND	ND	ND	No change	3					
					30							0.71	ND	ND	Slightly faded label ink on the fabric of the respirator	4
Bergman <i>et al.</i> , 2010 ⁷	Pennsylvania, USA	Fisher scientific	6%	30	NA	<4%	<17.6	NA	NA	No change	3					

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HPGP											
Bergman <i>et al</i> , 2010 ⁷	Pennsylvania, USA	STERRAD® 100S	59% H ₂ O ₂ at 45-50°C	55	NA	>5%	<17.6	NA	NA	No change	3
Ethylene oxide											
Study	Place of study	Energy	Time	Biocidal efficacy	Filtration performance (%)	Pressure drop (mm H ₂ O)	Fit	Residual toxicity	Structural integrity	Performance cycles	
Viscusi <i>et al</i> , 2007 ⁵	USA	883 mg/l	60+240 aeration	ND	1.2	ND	ND	ND	Straps were darkened slightly	1	
		725 mg/l	60+240 aeration	ND	1.29	ND	ND	ND	Straps were darkened slightly	1	
Viscusi <i>et al</i> , 2009 ⁶	USA	725 mg/l 100% EtO, 55°C	60+240 aeration	ND	<2	<15.9	ND	ND	Maintained	1	
Bergman <i>et al</i> , 2010 ⁷	USA	736.4 mg/l 100% EtO, 55°C	60+720 aeration	NA	<4	<17.6	ND	ND	Maintained	3	
Alcohol based methods											
Study	Place of study	Concentration (%)	Time of exposure	Biocidal efficacy	Filtration performance (%)	Pressure drop (mm H ₂ O)	Fit	Residual toxicity	Structural integrity	Performance cycle	
Viscusi <i>et al</i> , 2007 ⁵	USA	70	One sec	ND	>17.8	ND	ND	ND	Severely degrading to N95 filters containing electret filter media	1	
Viscusi <i>et al</i> , 2007 ⁶	USA	70	1 min	ND	>21.6	ND	ND	ND	Severely degrading to N95 filters containing electret filter media	1	

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Study	Place of study	Concentration (%)	Time of exposure	Biocidal efficacy	Filtration performance (%)	Pressure drop (mm H ₂ O)	Fit	Residual toxicity	Structural integrity	Performance cycles
Liao, 2020 ¹⁴	USA	75	Until dry	ND	>56	ND	ND	ND	NM	1
Chlorine based treatment										
Study	Place of study	Concentration	Time of exposure (min)	Biocidal efficacy	Filtration performance (%)	Pressure drop (mm H ₂ O)	Fit	Residual toxicity	Structural integrity	Performance cycles
Viscusi <i>et al</i> , 2007 ⁵	USA	Bleach 0.53%	30	ND	<0.68	ND	ND	ND	Aluminum nose bands were tarnished	1
	USA	Bleach 5.25%	30	ND	<3.79	ND	ND	ND	Aluminum nose bands were tarnished	1
Viscusi <i>et al</i> , 2009 ⁶	USA	0.6% aqueous solution of sodium hypochlorite	30	ND	<2	<17	ND	ppm levels (<1)/NA/all hydrophobicity test positive	Residual bleach odor, metallic nosebands were slightly tarnished, inner nose comfort cushion was discolored	5
Bergman <i>et al</i> , 2010 ⁷	USA	0.60%	30	ND	<4	<17.6	ND	ND	Residual bleach odor, staples were oxidized, nosebands were slightly tarnished and visibly not as shiny, discolored (yellowed) inner nose pads	3
Liao <i>et al</i> , 2020 ¹⁴	USA	2%	5	ND	<27	0.9	ND	ND	NM	1

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Aerosolized peracetic acid and H ₂ O ₂											
Study	Place of study	Method	Concentration	Time (min)	Biocidal efficacy	Filtration performance (%)	Pressure drop	Fit	Residual toxicity	Structural integrity	Performance cycles
Cadnum <i>et al.</i> , 2020 ¹³	USA	HLD (aerosolized peracetic acid and H ₂ O ₂)	HLD (aerosolized peracetic acid and H ₂ O ₂)	21	Phi 6, MS2, MRSA	ND	ND	ND	ND	NM	3
		HLD (aerosolized peracetic acid and H ₂ O ₂)	HLD (aerosolized peracetic acid and H ₂ O ₂)	31	ND	ND	ND	ND	ND	NM	3
Soap and water											
Study	Place of study	Method	Concentration	Time (min)	Biocidal efficacy	Filtration performance (%)	Pressure drop	Fit	Residual toxicity	Structural integrity	Performance cycles
Viscui <i>et al.</i> , 2007 ⁵	USA	Soap and water	-	2	ND	38.8	ND	ND	ND	NM	1
		Soap and water	-	20	ND	34.9	ND	ND	ND	NM	1

*Porta sens IITM sensor to ensure hydrogen peroxide levels were below the OSHA PEL³ of 1.0 ppm; ^H₂O₂ sensor (Bio quell, Horsham, Pennsylvania); [§]Porta count quantitative fit test apparatus. ND, not done; NM, not mentioned; VHP, vaporous hydrogen peroxide; H₂O₂, hydrogen peroxide; iHP, ionized hydrogen peroxide; HPGP, H₂O₂ gas plasma; PEL, permissible exposure limit; HPV, human papillomavirus; NA, not available; ppm, parts per million; EtO, ethylene oxide; HLD, high-level disinfection; MRSA, methicillin resistant *Staphylococcus aureus*

Among other methods, HLD (aerosolized peracetic acid and H₂O₂) and decontamination with soap and water has also been discussed. In the few studies on these methods, structural integrity and charge on the electret mask were not maintained (Tables III E and F)^{5,13}. Hence these methods would not be useful for mask decontamination.

Comparison of physical and chemical methods

Decontamination processes must meet the three major objectives. Firstly, these should be effective against the target virus (SARS-CoV-2 in this case). Secondly, the method of decontamination should not damage the mask filter. Thirdly, the decontaminated masks should be able to pass the fit test and exhibit no residual toxicity.

Heat-based methods are the simplest to implement and cost-effective for mask decontamination. Moist heat was found to have better efficacy than dry heat for decontamination of the N95 masks. MH technology provided a homogeneous distribution of heat over the entire surface of the mask and hence contributed to a more efficient method of decontamination^{9,10}. The relative lack of efficacy of dry heat in these studies may be attributed to the fact that dry heat altered the N95 mask structure more than moist heat or steam interventions⁶. Among all heat-based methods, steam provides good BE, maintenance of structural integrity, filtration efficacy, and pressure reduction.

Other alternatives to heat are the low-temperature sterilization methods like UVGI, H₂O₂, and EtO, all of which exhibited excellent BE^{8,9,17}. The advantage of using H₂O₂ as a decontamination method is that commercial systems such as BIOQUELL and STERRAD have already been tested and validated by the manufacturing companies. The throughput capability of vaporous H₂O₂ processing is limited by the fact that cellulose-based products (*e.g.*, cotton, which may be present in some head straps or some mask layers) absorb H₂O₂ and can cause the cycle to abort due to low H₂O₂ vapour concentration⁵. Significant levels of residual H₂O₂ vapours off-gassing from mask materials following the sterilization process are unlikely and not of concern because the vapours decompose readily into water vapour and oxygen, both of which are harmless. Biological indicators (*Geobacillus stearothermophilus* spores) can be used to assess the quality control of the cycle¹⁹. The concentration of residual H₂O₂ in ppm levels should be checked before reusing the mask.

EtO meets the NIOSH performance requirements *i.e.*, the filter penetration and pressure resistance. Minor limiting factors such as slight tarnishing of metallic nose-bands in VHP and darkening of the straps by EtO decontamination do not preclude its usage⁵. UVGI is limited by the non-uniform effect of its rays on surfaces of the mask, due to the shadow effect. Among these three methods, H₂O₂ provides the best alternative as it allows a maximum number of recycling of masks. Setting up these systems might be expensive in larger set-ups.

Other disinfectants evaluated in the included studies are widely used in household, commercial, healthcare, and food industry settings. Both ethanol and chlorine-based solution degrade the efficiency of the filter to unacceptable levels. Soap and water, although easily available in all settings, is not recommended. There is a possibility that the soap would remove the static charge on the fiber similar to the effect observed with isopropyl alcohol exposure. The severe degradation with soap and water suggests that other possible decontamination methods involving soap (*e.g.*, washing machine, dishwasher) may have similar effects, but would need to be verified experimentally⁵.

An ideal decontamination method should not only demonstrate effective reductions in pathogen burden but also be able to preserve the structural and functional integrity of the mask without causing any residual chemical hazard to the wearer. In LMICs, the level of healthcare and availability of equipment are important factors that will guide the appropriate method to be used in a particular setting. Heat based methods can be used in settings with less patient inflow and basic equipment (autoclave /microwave) available. Though each of the methods has advantages along with disadvantages, the protocols need to be standardized and amended according to the requirement of the health care facility.

Another important factor is the acceptance of the recycled FFR by the healthcare workers. The transportation of masks from a healthcare facility to the place of decontamination requires a proper protocol to be followed. This mandates strict guidelines for transportation, treatment, and post-treatment storage and transportation of the masks to the designated place. Saini and Kaira²⁶ have developed an institutional work-flow for the segregation, transportation, disinfection, storage and supply of contaminated masks. This will prevent

the person transporting the FFRs from infecting oneself. The availability of the instrument along with adequate healthcare staff is also a challenge. All these factors need due consideration besides the actual decontamination procedure *per se*.

Limitations

All these studies have been performed on the surrogate virus like H1N1 and bacteriophage. The actual performance of decontamination methods with COVID-19 virus will have greater impact in the current pandemic. Fischer *et al*²⁷ demonstrated the inactivation of SARS-CoV-2 on the surface of N95 masks in the preliminary results. Another important limitation is the lack of clinical studies. There are no studies that have evaluated the efficacy of recycling methods in a clinical setting. Whether reuse of N95 masks after decontamination would prevent the infection in healthcare workers is not known currently. Future studies should incorporate this aspect as an outcome while planning.

Conclusion

For the decontamination of N95 masks, among heat-based methods, steam is best for an LMIC setting. H₂O₂-based methods, UVGI, and EtO, all exhibited both adequate biocidal efficacies and functionality (fit testing and structural integrity). Vapourous H₂O₂ is the best method as it maintains NIOSH's recommendations of the mask on re-use and one mask can be re-used 30 times. The selection and setting of the decontamination will have to be compared in terms of cost-effectiveness. Re-use of the N95 masks will decrease the pressure on increasing manufacturing demands. These conclusions have been derived from the studies performed on the surrogate virus. Further studies on logistics, HCW acceptability of reuse, and actual efficacy of protection against SARS-CoV-2 infection should be carried out to validate the use in real-life settings.

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