Applied Biosafety
Volume 26, Number 2, 2021

DOI: 10.1089/apb.20.0053

REVIEW ARTICLE

Heat and Humidity for Bioburden Reduction of N95 Filtering Facepiece Respirators

Loïc Anderegg[1,2], John Doyle[1,2], Margaret L. Gardel[3,4], Amit Gupta[5], Christian Hallas[1,2], Yuri Lensky[6], Nancy G. Love[7], Bronwyn A. Lucas[8], Edward Mazenc[6], Cole Meisenhelder[1,2], Ajay Pillarisetti[8,9], Daniel Ranard[6], Allison H. Squires[3], Jessica Vechakul[8], Nathaniel B. Vilas[1,2], Stuart Williams[10], Daniel Wilson[8], Tyler N. Chen[11,*], and the N95DECON Consortium[12]

Abstract

Introduction: The coronavirus disease 2019 (COVID-19) pandemic has caused a global shortage of single-use N95 filtering facepiece respirators (FFRs). A combination of heat and humidity is a promising method for N95 FFR decontamination in crisis-capacity conditions; however, an understanding of its effect on viral inactivation and N95 respirator function is crucial to achieving effective decontamination.

Objective: We reviewed the scientific literature on heat-based methods for decontamination of N95 FFRs contaminated with severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and viral analogues. We identified key parameters for SARS-CoV-2 bioburden reduction while preserving N95 fit and filtration, as well as methods that are likely ineffective.

Key Findings: Viral inactivation by humid heat is highly sensitive to temperature, humidity, duration of exposure, and the local microenvironment (e.g., dried saliva). A process that achieves temperatures of 70–85°C and relative humidity >50% for at least 30 min is likely to inactivate SARS-CoV-2 (>3-log reduction) on N95 respirators while maintaining fit and filtration efficiency for three to five cycles. Dry heat is significantly less effective. Microwave-generated steam is another promising approach, although less studied, whereas 121°C autoclave treatments may damage some N95 FFRs. Humid heat will not inactivate all microorganisms, so reprocessed N95 respirators should be reused only by the original user.

Conclusions: Effective bioburden reduction on N95 FFRs during the COVID-19 pandemic requires inactivation of SARS-CoV-2 and preservation of N95 fit and filtration. The literature suggests that humid heat protocols can achieve effective bioburden reduction. Proper industrial hygiene, biosafety controls, and clear protocols are required to reduce the risks of N95 reprocessing and reuse.

Keywords: decontamination, N95, respirator, heat, humidity, steam

Background and Overview

The coronavirus disease 2019 (COVID-19) pandemic has led to a global shortage of single-use N95 filtering facepiece respirators (FFRs) and has forced many facilities to develop protocols for decontamination and reuse of N95 FFRs for health care workers. A variety of heat-based N95 decontamination methods have been proposed for the COVID-19 pandemic, including elevated temperatures alone (dry heat), elevated temperature and humidity (moist or humid heat), and the application of high-temperature

[1]*Department of Physics, Harvard University, Cambridge, Massachusetts, USA.*
[2]*Harvard/MIT Center for Ultracold Atoms, Cambridge, Massachusetts, USA.*
[3]*Pritzker School of Molecular Engineering, The University of Chicago, Chicago, Illinois, USA.*
[4]*Department of Physics, The University of Chicago, Chicago, Illinois, USA.*
[5]*Consolidated Sterilizer Systems, Billerica, Massachusetts, USA.*
[6]*Department of Physics, Stanford University, Stanford, California, USA.*
[7]*Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, Michigan, USA.*
[8]*PPE Sanitizer Group, Vallejo, California, USA.*
[9]*Gangarosa Department of Environmental Health, Rollins School of Public Health, Emory University, Atlanta, Georgia, USA.*
[10]*University of Louisville, Louisville, Kentucky, USA.*
[11]*Department of Bioengineering, Stanford University, Stanford, California, USA.*
[12]*Consortium members are listed at https://www.n95decon.org/team.*

*Address correspondence to: *Tyler N. Chen, Department of Bioengineering, Stanford University, Stanford, CA 94305, USA,* Email: tyler.chen@stanford.edu

steam (steam heat). These modalities differ in virucidal activity and their effects on N95 respirator integrity. In this review, we examine the current scientific literature on the use of heat-based methods for decontamination and bioburden reduction of N95 FFRs contaminated with severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the novel coronavirus that causes COVID-19.

Recently, moist or humid heat has been identified by the U.S. Centers for Disease Control and Prevention (CDC) as one of the most promising methods for N95 FFR decontamination in crisis-capacity conditions. At a minimum, effective decontamination must (1) inactivate the SARS-CoV-2 virus, (2) maintain both the fit and filtration efficiency of the N95 FFR, and (3) not harm the end-user of the FFR.[1] Higher level decontamination methods such as exposure to vaporized hydrogen peroxide may also inactivate more resistant organisms, such as bacterial spores. Because data on SARS-CoV-2 inactivation on N95 FFRs are sparse, we also examined studies on other viruses, which collectively inform a set of parameters that are likely to achieve inactivation of SARS-CoV-2.

It is increasingly clear from this growing body of literature that while SARS-CoV-2 and related viruses are likely to be susceptible to heat-based inactivation, the degree of inactivation is critically sensitive to (1) temperature, (2) humidity, (3) duration of exposure, and (4) the local microenvironment (surface, mask material, and deposition solution, among others). As such, studies reporting viral inactivation should be interpreted only within the context of the experiment that was carried out. Seemingly small changes in any of these parameters (e.g., changing the deposition solution[2]) have been shown to have a large effect on viral inactivation.

Although only a few studies have been published on heat-based inactivation of SARS-CoV-2 on N95 FFRs, these data point toward the use of temperatures >70°C for >60 min to achieve sufficient viral inactivation.[3] Existing data from multiple influenza strains, bacteriophages, and a mouse coronavirus suggest that elevated humidity significantly increases heat-based inactivation of a variety of viruses on surfaces.[2,4] It has also been found in recent reports that several N95 FFRs can withstand five cycles at up to 75–85°C with 60–90% relative humidity for 30 min while maintaining adequate performance.[5,6] These findings together suggest that the most promising conditions for SARS-CoV-2 inactivation on N95 FFRs are likely to be temperatures between 70°C and 85°C at a relative humidity >50%, for 30 min or more. Viral inactivation using dry heat is likely to require significantly higher temperatures and longer cycle times as compared with humid heat, although the effect of these higher temperatures on N95 performance is not well studied.[2,7] A significant parameter space, including higher temperatures for less time, or lower temperatures at higher humidity and/or longer times, may allow for sufficient inactivation and should be investigated. Further studies with deposition solutions that more closely match saliva and/or mucus are also warranted, as heat-based viral inactivation is highly dependent on the solution used to deposit the virus on a surface.[2,8–10] As early data suggest reduced SARS-CoV-2 inactivation on metal surfaces as compared with N95 fabric,[3] additional decontamination of the metal nose piece on N95 FFRs using liquid disinfectant (on the metal only) may be desired.

This review also examined the effects of repeated applications of heat and humidity on N95 FFR fit and filtration performance. Many models of N95 FFR have been shown to retain fit and filtration performance up to three to five cycles of humid heat treatment (see Integrity of N95 FFRs; Table 2). The literature on N95 integrity after steam heat treatment shows mixed results depending on the protocol by which steam is applied. As these studies show, different makes and models of N95 FFR exhibit different levels of robustness under various sets of inactivation conditions. Therefore, in all cases only make- and model-appropriate inactivation protocols should be considered for implementation. Furthermore, repeated donning and doffing of an N95 is likely to reduce N95 integrity; some models failed fit tests after 5 don/doff cycles, whereas others maintained fit performance for >15 don/doff cycles.[11]

Although this review highlights a range of conditions that are most likely to inactivate SARS-CoV-2 on an N95 while preserving respirator function, the boundary conditions for SARS-CoV-2 inactivation on N95 FFRs have not been elucidated, and further study is necessary. Furthermore, the heat and humidity conditions listed here are not likely to inactivate other pathogens such as bacterial spores. Therefore, treated N95 FFRs should be handled as if contaminated, and only reused by the original user in the event of an emergency shortage. This review is intended to inform health care professionals and decision makers in the time-critical period of the COVID-19 pandemic.

U.S. Federal Guidelines: CDC, Food and Drug Administration, Occupational Safety and Health Administration

In this unprecedented COVID-19 pandemic, because of a limited supply of N95 FFRs, the CDC has provided guidance that health care workers can practice extended use or limited reuse of N95 FFRs.[12] In addition, the CDC has provided guidance to hospitals on methods for decontaminating N95 FFRs during a crisis.[13]

The Occupational Safety and Health Administration (OSHA) states that cosmetics or other barriers should not be present during respirator use.[14] Emergency use authorizations (EUAs) that the Food and Drug Administration (FDA) has granted for N95 FFR decontamination during the COVID-19 pandemic also stipulate that cosmetics not be present on respirators sent for decontamination.[15]

After decontamination, the CDC recommends that a ''user seal check'' is performed when the respirator is donned to ensure adequate seal.[13] A user seal check after every decontamination cycle is especially important because there is evidence that the fit factor of N95 respirators decreases with numerous dons/doffs.[11]

Per FDA guidelines for N95 FFR decontamination EUAs, *bioburden reduction* requires ≥3-log reduction (corresponding to a 99.9% reduction) in nonenveloped viral activity, whereas *virucidal decontamination* requires ≥6-log reduction (corresponding to a 99.9999% reduction) in viral activity.[16] Based on this guideline, we describe a process as sufficiently ''decontaminating'' only when it leads to a ≥6-log reduction in viral activity and describe a 3-log reduction in viral activity as ''bioburden reducing'' or ''reduction in viral activity.'' Here, bioburden reduction and decontamination only consider virucidal activity, unless otherwise specified. Considerations of mycobactericidal or sporicidal activity have separate FDA guidelines, and are not considered here. Heat-based N95 FFR bioburden reduction processes for SARS-CoV-2 are not expected to result in sterilization (killing of all microorganisms).

The CDC released guidance on the decontamination and reuse of N95 FFRs on March 31, 2020, which identifies the use of humid heat as one of the most promising methods for treatment of N95 respirators under crisis conditions.[13] As of June 2020, a single FDA EUA has been granted for humid heat decontamination using the STERIS STEAM Decon Cycle in AMSCO Medium Steam Sterilizers.[17] Any new methods for decontamination should be verified through an institution's internal review processes before implementation, which may include FDA clearance and reference to frequently updated CDC guidelines.

Mode of Action

The exact mechanism of heat- and humidity-based inactivation of SARS-CoV-2 on surfaces has not been fully elucidated. SARS-CoV-2 is an enveloped, single-stranded RNA virus.[18] Heat-based viral inactivation is thought to occur by thermal disruption of the viral capsid, viral envelope, and/or denaturation of viral proteins.[19] In droplets at room temperature, inactivation of some other enveloped viruses has been shown to be enhanced at intermediate humidity values, which is hypothesized to be because of increasing solute concentrations as droplets evaporate but are not fully dried.[20,21] Early studies also suggest that the use of heat with relative humidity >50% will significantly increase viral inactivation on surfaces compared with heat at low humidity, although the mechanism behind this is not fully understood.[2]

Of importance, heat and humidity may not inactivate all pathogens on the FFR, and bacterial spores, including *Clostridium difficile*, may remain.[22] This indicates that users of heat and humidity protocols for N95 decontamination or bioburden reduction must be aware of other pathogens that may survive the decontamination process. Respirators reprocessed by humid heat methods should be reused only by the original user. Proper industrial hygiene, biosafety controls, and clear reuse protocols are crucial to reduce the risks of N95 reprocessing and reuse.

Liquid Media Versus Surfaces: SARS-CoV-2 Inactivation

Although there is evidence that SARS-CoV-1 and SARS-CoV-2 can be rapidly inactivated by heat when in liquid media (30 min at 56°C),[23] literature suggests that these viruses are much more resistant to heat inactivation when on surfaces than when suspended in liquid media. A recent, non-peer-reviewed report indicates that 70°C dry heat for 30 min was NOT sufficient to reduce bioburden of SARS-CoV-2 on N95 FFR fabric.[3] Only a 1.9-log reduction was observed, as compared with the 5-log reduction observed after treatment at 56°C for 30 min in liquid media. Therefore, results for heat-based viral inactivation in liquid media should not be directly compared with those for inactivation on surfaces.

Humid Heat: SARS-CoV-2 Inactivation

Studies on heat-based inactivation of SARS-CoV-2 on N95 FFRs are limited. As of August 2020, there exist only two studies of SARS-CoV-2 inactivation on N95 FFRs through the application of heat without steam (of which one is peer reviewed),[3,24] and only one study of inactivation by steam heat.[25] In this section, we review reports on the inactivation of SARS-CoV-2 and other viruses to determine a consensus set of parameters for likely inactivation of SARS-CoV-2 without steam (see Autoclave and Microwave-Generated Steam [MGS] sections for discussion of steam protocols).

The two reports mentioned above provide the only data for heat-based inactivation of SARS-CoV-2 on an N95 FFR, although it is not currently clear that the results can be extrapolated to a real-world scenario. Although both reports found sufficient inactivation (>3-log reduction) of SARS-CoV-2 after 70°C dry heat for 60 min, the media used for deposition on the N95 FFRs was not listed.[3,24] If culture media was used, as is commonly performed, this result may significantly *overestimate* viral inactivation from dry heat. Human saliva, mucus, and other proteins have been shown to stabilize viral particles to a greater degree than culture media (see Phi6 data in Table 1), indicating that a more stringent bioburden reduction protocol may be required to sufficiently inactivate SARS-CoV-2 on N95 FFRs in a hospital setting.[2,8–10] One recent study found that deposition using Dulbecco's modified Eagle medium (DMEM) overestimated viral inactivation by over 3-log compared with deposition in human saliva, whereas deposition using PBS more closely matched the

Table 1. Impact of heat and humidity on SARS-CoV-2 and other viruses on N95 filtering facepiece respirators and surfaces

Strain(s) (medium, if known)	*Surface*	*Temp* and RH (method)[c]*	*Time (minutes)*	*Effectiveness (log reduction)*	*Study*
SARS-CoV-2 (unknown)	3M 1860S,[e] 8110S, 8210S, 9105S	70°C, dry heat	60	>3.0	Daeschler et al.[24]
	AO Safety N9504C (N95 fabric)		30	1.9 (insufficient)	
			60	>3.3	
	Stainless steel 304		60	2.0 (insufficient)	Fischer et al.[3,*]
SARS-CoV-2 (bovine serum albumin, tryptone, mucin)	3M 1860[e] and 1870[e]	121°C, steam (autoclave)	15	≥4.6	Kumar et al.[25,*]
	3M Vflex 1804[e]			≥5.3	
	AO Safety 1054			≥5.6	
Murine coronavirus MHV (DMEM)	3M 1860[e]	72°C, 1% RH	30	1.25 (insufficient)	Rockey et al.[2]
		82°C, 1% RH		2.71 (insufficient)	
		72°C, 25% RH		>3.5	
Influenza H1N1 (mucin, aerosol and/or droplets)	3M 1860,[e] 3M 1870,[e] 3M 8210, 3M 8000 KC PFR95-270[e] Moldex 2200	65 ± 5°C, 85% RH (1250 W MGS,[a] water reservoir)	30	>3.0–7.0 (FFR dependent)	Heimbuch et al.[26]
			2	>3.3–6.3 (FFR dependent)	
Influenza H1N1 (unknown)	Stainless steel	60°C, 25% RH	30	1.5 (insufficient)	McDevitt et al.[4]
		60°C, 50% RH		>5.0	
		60°C, 75% RH		>5.2	
		65°C, 25% RH		2.2 (insufficient)	
		65°C, 50% RH		>5.1	
Influenza H5N1 (aerosolized allantoic fluid)	3M 1860S[e]	65°C, humid heat	30	>4.62	Lore et al.[27]
	3M 1870[e]			>4.65	
	3M 1860S[e]	(1250 W MGS,[a] water reservoir)	2	>4.81	
	3M 1870[e]			>4.79	
Bacteriophage MS2[b] (PBS)	3M 1860[e]	72°C, 25% RH	30	1.4 (insufficient)	Rockey et al.[2]
		72°C, 36% RH		3.7	
		72°C, 48% RH		>6.7	
Bacteriophage MS2[b] (ATCC medium 271 or unknown medium)	3M 1870[e] KC PFR95-270[e] Moldex 2200	(1100 W MGS,[a] in steam bag)	1.5	3.1	Fisher et al.[43]
				3.45	
				≥3.1	
	3M 1860[e]	(1100 W MGS,[a] water reservoir)	3	5	Zulauf et al.[45]
Phi6 (DMEM)	3M 1860[e]	72°C, 13% RH	30	4.3	Rockey et al.[2]
Phi6 (PBS)		72°C, 13% RH		1.62 (insufficient)	
Phi6 (Saliva)		72°C, 13% RH		0.95 (insufficient)	
Phi6 (Saliva)		82°C, 13% RH		2.62 (insufficient)	
Phi6 (PBS)		72°C, 48% RH		7.09	
Tulane virus[b,d]	3M 1860[e]	100°C, 5% RH	50	>5.2	Oh et al.[7]
Rotavirus OSU[b,d]				>6.6	
Adenovirus[b,d]				>4.0	
Transmissible gastroenteritis virus[d]				>4.7	
Porcine parvovirus[b]	3M 1860[e]	60°C, 80% RH	30	No inactivation (Insufficient)	Oral et al.[28,*]

*Not peer-reviewed.
[a]Microwave-generated steam. Listed power is microwave specification; actual power may be somewhat lower.
[b]Nonenveloped virus; may be more resistant than SARS-CoV-2 or influenza to certain treatments.
[c]Heating method is using oven, unless otherwise specified.
[d]All viruses from (Oh et al.[7]) were inoculated after mixing 1:1 with an artificial saliva solution.
[e]These are surgical respirators and are certified for fluid resistance. Fluid resistance was not characterized after heat treatment.
ATCC, American Type Culture Collection; DMEM, Dulbecco's modified Eagle medium; FFR, filtering facepiece respirator; MGS, microwave-generated steam; MHV, murine hepatitis virus; OSU, Ohio State University strain; PBS, phosphate-buffered saline; RH, relative humidity; SARS-CoV-2, severe acute respiratory syndrome coronavirus 2.

saliva results.[2] The SARS-CoV-2 study performed by Fischer et al. also found that 60 min of 70°C dry heat only resulted in a 2-log reduction of viable virus on a stainless steel surface,[3] further indicating that 70°C dry heat may not sufficiently decontaminate N95 FFRs (which often contain metallic components). Therefore, further studies with viruses in different deposition solutions on N95 FFRs are necessary to find a safe working range of temperature, time, and humidity that will inactivate SARS-CoV-2.

Given the sparse data on SARS-CoV-2, we also analyzed the literature on humid heat inactivation of other viruses. Heat and humidity have been used to inactivate other enveloped viruses (H1N1 and H5N1 influenza) on various N95 FFRs[26,27] and surfaces.[4] N95 FFRs contaminated with some known varieties of influenza can be adequately decontaminated at temperatures >60°C with sufficient humidity and exposure times, although these conditions were insufficient for inactivation of a nonenveloped DNA virus, porcine parvovirus[28] (Table 1). One study, using a dried solution of H1N1 on stainless steel, found inactivation was more effective when either temperature or relative humidity was increased.[4] A recent study measured inactivation of H3N2 influenza, MS2 and Phi6 bacteriophage, and a mouse coronavirus (murine hepatitis virus [MHV]) on N95 respirators under various heat and humidity conditions.[2] This study found that for all tested humidity values >50%, all four viruses were inactivated beyond their detection limits after a 30-min treatment at 72°C or 82°C (>6-log for MS2 and Phi6 inoculated with PBS, >3-log for MHV and H3N2 inoculated with DMEM). However, neither MS2 nor Phi6 were sufficiently inactivated at low humidity (≤13%) after a 30-min treatment at 82°C when deposited in saliva. This indicates that elevated humidity is crucial for heat-based viral decontamination. Multiple studies using various viral samples have also shown a correlation between mid to high relative humidity and increased viral inactivation.[2,20,29–31] Therefore, heat-based protocols for bioburden reduction of SARS-CoV-2 are likely to be significantly more effective at intermediate to high humidity levels and higher temperatures.

The literature for viral inactivation on N95 FFRs indicates that relative humidity >50% and temperatures >70°C for >30 min can achieve >3-log decrease in active viral particles. These experiments include enveloped and nonenveloped RNA viruses, and many of them achieve viral inactivation levels greater than the detection limits of the assays performed. This includes some results showing >6-log inactivation at humidity >50% when inoculated in representative media.[2] Given this evidence, it is likely that SARS-CoV-2 will also be sufficiently inactivated after treatment at >50% relative humidity with temperatures of >70°C for at least 30 min. More resistant pathogens such as bacterial spores[22] are unlikely to be sufficiently inactivated by this heat-humidity treatment, so this method should be considered as a method of bioburden reduction only.

Humid Heat: N95 FFR Integrity

N95 FFRs are intended as single-use respirators. There is, however, literature on the performance of N95 FFRs after multiple heat and humidity cycles, summarized in Table 2. This table lists, for each specific N95 FFR model, the filtration and quantitative fit tests for the most relevant studies on N95 FFR durability under heat-humidity treatments.

When considering the integrity of N95 FFRs after reprocessing, an important distinction should be made between surgical N95 FFRs and nonsurgical N95 FFRs. Although both surgical and nonsurgical N95 FFRs are NIOSH-certified for their filtration efficiency, surgical N95 FFRs are additionally FDA-certified for maintaining a fluid barrier. It is not well studied whether surgical N95 FFRs maintain their fluid resistance after heat and humidity treatment. Different materials are used in the construction of surgical and nonsurgical N95 FFRs,[32] although the studies reviewed here found similar results for fit and filtration of surgical and nonsurgical N95 FFRs after humid heat treatment.

Initial studies on N95 FFR durability showed that many common N95 FFR models can undergo one to three cycles of 30 min at 60°C and 80% relative humidity while maintaining both fit and filtration performance.[33–35] Data from more recent reports suggest that many models may be capable of withstanding multiple heat-humidity treatments at even higher temperatures up to 85°C, and dry heat up to 95°C. In particular, several N95 FFR models (3M 1860, 3M 1870, and 3M 8210+) have been demonstrated to pass both quantitative fit and filtration tests for at least five 30-min cycles with temperatures of 85°C and relative humidity of 60–85%, and with dry heat at 95°C.[5,36] Several other models (3M 1860S, 3M 8110S, 3M 8210S, and 3M 9105S) were found to pass both fit and filtration tests after ten 60-min cycles of 70°C and 50% humidity.[7] Other models (3M 8200, 3M 8511, and more) were shown to pass quantitative fit tests for at least five 30-min cycles of dry heat at 75°C.[37] A single non health care model (3M 9211+) was found to maintain fit after two cycles of 70°C dry heat, although fit became unacceptable after three cycles.[3] One recent study evaluated filtration of 3M 8210 respirators at a wide range of particle sizes, and found that filtration remained >95% for all particle sizes after 10 cycles of dry or steam heat.[38] Another recent study supports this result, and indicates that the filtration efficiency of the meltblown fabric used as a filtering material in some N95 FFRs may be unaffected for up to twenty 20-min cycles at elevated temperature (75°C) and humidity (100%).[39] Four models (including 3M 8210) tested under these conditions showed no degradation in filtration efficiency after 20 cycles, although fit was not measured.

Table 2. Impact of heat-humidity treatment on N95 filtering facepiece respirator fit and filtration efficiency

Model	Temp. and relative humidity (30-min cycles)	No. of cycles filtration tested	No. of cycles fit tested	Autoclave 121°C steam, 15 min	MGS 1100 W,[d] 2 min	Study
3M 1860[e]	85°C, 60–85% 70°C, 50% 100°C, dry, 50 min	Passed[a] 5 Passed 10 Passed 20	Passed[b] 5 Passed 15 Passed 20	Failed fit after 1–2 cycles	Filtration passed 3 cycles Passed fit after 20 cycles	Anderegg et al.,[5] Oh et al.,[7] Daeschler et al.,[24] Kumar et al.,[25,*] Bergman et al.,[33] Bergman et al.,[34] Meisenhelder et al.,[36,*] Viscusi et al.,[41] Zulauf et al.[45]
3M 8210+	85°C, 60–85% 95°C, dry	Passed 5 Passed 5	Passed 5 Passed 5	Failed fit after 1 cycle Close to failing filtration (~95% after 5 cycles)	—	Anderegg et al.,[5] Meisenhelder et al.[36,*]
3M 1870[e]	85°C, 60–85% 95°C, dry	Passed 5 Passed 5	Passed 5 Passed 5	Passed fit after 10 cycles Failed filtration (<95% after 5 cycles)	Passed fit and filtration after 3 cycles	Kumar et al.,[25,*] Bergman et al.,[33] Bergman et al.,[34] Meisenhelder et al.,[36,*] Fisher et al.[43]
3M 8000	60°C, 80%	Passed 3	Passed 1	Fit and filtration failed after 1 cycle	Filtration passed 3 cycles Passed fit after 1 cycle	Bergman et al.,[33] Viscusi et al.,[35] Viscusi et al.[41]
Moldex 2200	60°C, 80%	Passed 3	Passed 1	—	Filtration passed 3 cycles Passed fit after 1 cycle	Bergman et al.,[33] Viscusi et al.,[35] Fisher et al.[43]
KC PFR95-270[e]	60°C, 80%	Passed 3	Passed 3[c]	—	Passed fit and filtration after 3 cycles	Bergman et al.,[33] Bergman et al.,[34] Fisher et al.[43]
3M 8210	75°C, 90% 85°C, 100%	— Passed 20	Passed 10 —	Failed fit after 1 cycle	Filtration passed 3 cycles Passed fit after 1 cycle	Massey et al.,[6,*] Daeschler et al.,[24] Kumar et al.,[25,*] Bergman et al.,[33] Viscusi et al.,[35] Ou et al.,[38,*] Liao et al.,[39] 3M[47,*]
3M 8110S	70°C, 50%	Passed 10	Passed 15	—	—	Daeschler et al.[24]
3M 9105S	70°C, 50%	Passed 10	Passed 15	—	—	Daeschler et al.[24]
3M 8200	75°C, dry	—	Passed 5	—	—	Price et al.[37,*]
3M 8511	75°C, dry	—	Passed 5	—	—	Price et al.[37,*]
4C Air	75°C, dry 85°C, 100%	— Passed 20	Passed 5 —	—	—	Price et al.,[37,*] Liao et al.[39]
Jackson 20	75°C, dry	—	Passed 5	—	—	Price et al.[37,*]
3M 9211+	70°C, dry	—	Failed after 3 cycles	—	—	Fischer et al.[3,*]
3M 9210	—	—	—	Fit passed 10 cycles	—	Kumar et al.[25,*]
3M 1804S[e]	—	—	—	Fit passed 10 cycles	—	Kumar et al.[25,*]
3M 1862+[e]	—	—	—	Filtration passed 5 cycles	—	van Straten et al.[42]
Aearo 1054S	—	—	—	Fit passed 10 cycles	—	Kumar et al.[25,*]
Cardinal health[e]	—	—	—	—	Filtration passed 1 cycle (1.5 min)	Fisher et al.[43]

*Not peer reviewed.
[a]"Passed" implies that filtration efficiency was >95% after the specified number of cycles.
[b]"Passed" implies that quantitative fit tests resulted in fit factors >100.
[c]Fit tests were performed with 15-min cycles, rather than 30-min cycles used in most literature.
[d]Studies cited here for MGS all used 1100 W rated microwaves. The authors note that the actual power might have been lower.
[e]These are surgical respirators and are certified for fluid resistance. Fluid resistance was not characterized after heat treatment.

The literature suggests that N95 FFR models have varying susceptibilities to elevated temperature and humidity, so any protocol implemented should be tested with the specific N95 FFR models used locally. See Table 2 for a list of heat, humidity, and cycle parameters that have been tested on various N95 FFR models. For health care personnel utilizing any kind of FFR, a user seal check is crucial before reuse to ensure the respirator still seals properly to the face.[13] Finally, as an important additional consideration for N95 FFR reuse, repeated donning/doffing has been shown to have an impact on N95 integrity: for some N95 models, fit was found to fall below OSHA standards after 5 don/doff cycles, whereas others maintained fit for >15 don/doff cycles.[11] Higher temperature and humidity will likely lead to more effective inactivation of highly resistant microorganisms, which warrants studies of N95 FFR durability at high humidity and temperatures >85°C for common N95 FFR models. This being said, current literature indicates that 85°C is the highest temperature that has been studied at high humidity and found to preserve fit and filtration for multiple models of N95 FFR. Given the requirements for SARS-CoV-2 bioburden reduction mentioned previously, the range of parameters for inactivation of SARS-CoV-2 without compromising N95 respirator integrity is likely to be temperatures of 70–85°C and relative humidity >50% for least 30 min. As discussed earlier, the impact of multiple cycles of humid heat bioburden reduction on N95 performance may vary by model, so all protocols require careful validation with the N95 model and cycle parameters used.

Autoclave: SARS-CoV-2 Inactivation and N95 FFR Integrity

Autoclave treatment is a readily accessible hospital sterilization procedure that has the potential to be used for decontamination and reuse of N95 FFRs. Although there are few studies specifically examining the inactivation of SARS-CoV-2 on these respirators under autoclave treatment, there is at least one piece of recent evidence, from a non-peer-reviewed report, suggesting that a 15-min autoclave cycle at 121°C can effectively inactivate the virus on N95 FFRs (Table 1).[25] Furthermore, autoclave treatment at 121°C for 30 min is considered a general sterilization process in medical settings.[40]

There exist a handful of studies on N95 FFR integrity after autoclave treatment, included in Table 2. These data show that the impact of autoclave treatment depends on the style of the specific N95 FFR model (molded vs. pleated). Studies indicate that three molded models (3M 1860, 3M 8000, and 3M 8210) fail fit tests after only 1 or 2 cycles of autoclave treatment, whereas some layered fabric, pleated models (3M 1870 and 3M 1862+) maintain fit performance for up to 10 cycles of autoclave treatment.[25,41,42] There are limited data on how autoclave treatment impacts filtration efficiency, but a recent study indicates that filtration performance may be significantly reduced (below the 95% NIOSH standard for N95 FFRs) after multiple autoclave cycles. In this study, the filtration efficiency of two layered fabric, pleated models (3M 1870 and 3M 8210+) decreased from ~99–100% to ~94–95% after five cycles of autoclave treatment.[36] Additional autoclave studies that include filtration tests are required to verify and supplement these findings. More generally, given the limited amount of data, additional studies are needed to fully understand the effects of autoclave treatment on N95 FFR durability for different models. However, in view of the demonstrated loss of filtration efficiency, as well as fit damage observed for molded N95 models, the current data suggest 121°C autoclave treatment may not be appropriate for N95 FFR decontamination.

Microwave-Generated Steam: SARS-CoV-2 Inactivation and N95 FFR Integrity

Whereas there is limited literature on the deactivation of SARS coronaviruses through microwave-generated steam (MGS) treatment, studies examining the bioburden reduction of N95 FFRs containing influenza viruses (H5N1 and H1N1) or bacteriophage MS2 suggest that MGS treatment can be an effective means of decontaminating FFRs of some viruses. Two minutes of steam treatment over a water reservoir in a 1250 W microwave oven was found to inactivate influenza viruses by over 3.3-log, and 1.5 min of steam treatment in a 1100 W microwave was found to inactivate MS2 bacteriophage by 3.1-log.[26,27,43] These studies caution that only areas of the respirator that are exposed to steam are likely to be decontaminated, so MGS protocols should ensure that all areas of the respirator are exposed. A summary of these studies is given in Table 1. Specific studies of SARS-CoV-2 are limited, so the effectiveness of MGS for bioburden reduction of SARS-CoV-2 contaminated N95 FFRs cannot currently be confirmed. In addition, it is important to note that MGS treatment may not fully inactivate bacterial spores, or may require additional time. It was found in one study that *Bacillus cereus* spores required at least 4 min of microwave radiation to be fully inactivated on a wet sponge.[44]

The literature on the durability of N95 FFRs under MGS treatment, included in Table 2, suggests little to no impact on structural integrity and quantitative fit after three treatment cycles in a 1100 W microwave, although one study found respirator damage on the inner foam nose cushion and head straps.[34,35,45] Furthermore, one peer-reviewed study found that six models of N95 (3M 8210, 3M 8000, Moldex 2200, KC PFR95-270, 3M 1870, 3M 1860, models listed in Bergman et al.[34]) maintained >95% filtration efficiency after three cycles of microwave generated steam from a water reservoir in a 1100 W microwave oven.[33] However, recent tests

on the meltblown fabric used as the filtering material in N95 FFRs suggest that steam treatment can have adverse effects on filtration efficiency beyond three cycles.[39] In addition, there are insufficient data on N95 fit and filtration performance after MGS treatment in high-power, 1250 W microwave ovens used for several viral inactivation studies described previously. One study using an even higher power microwave oven observed arcing on the metal nosepiece for certain N95 models.[46] Extending these studies to test N95 FFR filtration performance beyond three treatment cycles or in higher power microwave ovens would be beneficial to our understanding of the effects of MGS on N95 FFR durability. Given the evidence thus far, microwave-generated steam for 2 min in a 1100 W microwave oven over a water reservoir is a promising method for inactivation of SARS-CoV-2 on an N95 respirator, although N95 filtration efficiency has not been characterized beyond three cycles.

When evaluating MGS as a method of N95 bioburden reduction, it is also important to consider variations in power and geometry between different microwave models. In particular, the impact of powers higher than 1100 W on N95 integrity is not well characterized, and merits caution. The metallic components of many N95 FFR models (e.g., nosepieces) may present additional risks owing to extreme heat or sparking,[46] although no such effects have been reported for 1100 W or 1250 W microwave ovens in studies to date.[26,33–35,45] N95 FFRs have been shown to melt in microwave ovens in the absence of steam,[32] and care should be taken to introduce steam in an appropriate manner. In the literature, steam is introduced either by placing an N95 FFR above a water reservoir or by sealing it within a commercial microwave steam bag.[43] MGS treatment may be sensitive to the N95 model used and the specific protocol used (water reservoir vs. steam bag). The references in Tables 1 and 2 may be consulted for details on their specific implementation.

Implementation Strategies

Many hospitals are currently equipped with or can readily procure devices that can achieve the 70–85°C temperatures and >50% humidity mentioned previously, including warming cabinets, convection ovens, circulating water baths, autoclaves, or microbial incubators. Devices with direct heating elements should not be used, as they create local temperatures that are higher than the target, therefore risking damage to the respirator. Target humidity could be achieved in heating devices, for example, by temporarily placing N95 FFRs in impermeable heat-stable boxes (e.g., plastic containers) with a source of moisture inside each box, or by isolating N95 FFRs in permeable containers and increasing the humidity of the heating device.[5] This approach may be adapted for low-resource settings by using gas-powered stoves to create a heated water bath.[48] Individual containment of N95 FFRs is recommended, as it ensures that N95 FFRs are kept physically separated (reducing possible cross-contamination) and enables decontaminated N95 FFRs to be returned to their original users. We emphasize that airing of N95 FFRs *immediately* after a thermal cycle is recommended and could reduce risk of pathogen growth. Crucially, because humid heat is unlikely to inactivate all pathogens on N95 FFRs, respirators should be considered contaminated both before and after humid heat treatment. Proper infection control workflows for respirator collection, bioburden reduction, and redistribution to the original user are required to prevent cross-contamination.

For any given device and method, the critical process parameters should be validated to ensure proper control and performance. It is important to determine that any chosen method is able to achieve and remain at the target temperature and relative humidity for the target time, with maximal spatial homogeneity across the device. This validation should be performed under conditions as close to regular process conditions as possible with sufficient monitoring by electronic temperature and humidity sensors. Care should be used when choosing an appropriately rated sensor. This validation should be repeated periodically at a frequency determined by the facility's established quality control practices and the party responsible for oversight and implementation of the procedure.

When donning an N95 FFR that has been through any decontamination or bioburden reduction process, the user should perform the locally recommended steps to ensure N95 FFR fit, so as to ensure that the seal is not compromised.

Primary Risks and Unknowns

Only three studies described in this report directly examined the efficacy of decontamination of N95 FFRs contaminated with SARS-CoV-2. Recent data suggest that humidity and deposition solution (mucus, saliva, culture media, aerosolized droplets, etc.) have a strong influence on viral inactivation by heat, although further study is needed for a mechanistic understanding of these observations. Future experiments validating these effects for SARS-CoV-2 are important for improving guidance on N95 decontamination and reuse for the COVID-19 pandemic. Because viral inactivation is highly dependent on temperature, humidity, and time, quality assurance measures are critical to achieving decontamination or bioburden reduction. Process variability in heating elements or humidity sources could result in cycles with inadequate virucidal activity.

In this review we have only examined conditions that would likely result in the inactivation of SARS-CoV-2, so the risk of other pathogens remains. Because the current practice of many hospitals is to keep N95 FFRs at room temperature between uses, it is crucial to evaluate whether the microbial load on an N95 will increase

over time during storage. When testing heat as a possible method for viral inactivation, N95 FFRs should stay physically separated from each other and should only be reused by the same clinician.

Conclusions

When possible, unused N95 FFRs and other personal protective equipment should be provided. However, this is not always feasible in crisis situations. We are sharing this review to aid in the development of real-world processes to protect clinical staff by employing equipment and supplies that may be readily available or easily obtained. This review may help guide health care institutions that face the need to decontaminate and reuse N95 FFRs during the COVID-19 pandemic. For heat-humidity-based bioburden reduction, we stress that (1) after each round of bioburden reduction, a user seal check should be performed, (2) extended cycles of doffing and redonning may affect FFR fit, and (3) that the FFR should not be considered fully sterilized, as more resistant organisms including bacterial spores may remain even after viral inactivation.

Our review of the available literature revealed that the conditions required for inactivation by heat and humidity are pathogen specific. Therefore, studies to determine appropriate conditions for SARS-CoV-2 inactivation on N95 FFRs are urgently needed. Preliminary inactivation data for SARS-CoV-2 on N95 FFRs, considered alongside data for other viral pathogens, suggest that conditions of humid heat at 70–85°C with >50% relative humidity for 30 min are likely to achieve bioburden reduction of N95 FFRs contaminated with SARS-CoV-2. Experiments are underway to evaluate the efficacy of heat-humidity inactivation of SARS-CoV-2 on N95 FFRs.

The available literature on autoclave treatment indicates that although certain N95 FFR model types (i.e., layered, pleated models such as the 3M 1870) can maintain fit performance after several cycles of autoclave treatment, significant reduction of filtration efficiency has been demonstrated for at least two models (3M 1870 and 3M 8210+). Although there are currently limited data on filtration efficiency, this suggests autoclave treatment may not be an appropriate decontamination method for SARS-CoV-2 on N95 FFRs.

The literature on microwave-generated steam suggests that bioburden reduction may be achieved for a 2-min cycle in a 1100 W microwave oven with a sufficiently sized water reservoir. Several N95 FFR models have been shown to retain fit and filtration performance after three cycles of microwave-generated steam treatments, but the efficacy of this treatment on other respirator models is unclear. These positive preliminary results suggest that microwave-generated steam deserves further study to verify its effectiveness on more N95 models, especially because of its high accessibility in lower resource settings.

The strategies considered here are potentially compatible with implementation in numerous clinical settings with different heating appliances (e.g., warming cabinets, water baths, autoclaves, microbial incubators, industrial convection ovens, and microwave ovens). We emphasize that proper industrial hygiene workflows for respirator collection, bioburden reduction, and redistribution to the original user are crucial to reduce the risks of N95 reprocessing and reuse. The strategies discussed here focus only on inactivation of the SARS-CoV-2 virus and its surrogates, and do not serve as a means of complete N95 sterilization. Ultimately, we hope that this review can aid hospitals in formalizing improved N95 FFR decontamination strategies for approval with regulatory agencies to better protect the health of essential health care workers and front-line personnel.

Acknowledgments

N95DECON is an international consortium of scientists, engineers, clinicians, and students from universities and the private sector. The mission of N95DECON is to review and disseminate scientific information about decontamination of N95 FFRs during crisis-capacity conditions and emergency shortages such as those experienced during the COVID-19 pandemic. The authors thank the following N95DECON team members for their contributions to this article: Sumner Barenberg, Grace Hu, Larissa Little, Simone Marini, Andrew Preecha, Sara Rampazzi, Sylvia Smullin, and Nichole Starr, MD, MPH.

Ethical Approval

This research was completed virtually and did not require IRB approval.

Author Disclosure Statement

A.G. is an employee of Consolidated Sterilizer Systems, which manufactures products similar to those evaluated in this article.

Funding Information

Heising-Simons Foundation support (to L.A.). Heising-Simons Foundation (for Harvard). Hertz Foundation Fellowship (to Y.L.). HERCULES Center P30ES019776 (partial support, A.P.). National Defense Science and Engineering Graduate (NDSEG) Fellowship (to N.V.). National Science Foundation Graduate Research Fellowship (to T.N.C.).

References

1. Reusability of Facemasks During an Influenza Pandemic. https://www8.nationalacademies.org/onpinews/newsitem.aspx?RecordID=s04272006. Accessed July 8, 2020
2. Rockey N, Arts PJ, Li L, et al. Humidity and deposition solution play a critical role in virus inactivation by heat treatment of N95 respirators. mSphere. 2020;5(5):e00588-20. doi: 10.1128/mSphere.00588-20.
3. Fischer R, Morris DH, van Doremalen N, et al. Assessment of N95 respirator decontamination and re-use for SARS-CoV-2 [published online April 24, 2020]. *medRxiv*. doi:10.1101/2020.04.11.20062018

4. McDevitt J, Rudnick S, First M, Spengler J. Role of absolute humidity in the inactivation of influenza viruses on stainless steel surfaces at elevated temperatures. *Appl Environ Microbiol*. 2010;76(12):3943–3947.
5. Anderegg L, Meisenhelder C, Ngooi CO, et al. A scalable method of applying heat and humidity for decontamination of N95 respirators during the COVID-19 crisis. *PLoS One*. 2020;15(7):e0234851.
6. Massey T, Borucki M, Paik S, et al. Quantitative form and fit of N95 filtering facepiece respirators are retained and coronavirus surrogate is inactivated after heat treatments [published online April 22, 2020]. *medRxiv*. doi:10.1101/2020.04.15.20065755
7. Oh C, Araud E, Puthussery JV, et al. Dry heat as a decontamination method for N95 respirator reuse [published online July 15, 2020]. *Environ Sci Technol Lett*. doi:10.1021/acs.estlett.0c00534
8. Darnell MER, Subbarao K, Feinstone SM, Taylor DR. Inactivation of the coronavirus that induces severe acute respiratory syndrome, SARS-CoV. *J Virol Methods*. 2004;121(1):85–91.
9. Darnell MER, Taylor DR. Evaluation of inactivation methods for severe acute respiratory syndrome coronavirus in noncellular blood products. *Transfusion*. 2006;46(10):1770–1777.
10. Rabenau HF, Cinatl J, Morgenstern B, Bauer G, Preiser W, Doerr HW. Stability and inactivation of SARS coronavirus. *Med Microbiol Immunol*. 2005;194(1):1–6.
11. Bergman MS, Viscusi DJ, Zhuang Z, Palmiero AJ, Powell JB, Shaffer RE. Impact of multiple consecutive donnings on filtering facepiece respirator fit. *Am J Infect Control*. 2012;40(4):375–380.
12. CDC. Recommended Guidance for Extended Use and Limited Reuse of N95 Filtering Facepiece Respirators in Healthcare Settings | NIOSH | CDC [published June 8, 2020]. https://www.cdc.gov/niosh/topics/hcwcontrols/recommendedguidanceextuse.html. Accessed July 8, 2020.
13. CDC. Decontamination and Reuse of Filtering Facepiece Respirators [published April 9, 2020]. https://www.cdc.gov/coronavirus/2019-ncov/hcp/ppe-strategy/decontamination-reuse-respirators.html. Accessed April 21, 2020.
14. OSHA. OSHA Technical Manual, Section VIII—Use of Respirators. https://www.osha.gov/dts/osta/otm/otm_viii/otm_viii_2.html#8. Accessed April 22, 2020.
15. Battelle. Instructions for Healthcare Personnel: preparation of Compatible N95 Respirators for Decontamination by the Battelle Memorial Institute Using the Battelle Decontamination System [published March 29, 2020]. https://www.fda.gov/media/136532/download. Accessed April 22, 2020.
16. Center for Devices and Radiological Health. Recommendations for Sponsors Requesting EUAs for Decontamination and Bioburden Reduction Systems for Surgical Masks and Respirators During the Coronavirus Disease 2019 (COVID19) Public Health Emergency. U.S. Food and Drug Administration [published 2020]. https://www.fda.gov/regulatory-information/search-fda-guidance-documents/recommendations-sponsors-requesting-euas-decontamination-and-bioburden-reduction-systems-face-masks. Accessed July 8, 2020.
17. Center for Devices and Radiological Health. Decontamination Systems for Personal Protective Equipment EUAs. U.S. Food and Drug Administration [published 2020]. https://www.fda.gov/medical-devices/coronavirus-disease-2019-covid-19-emergency-use-authorizations-medical-devices/decontamination-systems-personal-protective-equipment-euas. Accessed July 8, 2020.
18. Zumla A, Chan JFW, Azhar EI, Hui DSC, Yuen K-Y. Coronaviruses—drug discovery and therapeutic options. *Nat Rev Drug Discov*. 2016;15(5):327–347.
19. Gröner A, Broumis C, Fang R, et al. Effective inactivation of a wide range of viruses by pasteurization. *Transfusion*. 2018;58(1):41–51.
20. Lin K, Marr LC. Humidity-dependent decay of viruses, but not bacteria, in aerosols and droplets follows disinfection kinetics. *Environ Sci Technol*. 2020;54(2):1024–1032.
21. Vejerano EP, Marr LC. Physico-chemical characteristics of evaporating respiratory fluid droplets. *J R Soc Interface*. 2018;15(139). doi:10.1098/rsif.2017.0939
22. Rodriguez-Palacios A, Lejeune JT. Moist-heat resistance, spore aging, and superdormancy in Clostridium difficile. *Appl Environ Microbiol*. 2011;77(9):3085–3091.
23. Pastorino B, Touret F, Gilles M, de Lamballerie X, Charrel RN. Evaluation of heating and chemical protocols for inactivating SARS-CoV-2 [published online April 11, 2020]. *bioRxiv*. doi:10.1101/2020.04.11.036855
24. Daeschler SC, Manson N, Joachim K, et al. Effect of moist heat reprocessing of N95 respirators on SARS-CoV-2 inactivation and respirator function [published online July 30, 2020]. *CMAJ*. doi:10.1503/cmaj.201203
25. Kumar A, Kasloff SB, Leung A, et al. N95 mask decontamination using standard hospital sterilization technologies [published online 2020]. *medRxiv*. doi:10.1101/2020.04.05.20049346
26. Heimbuch BK, Wallace WH, Kinney K, et al. A pandemic influenza preparedness study: use of energetic methods to decontaminate filtering facepiece respirators contaminated with H1N1 aerosols and droplets. *Am J Infect Control*. 2011;39(1):e1–e9.
27. Lore MB, Heimbuch BK, Brown TL, Wander JD, Hinrichs SH. Effectiveness of three decontamination treatments against influenza virus applied to filtering facepiece respirators. *Ann Occup Hyg*. 2012;56(1):92–101.
28. Oral E, Wannomae KK, Gil D, et al. Efficacy of moist heat decontamination against various pathogens for the reuse of N95 respirators in the COVID-19 emergency [published online May 19, 2020]. *medRxiv*. doi:10.1101/2020.05.13.20100651
29. Prussin AJ, Schwake DO, Lin K, Gallagher DL, Buttling L, Marr LC. Survival of the enveloped virus Phi6 in droplets as a function of relative humidity, absolute humidity, and temperature. *Appl Environ Microbiol*. 2018;84(12). doi:10.1128/AEM.00551-18
30. Casanova LM, Jeon S, Rutala WA, Weber DJ, Sobsey MD. Effects of air temperature and relative humidity on coronavirus survival on surfaces. *Appl Environ Microbiol*. 2010;76(9):2712–2717.
31. Guan J, Chan M, VanderZaag A. Inactivation of avian influenza viruses on porous and non-porous surfaces is enhanced by elevating absolute humidity. *Transbound Emerg Dis*. 2017;64(4):1254–1261.
32. Viscusi DJ, Bergman MS, Eimer BC, Shaffer RE. Evaluation of five decontamination methods for filtering facepiece respirators. *Ann Occup Hyg*. 2009;53(8):815–827.
33. Bergman M, Viscusi D, Heimbuch B, Wander J, Sambol A, Shaffer R. Evaluation of multiple (3-cycle) decontamination processing for filtering facepiece respirators. *J Eng Fiber Fabr*. 2010;5:33–41.
34. Bergman MS, Viscusi DJ, Palmiero AJ, Powell JB, Shaffer RE. Impact of three cycles of decontamination treatments on filtering facepiece respirator fit. *J Int Soc Respir Prot*. 2011;28(1):48–59.
35. Viscusi DJ, Bergman MS, Novak DA, et al. Impact of three biological decontamination methods on filtering facepiece respirator fit, odor, comfort, and donning ease. *J Occup Environ Hyg*. 2011;8(7):426–436.
36. Meisenhelder C, Anderegg L, Preecha A, et al. Effect of dry heat and autoclave decontamination cycles on N95 FFRs [published online June 2, 2020]. *medRxiv*. doi:10.1101/2020.05.29.20114199
37. Price AD, Cui Y, Liao L, et al. Is the fit of N95 facial masks effected by disinfection? A study of heat and UV disinfection methods using the OSHA protocol fit test [published online April 17, 2020]. *medRxiv*. doi:10.1101/2020.04.14.20062810
38. Ou Q, Pei C, Chan Kim S, Abell E, Pui DYH. Evaluation of decontamination methods for commercial and alternative respirator and mask materials—view from filtration aspect. *J Aerosol Sci*. 2020;150:105609.
39. Liao L, Xiao W, Zhao M, et al. Can N95 Respirators Be Reused after Disinfection? How Many Times? *ACS Nano*. 2020;14(5):6348–6356.
40. CDC. Steam Sterilization | Disinfection and Sterilization Guidelines | Guidelines Library | Infection Control | CDC [published April 4, 2019]. https://www.cdc.gov/infectioncontrol/guidelines/disinfection/sterilization/steam.html. Accessed July 8, 2020.
41. Viscusi DJ, King WP, Shaffer RE. Effect of decontamination on the filtration efficiency of two filtering facepiece respirator models. *J Int Soc Resp Prot*. 2007;24:15.
42. van Straten B, de Man P, van den Dobbelsteen J, Koeleman H, van der Eijk A, Horeman T. Sterilization of disposable face masks by means of standardized dry and steam sterilization processes; an alternative in the fight against mask shortages due to COVID-19 [published online 2020]. *J Hosp Infect*. doi:10.1016/j.jhin.2020.04.001
43. Fisher EM, Williams JL, Shaffer RE. Evaluation of microwave steam bags for the decontamination of filtering facepiece respirators. *PLoS One*. 2011;6(4):e18585.
44. Park D-K, Bitton G, Melker R. Microbial inactivation by microwave radiation in the home environment. *J Environ Health*. 2006;69(5):17–24; quiz 39–40.
45. Zulauf KE, Green AB, Nguyen Ba AN, et al. Microwave-generated steam decontamination of N95 respirators utilizing universally accessible materials. *MBio*. 2020;11(3). doi:10.1128/mBio.00997-20
46. Pascoe MJ, Robertson A, Crayford A, et al. Dry heat and microwave generated steam protocols for the rapid decontamination of respiratory personal protective equipment in response to COVID-19-related shortages [published online July 8, 2020]. *J Hosp Infect*. doi:10.1016/j.jhin.2020.07.008
47. 3M. Decontamination methods for 3M N95 respirators [published April 2020]. https://multimedia.3m.com/mws/media/1824869O/decontamination-methods-for-3m-n95-respirators-technical-bulletin.pdf. Accessed April 22, 2020.
48. Doshi S, Banavar SP, Flaum E, Kumar S, Chen T, Prakash M. Applying heat and humidity using stove boiled water for decontamination of N95 respirators in low resource settings [published online June 15, 2020]. *medRxiv*. doi:10.1101/2020.05.28.20113209