

# N95 Respirator Decontamination and Reuse: Current State of the Evidence

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*The pandemic severe acute respiratory syndrome coronavirus 2 that causes coronavirus disease 2019 has resulted in personal protective equipment shortages in hospitals and anesthesia departments. The necessity of N95 respirator masks for protection during a multitude of aerosol-generating procedures such as intubation has prompted conservation strategies, one of which is N95 mask decontamination and reuse. A literature review was performed examining the evidence for N95 decontamination and reuse. Decontamination methods discussed in the literature are chemical, physical, and energetic, with the most promising evidence available for vaporized hydrogen peroxide, warm moist heat,*

*and ultraviolet germicidal irradiation. There are several methods that are less effective or decrease postdecontamination performance of N95 masks. Any decontamination method should consider the equipment needed for the required scalability, because some methods require more specialized tools than others. Vast variabilities in the construction and design of available N95 masks mean that adaptation of any method discussed in the literature should be tested in a trial with the specific model of N95 mask to be decontaminated.*

**Keywords:** Aerosol, coronavirus, COVID-19, N95 mask conservation, personal protective equipment shortage.

**T**he severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) pandemic has strained the supply of personal protective equipment (PPE) because of the combination of respiratory transmission and high contagiousness. Multiple organizations have detailed PPE guidelines for instrumenting the airway in patients suspected or confirmed of being infected with coronavirus disease 2019 (COVID-19).<sup>1-4</sup> In addition to contact and droplet precautions, it is recommended that anesthesia practitioners don N95-type filtering facepiece respirators (FFRs) during aerosol-generating procedures such as intubation, suctioning, or extubation.<sup>5</sup> The necessity of N95 FFRs for such procedures, coupled with their increased demand among both healthcare professionals and members of the public, has inspired novel conservation techniques at many hospitals. One plausible technique now being explored at Wake Forest Baptist Medical Center in Winston-Salem, North Carolina, is the reclamation, decontamination, and reuse of N95 FFRs.

Although the pandemic crisis has led to relaxation of many typical PPE practices and protocols, N95 FFR decontamination remains especially important because masks that have not been decontaminated may serve as fomite vectors of SARS-CoV-2 virions.<sup>6</sup> The US Centers for Disease Control and Prevention, Food and Drug Administration (FDA), and National Institute for Occupational Safety and Health (NIOSH) all contribute to the standards and regulation of the quality of N95 FFRs and intend them for single use (ie, discarded between patients).<sup>7</sup> In the event that N95 FFRs are to be reused, the

Occupational Safety and Health Administration dictates that they be cleaned and decontaminated.<sup>8</sup>

There are several possible decontamination methods proposed in the literature, although it is unclear which are most effective. It is also unclear as to how decontamination, extended use, and reuse of N95 FFRs may affect their performance. Although soaking N95 FFRs in strong acids may completely decontaminate them, this method would render the masks essentially useless. Thus, finding a method that is effective and avoids mask destruction is important. To examine the efficacy of N95 FFR decontamination methods and their effects on the postdecontamination performance (PDP), the authors performed a literature review. The following questions guided the literature review:

- In the event of a severe N95 shortage such as that faced during a viral pandemic, can N95 FFRs be decontaminated and, if so, which method is most effective at eliminating the virus from the masks?
- What is the state of the evidence surrounding N95 FFR decontamination and reuse?
- What effect if any, does decontamination of the device have on its PDP?

## Methods

The literature search was performed on March 30, 2020, using 3 large databases: Cumulative Index to Nursing & Allied Health Literature (CINAHL) Complete, Ovid, and PubMed. An ancestry approach was also used. The Boolean search term sequence was as follows: *N95 and decontamination or disinfection or sterilization or recycle*

Evidence source	N95-D method	Contaminant LR	Comments
Mills et al, <sup>13</sup> 2018	UVGI	≥ 3 <sup>a</sup>	Facepiece LR > strap LR
Battelle Memorial Institute, <sup>9</sup> 2016	VHP	> 6 <sup>a</sup>	Bacterial contaminant, 1 mask tested
Heimbuch et al, <sup>20</sup> 2014	Antimicrobial wipes	3-5 <sup>a</sup>	Mucin removal/cleaning was poor
Lore et al, <sup>19</sup> 2012	UVGI, MGS, WMH	> 4 <sup>a</sup>	Two models tested
Fisher et al, <sup>11</sup> 2011	MGS	> 3 <sup>a</sup>	In sealed microwavable bags
Fisher et al, <sup>10</sup> 2011	UVGI	Variable	UVGI dose depends on model
Heimbuch et al, <sup>14</sup> 2011	UVGI, MGS, WMH	> 4 <sup>a</sup>	Aerosol application of H1N1
Rengasamy et al, <sup>12</sup> 2010	Antimicrobial N95s	Variable <sup>b</sup>	3.7 LR on iodine resin (37° C/80% RH)

**Table 1. Summary of Evidence Examining Decontamination Methods**

Abbreviations: H1N1, hemagglutinin type 1 and neuraminidase type 1; LR, log reduction; MGS, microwave-generated steam; N95-D, N95 respirator decontamination; RH, relative humidity; UVGI, ultraviolet germicidal irradiation; VHP, vaporized hydrogen peroxide; WMH, warm moist heat.

<sup>a</sup>  $P < .05$ .

<sup>b</sup>  $P > .05$  in LRs of all antimicrobial agents except iodinated resins.

or *reuse*. The search terms were searched in all fields including titles and abstracts. The inclusion criteria were any study type published in a peer-reviewed journal in the English language within the last 10 years with full text availability. Studies were reviewed by 1 researcher (K.W.), and only control studies dealing specifically with the effectiveness of decontamination and/or PDP of N95 FFRs were included. Final inclusion of a study was determined after title, abstract, and full text evaluation for relevance to the aforementioned criteria. Studies meeting final inclusion criteria were selected by this same author and were assessed for limitations.

## Results

The initial search parameters yielded 62 results. CINAHL Complete yielded 6 results, with 1 letter to the editor eliminated as low level evidence and 1 duplicate eliminated. Ovid yielded 26 results, with 8 eliminated based on title examination, 12 eliminated based on abstract examination, 1 eliminated based on lack of full text availability, and 1 letter to the editor eliminated. PubMed yielded 30 results, with 14 eliminated as duplicates and 14 eliminated based on title and abstract examination. The high number of duplicate articles encountered in the third database led to a reasonable degree of certitude as to the completeness of the review.

Two more studies were found during ancestry review and were added to the 10 studies remaining after the database search, for a final total of 12 studies.

The remaining studies had only a moderate quality of evidence given that no study was performed on a multi-center scale in adequately powered human populations testing multiple models of N95 FFRs. All studies were nonpopulation-based studies with true experimental research designs and strictly controlled variables. One nonblinded trial came from an FDA-contracted company, which used a specific brand of equipment.<sup>9</sup>

• **State of the Evidence.** The resulting studies could be

broadly categorized as examining either N95 FFR decontamination or PDP (Tables 1 and 2). Five studies investigated decontamination efficacy,<sup>10-14</sup> and 4 studies<sup>15-18</sup> investigated PDP. Three studies examined both N95 FFR decontamination and PDP,<sup>9,19,20</sup> and these studies are compared in discussion of both N95 FFR decontamination and PDP studies. Chemical, physical, and energetic decontamination methods were found in the literature, with some researched more than others. Ultraviolet (UV) irradiation (eg, UV germicidal irradiation [UVGI]) was examined the most, with 6 studies testing either its decontamination efficacy or its effect on PDP of the N95 respirator.<sup>10,13-15,17,19</sup> Four studies examined microwave-generated steam.<sup>11,14,15,19</sup> Hydrogen peroxide was studied 3 times,<sup>9,16</sup> twice in one study in 2 different forms.<sup>16</sup> Three studies examined warm moist heat.<sup>14,15,19</sup> Antimicrobial agents, either manufactured into the N95 FFRs or in wipe form, were examined in 2 studies.<sup>12,20</sup> An autoclave and a rice cooker method were tested separately in 1 study along with separate testing of ethanol, isopropyl alcohol, and bleach.<sup>18</sup> Any study examining exclusively bacterial contaminants was excluded unless it was also examining PDP. Contaminants were hemagglutinin type 1 and neuraminidase type 1 (H1N1),<sup>13,14</sup> MS2 bacteriophage (a surrogate for SARS-CoV-2),<sup>10-12</sup> mucin,<sup>14</sup> H5N1,<sup>19</sup> and *Geobacillus stearothermophilus*.<sup>9</sup> The number of different models tested in all studies varied from 15 in one study<sup>13</sup> to 1.<sup>9</sup> The mean number of models tested was 4.6, and the median and mode were 6.

• **Comparison of Decontamination Studies.** The most recent study (testing UVGI) also tested the greatest variety of N95 FFR models, testing more than twice as many models as any other study.<sup>13</sup> This study did note that researchers attempted to incorporate models with a variety of different shapes, sizes, and material types<sup>13</sup>; however, there were more than 100 models of N95 FFRs available on the market as of March 2, 2020. Not only are there numerous models but there also exists great varia-

Evidence source	N95-D method	Change in PDP	Comments
Lin et al, <sup>18</sup> 2017	Rice cooker, autoclave, ethanol, IPA, bleach	Variable	Physical-D > chemical-D
Lindsley et al, <sup>17</sup> 2015	UVGI	0 filtration, ↓ integrity	Repeated, high doses ↓ PDP
Heimbuch et al, <sup>20</sup> 2014	Antimicrobial wipes	0	< 5% increase in penetration
Lore et al, <sup>19</sup> 2012	UVGI, MGS, WMH	0	< 5% increase in penetration
Viscusi et al, <sup>15</sup> 2011	UVGI, MGS, WMH	↓ fit in 2/6 post-WMH-D <sup>a</sup>	Did not test penetration
Salter et al, <sup>16</sup> 2010	UVGI, VHP, 5 chemicals <sup>b</sup>	Residual oxidants below PEL	Did not test penetration

**Table 2.** Summary of Evidence Examining N95 Postdecontamination Performance (PDP)

Abbreviations: Chemical-D, chemical decontamination; IPA, isopropyl alcohol; MGS, microwave-generated steam; PDP, postdecontamination performance; PEL, permissible exposure limit; Physical-D, physical decontamination; UVGI, ultraviolet germicidal irradiation; VHP, vaporized hydrogen peroxide; WMH, warm moist heat; ↓, decreased.

<sup>a</sup>  $P < .05$ .

<sup>b</sup> Ethylene oxide, 3% hydrogen peroxide, 0.6% sodium hypochlorite, mixed oxidants, and dimethyl dioxirane.

tion in how different N95 FFR models respond to certain antimicrobial and even inert chemical decontaminations depending on how the electrostatic materials interact with ionic and nonionic agents in the wipes.<sup>20</sup> The low number of models tested and/or the testing of only one brand of N95 FFRs is an obvious limitation in all the literature thus far, especially given the heterogeneity of N95 material construction (eg, duckbill-shaped vs cup-shaped and electret vs nonelectret media).

• **Chemical Decontamination.** The study by Heimbuch et al<sup>20</sup> from 2014 concluded that chemical decontamination is plausible but that several concerns, including only a 1 log reduction in contaminants on the inside of the mask, demonstrate the need for further studies. Examining antimicrobials, Rengasamy et al<sup>12</sup> found that only antimicrobial masks incorporating iodinated resin and stored at 37° C and 80% relative humidity showed significant reduction (log reduction = 3.7) in MS2 bacteriophage compared with controls, making this a comparatively promising mask.

In the Battelle pilot study of vaporized hydrogen peroxide (VHP) decontamination, only 1 model of N95 was used, the healthcare particulate respirator and surgical mask 3M 1860 (3M Science).<sup>9</sup> Researchers found an impressive 6 log reductions in *b thermophilus*.<sup>9</sup> Although not a virus, *b thermophilus* was chosen for its unique resilience to hydrogen peroxide. The specific conditions detailed were use of the Clarus C VHP system (Bioquell) with a static glovebox (model No. 830-ABC, Plas-Labs Inc) with a decontamination chamber of 310 L.<sup>9</sup> Further testing of this method using other mask models or VHP delivery systems has yet to be performed, and any implementation of VHP should ensure that the shape, material, and construction of the N95 to be decontaminated is similar to that of the 3M 1860 or should pilot VHP on the specific model and virion to be decontaminated. The only other study evaluating hydrogen peroxide decontamination of N95 FFRs tested PDP alone and did so only in terms of residual oxidants.<sup>16</sup> Researchers of this study concluded that VHP did leave residual oxidants, but they

deemed this amount nonhazardous to health and suggested further testing be implemented.<sup>16</sup>

One study of half-mask elastomeric respirators contaminated with H1N1 found that bleach decontamination of these types of respirators was successful even in the presence of sebum soiling. More research is needed to understand N95 FFR decontamination in the presence of other contaminants such as cosmetics.<sup>22</sup> One concern in this regard is that N95 FFRs soiled with cosmetics may not be able to meet the FDA stipulation that cleaned devices have “no visual contamination present”.<sup>20</sup> Simply because an N95 FFR has been effectively decontaminated (eg, > 3 log reductions in H1N1) does not mean that it has been effectively cleaned. It has been demonstrated, for example, that bleach wiping of N95 FFRs that are visibly contaminated with mucin was effective in decontaminating *Staphylococcus aureus* but not in removing visible mucin (ie, cleaning the FFR).<sup>20</sup> Whether this conclusion holds for skin and cosmetic-type contaminants is an area for further research.

• **Physical Decontamination.** Physical decontamination methods tested included microwave-generated steam and warm moist heat. Neither microwave-generated steam nor UVGI was as effective as warm moist heat, but this was thought to be due only to the inability to deliver the steam and irradiation uniformly to the surface of the N95 FFR.<sup>14</sup> Steam bags in one study<sup>11</sup> repeatedly produced 3 log reductions of MS2 surrogate and could be seen to overcome the nonuniform application of steam that limited the success of microwave-generated steam in the 2011 study by Heimbuch et al.<sup>14</sup> One significant difference is the treatment time with microwave-generated steam (2 minutes) vs warm moist heat (30 minutes); however, this could theoretically be overcome if the size of the warm moist heat generator were sufficiently large.<sup>14</sup> It was noted that 1 mask in the microwave-generated steam group showed some deterioration and that this was consistent with previous findings.<sup>14</sup> The 2011 study by Heimbuch et al<sup>14</sup> was unique in that it studied the aerosolized application of surrogate pathogen to the masks instead of solu-

tion-based application. The aerosolization of pathogen is theoretically a more rigorous contamination method since the droplets may provide a protective barrier to evaporative decontamination of the pathogen.

A common limitation in the literature is the deficit in knowledge regarding features of respiratory virions and their mucin media aerosolizing in vivo, for example, how much mucin and what type of distribution pattern is generated during extubation, typically? This is an area of need for further research because the existing evidence of literature regarding aerosol-generating medical procedures (AGMPs) was recently found to be of low quality.<sup>23</sup> Although a full description of AGMPs is outside the scope of this review, the common underlying physical phenomenon to all such procedures is the exposure of the respiratory tract lining to laminar or turbulent shear forces.<sup>23</sup> The highest aerosol-generating AGMPs are probably percutaneous tracheostomy, bronchoscopy, bag-valve mask ventilation, and cardiopulmonary resuscitation (CPR).<sup>23</sup> Suctioning, laryngoscopy, frequent cough, extubation, and dyspneic breathing are highly aerosol-generating as well, but generally less so than bronchoscopy, tracheostomy, bag-valve-mask ventilation, and CPR.<sup>23</sup> Finally, face mask oxygen delivery, nebulizer treatment, and high-flow nasal cannula are moderately high AGMPs.<sup>23</sup> Categorical classification of what constitutes an AGMP is useful, but it may also be helpful to again consider the underlying physics. Aerosol generation exists on a continuum based on how likely it is that a given procedure will expose the lining of the airway to shearing forces. Using the lowest possible oxygen delivery flow to maintain adequate oxygenation is one practical way to apply minimal shearing forces along the airway.

- **Energetic Decontamination.** Ultraviolet germicidal irradiation was studied the most and was demonstrated to be an effective decontaminant.<sup>10,13,14,17,19</sup> However, it was found that UV exposure times are specific to the model of N95 FFR.<sup>10</sup> Additionally, UVGI was largely effective even in the presence of sebum and cosmetics (also depending on the N95 FFR model type).<sup>13</sup> The 2018 study by Mills et al<sup>13</sup> should emphasize concerns regarding proper doffing of an N95 FFR because UVGI did not lead to significant log reduction in the straps in 8 of 15 models. The researchers attributed this to a possible shadowing effect wherein the straps were shaded by the facepieces or turned on themselves.<sup>13</sup>

- **Comparison of Postdecontamination Performance Studies.** Before decontamination, one study noted that in at least 5 models there was more than 99% filtration of particles as small as 100 nm at 85 L/min flow.<sup>24</sup> Certification by the NIOSH of N95 FFRs requires that they are able to filter at least 95% of 300-nm particles. Unfortunately, these findings do not generalize to their performance after decontamination. Postdecontamination performance is dependent on the

model; some models demonstrated significantly decreased PDP after treatment.<sup>20</sup> Warm moist heat, UVGI, and microwave-generated steam are all probably safe methods in that they do not leave any toxic residue or odors and do not seem to decrease PDP.<sup>15,19</sup> Each of these methods were found to increase 300-nm particle penetration by less than 5%.<sup>19</sup> One study noted that there was a particular model of N95 that showed decreased PDP after microwave-generated steam.<sup>14</sup> Another study found that warm moist heat leaves more of a noticeable odor than UVGI or microwave-generated steam does, but this is much less than bleach odor, for example, and the sample size was small.<sup>15,16</sup> Chemical decontamination with isopropanol, ethanol, or bleach (Lin et al<sup>18</sup> did not test hydrogen peroxide in electret N95 FFRs) are more destructive than physical decontamination on electret-type N95 FFRs.<sup>18</sup> Vaporized hydrogen peroxide did not decrease PDP until after 30 decontamination cycles.<sup>9</sup> Energetic decontamination with UVGI minimally affects PDP unless at high or repeated doses, and this is highly model-dependent.<sup>17</sup> A consideration of repeatedly applying UVGI decontamination should be to find the minimal UV dose required to destroy the concerning virion. As in studies dealing with N95 FFR decontamination, the major limitation of PDP studies was that there were not enough models tested (ie, underpowered) and that the amount and time of exposure to the respective decontamination method was not similar between all studies (ie, design heterogeneity). This review did not examine what effect, if any, repeated donning and doffing has on PDP, but over time with extended reuse, this could theoretically decrease mask fit and the strap tensile strength.

## Discussion

Researchers in the area of N95 FFR decontamination and PDP have corroborated some of each other's results, but large randomized clinical trials (RCTs) with human participants have not verified any of the findings. One recent RCT (N = 2,371 after attrition) tested the incidence of laboratory-confirmed influenza in healthcare workers after randomization to wear simple surgical masks or N95 FFRs when caring for patients with suspected respiratory tract infection.<sup>25</sup> These researchers found no significant difference in the incidence of laboratory-confirmed influenza; however, this study had major limitations.<sup>25</sup> One limitation was the use of only 4 models of N95 FFRs and 2 models of simple surgical masks.<sup>25</sup> Another limitation was there was no way to discriminate influenza acquired while wearing the mask (ie, at work) from influenza acquired while not wearing the mask (ie, outside work).

Finally, that study is not generalizable to a viral strain for which there is no vaccine. Many healthcare workers are required to get influenza vaccination, and exposure to influenza may have been much higher in the simple surgical mask group, but because of vaccination, it led

to no symptoms to prompt testing. Thus, N95 FFR conservation remains as relevant as ever and particularly in times of material and financial depletion. Another alternative to N95 FFRs during aerosol-generating procedures in patients who are COVID-19 positive is powered air-purifying respirators (PAPRs). Researchers at Wake Forest Baptist Medical Center have shown that these devices may confer up to 10% more protection to people than the N95 FFR against influenza.<sup>26</sup> This degree of added protection is significant; however, PAPRs are generally less available than N95 FFRs and would not be able to replace N95 FFRs in all such high-risk cases. In the event that PAPRs became more available, they may be a suitable alternative to N95 FFRs even in sterile environments, because preliminary research has suggested that PAPRs are unlikely to contaminate sterile fields.<sup>27</sup>

This review demonstrates a need for more studies regarding N95 FFR decontamination and PDP. Especially lacking are studies on the cost-effectiveness and large-scale scalability of decontamination methods. All studies reviewed had small samples and therefore low degrees of representativeness with respect to the plethora of N95 FFR models on the market. There was a moderate level of evidence that UVGI was an effective method and only decreased PDP at multiple and high doses.<sup>17</sup> There was concern in the literature that depending on the N95 FFR model, UVGI and microwave-generated steam could not be as uniformly applied as warm moist heat.<sup>13,14</sup> Warm moist heat and microwave-generated steam were similarly effective as UVGI, but potential postdecontamination odor may be a concern with warm moist heat.<sup>14</sup> It stands to reason that warm moist heat does not require too much special equipment, is readily scalable, is nontoxic, and uniformly distributes around N95 FFRs. Although microwave-generated steam generated within sealable microwavable bags solves the uniform distribution problem of larger-scale microwave-generated steam, it may not be as easily replicable in large hospital settings.<sup>11</sup> Chemical decontamination, including with VHP, was found to be generally more destructive to masks than physical decontamination with microwave-generated steam or warm moist heat, but the amount of residual chemicals after chemical decontamination was deemed safe.<sup>16,18</sup> The Battelle study showed that after 30 decontamination cycles, the straps began to degrade in the models tested.<sup>9</sup> An advantage of the VHP method, however, is the demonstrated ability to decontaminate more than 50 N95 FFRs at a time.<sup>9</sup> The warm moist heat studies attempted to decontaminate only a handful of masks at a time.<sup>14,19</sup> It is also unclear how other electret and particulate N95 FFRs would be affected by hydrogen peroxide since the Battelle group tested only one type of surgical N95.<sup>9</sup>

## Conclusion

Anesthesia professionals frequently engage in aerosol-

generating procedures in patients. Given the possibility of critical shortages in N95 FFRs during an influenza or SARS pandemic, N95 FFR decontamination and reuse is one plausible PPE conservation method. The evidence supporting N95 FFR decontamination and reuse is limited and moderate in quality but supports some diverse methods. Any method used should consider the particular features of the N95 FFRs to be decontaminated and reused, including particle penetration and residual toxins, odor, and fit after decontamination. It is also prudent to assess what equipment is available to decontaminate, because certain methods require specialized decontamination technologies while others are more rudimentary.

Despite parity of efficacy across chemical, physical, and energetic methods, VHP, warm moist heat, and UVGI seem to be the most promising decontamination methods. An algorithm for VHP decontamination with the Clarus C VHP system (Bioquell) has been established by the Battelle group and is accessible to the public.<sup>9</sup> Warm moist heat could also be established as a more cost-effective method at 65° C and 85% relative humidity for 30 minutes.<sup>20</sup> Already, UVGI is used by many facilities as a decontamination method for medical equipment. Implementation of this method should ensure that all sides of the mask are exposed to irradiation and that strap integrity is assessed over the lifetime of the mask. Chemical decontamination with various bleach and alcohol solutions as well as autoclaving should be avoided because of decreases in PDP of the N95 mask. Vaporized hydrogen peroxide, warm moist heat, and UVGI all decrease the strength of the mask over time, but it remains unclear by how much, and this is probably highly dependent on the type of N95 FFR. Vaporized hydrogen peroxide is the only N95 FFR decontamination method tested in which masks withstood up to 30 cycles of decontamination before straps began breaking down.<sup>9</sup> However, this finding should not suggest inferiority of other methods in this regard, and the potential influence of repeat donning and doffing cannot be ignored.<sup>9</sup> An avenue for future research and development is the creation of N95 FFRs that are designed for reuse.

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## DISCLOSURES

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