Efficacy and Safety of Disinfectants for Decontamination of N95 and SN95 Filtering Facepiece Respirators: A Systematic Review

Katie O’Hearn¹; Shira Gertsman¹; Richard Webster²; Anne Tsampalieros²; Rhiannon Ng¹; Jess Gibson¹; Margaret Sampson³; Lindsey Sikora⁴; and James Dayre McNally^{1,5}

¹ Children’s Hospital of Eastern Ontario Research Institute, Ottawa, Ontario, Canada

² Clinical Research Unit, Children’s Hospital of Eastern Ontario, Ottawa, Ontario, Canada

³ Library Services, Children's Hospital of Eastern Ontario, Ottawa, Ontario, Canada

⁴ Health Sciences Library, University of Ottawa, Ottawa, Ontario, Canada

⁵ Department of Pediatrics, Children's Hospital of Eastern Ontario, Ottawa, Ontario, Canada

Corresponding author:

Katie O’Hearn

401 Smyth Road, Ottawa, Ontario, Canada, K1H 8L1

Phone: 613-737-7600 ext. 4006

Fax: 613-738-4287

E-mail: kohearn@cheo.on.ca

Abstract

Background: Decontaminating and re-using filtering facepiece respirators (FFR) for healthcare workers is a potential solution to address inadequate FFR supply during a global pandemic.

Aim: The objective of this review was to synthesize existing data on the effectiveness and safety of using disinfectants to decontaminate N95 FFR.

Methods: We conducted a systematic review on disinfectants to decontaminate N95 FFRs using Embase, Medline, Global Health, Google Scholar, WHO feed, and MedRxiv. Two reviewers independently determined study eligibility and extracted and verified predefined data fields. Original research reporting on N95 FFR function, decontamination, safety, or mask fit following decontamination with a disinfectant was included.

Findings and Conclusions: A single cycle of vaporized H₂O₂ successfully removes infectious pathogens without affecting mask function or fit, and with little change in FFR physical appearance. Residual hydrogen peroxide levels following decontamination were below the safety limit. More than one decontamination cycle of vaporized H₂O₂ may be possible but further information is required on how multiple cycles would affect mask fit in a real world setting before the upper limit can be established. Although immersion in liquid H₂O₂ does not appear to adversely affect mask function, there is no available data on its ability to remove infectious pathogens from FFRs or its impact on mask fit. Sodium hypochlorite, ethanol, isopropyl alcohol and EtO are not recommended due to safety concerns or negative effects on mask function.

Keywords: PPE, Decontamination, Masks, N95, Disinfectants, COVID-19, Pandemic

Introduction

Shortages of personal protective equipment (PPE), including N95 filtering facepiece respirators (FFRs), are common during pandemics. The Centres for Disease Control (CDC) recommends N95 FFRs, which filter 95% of airborne particles¹, as the preferred PPE when entering the room of a patient with suspected or confirmed COVID-19 patients, and that an N95 FFR should be worn during all aerosol generating procedures². Unfortunately, during the ongoing COVID-19 pandemic, some hospitals and healthcare workers are faced with an inadequate supply of N95 FFR^{3,4} while also dealing with an increase in SARS-CoV-2 positive patients. Project N95, a COVID-19 initiative that transfers PPE from manufacturers and other disciplines to healthcare institutions in need, received requests for over 253 million units of equipment from 6m962 health centres globally since March 20th⁵. Consequently, addressing the N95 FFR shortage has become a matter of increasing urgency as cases of COVID-19 continue to rise.

A potential solution to FFR shortages becoming a substantial problem would be to decontaminate and re-use the masks. However, prior to utilizing this strategy, it is essential to demonstrate that decontamination does not compromise structural integrity, fit, filter efficiency (aerosol penetration), and/or airflow resistance of the FFR⁶. Several decontamination methods have been previously investigated, including energetic (e.g. microwave irradiation, ultraviolet germicidal irradiation (UVGI))⁷⁻¹⁸, gaseous (e.g. ethylene oxide, vaporized hydrogen peroxide)^{7,9,11,19,20}, and liquid protocols (e.g. hydrogen peroxide, sodium hypochlorite)^{7,9,11-13,18,19,21,22}. The CDC recently released crisis standards of care decontamination recommendations, with a brief summary of evidence for several of these approaches²³. However, detailed information on the safety and efficacy of a variety of decontamination methods is

essential to allow hospital decision makers to evaluate the evidence and determine the feasibility of rapidly implementing different protocols at their institutions.

To help inform FFR-reuse policies and procedures, our team has conducted three systematic reviews to synthesize existing published data regarding the effectiveness of UVGI²⁴, heat and microwave irradiation²⁵, and chemical disinfectants for N95 FFR decontamination. This review will focus on chemical disinfectants, with the following objectives: (1) to assess the impact of the each disinfectant method on FFR performance, with a specific focus on aerosol penetration and airflow resistance; (2) to determine the effectiveness of each disinfectant method at reducing viral or bacterial load; (3) to describe observations related to physical degradation following decontamination with a disinfectant; (4) to determine the impact of each disinfectant on FFR fit; and (5) to describe findings or observations related to, potential health risks or irritation from residual disinfectant remaining on FFRs following decontamination.

Methods

The study protocol and objectives were established a priori and registered on PROSPERO on April 5th, 2020 (protocol registration number pending), and reported here according to the PRISMA guidelines for systematic reviews²⁶. The protocol was also uploaded as a pre-print to OSF on April 5th, 2020 (<https://osf.io/8usx6/>).

Eligibility Criteria

Studies were eligible for inclusion in this systematic review if they satisfied all of the following criteria: (1) Original publication or systematic review; (2) Study reported on decontamination procedures for N95 (including SN95) filtering facemask respirators or their components; (3) At least one of the decontamination procedures evaluated used one of the following chemical disinfectants: sodium hypochlorite; liquid hydrogen peroxide, vaporized

hydrogen peroxide, hydrogen peroxide gas plasma, or ionized hydrogen peroxide; ethanol or isopropyl alcohol; (4) The study reported on at least one of the following outcomes of interest: (i) impact of the disinfectant on filtering face mask performance, with a specific focus on aerosol penetration and airflow resistance (pressure drop); (ii) effectiveness of the disinfectant at removing viral or bacterial load; (iii) observations related to physical degradation following decontamination with a disinfectant; (iv) impact of each disinfectant on FFR fit; or (v) findings or observations related to user safety or irritation. Only studies published in English or French were included. Studies published prior to 1972, the year that the N95 FFR was invented, were excluded. We included peer-reviewed literature and pre-prints. Editorials, narrative reviews, book chapters, patents, and non-peer-reviewed commissioned reports were excluded.

Search and Selection

The following databases were searched by two health sciences librarians (LS and MS) during the electronic component of the systematic review: Medline and Medline in Process via OVID (1946 - March 31, 2020), Embase Classic + Embase via OVID (1947 - March 31, 2020), and Global Health via CAB Direct (1913 – March 31, 2020). A search strategy was developed in Medline, and then translated into the other databases, as appropriate (Appendix A). All databases were searched from their dates of inception on March 31, 2020. Additional restrictions were English or French language and a publication date starting from 1972, the year N95 masks were invented²⁷.

Two journals were also hand-searched, as they were particularly relevant to the review but are not indexed in any of the databases: *Journal of the International Society for Respiratory Protection*, and the *Journal of Engineered Fibers and Fabrics*. A search of Google Scholar (March 31, 2020) through Publish or Perish was screened until 50 consecutive apparently

irrelevant records were found. Results to that point were saved as an RIS file and edited to remove patents, reports and books. The WHO database on COVID-19 was downloaded and searched within Reference Manager. Disaster Lit: Database for Disaster Medicine and Public Health, Medrxiv and OSF Preprints were searched March 31, 2020 for the term “N95” and records pertaining to decontamination were selected and downloaded. All references were entered into an Endnote file for processing (n = 454) and duplicate records were removed.

Citation screening and data extraction

Citations were uploaded to InsightScope (www.insightscope.ca) for title and abstract screening and full text review. At both title/abstract and full text screening levels, citations were assessed in duplicate and independently. Each reviewer completed a qualification or test set of 30 citations (5 true positives, 25 true negatives), and were required to achieve a sensitivity in excess of 80%. At both title/abstract and full text review, records were removed only if both reviewers agreed it to exclude. Cases with screening conflicts were resolved by review by the study lead (KO). At the completion of full text review, the study lead reviewed the eligible citations to identify potential duplicates and confirm eligibility. A data extraction tool was developed in REDCap^{28,29} by the study lead and piloted on five eligible studies. Eligible studies were divided equally among the reviewers for duplicate, independent data extraction into REDCap and Microsoft Excel, followed by conflict resolution by the study lead.

Outcome data is reported for N95 (particulate, including surgical) masks or their components only. Other mask types (e.g. R or P-filter type) were not included in the analysis. Mask “component” was defined as a piece of an N95 mask that had been cut out with all layers still intact. When necessary, data was extracted from figures using SourceForge Plot Digitizer (<http://plotdigitizer.sourceforge.net/>). Intervention arms described by authors as vaporized

hydrogen peroxide, hydrogen peroxide gas plasma, and ionized hydrogen peroxide were analyzed together and, for convenience, are collectively referred to as vaporized hydrogen peroxide for the remainder of this review.

Study analysis and Statistics

All statistical analysis were performed using the R statistical programming language ³⁰. Data was meta-analyzed using a random effects model with the R package ‘metafor’³¹. Random effects meta-analysis were employed to present either the pooled absolute value pre / post chemical disinfectant intervention or relative change (from control or no treatment arm).

For both the aerosol penetration and airflow resistance outcomes, the data was presented as an absolute value. Random effects meta-analysis was used to calculate the effect size for each type of chemical disinfectant. Heterogeneity was assessed by calculating an I^2 statistic from a fixed effect model. The standard deviation for each control and treatment arm within a chemical disinfectant class was calculated from the pooled absolute values post intervention.

Risk of Bias

Risk of bias was assessed for each study by outcome based on study design, methodological consistency, population heterogeneity, sampling bias, outcome evaluation, and reporting of results using an evaluation matrix (Appendix B).

Results

Identification of Eligible Studies

A total of 454 records were identified through the initial database search. After removing duplicate citations in Endnote, there were 417 citations remaining. Both reviewers correctly identified all true positives and true negatives in the test set. Title and abstract screening excluded 401, with the review team achieving a kappa of 0.9. At full text level the reviewers

excluded six of the records, with a kappa of 0.86. An additional three eligible pre-print articles were identified following the initial search and included in the analysis, resulting in a total of 13 eligible articles^{7,9,11-13,18-22,32-34}. An overview of the search process, results and reason for exclusions are shown in the PRISMA diagram (Figure 1).

Study Demographics

Nine studies originated from the United States, three from East Asia, and the remaining one originated from Canada. The studies included a total of 58 intervention arms, including sodium hypochlorite (n = 21), liquid hydrogen peroxide (liquid H₂O₂, n = 4), vaporized hydrogen peroxide (vaporized H₂O₂, n = 12), ethanol (n = 9), isopropyl alcohol (n = 3), ethylene oxide (EtO, n = 6), or other (n = 3). Thirty-four N95 mask models were evaluated across the 13 studies. The most common models studied were the 3M 1870 (n = 7), 3M 1860 (n = 6) and the 3M 8210 (n = 5). The number of articles evaluating the main study outcomes were aerosol penetration (n = 5), airflow resistance (n = 3), germicidal activity (n = 8), fit (n = 2), physical appearance (n = 6), and safety/irritation (n=3). A summary of the intervention arms, outcomes, and numbers of N95 FFR models evaluated is presented in Table I. The majority of studies reported on outcomes following a single cycle of decontamination. Bergman *et al.*⁷ evaluated 3 decontamination cycles, and Kenney *et al.*²⁰ reported on changes in physical appearance following 5 cycles. Fischer *et al.*³³ and Kumar *et al.*³⁴ reported on mask fit following 3 decontamination cycles and 1, 3, 5, 10 and 20 cycles respectively. Three studies were published as pre-prints^{20,33,34}, the remaining were peer-reviewed publications.

Aerosol Penetration

There were 5 studies identified that evaluated aerosol penetration following decontamination with a disinfectant^{7,9,11,13,21}, including intervention arms that evaluated sodium

hypochlorite (n = 6), liquid H₂O₂ (n = 3), vaporized H₂O₂ (n = 5), ethanol (n = 1), isopropyl alcohol (n = 3), and EtO (n = 3) (Table II). Some of the included studies, such as Viscusi *et al*¹¹ and Bergman *et al*⁷, evaluated different concentrations of sodium hypochlorite or different methodologies for vaporized H₂O₂ and therefore had more than one arm included. We choose not to provide a pooled estimate of particle penetration between chemical sterilization, as this metric would not be relevant for decision makers. Instead we calculated mean difference from the random effects model and the I² from a fixed effects model for each decontamination type (Figure 2). Studies on ethylene oxide and liquid H₂O₂ provided consistent findings of no change in particle penetration post-sterilization, with low between study heterogeneity. Studies on isopropyl provided consistent findings that particle penetration post-sterilization was impaired and no longer met NIOSH standards (average particle penetration 22.9% ± 5.8), with high between study heterogeneity. Studies on sodium hypochlorite showed no change in particle penetration post-sterilization, with large between study heterogeneity; with findings from Lin *et al*²¹ being qualitatively different from the other five studies. Studies on vaporized H₂O₂ showed no change in particle penetration post sterilization, with large between study heterogeneity driven by three decontamination cycles using the STERRAD® 100S H₂O₂ Gas Plasma Sterilizer in Bergman *et al*⁷. A summary of the aerosol penetration results for each disinfectant is provided in Table III.

Airflow Resistance

Three studies reported on airflow resistance^{7,9,21}, including intervention arms that evaluated sodium hypochlorite (n = 3), liquid H₂O₂ (n = 1), vaporized H₂O₂ (n = 3), ethanol (n = 1) and EtO (n = 2) (Table II). The mean difference for sodium hypochlorite was 0.29 9.69 mm H₂O (95% CI -1.70-2.29) with an I² of ~0.%. It was not possible to include the results from Lin

*et al*²¹ there was no SD for the treatment arm. The mean difference for EtO was 0.21 9.69 mm H₂O (95% CI -1.52-1.95) with an I² of 0%. The mean difference for vaporized H₂O₂ was 0.16 9.69 mm H₂O (95% CI -1.39- 1.70), with an I² of 0%. The estimate for liquid H₂O₂ (n=1) was -0.67 9.69 mm H₂O (95% CI -5.12 -3.78) (Figure 3). The study by Lin *et al*²¹ evaluated ethanol but did not provide SD for the treatment and therefore could not be evaluated. FFRs treated with ethanol maintained NIOSH airflow resistance standards (9.69 mm H₂O). For airflow resistance, all meta-analyses showed consistent findings of no change post sterilization, and all FFRs maintained NIOSH certification standards irrespective of the chemical disinfectant type (sodium hypochlorite, ethylene oxide, liquid H₂O₂ and vaporized H₂O₂). A summary of the airflow resistance results for each disinfectant type is provided in Table III.

Germicidal

Eight studies evaluated the germicidal impact of one or more disinfectants, including two studies on bacteria^{13,22}, five studies on viruses^{12,18,32-34}, and one study on bacteriophages²⁰ (Figure 4). Intervention arms included in the five studies were sodium hypochlorite (n = 15), vaporized H₂O₂ (n = 6), ethanol (n = 8) and EtO (n = 1) (Table IV). No studies evaluated germicidal removal following decontamination with liquid H₂O₂ or isopropyl alcohol. The only chemical disinfectant with more than one virology study was sodium hypochlorite, which was meta-analysed. Studies on sodium hypochlorite provided consistent findings that there was a large reduction in viral load post-sterilization, with low between study heterogeneity. Overall these studies using sodium hypochlorite, as well as ethanol, EtO and vaporized H₂O₂ had qualitatively homogeneous findings that viral load was reduced. N95 FFRs that were inoculated with SARS-CoV-2 virus, then sprayed with 70% ethanol until saturation showed viral levels below the limit of detection of the assay (<10^{0.5} TCID₅₀/mL) at five, ten, 30 and 60 minutes post-sterilization³³.

However, ethanol was not as effective at eradicating bacteria. Immersion in an ethanol solution for 10 minutes at concentrations of 50, 70, 80 and 95% resulted in relative survival rates of *Bacillus subtilis* of $89 \pm 6\%$, $72.01 \pm 10.69\%$, $68 \pm 3\%$ and $73 \pm 7\%$ respectively. By 24 hours post-sterilization, survival rates declined to $33 \pm 8\%$, $22.28 \pm 7.88\%$, $20 \pm 2\%$ and $26 \pm 7\%$.²¹ EtO decontamination removed all viable vesicular stomatitis virus (VSV) from four N95 FFR models. In the same study, a single cycle of vaporized H₂O₂ also removed all viable VSV and SARS-CoV-2³⁴. One cycle of vaporized H₂O₂ also resulted in bacteriophage levels (<10 PFU)²⁰ or viral levels ($<10^{0.5}$ TCID₅₀/ml)³³ below the detectable limit of the assay on one N95 FFR model each, and no growth of H1N1 on two N95 FFR models at seven days following decontamination with vaporized H₂O₂³².

A summary of the germicidal results for each disinfectant evaluated is provided in Table III.

Physical appearance and odor

Six studies were identified that evaluated change in physical appearance following decontamination (Table V). Five studies included at least one sodium hypochlorite intervention arm, and four reported changes in FFR appearance including tarnished metallic nosepieces^{7,9,11,19}, oxidized staples^{7,19}, yellowing of nose pads^{7,9}, bleeding of lettering⁷, and stiffening of filter media and elastic straps¹¹. In the study by Bergman *et al.*⁷, 50% of the nosepieces dissolved for the 3M 1870 model⁷, however, this same change was not reported by Viscusi *et al.* using the same mask model¹². Sodium hypochlorite treatment left a characteristic bleach odor on the FFRs^{7,9,19}.

Changes in appearance following liquid H₂O₂ exposure were reported in two of three studies^{7,11,19}. Liquid H₂O₂ was reported to result in FFR staple oxidation⁷ or slight fading of the

label lettering¹¹. Vaporized H₂O₂ caused slight tarnishing of metallic nosebands^{9,11} in two of five studies^{7,9,11,19,20}, with the other three reporting no observable physical changes. One study incorporated the addition of a five minute steam sterilization cycle following vaporized H₂O₂ treatment, and reported FFR degradation²⁰. No changes in odor were reported for liquid H₂O₂⁷ or for vaporized H₂O₂^{7,9,19}.

Isopropyl alcohol resulted in fading of strap ink in one study¹¹, and no reported changes in another²¹. No changes in appearance were reported following treatment with ethanol²¹ or EtO^{7,11,12,19}. Three studies reported on FFR odor following disinfectant treatment. Sodium hypochlorite treatment left a characteristic bleach odor on the FFRs^{7,9,19}. EtO did not result in any changes in FFR odor^{7,9,19}. Odor was not assessed for ethanol or isopropyl alcohol. A summary of the changes in physical appearance for each disinfectant is presented in Table III.

FFR Fit

A summary of the effects of each disinfectant on mask fit is presented in Table III. Two studies evaluated mask fit following decontamination, including the following intervention arms: EtO (n = 1), vaporized H₂O₂ (n = 3) and ethanol (n = 1). Kumar *et al.* evaluated mask fit using the PORTACOUNT Fit Tester and two exercises (normal and deep breathing) following multiple decontamination bouts³⁴ on new (unworn) FFRs. A single measurement was taken for each of the four mask models for a given number of decontamination cycles. All four FFR models passed the fit test (achieved a fit factor >100 as per Occupational Safety and Health Administration standards) following one, three, five and ten decontamination cycles of vaporized H₂O₂ using the VHP ARD System, but not with the standard cycle of the STERRAD 100NX sterilizer (fit factor >100 after one cycle, but <100 following five, ten and 20 cycles). A passing fit factor score was achieved following 1 and 3 decontamination cycles of EtO.

Fischer *et al.* evaluated mask fit following three cycles of two-hour wear and decontamination using an AO Safety N9504C FFR. Six replicate masks were evaluated following each decontamination cycle. A fit factor >100 was achieved following the three vaporized H₂O₂ wear-decontamination cycles. The six replicate masks achieved a fit factor >100 following one ethanol decontamination cycle, but two out of the six replicate masks did not achieve a passing fit factor score following two decontamination cycles, and four replicate masks had a fit factor <100 following three cycles³³.

Potential Health Risks

A summary of the potential health risks of disinfectant evaluated is presented in Table III. Potential health-risks associated with disinfectant decontamination was evaluated in three studies. Viscusi *et al.*⁹ reported that, while letting the sodium hypochlorite treated masks air-dry overnight significantly reduced off-gassing (2 to 12 p.p.m. when wet vs. 0 to ~0.05 p.p.m.), low level chlorine off-gassing (~0.1 p.p.m.) was observed when the FFR was rehydrated. Salter *et al.*¹⁹ measured the oxidant remaining on FFRs following decontamination and found that the mass of oxidant remaining on the treated FFRs varied by mask model and disinfectant. For each disinfectant, the FFR with the highest oxidant masses evaluated using iodometric back titrations at 18 hours following decontamination were as follows: vaporized H₂O₂ (3M 1860 - 1.23 mg 95% CI (0.68, 1.77)); sodium hypochlorite (3M 1820 - 1.66 mg 95% CI (-2.03-5.34)); and liquid H₂O₂ (Moldex 1500 - 0.70 mg 95% CI (0.38, 1.02)). FFRs treated with ethylene oxide were evaluated using GC-MS. Although no residual EtO was detected on any of the FFR, there were 15 occurrences where ethylene glycol monoacetate was detected on FFR straps. Cheng *et al.* evaluated residual hydrogen peroxide following decontamination using vaporized H₂O₂. The

level of hydrogen peroxide on the FFRs inner surface at two hours was 0.6 p.p.m. and undetectable at three hours³².

Risk of Bias

Risk of bias was evaluated by study for each outcome and is presented in Appendix C.

Discussion

This is the first systematic review to synthesize the existing evidence on using disinfectants to decontaminate N95 FFRs. We found that a single cycle of vaporized H₂O₂ successfully removes infectious pathogens without affecting mask function or fit, and with little change in FFR physical appearance. Further research is required before the acceptability of decontamination using liquid H₂O₂ can be determined. Sodium hypochlorite, ethanol, isopropyl alcohol and EtO are not recommended due to safety concerns and/or adverse effects on mask function.

This systematic review identified five studies that reported on changes in aerosol penetration following decontamination with a chemical disinfectant. The National Institute of Occupational Safety and Health (NIOSH) has established a 95% filter efficiency standard (i.e. aerosol penetration of <5%) for N95 FFR³⁵. Results showed that filter efficiency was generally maintained following decontamination with sodium hypochlorite, liquid H₂O₂, vaporized H₂O₂ and EtO under laboratory test conditions. However, while the majority of studies evaluating sodium hypochlorite and vaporized H₂O₂ reported a post-decontamination filter efficiency of >95%, there were conflicting findings in one study for each method. Four of the five studies that evaluated sodium hypochlorite reported that filter penetration of <5% was maintained following submersion (0.3 to 5.25%, 30 min submersion)^{7,11,12} or wiping (3 times) with hypochlorite wipes¹³; however, the study by Lin *et al.*, using the same mask model as Bergman *et al.*⁷ and

Viscusi *et al.*⁹, reported a filter penetration of $18.33\% \pm 16.72^{21}$ (0.5%, 10 min submersion). The explanation for the different results from Lin *et al.* is not clear, as the concentration of sodium hypochlorite was similar to Bergman *et al.*⁷ and Viscusi *et al.*^{9,11} and included a shorter submersion time. Vaporized H₂O₂ maintained filter performance in the majority of the studies where it was evaluated, with the exception of Bergman *et al.*⁷. In this study, three 55-minute cycles with the STERRAD® 100S H₂O₂ Gas Plasma Sterilizer resulted in filter penetration levels >5% in four of six mask models (3M 8000, Moldex 2201, Kimberly Clark KC PFR95-174, 3M 1860), but this was not observed following three cycles with the Clarus® R HPV Generator. Degradation in filter performance seemed to be related to level of exposure to the vaporized H₂O₂ during processing (i.e. masks packed near the top or bottom of the pouch during treatment). Interestingly, a single cycle with the same STERRAD® 100S H₂O₂ Gas Plasma Sterilizer and almost identical mask models did not adversely affect filter efficiency in a previous study⁹. These observations suggest the effects of vaporized H₂O₂ on filter performance and the number of decontamination cycles that can be employed are dependent on the system used. A recent U.S. Food and Drug Administration (FDA)-commissioned report on the Bioquell Clarus C HPV generator provides further evidence on the impact of repeated vaporized H₂O₂ cycles on filter performance³⁶. Using NIOSH testing standards, the report showed that filter efficiency was 99.6 ± 0.2 following fifty cycles of vaporized H₂O₂, safely exceeding the NIOSH requirement of 95%. Findings from the included studies showed that submersion in ethanol and isopropyl alcohol resulted in significantly higher filter penetration values that exceeded the levels permissible by NIOSH. This is not surprising, as both ethanol and isopropyl alcohol have been shown to eliminate the electrostatic charges on the FFR filter³⁷, and the filter efficiency of an uncharged media is typically ten-fold lower than a charged media³⁸.

In addition to standards for aerosol penetration, NIOSH has also established standards for airflow resistance of N95 FFRs (peak average inhalation of 35 mm H₂O pressure (343.2 Pa) and an exhalation resistance to airflow 25 mmH₂O (245.1 Pa))³⁵. These standards ensure that breathing is not impaired while wearing an N95 FFR. Evaluations from three studies showed that measured values for airflow filtration were within the NIOSH standards following a single cycle (sodium hypochlorite, ethanol, EtO, vaporized H₂O₂)^{9,21} or three decontamination cycles (sodium hypochlorite, liquid H₂O₂, vaporized H₂O₂, EtO)⁷ across three different mask models.

In addition to maintaining mask function, a successful decontamination protocol must also remove infectious pathogens from the mask surface. Published literature on the ability of disinfectants to eradicate germicidal activity from N95 FFRs was only available for four of the disinfectants of interest (sodium hypochlorite, ethanol, EtO and vaporized H₂O₂). The ability of other methods (liquid H₂O₂, isopropyl alcohol) to reduce pathogen load N95 FFRs specifically is not known at this time. Ethanol (at a sufficiently high concentration), sodium hypochlorite, and EtO can effectively remove viral pathogens from FFR surfaces; however, given the negative impact of ethanol on filter performance and inadequate ability to reduce bacteria from FFR, and the potential health risks associated with sodium hypochlorite and EtO, vaporized H₂O₂ is the most promising of the four disinfectants evaluated. A single cycle of five different vaporized H₂O₂ protocols effectively sterilized five infectious pathogens^{20,32-34} (see Appendix D for details of the vaporized H₂O₂ protocols used in all studies included in this review). The FDA-commissioned Bioquell report further confirms the germicidal efficacy of vaporized H₂O₂, reporting a six-log reduction in *G. stearothersophilus* spore viability using a vaporized H₂O₂³⁶. The ability of vaporized H₂O₂ to eradicate virus and bacteria from N95 FFRs could be further enhanced by allowing the FFR to sit for an extended time period between re-use. It is well

established that bacteria and virus levels on surfaces decrease over time^{39,40}. For example, the infectiveness of SARS-CoV-2 declines by at least one log every 24 hours across a variety of surfaces⁴¹. Therefore, building a “holding period” into the decontamination protocol, where FFRs sit for a one-week period following exposure to vaporized H₂O₂, would further guarantee the absence of viable viral particles.

Mask fit is an important outcome of interest when considering whether a decontamination protocol is acceptable to use. Improper fit results in an inadequate seal of the mask against the wearer’s face, reducing the mask’s ability to prevent particle penetration⁴². Two studies evaluated mask fit following decontamination. FFR fit was not affected by one cycle of decontamination with ethanol³³ or by multiple cycles of EtO or vaporized H₂O₂^{33,34}. The multiple decontamination cycle results from Kumar *et al.*³⁴ should be interpreted with some caution, however, as mask fit was evaluated using only normal breathing and deep breathing exercises. The additional exercises from the Occupational Health and Safety Administration (OHSa) protocol that involve movement of the mouth, head and body (to mimic movements performed by health care workers) were not included in the evaluation. Therefore, it is not clear if a fit factor >100 would have still been achieved had the full OHSa protocol been used. Additionally, the masks that were evaluated were new masks that had not been worn by health care workers prior to decontamination, or between decontamination cycles. There is evidence that mask fit deteriorates through repeated donning and doffing⁴³, therefore the number of decontamination and re-use cycles that can be applied to a FFR will be limited by physical stress imposed by both decontamination and donning and doffing. The FDA-commissioned Bioquell report³⁶ also evaluated fit following multiple decontamination cycles using vaporized H₂O₂ and achieved similar results to Kumar *et al.* (fit was maintained following 10 and 20 decontamination cycles).

However, these findings are limited by the fact that fit testing was performed using a mannequin and, by 30 vaporized H₂O₂ cycles, FFR straps degraded such that fit testing was no longer possible. The methods used by Fischer *et al*³³ are more representative of the real world, as it involved three cycles of decontamination and two-hour wearing. While they showed that one model of N95 FFR (AOSafety N9504C) maintained a fit factor >100 following three cycles of vaporized H₂O₂, they used a small sample size (six replicates) and tested no other models. Further testing should be conducting using FFRs worn by health care workers prior to and between decontamination cycles in order to confirm whether FFRs maintain fit in the real-world setting following multiple decontamination cycles with vaporized H₂O₂.

Sodium hypochlorite was the only disinfectant that consistently resulted in significant changes to FFR appearance. Some of the changes reported were substantial enough that they could result in changes in mask fit or comfort, such as stiffening of filter media and elastic straps and dissolving of half of the FFR nosepiece. Sodium hypochlorite also consistently resulted in a bleach odor on the FFRs that would be unpleasant to the wearer. Some chlorine off-gassing was observed on FFRs that had been submerged in sodium hypochlorite and rehydrated, which the authors felt could be significant given that rehydration of the FFR could be compared with moisture in the exhaled breath of an individual wearing the FFR⁹. Therefore, as low level exposure to chlorine may occur when wearing an FFR that has been decontaminated by submersion in sodium hypochlorite, sodium hypochlorite is not recommended for FFR decontamination and reuse. There are also potential safety concerns with the use of EtO. EtO in itself is hazardous and a known human carcinogen, and decontamination with EtO requires a lengthy aeration process to remove residual EtO⁴⁴. Following a 12-hr aeration cycle, Salter *et al.* did not find any EtO on six FFRs models, but did find traces of a hazardous contaminant,

ethylene glycol monacetate¹⁹. Whether residual EtO remains on N95 FFRs when using a shorter aeration cycle, such the four-hour cycle used by Viscusi et al^{9,11}, is unknown. Given the potential safety concerns and the impracticality of a lengthy aeration cycle, the results of this review do not endorse EtO sterilization for N95 decontamination, which is consistent with the CDCs recommendations⁴⁵. Residual levels of liquid and vaporized H₂O₂ were reported in one and two studies respectively, though they remained within established safety limits, and in the case of vaporized H₂O₂, decreased over time. A “holding period” following decontamination, as described above, would provide extra assurance that hydrogen peroxide levels were under the permissible exposure limit set by OSHA (1 ppm)⁴⁶.

The overall risk of bias in results for aerosol penetration, airflow resistance, and fit were low in all studies. The moderate overall risk of bias noted for germicidal outcomes is largely due to the use of unblinded assays to quantify bacterial and viral loads; although these are generally accepted as appropriate means of pathogen quantification, counting of plaques and colonies may be subjective. Assessments of physical appearance and odor were unblinded in all cases and results were often reported as additional comments about observations of damage, rather than through a systematic procedure for all mask models, which makes it unclear to what degree sampling and assessment biases may have influenced these outcomes. The potential for bias in evaluations of post-decontamination safety was increased by the lack of control group in any study which reduces confidence in accuracy of the machine measurements.

Limitations

Although this systematic review provides valuable information regarding the use of chemical disinfectants for the decontamination of N95 FFRs, a number of limitations must be acknowledged. Each study used a different combination of mask types. In order to address this

we aggregated across mask types within each study, treating the pooled replicates across mask types as our statistically independent sampling unit. This is appropriate for our research question aimed at performance of FFRs in general (where we assume little difference between mask types). If there are large differences between mask types, our approach might artificially inflate our sample size; if this were the case it would unlikely change our findings, due to the consistency of these studies conclusions and low heterogeneity. With the exception of the fit data from Fischer *et al*³³, all of the reported outcomes were evaluated on new, unworn FFRs. It is not clear whether extended FFR use prior to decontamination would alter our findings. For ease of completion, our review was limited to studies available in English or French, therefore evidence available in other languages is not included in our analysis.

Conclusions

We found that a single cycle of vaporized H₂O₂ successfully removes infectious pathogens without affecting mask function or fit, and with little change in FFR physical appearance. Residual hydrogen peroxide levels following decontamination were below the safety limit. More than one decontamination cycle of vaporized H₂O₂ may be possible but further information is required on how multiple cycles would affect mask fit in a real world setting before the upper limit can be established. Although immersion in liquid H₂O₂ does not appear to adversely affect mask function, there is no available data on its ability to remove infectious pathogens from FFRs or its impact on mask fit. Sodium hypochlorite, ethanol, isopropyl alcohol and EtO are not recommended due to safety concerns or negative effects on mask function.

Abbreviations: CDC - Centres for Disease Control; EtO - Ethylene oxide; FDA - U.S. Food and Drug Administration; FFR - Filtering facepiece respirator; H₂O₂ - Hydrogen peroxide; NIOSH - The National Institute of Health and Safety; OSHA - Occupational Safety and Health Administration; PPE - Personal protective equipment; UVGI - Ultraviolet germicidal irradiation

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References

- 1) Balazy, A. *et al.* Do N95 respirators provide 95% protection level against airborne viruses, and how adequate are surgical masks? *American Journal of Infection Control* 34, 49-56 (2006).
- 2) CDC. *Interim Infection Prevention and Control Recommendations for Patients with Suspected or Confirmed Coronavirus Disease 2019 (COVID-19) in Healthcare Settings* <https://www.cdc.gov/coronavirus/2019-ncov/hcp/infection-control-recommendations.html> Last Updated on April 12, 2020. Accessed on April 17, 2020.
- 3) Patel, A. *et al.* Personal Protective Equipment Supply Chain: Lessons Learned from Recent Public Health Emergency Responses. *Health Secur* 15, 244-252, doi:10.1089/hs.2016.0129 (2017).
- 4) Srinivasan, A., Jernign, D. B., Liedtke, L. & Strausbaugh, L. Hospital preparedness for severe acute respiratory syndrome in the United States: views from a national survey of infectious diseases consultants. *Clin Infect Dis* 39, 272-274, doi:10.1086/421777 (2004).
- 5) Project N95. The national COVID-19 medical equipment clearinghouse. .
- 6) Bauchner, H., Fontanarosa, P. B. & Livingston, E. H. Conserving Supply of Personal Protective Equipment-A Call for Ideas. *JAMA* 10.1001/jama.2020.4770, doi:10.1001/jama.2020.4770 (2020).
- 7) Bergman, M. S., Viscusi, D. J., Heimbuch, B. K., Wander, J. D. & Sambol, A. R. Evaluation of Multiple (3-Cycle) Decontamination Processing for Filtering Facepiece Respirators. *DigitalCommons@University of Nebraska - Lincoln*. (2010).
- 8) Bergman, M. S., Viscusi, D. J., Palmiero, A. J., Powell, J. B. & Shaffer, R. E. Impact of Three Cycles of Decontamination Treatments on Filtering Facepiece Respirator Fit. *Journal of the International Society for Respiratory Protection* 28, 48-59 (2011).
- 9) Viscusi, D. J., Bergman, M. S., Eimer, B. C. & Shaffer, R. E. Evaluation of five decontamination methods for filtering facepiece respirators. *Annals of Occupational Hygiene* 53, 815-827, doi:<https://dx.doi.org/10.1093/annhyg/mep070> (2009).
- 10) Viscusi, D. J. *et al.* Impact of three biological decontamination methods on filtering facepiece respirator fit, odor, comfort, and donning ease. *Journal of Occupational and Environmental Hygiene* 8, 426-436, doi:10.1080/15459624.2011.585927 (2011).
- 11) Viscusi, D. J., King, W. P. & Shaffer, R. E. Effect of Decontamination on the Filtration Efficiency of Two Filtering Facepiece Respirator Models. *Journal of the International Society for Respiratory Protection* 24, 93-107 (2007).
- 12) Fisher, E., Rengasamy, S., Viscusi, D., Vo, E. & Shaffer, R. Development of a test system to apply virus-containing particles to filtering facepiece respirators for the evaluation of decontamination procedures. *Appl Environ Microbiol* 75, 1500-1507, doi:<https://dx.doi.org/10.1128/AEM.01653-08> (2009).
- 13) Heimbuch, B. K. *et al.* Cleaning of filtering facepiece respirators contaminated with mucin and *Staphylococcus aureus*. *American Journal of Infection Control* 42, 265-270, doi:10.1016/j.ajic.2013.09.014 (2014).
- 14) Lore, M. B., Heimbuch, B. K., Brown, T. L., Wander, J. D. & Hinrichs, S. H. Effectiveness of three decontamination treatments against influenza virus applied to filtering facepiece respirators. *Annals of Occupational Hygiene* 56, 92-101, doi:10.1093/annhyg/mer054 (2012).

- 15) Lindsley, W. G. *et al.* Effects of Ultraviolet Germicidal Irradiation (UVGI) on N95 Respirator Filtration Performance and Structural Integrity. *J Occup Environ Hyg* 12, 509-517, doi:<https://dx.doi.org/10.1080/15459624.2015.1018518> (2015).
- 16) Mills, D., Harnish, D. A. & Lawrence, C. Ultraviolet germicidal irradiation of influenza-contaminated N95 filtering facepiece respirators. *American journal of ...* (2018).
- 17) Woo, M. H., Grippin, A., Anwar, D. & Smith, T. Effects of relative humidity and spraying medium on UV decontamination of filters loaded with viral aerosols. *Appl. Environ ...* (2012).
- 18) Vo, E., Rengasamy, S. & Shaffer, R. Development of a test system to evaluate procedures for decontamination of respirators containing viral droplets. *Appl Environ Microbiol* 75, 7303-7309, doi:<https://dx.doi.org/10.1128/AEM.00799-09> (2009).
- 19) Salter, W. B. *et al.* Analysis of residual chemicals on filtering facepiece respirators after decontamination. *J Occup Environ Hyg* 7, 437-445, doi:<https://dx.doi.org/10.1080/15459624.2010.484794> (2010).
- 20) Kenney, P. *et al.* Hydrogen Peroxide Vapor sterilization of N95 respirators for reuse. *medRxiv* 10.1101/2020.03.24.20041087, 2020.2003.2024.20041087, doi:10.1101/2020.03.24.20041087 (2020).
- 21) Lin, T. H. *et al.* Filter quality of electret masks in filtering 14.6-594 nm aerosol particles: Effects of five decontamination methods. *PLoS ONE* 12, e0186217, doi:<https://dx.doi.org/10.1371/journal.pone.0186217> (2017).
- 22) Lin, T. H., Tang, F. C., Hung, P. C., Hua, Z. C. & Lai, C. Y. Relative survival of *Bacillus subtilis* spores loaded on filtering facepiece respirators after five decontamination methods. *Indoor Air* 31, 31, doi:<https://dx.doi.org/10.1111/ina.12475> (2018).
- 23) CDC. *Decontamination and Reuse of Filtering Facepiece Respirators* <https://www.cdc.gov/coronavirus/2019-ncov/hcp/ppe-strategy/decontamination-reuse-respirators.html> Last Updated on April 1, 2020. Accessed on April 4, 2020.
- 24) O'Hearn, K. *et al.* Decontaminating N95 masks with Ultraviolet Germicidal Irradiation (UVGI) does not impair mask efficacy and safety: A Systematic Review. *OSF Preprints* 10.31219/osf.io/29z6u, doi:10.31219/osf.io/29z6u (2020).
- 25) Gertsman, S. *et al.* Microwave-and Heat-Based Decontamination of N95 Filtering Facepiece Respirators (FFR): A Systematic Review. *OSF Preprints* 10.31219/osf.io/4whsx, doi:10.31219/osf.io/4whsx (2020).
- 26) Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G. & Group, P. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Int J Surg* 8, 336-341, doi:10.1016/j.ijsu.2010.02.007 (2010).
- 27) Wilson, M. *The untold origin story of the N95 mask* <https://www.fastcompany.com/90479846/the-untold-origin-story-of-the-n95-mask> Last Updated on March 24, 2020. Accessed on April 18, 2020.
- 28) Harris, P. A. *et al.* The REDCap consortium: Building an international community of software platform partners. *J Biomed Inform* 95, 103208, doi:10.1016/j.jbi.2019.103208 (2019).
- 29) Harris, P. A. *et al.* Research electronic data capture (REDCap)--a metadata-driven methodology and workflow process for providing translational research informatics support. *J Biomed Inform* 42, 377-381, doi:10.1016/j.jbi.2008.08.010 (2009).

- 30) R Core Team (2012). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL <http://www.R-project.org/>.
- 31) Viechtbauer, W. Conducting Meta-Analyses in R with the metafor Package. *Journal of Statistical Software* 36 (2010).
- 32) Cheng, V., Wong, S.-C., Kwan, G., Hui, W.-T. & Yuen, K.-Y. Disinfection of N95 respirators by ionized hydrogen peroxide in pandemic coronavirus disease 2019 (COVID-19) due to SARS-CoV-2. *Journal of Hospital Infection* <https://doi.org/10.1016/j.jhin.2020.04.003>, doi:<https://doi.org/10.1016/j.jhin.2020.04.003> (2020).
- 33) Fischer, R. *et al.* Assessment of N95 respirator decontamination and re-use for SARS-CoV-2. *medRxiv* 10.1101/2020.04.11.20062018, 2020.2004.2011.20062018, doi:10.1101/2020.04.11.20062018 (2020).
- 34) Kumar, A. *et al.* N95 Mask Decontamination using Standard Hospital Sterilization Technologies. *medRxiv* 10.1101/2020.04.05.20049346, 2020.2004.2005.20049346, doi:10.1101/2020.04.05.20049346 (2020).
- 35) National Institute for Occupational Safety and Health. *NIOSH Guide to the Selection and Use of Particulate Respirators* <https://www.cdc.gov/niosh/docs/96-101/default.html> Last Updated on June 6, 2014. Accessed on March 27, 2020.
- 36) Battelle. Final Report for Bioquell HPV Decontamination for the Reuse of N95 Respirators. (Columbus, Ohio, 2016).
- 37) Chen, C. C. & Huang, S. H. The effects of particle charge on the performance of a filtering facepiece. *American Industrial Hygiene Association Journal* 59, 227-233, doi:<http://dx.doi.org/10.1080/15428119891010488> (1998).
- 38) Tsai, P. P. *Information and FAQs on the Performance, Protection, and Sterilization of Face Mask Materials*. https://utr.tennessee.edu/information-faqs-performanceprotection-sterilization-of-face-mask-materials/#abstract_link Last Updated on 2020. Accessed on April 5, 2020.
- 39) Bean, B. *et al.* Survival of influenza viruses on environmental surfaces. *J Infect Dis* 146, 47-51, doi:10.1093/infdis/146.1.47 (1982).
- 40) Yeargin, T., Buckley, D., Fraser, A. & Jiang, X. The survival and inactivation of enteric viruses on soft surfaces: A systematic review of the literature. *Am J Infect Control* 44, 1365-1373, doi:10.1016/j.ajic.2016.03.018 (2016).
- 41) van Doremalen, N. *et al.* Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1. *N Engl J Med* 10.1056/NEJMc2004973, doi:10.1056/NEJMc2004973 (2020).
- 42) Reponen, T., Lee, S. A., Grinshpun, S. A., Johnson, E. & McKay, R. Effect of fit testing on the protection offered by n95 filtering facepiece respirators against fine particles in a laboratory setting. *Ann Occup Hyg* 55, 264-271, doi:10.1093/annhyg/meq085 (2011).
- 43) Bergman, M. S. *et al.* Impact of multiple consecutive donnings on filtering facepiece respirator fit. *American Journal of Infection Control* 40, 375-380, doi:10.1016/j.ajic.2011.05.003 (2012).
- 44) CDC. *Ethylene Oxide "Gas" Sterilization* <https://www.cdc.gov/infectioncontrol/guidelines/disinfection/sterilization/ethylene-oxide.html> Last Updated on September 18, 2016. Accessed on April 17, 2020.

- 45) CDC. *Strategies for optimizing the supply of N95 respirators: Crisis/alternate strategies* <https://www.cdc.gov/coronavirus/2019-ncov/hcp/respirators-strategy/crisis-alternate-strategies.html> Last Updated on March 17, 2020. Accessed on March 27, 2020.
- 46) OSHA. *Permissible Exposure Limits* <https://www.osha.gov/dsg/annotated-pels/tablez-1.html> Last Updated on October 2, 2019. Accessed on April 17, 2020.

Figure 1: PRISMA Diagram

Figure 2. Pooled results assessing aerosol penetration by chemical disinfectant type

This forest plot illustrates the mean particle penetration in N95 FFR. The experimental arm refers to the type of chemical disinfectant, treated arm. Mask type examined varied by study. N refers to the treatment arm sample size.

Figure 3. Airflow resistance forest plot of pooled results by chemical disinfectant types

This forest plot illustrates the airflow resistance in N95 FFR. The experimental arm refers to the type of chemical disinfectant, treated arm. Mask type examined varied by study. N refers to the treatment arm sample size.

Figure 3. Pooled results assessing germicidal effect of chemical disinfectants on viruses

This forest plot illustrates the germicidal effect of chemical disinfectants on N95 FFR inoculated with viral pathogens. The experimental arm refers to the type of chemical disinfectant, treated arm. Mask type examined varied by study. N refers to the treatment arm sample size. *Note: Only studies that reported germicidal outcome data in units allowing calculation of log change are included in the figure.*

Table I: Characteristics of studies included in a systematic review of decontaminating N95 filtering facepiece respirators using disinfectants

Author, Year	Intervention Arms							Outcomes Evaluated						Number N95 Models
	NaOCl or ClO ⁻	Liquid H ₂ O ₂	Vapor- ized H ₂ O ₂	EtOH	IP	EtO	Other ^a	Aerosol Penetration	Airflow resistance	Germicidal Activity	Fit	Physical appearance	Potential health risks	
Bergman 2010	1	1	2			1		Yes	Yes	No	No	Yes	No	6
Cheng 2020			1					No	No	Yes	No	No	Yes	2
Fischer 2020			1	1				No	No	Yes	Yes	No	No	1
Fisher 2009	4							No	No	Yes	No	No	No	1
Heimbuch 2014	1						1	Yes	No	Yes	No	No	No	3
Kenney 2020			2					No	No	Yes	No	Yes	No	1
Kumar 2020			2			1		No	No	Yes	Yes	No	No	4
Lin 2017	1			1	1			Yes	Yes	No	No	Yes	No	1
Lin 2018	3			7				No	No	Yes	No	No	No	1
Salter 2010	1	1	1			1	2	No	No	No	No	Yes	Yes	6
Viscusi 2007	2	2	2		2	2		Yes	No	No	No	Yes	No	1
Viscusi 2009	1		1			1		Yes	Yes	No	No	Yes	Yes	6
Vo 2009	7							No	No	Yes	No	No	No	1

Abbreviations: NaOCL – Sodium hypochlorite; ClO⁻ - Hypochlorite; H₂O₂ – hydrogen peroxide, EtOH – ethanol, IP – isopropyl alcohol, EtO – ethylene oxide

^aOther includes benzalkonium chloride; Mixed oxidants (10% Oxone, 6%, sodium chloride, 5% sodium bicarbonate); and Dimethyl dioxirane (10% Oxone, 10% acetone, 5% sodium bicarbonate)

Table II: Disinfectants and N95 filtering facemask respirators used to evaluate the effects of decontamination using chemical disinfectants on FFR aerosol penetration and airflow resistance

Author, year	Intervention Arm	Description	Function Outcome(s) Evaluated	N95 Mask Models ^a
Bergman 2010	Sodium hypochlorite	0.6%, 30 minute submersion	Aerosol penetration Airflow resistance	3M 8210 3M 8000 Moldex 2201 KC PFR95-174 3M 1870 3M 1860s
	Liquid H ₂ O ₂	6%, 30 minute submersion		
	Vaporized H ₂ O ₂	Arm 1: Four portable modules: the Clarus® R HPV generator (utilizing 30% H ₂ O ₂), the Clarus R20 aeration unit, an instrumentation module and a control computer. The Clarus® R was placed in a room (64 m ³). The HPV concentration, temperature and relative humidity within the room were measured by the instrumentation module and monitored by a control computer situated outside the room. Room concentration= 8 g/m ³ , 15- min dwell, 125-min total cycle time. Following HPV exposure, the Clarus R20 aeration unit was run overnight inside the room to catalytically convert the HPV into oxygen and water vapor. Arm 2: STERRAD® 100S H ₂ O ₂ Gas Plasma Sterilizer, 59% H ₂ O ₂ , cycle time ~55-min (short cycle); 45°C–50°C.		
	EtO	Amsco® Eagle® 3017 100% EtO Sterilizer/Aerator on HI-TEMP setting (55°C, 736.4 mg/L). EtO exposure for 1 h followed by 12-hr aeration.		
Heimbuch 2014	Hypochlorite	0.9% hypochlorite wipes, wiped 3 times, left to dry 15 min	Aerosol penetration	3M 1860 3M 1870 KC PFR
	Other	Benzalkonium chloride wipes, wiped 3 times, left to dry 15 min		
Lin 2017	Sodium hypochlorite	0.5%, 10 minute submersion	Aerosol penetration	3M 8210
	Isopropyl alcohol	100%, 10 minute submersion	Airflow resistance ^b	
	Ethanol	70%, 10 minute submersion		
Viscusi 2007	Sodium hypochlorite	Arm 1: 5.25%, 30 minute submersion Arm 2: 0.525%, 30 minute submersion	Aerosol penetration	3M 8000
	Liquid H ₂ O ₂	Arm 1: 3%, 30 minute submersion Arm 2: 6%, 30 minute submersion		
	Vaporized H ₂ O ₂	Arm 1: STERRAD® NX Standard cycle, 28 min cycle Arm 2: STERRAD® 100S Standard cycle, 55 min cycle		
	EtO	Arm 1: EtO 3M Steri-Vac 4XL, warm cycle of 55° C and 883 mg/L ethylene oxide gas Arm 2: EtO 3M Steri-Vac 5XL, warm cycle of 55° C and 725 mg/L ethylene oxide gas EtO exposure for 1 h followed by 4 hr aeration.		
	Isopropyl alcohol	Arm 1: 70%, 1 minute submersion Arm 2: 70%, 10 minute submersion		
Viscusi 2009	Sodium hypochlorite	0.6%, 30 minute submersion. Dried overnight.	Aerosol penetration	3M 8210 3M 8000

Vaporized H ₂ O ₂	STERRAD® 100S H ₂ O ₂ Gas Plasma Sterilizer, 55 min cycle	Airflow resistance	Moldex 2201
EtO	Steri-Vac 5XL sterilizer. Single warm cycle (55°C, 725 mg/L 100% EtO Gas). EtO exposure for 1 h followed by 4 h of aeration.		KC PFR95-174
			3M 1870
			3M 1860s

Abbreviations: H₂O₂ - hydrogen peroxide; EtO - Ethylene oxide;

^aMask models for the following studies obtained through private correspondence: Bergman 2010, Viscusi 2007, Viscusi 2009

^bNot measured for isopropyl alcohol

Table III: Summary of results following N95 FFR decontamination for each outcome of interest and chemical disinfectant type. N refers to number of studies.

	Aerosol Penetration	Airflow Resistance	Viral/Bacterial Load	Fit	Physical Appearance, Odor	Odor, Potential Health Risks
Sodium hypochlorite	<p>No change in particle penetration, NIOSH standards maintained (n = 4)</p> <p>Particle penetration exceeded NIOSH's acceptable standard for particle penetration (n = 1)</p>	<p>No change in airflow resistance, NIOSH standards maintained (n = 3)</p>	<p>Log reduction in viral levels of 0.66 ± 0.47 to 4.37 ± 0.4 depending on concentration used (n = 2)</p> <p>0% relative survival of bacteria (n = 1)</p> <p>Mean reduction in bacteria levels >99% (n = 1)</p>	Not assessed	<p>Tarnished metallic nosepieces (n = 4)</p> <p>Oxidized staples (n = 2)</p> <p>Yellowing of nose pads (n = 1)</p> <p>Bleeding of lettering (n = 1)</p> <p>Stiffening of filter media and elastic straps (n = 1)</p> <p>Dissolved nose pad (50%) (n = 1)</p> <p>Bleach odor following treatment (n = 3)</p>	<p>Potential for low level chlorine exposure when FFR is rehydrated during respiration (n = 1)</p>
Liquid H₂O₂	<p>No change in particle penetration, NIOSH standards maintained (n = 2)</p>	<p>No change in airflow resistance, NIOSH standards maintained (n = 1)</p>	Not assessed	Not assessed	<p>Oxidized staples (n = 1)</p> <p>Slight fading of the label lettering (n = 1)</p> <p>No changes in odor (n = 1)</p>	<p>Did not deposit significant quantities of toxic residues on the FFRs (n = 1)</p>
Vaporized H₂O₂	<p>No change in particle penetration, NIOSH standards maintained following 1 (n = 2) and 3 decontamination cycles (n = 1)</p> <p>Particle penetration exceeded NIOSH's acceptable standard for particle penetration in 4 of 6 FFR following 3 decontamination cycles (n = 1)</p>	<p>No change in airflow resistance, NIOSH standards maintained (n = 2)</p>	<p>No viable virus, or virus or bacteriophage below detectable assay limit (n = 4)</p>	<p>Fit factor >100 achieved following 1, 3, 5, 10 cycles with the VHP ARD system, but only following 1 cycle using the STERRAD 100NX^a (n = 1)</p> <p>Fit factor >100 achieved following 3 X 2h wear + decontamination cycles (n = 1)</p>	<p>Slight tarnishing of metallic nosebands (n = 2)</p> <p>No changes in physical appearance (n = 3)</p> <p>No changes in odor (n = 3)</p>	<p>Did not deposit significant quantities of toxic residues on the FFRs (n = 2)</p>

	Aerosol Penetration	Airflow Resistance	Viral/Bacterial Load	Fit	Physical Appearance, Odor	Odor, Potential Health Risks
Ethanol	Particle penetration post-sterilization exceeded NIOSH's acceptable standard for particle penetration (n = 1)	NIOSH standards maintained post-sterilization (n = 1)	Relative bacterial survival rates of 68 to 89% depending on ethanol concentration (n = 1) Relative bacterial survival rates of 20 to 33% depending on ethanol concentration 24h post-sterilization (n = 1) Viral levels below detectable assay limit (n = 1)	Fit factor >100 achieved for 6 replicate masks following 1 decontamination cycle, but not all 6 replicates achieved a fit factor >100 following 2 and 3 decontamination cycles (n = 1)	No changes in physical appearance (n = 1)	Not assessed
Isopropyl alcohol	Particle penetration post-sterilization was impaired and no longer met NIOSH standards (n=2)	Not assessed	Not assessed	Not assessed	Fading of ink strap (n = 1) No changes in physical appearance (n = 1)	Not assessed
EtO	No change in particle penetration post-sterilization, NIOSH standards maintained (n = 3)	No change in airflow resistance post-sterilization, NIOSH standards maintained (n = 2)	No viable virus (n = 1)	Fit factor >100 achieved for 4 mask models following 1 and 3 decontamination cycles (n = 1) ^a	No changes (n = 4)	Presence of ethylene glycol monoacetate on FFR straps, safety currently unclear (n = 1) No changes in odor (n = 3)

Abbreviations: FFR – Filtering facepiece respirators, H₂O₂ – hydrogen peroxide, EtO – ethylene oxide

^aBased on normal breathing and deep breathing exercises only

Table IV: Disinfectants and N95 filtering facemask respirators used to evaluate the effects of decontamination using disinfectants on reductions in infectious pathogens

Author, year	Intervention Arm	Intervention Arm Description	Infectious Pathogen	Conditions	N95 Mask Models ^a
Cheng 2020	Vaporized H ₂ O ₂	SteraMist™ Surface Unit	influenza A virus subtype H1N1	1,000,000 TCID ₅₀ /ml viral concentration 100,000 TCID ₅₀ /ml viral concentration 10,000 TCID ₅₀ /ml viral concentration	3M 1860 3M 1870
Fisher 2020	Ethanol Vaporized H ₂ O ₂	70%, sprayed until saturated Panasonic 146 MCO-19AIC-PT	SARS-CoV-2	-	AO Safety N9504C
Fisher 2009	Sodium hypochlorite	Arm 1: 0.0006%, submerged 10 min, left to dry 2 min Arm 2: 0.006%, submerged 10 min, left to dry 2 min Arm 3: 0.06%, submerged 10 min, left to dry 2 min Arm 4: 0.60%, submerged 10 min, left to dry 2 min	MS2	Low Protective Factor Aerosol Medium (1% ATCC 271) High Protective Factor aerosol medium (100% ATCC 271)	Cardinal Health ^b
Heimbuch 2014	Hypochlorite Other	0.9% hypochlorite wipes, wiped 3 times, left to dry 15 min Benzalkonium chloride wipes, wiped 3 times, left to dry 15 min	Staphylococcus aureus	-	3M 1860 3M 1870 KC PFR
Kenney 2020	Vaporized H ₂ O ₂	Arm 1: Bioquell BQ-50 Arm 2: Bioquell BQ-50 + 5 min steam sterilization (135°C)	Phage phi-6 Phage T1 Phage T7	-	3M 1870
Kumar 2020	Vaporized H ₂ O ₂ EtO	Arm 1: Steris VHP® ARD System Arm 2: STERRAD® 100NX device 5XLP Steri-Vac Sterilizer/Aerator, 1 hr exposure, 12 hr aeration	VSV SARS-CoV-2	-	3M 1860 3M 1870 3M Vflex 1804 AO Safety 1054
Lin 2018	Sodium hypochlorite Ethanol	Arm 1: 5.4%, applied and left to dry for 10 min Arm 2: 2.7%, applied and left to dry for 10 min Arm 3: 0.54%, applied and left to dry for 10 min Arm 1: 50%, applied, left to dry 10 min Arm 2: 70%, 0.082 packing density ^c , applied, left to dry 10 min Arm 3: 70%, 0.23 packing density, applied, left to dry 10 min Arm 4: 70%, 0.44 packing density, applied, left to dry 10 min Arm 5: 70%, 0.87 packing density, applied, left to dry 10 min	Bacillus subtilis	Measured immediately after treatment 24 hours incubation @ 95% RH, 37°C	3M 8210

		Arm 6: 80%, applied, left to dry for 10 min		
		Arm 7: 95%, applied, left to dry for 10 min		
		Arm 1: 0.005%, submerged 10 min, left to dry 2 min,	-	
		Arm 2: 0.01%, submerged 10 min, left to dry 2 min		
		Arm 3: 0.05% %, submerged 10 min, left to dry 2 min		
Vo 2009	Sodium hypochlorite	Arm 4: 0.1%, submerged 10 min, left to dry 2 min	MS2	Wilson N1105
		Arm 5: 0.25%, submerged 10 min, left to dry 2 min		
		Arm 6: 0.5%, submerged 10 min, left to dry 2 min		
		Arm 7: 0.75%, submerged 10 min, left to dry 2 min		

Abbreviations: H₂O₂ – hydrogen peroxide; VSV – vesicular stomatitis virus;

^aMask models for the following studies obtained through private correspondence: Fisher 2009

^bNo longer commercially available

^cPacking density (=Vdisinfectant/Vmask)

Table V: Disinfectants and N95 filtering facemask respirators used to evaluate the effects of decontamination using disinfectants on mask appearance

Author, year	N95 Mask Models ^a	Intervention Arm	Changes in physical appearance following visual inspection of decontaminated masks	Changes in odor after sniffing decontaminated masks
Bergman 2010	3M 8210 3M 8000 Moldex 2201 KC PFR95-174 3M 1870 3M 1860s	Sodium hypochlorite	All FFR models: Metallic nosebands slightly tarnished 3M 8210: Discoloured (yellowed) nose pads 3M 8000: Staples oxidized Moldex 2201: Staples oxidized KC PFR95-174: Area adjacent to nose clip discolored 3M 1870: Staples oxidized, discoloured (yellowed) nose pads, 50% of nose pad dissolved, material adjacent to nose pad became yellowed 3M 1860s: Staples oxidized, discoloured (yellowed) nose pads, bleeding of printed ink lettering	Bleach odor
		Liquid H ₂ O ₂	3M 8000: Staples oxidized Moldex 2201: Staples oxidized 3M 1870: Staples oxidized 3M 1860s: Staples oxidized	No changes reported
		Vaporized H ₂ O ₂	No observable physical changes	No changes reported
		EtO	No observable physical changes	No changes reported
		Vaporized H ₂ O ₂	Appeared similar to new with no deformity	Not assessed
Kenny 2020	3M 1870	Vaporized H ₂ O ₂ + Steam	Degradation observed	Not assessed
Lin 2017	3M 8210	Sodium hypochlorite	No changes reported	Not assessed
		Isopropyl alcohol	No changes reported	Not assessed
		Ethanol	No changes reported	Not assessed
Salter 2010 ^b	3M 8000 3M 8210 Moldex 1500 3M 1860 3M 1870 Kimberly Clark PFR	Sodium hypochlorite	Corrosion and/or discolouration of metal parts of the FFRs (staples, nosepieces, etc.)	Bleach odor
		Liquid H ₂ O ₂	No changes reported	No changes reported
		Vaporized H ₂ O ₂	No changes reported	No changes reported
		EtO	No changes reported	No changes reported
Viscusi 2007	3M 8000	Sodium hypochlorite	Arm 1 (0.525%): Metallic nosebands slightly tarnished Arm 2 (5.25%): Metallic nosebands slightly tarnished, stiffening of filter media and elastic straps	Not assessed
		Liquid H ₂ O ₂	Arm 1 (3%): No visible changes	Not assessed

		Arm 2 (6%): Label ink slightly faded		
		HPV	Arm 1 (STERRAD® NX): Metallic nosebands slightly tarnished Arm 2 (STERRAD® 100S): Metallic nosebands slightly tarnished	Not assessed
		EtO	No visible changes reported for either EtO intervention arm	Not assessed
		Isopropyl alcohol	Fading of strap ink	Not assessed
Viscusi 2009	3M 8210	Sodium hypochlorite	All FFR Models: Metallic nosebands slightly tarnished	Bleach odor
	3M 8000		3M 1870: Inner nose comfort cushion discolored.	
	Moldex 2201 KC PFR95-174	Vaporized H ₂ O ₂	All FFR Models: Metallic nosebands slightly tarnished	No changes reported
	3M 1870 3M 1860s	EtO	All FFR Models: No visible changes observed for all samples	No changes reported

Abbreviations: H₂O₂ – hydrogen peroxide; EtO - Ethylene oxide, FFR – Filtering facepiece respirators

^aMask models for the following studies obtained through private correspondence: Bergman 2010, Salter 2010, Viscusi 2007, Viscusi 2009

^bSalter *et al* also evaluated two other disinfectants developed by the Department of Defense that are not widely distributed. These results are not reported in the table

Appendix A - Search Strategy

Medline

1. Respiratory Protective Devices/
2. Personal Protective Equipment/
3. (filtering adj3 (facepiece or face piece or facepieces or face pieces)).tw,kf.
4. (N95 or N 95).tw,kf.
5. (ffr or ffrs).tw,kf.
6. or/1-5
7. Sodium Hypochlorite/ or Disinfectants/
8. Hydrogen Peroxide/
9. (bleach* or clorox or antiformin or oxygenated water or hydrogen peroxyde or hydroperoxide or peroxygen).tw,kf.
10. sodium hypochlorite.tw,kf.
11. hydrogen peroxide.tw,kf.
12. Ethanol/
13. 2-Propanol/
14. Ethylene Oxide/
15. (ethanol* or isopropanol or iso-propanol or 2-propanol or isopropyl alcohol or ethylene oxid* or oxirane or rubbing alcohol*).tw,kf.
16. or/7-15
17. 6 and 16
18. limit 17 to (yr="1972 -Current" and (english or french))

Embase

1. surgical mask/
2. protective equipment/
3. (filtering adj3 (facepiece or face piece or facepieces or face pieces)).tw,kw.
4. (N95 or N 95).tw,kw.
5. (ffr or ffrs).tw,kw.
6. or/1-5
7. hypochlorite sodium/
8. hydrogen peroxide/
9. alcohol/
10. 2 propanol/
11. ethylene oxide/
12. (bleach* or clorox or antiformin or oxygenated water or hydrogen peroxyde or hydroperoxide or peroxygen).tw,kw.
13. sodium hypochlorite.tw,kw.
14. hydrogen peroxide.tw,kw.
15. (ethanol* or isopropanol or iso-propanol or 2-propanol or isopropyl alcohol or ethylene oxid* or oxirane or rubbing alcohol*).tw,kw.
16. or/7-15
17. 6 and 16
18. limit 17 to ((english or french) and yr="1972 -Current")

Global Health

All fields search:

((bleach* or hydrogen peroxide or ethanol) AND ("respiratory protective device*" or "face shield*" or faceshield* or n95 or n-95 or ffr or ffrs or "filtering face*"))

Google Scholar

(respiratory protective device*| n95|n-95|ffr|ffrs|filtering face*)(bleach*|hydrogen peroxide|ethanol|isopropyl alcohol)

WHO database

All Indexed Fields

{n95} OR {n-95} OR {n 95} OR {ffr} OR {ffrs} OR {respiratory protective device*} OR {filtering face} Or All Non-Indexed Fields {n95} OR {n-95} OR {n 95} OR {ffr} OR {ffrs} OR {respiratory protective device*} OR {filtering face} AND All Non-Indexed Fields {bleach*} OR {hydrogen peroxide} OR {ethanol} OR {isopropyl alcohol}

Scopus

(AUTHOR-NAME (bergman OR viscusi) AND TITLE-ABS-KEY (n95 OR "n 95"))

Appendix B: Definitions of low, moderate, and high risk of bias for each study outcome. Risks of bias evaluations based on this rubric are presented in **Appendix C**.

ROB Category	Outcome	Low Risk	Moderate Risk	High Risk	Unclear
Design	All	Controlled study or pre-post design	Partially controlled, quasi-experimental, or case-control design	Uncontrolled and no pre-post design	Insufficient information
Methodological Consistency	Aerosol Penetration	Aerosol diameter and airflow rate are consistent across arms	Some of the stated criteria not reported	None of the stated criteria reported	Insufficient information
	Airflow Resistance	Airflow rate is consistent across arms	Some of the stated criteria not reported	None of the stated criteria reported	Insufficient information
	Germicidal	Detailed description of viral/bacterial inoculation procedure (including inoculation medium and transmission mode) AND assay procedure (including times/temperatures where applicable); procedures consistent across arms unless they are experimental variables	Some of the stated criteria not reported	None of the stated criteria reported	Insufficient information
	Physical Characteristics	Description of how masks were evaluated, and consistent method of evaluation across arms	Some of the stated criteria not reported	None of the stated criteria reported	Insufficient information
	Fit	Ambient particle concentration checked by machine at least once per test day for quantitative fit tests AND fit test protocol specified and consistent across arms	Some of the stated criteria not reported	None of the stated criteria reported	Insufficient information
	Safety/Irritation	Detailed lab procedures with times/temps provided and consistent across arms	Some of the stated criteria not reported	None of the stated criteria reported	Insufficient information
Population Heterogeneity	All	Masks or mask components derived from the same batch/lot, AND each different model analyzed separately	Different mask models analyzed separately but lots not specified	None of the stated criteria reported	Insufficient information
Sampling Bias	All	No indication that any masks were excluded from tests, OR clear indication of exclusion with analyses accounting for the missing info	Data is missing for some samples and is not accounted for in analysis or conclusions	Some samples are replaced by new masks (e.g. if untestable due to degradation) and the exclusion of the original samples is not accounted for in analysis or conclusions	Insufficient information
Outcome Evaluation	All	Results determined by blinded evaluators OR a machine (objective)	Partially-machine measured and/or partially-blinded evaluation	Results determined by unblinded evaluator or other subjective manner	Insufficient information
Reporting of Results	All	Results for all specified objectives and tests are reported, and/or missing data is clearly accounted for in analysis; all results that were reported were mentioned in the methods/objectives.	Results of all objectives/tests are included or accounted for but results that were not specified in the methods/objective are also reported	Results for some objectives/tests are missing and not accounted for	Insufficient information

Appendix C: Risk of bias for all evaluated outcomes (Part 1). Each risk of bias rating applies to all included disinfectant interventions in that study.

Author, Year	Design*	Methodology*	Population Heterogeneity*	Sampling Bias*	Outcome Evaluation*	Reporting of Results*	Overall ROB (Score)**	Peer- Reviewed†
Aerosol Penetration								
Bergman, 2010	Low	Low	Low	Low	Low	Low	Low (0)	Yes
Heimbuch, 2014	Low	Low	Moderate	Low	Low	Low	Low (1)	Yes
Lin, 2017	Low	Low	Moderate	Low	Low	Low	Low (1)	Yes
Viscusi, 2007	Low	Low	Low	Low	Low	Low	Low (0)	Yes
Viscusi, 2009	Low	Low	Low	Low	Low	Low	Low (0)	Yes
Airflow Resistance								
Bergman, 2010	Low	Low	Low	Low	Low	Low	Low (0)	Yes
Lin, 2017	Low	Low	Moderate	Low	Low	High	Low (3)	Yes
Viscusi, 2009	Low	Low	Low	Low	Low	Low	Low (0)	Yes
Germicidal								
Cheng, 2020	Low	Moderate	Moderate	Low	High	Low	Moderate (4)	No
Fischer, 2020	Low	Moderate	Moderate	Low	High	Moderate	Moderate (5)	No
Fisher, 2009	Low	Low	Moderate	Low	High	Low	Low (3)	Yes
Heimbuch, 2014	Low	Low	Moderate	Low	High	Low	Low (3)	Yes
Kenney, 2020	Low	Moderate	Moderate	Low	High	Low	Moderate (4)	No
Kumar, 2020	Low	High	Moderate	Low	High	Low	Moderate (5)	No
Lin, 2018	Low	Moderate	Moderate	Low	High	Low	Moderate (4)	Yes
Vo, 2009	Low	Low	Moderate	Low	High	Low	Low (3)	Yes

* For evaluation criteria, see **Appendix B**

** An overall score was evaluated for each study for each outcome. Individual categories were assigned scores of 0, 1, and 2 for low, moderate, and high risk respectively. Possible total scores ranged from 0 to 12 indicating overall low (1–3), moderate (4–6), or high (7–12) risk of bias. For studies where one or more evaluations were unclear, a range of overall risk is provided based on the minimum and maximum possible scores for the unclear categories.

† No peer review indicates that article is a preprint.

Appendix C: Risk of bias for all evaluated outcomes (Part 2). Each risk of bias rating applies to all included disinfectant interventions in that study.

Author, Year	Design*	Methodology*	Population Heterogeneity*	Sampling Bias*	Outcome Evaluation*	Reporting of Results*	Overall ROB (Score)**	Peer-Reviewed†
Fit								
Fischer, 2020	Low	Moderate	Moderate	Low	Low‡	Low	Low (2)	No
Kumar, 2020	Low	High	Moderate	Low	Low	Low	Low (3)	No
Physical Appearance and Odor								
Bergman, 2010	Low	Moderate	Low	Unclear	High	High	Moderate to high (5–7)	Yes
Kenney, 2020	Low	High	Moderate	Unclear	High	Moderate	Moderate to high (6–8)	No
Lin, 2017	Low	High	Moderate	Unclear	High	Moderate	Moderate to high (6–8)	Yes
Salter, 2020	Low	High	Moderate	Unclear	High	Moderate	Moderate to high (6–8)	Yes
Viscusi, 2007	Low	Low	Low	Low	High	Low	Low (2)	Yes
Viscusi, 2009	Low	Low	Low	Low	High	Low	Low (2)	Yes
Safety/Irritation								
Cheng, 2020	High	Unclear	High	Unclear	Unclear	Unclear	Moderate to high (4–12)	No
Salter, 2020	High	Low	Moderate	Low	Low	Low	Low (3)	Yes
Viscusi, 2009	High	Low	Low	Unclear	Low	Low	Low to moderate (2–4)	Yes

* For evaluation criteria, **see Appendix B**

** An overall ROB score was calculated for each study for each outcome. Individual categories were assigned scores of 0, 1, and 2 for low, moderate, and high risk respectively. Possible total scores ranged from 0 to 12 indicating overall low (1–3), moderate (4–6), or high (7–12) risk of bias. For studies where one or more evaluations were unclear, a range of overall risk is provided based on the minimum and maximum possible scores for the unclear categories.

† No peer review indicates that article is a preprint.

‡ Applies to individual replicate data, not predicted medians/IQRs

Abbreviations: ROB – Risk of Bias

Appendix D: Details provided for the vaporized H₂O₂ protocols used in the included studies

Author, Year	Device Used	Duration	Additional Details Provided	Outcomes Evaluated
Bergman 2010	STERRAD® 100S H ₂ O ₂ Gas Plasma Sterilizer	55 min	59% H ₂ O ₂ , cycle time 45°C–50°C 6 FFR per pouch	Aerosol resistance Airflow penetration Physical Appearance
	Room Bio-Decontamination Service (RBDS™), which utilizes four portable modules: the Clarus® R HPV generator (utilizing 30% H ₂ O ₂), the Clarus R20 aeration unit, an instrumentation module and a control computer.	15- min dwell, 125-min total cycle time	30% H ₂ O ₂ FFRs hung on string	
Cheng 2020	SteraMist™ Surface Unit with SteraMist™ Binary Ionization Technology® (BIT™) solution (7.8% H ₂ O ₂ solution)	6 seconds	SteraMist™ Binary Ionization Technology® (BIT™) solution (7.8% H ₂ O ₂ solution)	Germicidal activity Safety
Fischer 2020	Panasonic 146 MCO-19AIC-PT incubator with vaporized hydrogen peroxide generation capabilities	10 minutes	Exposed to hydrogen peroxide (approximately 1000 ppm)	Germicidal activity Fit
Kenney 2020	Bioquell BQ-50	10 minute conditioning phase, 30-40 minute gassing phase (varies with humidity and room size) at 16 g/min, 25 minute dwell phase, and a 150 minute aeration phase	Respirators suspended by their elastics on racks	Germicidal activity Physical appearance
Kumar 2020	Sterrad® 100NX System	47 min		Germicidal activity Fit
	Steris VHP® ARD System	10 minutes dehumidification, 3 minutes conditioning (5 gram/minute), 30 minutes decontamination (2.2 gram/minute) and 30 minutes aeration	Peak concentration was >750 ppm	
Salter 2010	Sterrad® 100S Gas Plasma Sterilizer	55 min	45–55°C in One FFR per pouch	Safety Physical appearance
Viscusi, 2007	STERRAD® NX System	28 min		Aerosol penetration Physical appearance
	Sterrad® 100S Gas Plasma Sterilizer	55 min		
Viscusi, 2009	Sterrad® 100S Gas Plasma Sterilizer	55 min	On FFR per pouch	Aerosol penetration Airflow resistance Physical appearance Safety

Abbreviations: H₂O₂ – hydrogen peroxide, FFR – filtering facepiece respirator