Microwave- and Heat-Based Decontamination of N95 Filtering Facepiece Respirators (FFR): A Systematic Review

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Please Note:

The experiments summarized in this manuscript are performed under specialized laboratory conditions. Household appliances should **not** be used for any purposes that are not indicated in their manufacturer-supplied guidelines, including mask decontamination. Doing so may lead to damage or injury.

ABSTRACT

Background: In pandemic situations such as COVID-19, shortages of proper protective equipment are common. One solution may be to decontaminate equipment such as facemasks for reuse.

Aim: The aim of this review was to collect and synthesize existing information on decontamination of N95 filtering facepiece respirators (FFRs) using microwave and heat-based treatments, with special attention to impact on mask function (aerosol penetration, airflow resistance) and fit.

Methods: A systematic review (PROSPERO ID pending) of literature available on Medline, Embase, Global Health, JISRP and JEFF was conducted. Records were screened independently by two reviewers, and data was extracted and analyzed from studies that reported on the effects of microwave- or heat-based decontamination on N95 FFR performance and/or microbial load.

Results: All interventions successfully destroyed viral/bacterial contaminants. Other than autoclaving, which significantly increased aerosol penetration, moist and dry microwave and heat conditions did not significantly impact functional parameters or fit. However, several conditions caused physical damage to at least one N95 model.

Conclusions: Microwave irradiation and heat provides safe and effective decontamination options for N95 FFR reuse during critical shortages. However, autoclaving masks is not recommended by the evidence in this review. Any mask disinfected using these methods should be inspected for physical degradation before reuse.

Keywords: Personal Protective Equipment, PPE, N95, Mask, Filtering Facepiece Respirator, Health Care Workers, Hospital, Decontamination, Pandemic, COVID-19

INTRODUCTION

During the spread of SARS-CoV-2, there are fewer concerns more pressing than protecting frontline healthcare workers (HCWs). As SARS-CoV-2 can be transmitted through airborne particles, especially during aerosol generating procedures, the U.S. Centers for Disease Control and Prevention (CDC) and Public Health Agency of Canada (PHAC) have recommended that HCWs wear N95 filtering facepiece respirators (FFRs) when performing these procedures in suspected COVID-19 patients.¹⁻³ N95 FFRs filter 95% of airborne particles⁴ and are the personal protective equipment (PPE) preferred by HCWs during serious outbreaks of aerosol-borne viruses.⁵

It is widely understood that single-use of FFRs is not sustainable in a pandemic such as COVID-19,⁶⁻⁸ and FFR decontamination has been proposed⁹ as a safer method than standard “limited reuse” which involves no disinfection between wears.^{10,11} FFR decontamination must preserve the structural and functional characteristics of the mask (namely fit, aerosol penetration, and airflow resistance),¹² or else it may increase risk to healthcare workers. The lack of clear consensus on how to achieve safe decontamination of single-use FFRs has discouraged manufacturers¹³ and public health experts¹⁴ from endorsing decontamination protocols, although several analyses of FFR-decontamination methods have been published and the CDC has provided guidelines for decontamination in critical situations.¹⁵ Examined approaches include radiation (UV-C, microwaves), moist heat (autoclaves), and chemical methods (bleach, ethanol, hydrogen peroxide),¹⁶⁻¹⁹ which vary in their relative efficacies and feasibilities. Not all institutions have access to large UV lamps, and chemical disinfection appears to cause more damage to the masks²⁰ and may leave residues on FFRs after disinfection.²¹ Microwaves and

heat are known to inactivate viruses and bacteria,²²⁻²⁵ including coronaviruses,^{26,27} and these methods may be more accessible and scalable than ultraviolet germicidal irradiation.²⁸

To help inform FFR-reuse policies and procedures, our team has conducted three systematic reviews to synthesize existing published data regarding the effectiveness of ultraviolet germicidal irradiation (UVGI), heat, microwave irradiation, and chemical disinfectants for N95 FFR decontamination. This review will focus on microwave- and heat-based decontamination with the following objectives: (1) to assess the effect of microwave irradiation and heat on FFR performance, with a specific focus on aerosol penetration and airflow resistance; (2) to determine how effectively microwave radiation and heat reduce viral or bacterial load; (3) to describe changes in FFR fit or physical degradation caused by microwave irradiation or heat; and (4) to use the findings of this review to inform an evidence-based protocol for N95 FFR decontamination.

METHODS

The study protocol and methods were established *a priori* and submitted to PROSPERO on March 29th, 2020 (PROSPERO ID pending), and reported here according to the PRISMA guidelines of systematic reviews (Appendix A).²⁹ The protocol was uploaded as a pre-print to Open Science Framework (OSF) on March 30th, 2020 (<https://osf.io/4se6b/>).³⁰

Eligibility Criteria

Eligible studies met the following criteria: 1) Study was an original article or systematic review; 2) Study investigated decontamination of N95 (including surgical N95) filtering facepiece respirators; 3) Study included a decontamination arm involving microwave irradiation or heat

treatment; 4) At least one of the following outcomes of interest was reported: i) FFR filter performance (aerosol penetration, airflow resistance), ii) reduction in viral/bacterial load; iii) mask fit; or iv) changes in physical state. Articles also had to be available in English or French and published after 1972, the first year that an FFR was approved by the National Institute for Occupational Safety and Health (NIOSH).³¹ We excluded editorials, narrative reviews, book chapters and patents.

Database Search and Study Selection

Two health sciences librarians (LS and MS) searched the following databases during the electronic component of the systematic review: Medline and Medline in Process via OVID (1946-2020), Embase Classic + Embase via OVID (1947-2020), and Global Health via CAB Direct (1913-2020). A search strategy was developed in Medline, and then translated into the other databases as appropriate (Appendix B). All databases were searched from their dates of inception to March 29, 2020. The language was restricted to English or French, and a publication date starting from 1972.

Two journals were also hand-searched, as they were particularly relevant to the review but are not indexed in any of databases used: Journal of the International Society for Respiratory Protection (JISRP), and the Journal of Engineered Fibers and Fabrics (JEFF). Two authors had been previously identified as publishing frequently on mask decontamination. Scopus was searched March 29, 2020 for those authors and N95-related terms. A search of Google Scholar (March 29, 2020) yielded 1630 hits. The first 1000 were downloaded to Publish or Perish and screened until 50 consecutive apparently irrelevant records were found (this occurred at record 138). Records up to that point were saved as an RIS file and edited to remove patents, reports

and books. The WHO database on COVID-19 (March 29, 2020 edition) was searched. Disaster Lit: Database for Disaster Medicine and Public Health, MedRxiv and OSF Registries were searched March 29, 2020 for the term “N95” and records pertaining to decontamination were selected and downloaded. All references were entered into an Endnote file were duplicate records were removed. Following screening, one librarian (MS) reviewed the reference lists of included studies to identify any potentially relevant studies not included in the screening set.

Citation Screening and Data Extraction

Titles and abstracts were then uploaded to InsightScope (www.insightscope.ca) for title and abstract screening and full text review. At both title/abstract and full text review, citations were assessed in duplicate and independently by a team of six reviewers recruited from the Children’s Hospital of Eastern Ontario (CHEO), the University of Ottawa, and McMaster University. Four of these reviewers had experience screening for our previous review on N95 decontamination with ultraviolet light.¹⁸ Before gaining access to title/abstract screening, each reviewer completed a test set of size 30 citations (5 true positives, 25 true negatives), and achieved a sensitivity of at least 80%. At both title/abstract and full text review, records were removed only if both reviewers agreed it to exclude; any conflicts were reviewed and resolved by the study leads (SG, AA). Reference lists of studies included after full text review were reviewed for eligible studies that may have evaded the initial database search. Subsequently, the study leads reviewed the eligible citations to identify potential duplicates and confirm eligibility. An extraction tool for study demographics and methodology data was developed in Research Electronic Data Capture (REDCap) tools^{32,33} hosted at CHEO by the study leads and piloted by the same individuals on five eligible studies. Based on the methodology data extracted, the study leads designed and

piloted spreadsheets (Microsoft Excel) for outcome data extraction. In both phases of data extraction, eligible studies were divided equally among the reviewers for duplicate, independent data extraction, followed by conflict resolution by the study leads.

Study Analysis and Statistics

All statistical analysis were performed using the R statistical programming language.³⁴ Data was meta-analyzed using a random effects model with the R package ‘meta’.³⁵ We performed random effects meta-analysis for aerosol penetration outcomes in moist microwave interventions. We compared pooled absolute value of control (no microwave exposure) and treated (masks post microwave exposure). Heterogeneity was assessed using an I^2 statistic.

Missing values were dealt with as follows: Where standard deviation or standard error were not reported, either targeted or generic imputation was use. If other arms within the same study had values for uncertainty, the most conservative value would be imputed for missing data. If no arms within a study had a value for uncertainty, the average value between studies was imputed for missing data.

For values below minimum detectable limits, we adopted the strategy described by Heimbuch *et al.* for imputation of log quantity: "Based on a US Environmental Protection Agency guideline,³⁶ half of the BDL was used to calculate log reductions for treated samples that had no detectable virus."¹⁶

Risk of Bias and Strength of Evidence Assessments

The strength of the cumulative body of evidence will be evaluated based on the Grading of Recommendations, Assessment, Development, and Evaluation (GRADE) criteria of study quality and risk of bias, precision, directness, and consistency.³⁷ The quality of all included

studies was assessed using predetermined criteria about study design, methodology, population, and outcomes. The following characteristics were deemed to indicate low risk of bias in those four study aspects: (1) Controlled study and/or pre-post design; (2) Outcome evaluations performed in constant lab conditions; (3) N95 masks obtained from same lot to minimize confounding due to mask variation; and (4) Study outcomes provided by a machine or blinded individuals. Only studies examining certified N95 FFRs will qualify as direct evidence. Consistency will be defined as equivalent outcomes in at least two studies without major difference in any other study. Precision will be assessed through the number of studies examining each outcome of interest and the range of reported values for said outcome. No statistical analyses of publication bias were planned due to the limited number of eligible articles, and relatively small variance in sample sizes in laboratory studies. Evidence of success for each evaluated outcome will be defined as less than 5% aerosol penetration,⁴ airflow resistance under 25 mmH₂O,³⁸ at least two log reduction in viral/bacterial load, and fit factor (FF) greater than or equal to 100. For physical state, an absence of observable changes to the mask will constitute outcome success.

RESULTS

Study Selection

The initial database search identified 469 records, of which duplicates were removed to yield 416 unique records to screen (Appendix A). No additional studies were found from checking reference lists. All six reviewers achieved a sensitivity of 1.0 on the test set before beginning screening. The review team excluded 397 records throughout the test set and title/abstract screening ($\kappa = 0.79$). Three records were excluded at the full text stage, resulting in 16 reports

representing 11 unique studies that were eligible for data extraction. No additional studies were found from checking reference lists of included manuscripts.

Study Characteristics

Eleven studies were included in this review (Table 1). The studies were published between 2007 and 2018, and all were performed in the United States except for two from Taiwan. The 3M 1870, 3M 1860, and 3M 8210 (n = 4 each) were the most commonly specified FFR models studied. Microwave and heat-based interventions were investigated in nine studies each. Germicidal effects of the decontamination strategies were measured in four microwave intervention studies and three heat intervention studies, post-decontamination aerosol penetration was evaluated in six of each, airflow resistance was determined in three of each, fit was assessed in two of each, and physical state was appraised in seven of each.

Most microwave interventions^{16,39-43} included a reservoir of water within the microwave chamber, creating what is referred to as Microwave-Generated Steam (MGS). The addition of moisture was also common in heat interventions; five studies^{16,39-41,43} employed Moist Heat Incubation (MHI) by adding water reservoirs inside ovens or using laboratory incubators, and three^{17,20,44} used an autoclave.

N95 Mask Function (aerosol penetration & airflow resistance)

Aerosol penetration

All studies that measured aerosol penetration adhered to NIOSH testing standards.⁴ There were five studies^{41,43-46} that assessed aerosol penetration post-microwave intervention (Table 2), three^{41,43,46} of which used moist conditions for decontamination. The average percent particle

penetration of the FFRs was 1.26 (ranging from 0.70 – 1.90) and 1.52 (ranging from 1.05 – 2.25) for the control and moist-microwave treatment arms respectively. The random effects meta-analysis calculated a mean difference of 0.12 (95% CI -0.74 – 0.98) (Figure 1a). Statistical heterogeneity was low with an I^2 of 12%. Two studies^{44,45} examined percent aerosol penetration after dry microwave radiation and reported averages of 0.79 (ranging from 0.79 – 0.87) and 1.39 (ranging from 1.02 – 1.77) for the control and treatment arms respectively. One mask model (unspecified SN95) melted in dry microwave radiation (Table 6) and aerosol penetration could not be measured.⁴⁵ Where measurement was possible all microwave interventions led to a small increase in aerosol penetration; however, in post-treatment values still remained well-below NIOSH certification standards (< 5% penetration).⁴

Five studies^{20,41,43-45} assessed aerosol penetration after decontamination using heat (Table 2), and four^{20,41,43,44} of these had at least one moist condition (MHI or autoclave). The particle penetration in masks averaged 1.18 (ranging from 0.70 – 2.13) and 1.57 (ranging from 0.97 – 34.4) for the control and moist-heat treatment arms respectively. In all MHI interventions,^{41,43} the increase in aerosol penetrance was small (< 1%) and remained within NIOSH certification standards (< 5% penetration).⁴ Results in autoclave conditions varied: in one study²⁰ no increase was noted, but the other autoclave intervention⁴⁴ noted an increase of over 18% in both arms. Three studies^{20,44,45} examined particle penetration in masks post-dry heat treatment and reported on average 1.08 (ranging from 0.70-1.66) and 2.08 (ranging from 1.66-2.47) for the control and post-dry heat treatment arms respectively. For one mask model (unspecified N95), no measure for aerosol penetrance was obtained after high-temperature dry heat treatment due to melting of the mask (Table 6).⁴⁴ Where measurement was possible, dry heat interventions led to a small increase in aerosol penetration with final values remaining within NIOSH certification standards

(< 5% penetration).⁴The one exception to this was an unspecified N95 model at 110 degrees with an aerosol penetration of 5.35%;⁴⁵ data for this mask was obtained from only one replicate (rather than three) because the other two melted.

Airflow resistance (pressure drop)

Three studies examined airflow resistance^{20,43,45} (Table 3); out of these, there were two microwave decontamination arms (one moist and one dry) and three were heat arms (one MHI, one dry, and one autoclave). In the microwave arms, airflow resistance averaged 8.98 mmH₂O (ranging from 7.52–10.45 mmH₂O) and 9.21 mmH₂O (ranging from 7.78–10.63 mmH₂O) for the control and post microwave treatment arms, respectively. In heat decontamination studies^{20,43}, airflow resistance in FFRs averaged 9.53 mmH₂O (ranging from 9.07–10.45 mm H₂O) and 9.24 mmH₂O (ranging from 7.14–10.41 mmH₂O) for the control and post heat treatment arms, respectively. In all studies, small to no increase in airflow resistance was noted, and all final values were within NIOSH guidelines (< 25 mmH₂O).³⁸

Germicidal Effects

Five studies^{16,17,41,42,46} evaluated reduction in viral/bacterial load after microwave or heat interventions (Table 4). One study¹⁷ used bacterial pathogens, whereas the remaining four used viral pathogens including H1N1 (n=1), H5N1(n=1) and MS2 (n=2). Four studies^{16,41,42,46} examined the germicidal effect of MGS. In these studies, nearly all arms demonstrated a reduction in viral load greater than 1000 times (3 log); the only exceptions were two rapid-treatment arms (30 seconds or less) in Fisher *et al.*'s study (2009),⁴² which led to log reductions of less than two (Figure 2a). Out of three studies^{16,17,41} with heat-based interventions (dry heat,

MHI, and autoclave), pathogen reduction exceeded four log in the two studies^{16,41} that examined viral pathogens (Figure 2b). In the rapid high temperature intervention arm of Lin *et al.* (2018),¹⁷ relative bacterial survival was 0.3% (2.5 log reduction) immediately post-decontamination, and reduced to 0.1% (3 log reduction) 24 hours later; in the autoclave arm of this study, no spores were grown post-decontamination which the authors estimated to be 100% decrease in bacterial load.

Physical Changes (fit, odor, degradation)

Fit

Two studies assessed FFR fit after microwave and heat treatment (Tables 5-6).^{39,40} Viscusi *et al.* (2011)⁴⁰ utilized a modified version of the Occupational Safety and Health Administration (OSHA) fit test on untreated masks and those which had undergone MGS and MHI decontamination. A Fit Factor (FF), scored from 1 (poor fit) to 200 (best fit), was calculated for each test using a PORTACOUNT® Fit Tester by measuring the ratio of ambient particle concentration outside the respirator to the particle concentration inside. Each subject donned each mask five times, with two replicates per model-treatment combination, and a multi-donning fit factor (MDFF₁₀) was calculated as the harmonic mean of the 10 FFs. The MDFF₁₀ for all models and interventions exceeded the minimum passing threshold of 100, although two models (3M 8210 and Moldex 2200) demonstrated a significant drop in MDFF₁₀ after MHI with median decreases of 29 and 59 respectively. The study's subjects, who were blinded to the masks' intervention arms, also rated comfort and donning ease on visual analogue scales which revealed no significant differences in either after MGS or MHI. The authors also reported strap breaks during the multi-donning fit test, noting six relevant incidences with the Moldex 2200 (two

controls, three after MHI and one after MGS), one for the 3M 8210 (control) and one for the 3M 1870 (after MGS).

Bergman *et al.* (2011)³⁹ utilized a similar modified fit test to Viscusi *et al.* (2011), but performed three cycles of decontamination with a single donning fit test before treatment and after each of the three cycles. After all cycles, every model in the MGS and MHI arms had a 95% fit test pass rate, and the pass rate never dropped below 90% after any decontamination cycle in any condition. Correspondingly, mean face seal leakage (FSL), which is calculated as the reciprocal of FF, remained < 1% in both decontamination protocols.

Mask Degradation

All visual and tactile inspection of FFRs was carried out by unblinded experimenters. Six studies^{16,39,40,43-45} that studied microwave irradiation commented on observable mask deterioration caused by their treatment protocols (Table 5). Viscusi *et al.* (2007)⁴⁴ noted that a 240-second dry microwave irradiation cycle resulted in significant melting of filter media whereas the same treatment for 120 seconds caused no observable change. However, in a different study with the same microwave conditions, all three replicates of one mask model had melted after 120 seconds. Across studies that employed MGS,^{16,39,40,43} slight separation of the inner foam nose cushion foam occurred in one model from each, and melting of straps was also observed in two studies.

Several moist heat conditions caused notable degradation (Table 6). In both studies examining high-temperature, high-pressure autoclave decontamination,^{20,44} masks were found to be deformed, shrunken and stiff post-decontamination. Bergman *et al.* (2010, 2011)^{39,43} performed two studies with MHI arms at room pressure and temperatures of 60°C, and noted

slight separation of the inner foam nose cushion of one FFR model per study. No MHI-induced physical degradation was noted in any other studies.

The impact of dry heat on N95 mask integrity was temperature- and model-dependent (Table 6). In one study Viscusi *et al.* (2007)⁴⁴ reported mask-melting at 160°C after 22 minutes (but were unharmed at 80°C for 60 minutes), and another study by Viscusi *et al.* (2009)⁴⁵ reported that one mask model (unspecified SN95) melted when heated 100°C or above for 60 minutes, but not at 80°C or 90°C for the same length of time. However, five of the six tested N95 models did not melt at any tested temperature in the latter study, and the former only investigated one mask model total (unspecified N95). Lin *et al.*'s (2017)²⁰ high-temperature dry heat decontamination (149-164°C) for three minutes demonstrated no significant changes in the physical state of the one mask model tested.

Odour

Changes in odour were assessed in 3 studies^{40,43,45} (Table 6) by sniffing the masks after decontamination; Viscusi *et al.* (2011)⁴⁰ additionally quantified odour measurements by administering a subjective questionnaire with a visual analog scale to blinded participants who underwent fit testing. This questionnaire revealed a small odour increase (5.94 out of 100) in one model (3M 1860) after MHI treatment. Other than this, no significant differences in odour were reported in any study.

Water Retention

Fisher *et al.* (2011)⁴⁶ evaluated the physical integrity of various N95 mask models by measuring their water retention after decontamination using a microwave steam bag (Table 5). While three

mask models (3M 1860, 2M 8210, Cardinal Health) were eliminated from the experiment after one decontamination cycle due to water retention that exceeded standards for mask tolerability, the other three models (3M 1870, KC PFR95 and Moldex 2200) retained minimal water immediately after decontamination.

Risk of Bias and Strength of Cumulative Evidence

Risk of Bias was assessed using predetermined criteria regarding study design, methodology, population, and outcomes (Appendix C). All outcomes are considered direct because they were evaluated using N95 FFRs.

For aerosol penetration outcomes, all six studies^{20,41,43-46} had a control arm or pre-post design and measured percent penetration using a machine. Three of the studies⁴³⁻⁴⁵ used masks from the same lot to minimize variation, and two^{43,45} reported that outcomes were evaluated in constant lab conditions. The threshold for outcome success (percent penetration < 5%) was met consistently for all microwave and heat conditions except autoclaving which demonstrated mixed results. The moist and dry microwave interventions each contained many arms and reported average results well below the NIOSH criteria, supporting high precision. The precision of aerosol penetration for autoclave interventions was poor due to the vastly different results described by Viscusi *et al.*'s (2007)⁴⁴ and Lin *et al.* (2017).²⁰ The dry heat outcome was precise as the confidence interval was underneath the acceptable particle penetration.

Airflow resistance was also always evaluated by a machine and compared against a control or pre-treatment measurement. Two^{43,45} of the three studies used masks from the same lot and reported constant lab conditions. Successful outcomes (final resistance < 25 mmH₂O) were

consistent across all studies and reported results from all studies were considerably lower than NIOSH criteria, indicating good precision.

Germicidal effects were measured by unblinded lab technicians, no studies reported masks from the same lot, and only one⁴² reported constant lab conditions. However, all studies were controlled or a pre-post design, and consistent outcome success (log reduction > 2) was observed across all intervention types in all studies. With all studies reporting high log reduction values at appropriate exposures, the true effect is likely quite high, implying good precision.

Fit measurements met all criteria for low risk of bias in both studies.^{39,40} studies were controlled or pre-post design, masks were obtained from a single lot, and measurements were performed by a machine in constant lab conditions. Consistent outcome success (FF > 100) was found. Fit was not included in the meta-analysis, but precision is estimated to be high due to the very high FFs and pass-rates reported in each study and the large numbers of test arms.

Observations of physical changes were unblinded except for ratings of odour by participants in the study performed by Visucsi *et al.* (2011).⁴⁰ All studies with physical observations had a control or pre-post arm, five^{39,40,43-45} out of seven used masks from a single lot, and four^{39,40,43,45} reported constant lab conditions. Mask deformation after autoclaving was consistent in both studies^{20,44} that measured this. Other physical changes appeared to be FFR model-dependent, but many studies did not disclose the names of the mask models making consistency for these reactions unclear. Precision is likely to be high due to the large number of studies that evaluated physical changes but cannot be quantitatively determined.

DISCUSSION

In response to the shortage of PPE during the COVID-19 pandemic, we systematically reviewed the existing literature on N95 FFR-decontamination using microwave irradiation and heat. Our results indicate that moist/dry microwave irradiation and moist/dry heat between 60-90°C can effectively sterilize certain N95 FFR models while maintaining mask fit and function within acceptable ranges. General use of high heat (> 90°C) and autoclaving are not supported by the evidence in review as these interventions more consistently compromised mask integrity. A summary of results can be found in Appendix D.

Decontamination of N95 masks for reuse is only a worthwhile venture if the masks will retain their ability to remove at least 95% of viral particles from the air post-decontamination.⁴ In the six studies that evaluated aerosol penetration after microwave and/or heat treatment, only two studies showed an increase in penetration above the standard 5% threshold: Viscusi *et al.* (2009) measured an aerosol penetration of 5.35% in one model (unspecified SN95) post-dry heat intervention at 110°C; two of the three replicates were unmeasurable in this condition due to melting, and the same model also melted at 100°C and 120°C, indicating that this model is not tolerant of high temperatures. More notably, Viscusi *et al.* (2007)⁴⁴ demonstrated that autoclaving the masks for 15 and 30 minutes significantly increased penetration to three and seven times the maximum acceptable value respectively, which is unsurprising as the authors reported significant observable mask deformation. Interestingly, Lin *et al.* (2017)²⁰ reported no significant change to aerosol penetration after 15 minutes of autoclaving at the same temperature and pressure conditions. The origin of this discrepancy is unclear, but it is possible that it stems from the fact that Lin *et al.* utilized mask fragments rather than full masks and had to use a modified airflow rate during filter testing to account for this. For MGS interventions, the results

of the random effects meta-analysis was consistent with the interpretation that MGS does not significantly impact percent penetration. Mask usability is a function of tolerability in addition to performance. When PPE is in short supply, healthcare workers may wear N95 FFRs for entire shifts rather than single patient encounters.¹⁰ These masks cause breathing resistance and reduce air exchange volume even when brand new;⁴⁷ thus, any intervention that increases resistance significantly could render the masks intolerable, especially when worn for such extended periods. Three studies^{20,43,45} in this review evaluated airflow resistance, in a total of five different decontamination conditions (dry microwave, MGS, MHI, dry heat, and autoclave). The final average airflow resistance in any study did not reach even 50% of the maximum allowable resistance indicated in NIOSH-established guidelines³⁸ for any mask model, and most models actually experienced slight reductions in resistance after decontamination.

High study heterogeneity precluded meta-analysis of germicidal effects of the decontamination treatments; however, descriptive analysis shows that microwave irradiation and heat are both effective strategies of reducing viral load on FFRs. Discounting the two lowest timepoints in Fisher *et al.* (2009)⁴², (with exposure of ≤ 30 seconds at 750W/ft³) every arm of all five studies^{16,17,41,42,46} that investigated pathogen reduction reported a log reduction of greater than two, with all except one exhibiting a reduction of over three log. In fact, post-treatment pathogen load was below the limit of detection in at least 80% of the reported post-treatment results.^{16,41,42} The least successful pathogen reduction occurred in the highest-heat intervention,¹⁷ which may be related to the short duration of treatment (three minutes) or the nature of the pathogen (bacterial rather than viral). It should be noted that there was no data on the germicidal effect of dry microwave radiation. Even though all of the tested methodologies surpass our predetermined threshold for successful decontamination immediately after treatment, germicidal

impact can be further bolstered by leaving the masks for several days after decontamination before reuse, as viruses naturally decay over time on surfaces. For SARS-CoV-2, a wait time of at least three days is advisable as viable virus is detectable up to 72 hours after application on some surfaces.⁴⁸

The limited available data about post-decontamination mask fit was promising. Viscusi *et al.* (2011)⁴⁹ demonstrated that acceptable levels of fit, comfort, and donning ease are maintained over multiple decontamination cycles followed by multiple consecutive donnings, such as would occur when enacting a “limited reuse” strategy.^{10,11} However, one main goal of FFR-decontamination is to avoid the need for reuse of contaminated masks, and so Bergman *et al.*’s³⁹ method (2011) better represents a realistic case of repeated decontamination-donning cycles. The results of both studies indicated that fit may not be a barrier to using MGS and MHI decontamination methods, but the small number of studies and lack of extended use between decontamination cycles limit the strength of the conclusions that can be drawn. A careful user seal check should be performed by any healthcare worker who dons an FFR that has been decontaminated through a microwave or heat treatment.

Physical degradation of the mask will almost invariably cause changes in fit, function, and tolerability. Melting of mask components was observed in both microwave and heat interventions and varied according to mask model and temperature for heat treatments. High heat ($\geq 100^{\circ}\text{C}$) led to adverse physical changes in at least one mask model in all arms (unspecified N95 and SN95) except the very short high-heat intervention used by Lin *et al.* (2017).²⁰ This is unsurprising as polypropylene, the polymer that comprises the N95 filter, begins to melt between 90°C and 100°C .⁵⁰ Institutions that use microwave/heat methods should include frequent physical assessments of each mask in their decontamination protocol; if melting is observed, switching

the mask model or lowering the temperature to $\leq 90^{\circ}\text{C}$ (if using heat) are potential solutions. Reducing duration of high heat may not be a worthwhile modification, as the one study that did this showed weaker germicidal effects than lower heat for longer duration. Separation of the inner foam nose cushion was a common issue across several microwave and heat arms, but was shown not to impact fit⁴⁰ and should not preclude reuse if the mask feels tolerable to the user. Autoclaving does not appear to be a suitable decontamination option for FFRs as it consistently caused significant physical deformations to the masks, although these results come from only two studies that observed one mask model each. Only one study⁴⁶ examined water retention, but this should also be a consideration when choosing which mask models to sterilize using moist microwave or heating methods if drying time is limited.

Future Directions

While the results of this review provide a starting point for the development of institutional microwave- or heat-based FFR decontamination protocols, there are several key gaps in the existing evidence. For example, it is curious that so few studies investigated fit; without a tight seal, air will flow through the gaps between the mask and the wearer's face, bypassing the filter altogether and making outcomes of aerosol penetration and airflow resistance irrelevant. It is also important to note that the high filtration efficiency of N95 FFRs is, in large part, due to the electrostatic charge of the polypropylene filter media.⁵¹ Thus, the tendency of any decontamination procedure to alter the electret's charges will significantly impact mask function post-decontamination, even if no physical changes are observable. The latest research from the inventor of the charging technology used to make N95 filters indicates that FFR filters should retain their charges in moderate heat (such as 70°C), but only if suspended on non-metal

materials, as heated metal can lead to significant charge decay if within six inches of the mask. In this review, no heating studies indicated that the incubator/oven racks and rice cooker bowls – all typically metal – were replaced with alternate materials, and one specifically mentioned a metal oven rack.⁴⁴ Therefore, if impact on airflow and penetration are a concern, it is possible that they could be diminished by using plastic or wooden racks, without compromising the germicidal effects. Further research on the impacts of the various heat and microwave conditions on the charge of the electret is needed to refine decontamination protocols and maximize preservation of filter efficiency.

The characteristics of the microorganisms used in the germicidal studies must also be taken into account when extrapolating these results to SARS-CoV-2. Influenza A viruses, like H1N1 and H5N1 as studied by Heimbuch *et al.*¹⁶ and Lore *et al.*,⁴¹ are enveloped, approximately 120 nm in diameter, and covered in glycoproteins; coronaviruses share all of these characteristics and it is plausible, therefore, that SARS-CoV-2 virions would respond in a similar manner. MS2, as investigated by Fisher *et al.* (2009, 2011),^{42,46} is less comparable as it consists of a non-enveloped 26 nm virion, and bacteria are even more distinct. However, until tests are performed using the new coronavirus itself, the consistent strong germicidal effects across all intervention conditions and all pathogens offers reassurance that these methods should be capable of reducing the load of SARS-CoV-2 to undetectable levels. Additionally, it should be noted that no studies using moderate-temperature MHI interventions quantified growth of non-target bacteria, which could increase under moist heat conditions and pose a separate infectious risk.

Strength of Evidence

The risk of bias across all outcomes was relatively low. While the objectivity of lab measurements of viral/bacterial load are not certain due to lack of blinding, it is unlikely that knowledge of the mask's condition would have significantly impacted lab technique. Physical observations of mask degradation are by nature subjective and must be interpreted as such. Consistency of results for all outcomes (aside from aerosol penetration in autoclave interventions) across studies supports the strength of the findings.

Limitations

Despite there being a reasonable number of studies in this review, the heterogeneity in the conditions under which microwave irradiation and heat were applied limits the ability to draw overarching conclusions about any one set of conditions. Temperature, pressure, and moisture all influenced outcomes, especially in heat-decontamination arms where an autoclave provides a vastly different environment than a dry heat rice cooker. There was also significant variability in mask models between the studies, especially since five studies^{16,40,43-45} did not specify which models were used. The differential physical vulnerabilities of mask models to the microwave and heat interventions were evident from the visual observations of mask melting and deterioration. Thus, the response of a given mask model to a particular set of heat or microwave conditions can help inform decontamination protocol development but does not predict how any other model of mask will react. The results of this review should therefore be used as a resource for determining which microwave and heat conditions may be most auspicious but cannot guarantee the success of any specific protocol.

CONCLUSION

This systematic review indicates that microwaves and heat may both be suitable options for decontamination of N95 FFRs during a PPE shortage, especially for institutions that do not have access to UVGI apparatus. Microwave irradiation and moderate temperature heat ($\leq 90^{\circ}\text{C}$), in both moist and dry conditions, demonstrate effective sterilization without compromising mask performance or function. The most significant disadvantage of both methods was damage to certain mask models. Autoclaving is an effective germicidal but caused significant degradation and reduction of filter efficiency in some mask types, and so its use is not supported by the results of this review. Overall, it is recommended that any mask decontaminated by microwave irradiation or heat is assessed for physical damage before reuse.

Abbreviations:

HCW – Healthcare worker; COVID-19 – Coronavirus Disease 19; CDC – U.S. Centers for Disease Control and Prevention; PHAC – Public Health Agency of Canada; FFR – Filtering facepiece respirator; PPE – Personal Protective Equipment; UV-C – Ultraviolet C; UVGI – Ultraviolet Germicidal Irradiation; PROSPERO - International prospective register of systematic reviews; OSF – Open Science Framework; PRISMA - Preferred Reporting Items for Systematic Reviews and Meta-Analyses; SN95 – Surgical N95; NIOSH – National Institute for Occupational Safety and Health; JISRP - Journal of the International Society for Respiratory Protection; JEFF - Journal of Engineered Fibers and Fabrics; WHO – World Health Organization; CHEO – Children's Hospital of Eastern Ontario; REDCap – Research Electronic Data Capture; GRADE – Grading of Recommendations, Assessment, Development, and Evaluation; FF – Fit Factor; MGS – Microwave-generated steam; MHI – Moist heat incubation; OSHA – Occupational Safety and Health Administration; MDFF₁₀ = Multi-donning fit factor; FSL – face seal leakage; MW – Microwave; MH – Relative humidity; NR – Not reported; AC – Autoclave;

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Figure 1.

Figure 1. Pooled Results assessing Particle Penetration post microwave treatment under moist conditions. This forest plot illustrates the mean particle penetration in masks under after moist microwave treatment. The experimental arm refers to the microwave treated arm. Mask type examined varied by study: Bergman et al. (N95-A, N95-B, N95-C, SN95-D, SN95-E, SN95-F), Fisher et al. (3M 1860, 3M 1870, 3M 8210, KC PFR95), Lore et al. (3M 1860, 3M 1870). Total refers to the number of replicates per mask.

Figure 2. Forest plots showing the log10 reductions of viral load on N95 filtering facepiece respirators

Figure 2a. Log reduction of viral load after moist microwave treatment.

This plot illustrates the viral load log10 reduction in masks after decontamination using microwave-generated steam. Powers and times are reported as described in their respective papers.

Figure 2b. Log reduction of viral load after moist heat incubation.

This plot illustrates the viral load log10 reduction in masks after decontamination using moist heat incubation.

Table 1. Characteristics of studies included in the systematic review of microwave- and heat-based decontamination of N95 filtering facepiece respirators.

Author	Year	Region of origin	Number of decontamination conditions		Number of inoculation conditions (varied parameter)	Number of unique N95 models	Outcomes Evaluated				
			MW	Heat			Aerosol penetration	Airflow resistance	Germicidal effect (pathogen)	Fit	Physical state
Bergman	2010	United States	1	1	–	6	Yes	Yes	No	No	Yes
Bergman	2011	United States	1	1	–	3	No	No	No	Yes	Yes
Fisher	2009	United States	5	–	2 (inoculation medium)	1	No	No	Yes (MS2)	No	No
Fisher	2011	United States	2	–	1	6	Yes	No	Yes (MS2)	No	Yes
Heimbuch	2011	United States	1	1	2 (transmission mode)	6	No	No	Yes (H1N1)	No	Yes
Lin	2017	Taiwan	–	2	–	1	Yes	Yes	No	No	Yes
Lin	2018	Taiwan	–	2	1	1	No	No	Yes (Bacillus subtilis)	No	No
Lore	2012	United States	1	1	1	2	Yes	No	Yes (H5N1)	No	No
Viscusi	2007	United States	2	4	–	1	Yes	No	No	No	Yes
Viscusi	2009	United States	1	5	–	6	Yes	Yes (MW only)	No	No	Yes
Viscusi	2011	United States	1	1	–	6	No	No	No	Yes	Yes

Abbreviations: MW – Microwave

Table 2: Microwave and heat intervention parameters and N95 filtering facepiece respirators (FFRs) for which post-decontamination Aerosol Penetration was evaluated.

Author, Year	Power or Temperature	Time	Cycles per Condition	Moisture	Pressure	N95 Masks Evaluated	
Microwave	Bergman, 2010	750W/ft³	120 s	3	MGS	Room	N95-A N95-B N95-C SN95-D SN95-E SN95-F
	Fisher, 2011	750W/ft³	90 s	3	MGS, Steam Bag X ----- MGS, Steam Bag Y	Room	3M 1860 3M 1870 3M 8210 KC PFR95 Moldex 2200 Cardinal Health
	Lore, 2012	1250 W*	120 s	1	MGS	Room	3M 1860 3M 1870
	Viscusi, 2007	750W/ft³	120 s 240 s	1	Dry	Room	N95 (1 model, unspecified)
	Viscusi, 2009	750W/ft³	120 s	1	Dry	Room	N95-A N95-B N95-C SN95-D SN95-E SN95-F
	Bergman, 2010	60°C	30 min	3	MHI (80% RH)	Room	N95-A N95-B N95-C SN95-D SN95-E SN95-F
	Lin, 2017	149-164°C ----- 121°C	3 min 15 min	1	Dry ----- Steam (autoclave)	Room ----- 1.06 kg/cm²	3M 8210
	Lore, 2012	65°C	20 min	1	MHI (RH unspecified)	Room	3M 1860 3M 1870
	Viscusi, 2007	80°C ----- 160°C ----- 121°C	60 min 15 min 30 min	1	Dry ----- Steam (autoclave)	Room ----- 1.05 kg/cm²	N95 (1 model, unspecified)
	Viscusi, 2009	80°C 90°C 100°C 110°C 120°C	60 min	1	Dry	Room	N95-A N95-B N95-C SN95-D SN95-E SN95-F

Abbreviations: MGS – Microwave-generated steam; MHI – Moist heat incubation; RH – Relative humidity

*Power units per volume not specified

Table 3: Microwave and heat intervention parameters and N95 filtering facepiece respirators (FFRs) for which post-decontamination Airflow Resistance was evaluated.

Author, Year	Power or Temperature	Time	Cycles per condition	Moisture	Pressure	N95 Masks Evaluated
Bergman, 2010	750W/ft ³	120 s	3	MGS	Room	N95-A SN95-D N95-B SN95-E N95-C SN95-F
Viscusi, 2009	750W/ft ³	120 s	1	Dry	Room	N95-A SN95-D N95-B SN95-E N95-C SN95-F
Bergman, 2010	60°C	30 min	3	MHI (80% RH)	Room	N95-A SN95-D N95-B SN95-E N95-C SN95-F
Heat	149-164°C	3 min	1	Dry	Room	
Lin, 2017	121°C	15 min	1	Steam (autoclave)	1.06 kg/cm ²	3M 8210

Abbreviations: MGS – Microwave-generated steam; MHI – Moist heat incubation; RH – Relative humidity

Table 4: Microwave and heat intervention parameters, inoculation conditions, and N95 filtering facepiece respirators (FFRs) for which germicidal effect was evaluated.

Author, Year	Power or Temperature	Time	Cycles per Condition	Moisture	Pressure	Inoculation Parameters			N95 Masks Evaluated
						Pathogen	Inoculation Medium	Transmission Mode	
Fisher, 2009	750W/ft ³	15 s	1	MGS	Room	MS2	100% ATCC 271	Aerosol	N95-A SN95-D N95-B SN95-E N95-C SN95-F
		30 s							
		45 s 60 s 75 s							
Fisher, 2011	750W/ft ³	90 s	1	MGS, Steam Bag X MGS, Steam Bag Y	Room	MS2	100% ATCC 271	Droplet	3M 1870 KC PFR95 Moldex 2200
Heimbuch, 2011	1250 W*	120 s	1	MGS	Room	H1N1	Mucin	Aerosol Droplet	N95-1 SN95-1 N95-2 SN95-2 N95-3 SN95-3
Lore, 2012	1250 W*	120 s	1	MGS	Room	H5N1	NR	Aerosol	3M 1860 3M 1870
Heat	65°C	30 min	1	MHI (85% RH)	Room	H1N1	Mucin	Aerosol Droplet	N95-1 SN95-1 N95-2 SN95-2 N95-3 SN95-3
		149-164°C	3 min	Dry	Room	Bacillus subtilis	Water	Aerosol	3M 8210
		121°C	15 min	1	Steam (autoclave)	1.05 kg/cm ²			
Liu, 2018	121°C	15 min	1	Steam (autoclave)	1.05 kg/cm ²	Bacillus subtilis	Water	Aerosol	3M 8210
Lore, 2012	65°C	20 min	1	MHI (RH unspecified)	Room	H5N1	NR	Aerosol	3M 1860 3M 1870

Abbreviations: MGS – Microwave-generated steam; NR – Not reported; MHI – Moist heat incubation; RH – Relative humidity

*Power units per volume not specified

Table 5. Impacts of microwave-based decontamination strategies on physical characteristics and fit of N95 filtering facepiece respirators.

Author, Year	Microwave Intervention	N95 Models Examined	Method of Physical Assessment	Physical Changes	Odour	Fit
Bergman, 2010	Power: 750W/ft ³ Time: 120s Cycles: 3 Moisture: MGS	N95-A N95-B N95-C	SN95-A SN95-B SN95-C	Physical changes: Visual inspection Odour: Sniffing the mask	SN95-E: slight separation of inner foam nose cushion SN95-D: slight melting of head straps after 1 cycle	No odour reported Not assessed
Bergman, 2011	Power: 750W/ft ³ Time: 120s Cycles: 3 Moisture: MGS	3M 1860 3M 1870 KC PFR95-270	Physical changes: Visual inspection Fit: Fit testing using modified OSHA-standard protocol	3M 1870: slight separation of inner foam nose cushion KC PFR95: strap melted during third cycle	Not assessed	Fit test pass rate remained $\geq 90\%$ for all masks No significant changes in faceseal leakage
Fisher, 2011	Power: 750 W/ft ³ Time: 90s Cycles: 1, 3 Moisture: MGS (steam bag)	3M 1870 3M 1860 KC PFR95 3M 8210 Cardinal Health Moldex 2200	Physical changes: Water retention evaluated by comparing initial mask weight to weight after sterilization and drying at room conditions	3M1860, 3M8210 & Cardinal Health: water retained after 60 min drying 3M 1870, KC PFR95 & Moldex 2200: low water absorbency, dry within 30 min	Not assessed	Not assessed
Heimbuch, 2011	Power: 1250W Time: 120s Cycles: 1 Moisture: MGS	N95-1 N95-2 N95-3	SN95-1 SN95-2 SN95-3	Physical changes: Visual inspection	S2: slight separation of inner foam nose cushion	Not assessed
Viscusi, 2007	Power: 750W/ft ³ Time: 120s, 240s Cycles: 1 Moisture: Dry	N95 (1 model, unspecified)	Physical changes: Visual inspection	240s: exposure filter media melted at ends of aluminum nose bands	Not assessed	Not assessed
Viscusi, 2009	Power: 750W/ft ³ Time: 120s Cycles: 1 Moisture: Dry	N95-A N95-B N95-C	SN95-D SN95-E SN95-F	Physical changes: Visual inspection Odour: Sniffing the mask	SN95-E: all replicates had respirator components melted	No odour reported Not Assessed
Viscusi, 2011	Power: 750W/ft ³ Time: 120s Cycles: 1 Moisture: MGS	3M 8000 3M 8210 Moldex 2200 KC PFR95-270 3M 1860 3M 1870	Physical changes: Visual inspection Odour: Sniffing the mask, questionnaire Fit: Multiple donning fit testing using modified OSHA-standard protocol Comfort/Donning Ease: questionnaire	Moldex 2200: strap breaks in both control and treatment 3M 1870: slight separation of inner foam nose cushion and one strap break	No odour reported	Fit: No significant difference Comfort/Donning Ease: No significant difference

Abbreviations: MGS – Microwave-generated steam; SN95 – Surgical N95

Table 6. Impacts of heat-based decontamination strategies on physical characteristics and fit of N95 filtering facepiece respirators.

Author, Year	Heat Intervention*	N95 Models Examined	Method of Physical Assessment	Physical Changes	Odour	Fit
Bergman, 2010	Temperature: 60°C Time: 30 min Cycles: 3 Moisture: MHI (80% RH)	N95-A N95-B N95-C	Physical changes: Visual inspection Odour: Sniffing the mask	SN95-E: slight separation of inner foam nose cushion	No odour reported	Not assessed
Bergman, 2011	Temperature: 60°C Time: 30 min Cycles: 3 Moisture: MHI (80% RH)	3M 1860 3M 1870 KC PFR95-270	Physical changes: Visual inspection Fit: Fit testing using modified OSHA-standard protocol	3M 1870: slight separation of inner foam nose cushion	Not assessed	Fit test pass rate remained $\geq 90\%$ for all masks No significant changes in faceseal leakage
Heimbuch 2011	Temperature: 65°C Time: 30 min Cycles: 1 Moisture: MHI (85% RH)	N95-1 N95-2 N95-3	Physical changes: Visual inspection	No significant changes	Not assessed	Not assessed
Lin, 2017	Temperature: 149-164°C Time: 3 min Cycles: 1 Moisture: Dry	3M 8210	Physical changes: Visual inspection	No significant changes reported	Not assessed	Not assessed
	Temperature: 121°C Time: 15 min Cycles: 1 Moisture: Steam (AC) Pressure: 1.06 kg/cm ²	3M 8210	Physical changes: Visual & tactile inspection	Outer layers of masks were deformed, shrunken, and stiff with no remarkable mottle	Not assessed	Not assessed
	Temperature: 80°C & 160°C Time: 60 min Cycles: 1 Moisture: Dry	N95 (1 model, name unspecified)	Physical changes: Visual & tactile inspection	80°C: No significant changes 160°C: Masks melted and unusable after 22 min	Not assessed	Not assessed
Viscusi, 2007	Temperature: 121°C Time: 15 min & 30 min Cycles: 1 Moisture: Steam (AC) Pressure: 1.05 kg/cm ²	N95 (1 model, name unspecified)	Physical changes: Visual & tactile inspection	Masks deformed, shrunken, stiff, and mottled at both durations.	Not assessed	Not assessed
Viscusi, 2009	Temperature: 80°C, 90°C, 100°C, 110°C, 120°C Time: 60 min Cycles: 1 Moisture: Dry	N95-A N95-B N95-C	Physical changes: Visual inspection Odour: Sniffing the mask	SN95-D samples at 100°C, 110°C, and 120°C: inner moisture barrier melted into the filtration media	No odour reported	Not assessed
Viscusi, 2011	Temperature: 60°C Time: 30 min Cycles: 1 Moisture: MHI (80% RH)	3M8000 3M8210 3M1860 3M1870	Physical changes: Visual inspection Odour: Sniffing mask, questionnaire Fit: Multiple donning fit testing using modified OSHA-standard protocol Comfort/Donning Ease: questionnaire	Moldex 2200: strap breaks in both control and treatment	3M 1860: increased odor No other odours reported	Fit: 3M 8210 & Moldex 2200 had reduced MDFE ₁₀ , but passed fit test Comfort/Donning Ease: No significant difference

*Room pressure unless specified otherwise.

Abbreviations: MHI – Moist heat incubation; RH – Relative humidity; SN95 – Surgical N95; AC = Autoclave; MDFE₁₀ = Multi-donning fit factor

APPENDIX A. PRISMA Flow Diagram

APPENDIX B. 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. Microwaves/
8. (microwav* or micro wav*).tw,kf.
9. ((ehf or extremely high frequenc*) adj2 (wave or waves)).tw,kf.
10. ((ultrahigh or ultra high) adj2 (wave or waves)).tw,kf.
11. Steam/ or Hot Temperature/
12. (Heat or heated or heating or moist or steam or oven or pasteur* or autoclave).tw,kf. not (Body Temperature/ or Body Temperature Regulation/ or exp Heat Stress Disorders/)
13. or/7-12
14. 6 and 13
15. limit 14 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. microwave radiation/
8. (microwav* or micro wav*).tw,kw.
9. ((ehf or extremely high frequenc*) adj2 (wave or waves)).tw,kw.
10. ((ultrahigh or ultra high) adj2 (wave or waves)).tw,kw.
11. water vapor/
12. high temperature/
13. (Heat or heated or heating or moist or steam or oven or pasteur* or autoclave).tw,kw. not (Body Temperature/ or Body Temperature Regulation/ or exp Heat Stress Disorders/)
14. or/7-13
15. 6 and 14
16. limit 15 to ((english or french) and yr="1972 -Current")

Global Health

All fields search:

((microwav* or "ultrahigh wav* or "ultra high wav*" or heat or steam or moist or oven or autoclave or pasteur* or decontaminate or decontamination) AND ("respiratory protective device*" or "face shield*" or faceshield* or n95 or n-95 or ffr or ffrs or "filtering face*"))

Scopus

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

Google Scholar

**(respiratory protective device*| n95|n-95|ffr|ffrs|filtering
face*)(microwav*|heat|steam|moist|oven|pasteurize|autoclave)**

WHO database

Records were downloaded from <https://www.who.int/emergencies/diseases/novel-coronavirus-2019/global-research-on-novel-coronavirus-2019-ncov> and imported into Reference Manager where relevant records were identified with the following search strings:

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
{decontam*} OR {sterili*} OR {microwav*} OR {heat} OR {steam} OR {moist} OR {oven}
OR {pasteurize} OR {autoclave}

APPENDIX C. Risk of bias in studies included in the systematic review.

Author, Year	Design: Controlled study and/or pre-post design	Methodology: Outcome evaluations performed in constant lab conditions	Population: Masks obtained from same lot to minimize lot-to-lot variation	Outcome: Evaluators blinded to study arm or outcome evaluated objectively (result provided by a machine)
Bergman, 2010	Yes	Yes	Yes	Aerosol Penetration: Objective Airflow Resistance: Objective Physical State: Not blinded
Bergman, 2011	Yes	Yes	Yes	Fit: Objective Physical state: Not blinded
Fisher, 2009	Yes	Yes	Not reported	Germicidal: Not blinded
Fisher, 2011	Yes	Not reported	Not reported	Aerosol Penetration: Objective Germicidal: Not blinded
Heimbuch, 2011	Yes	Not reported*	Not reported	Germicidal: Not blinded Physical State: Not blinded
Lin, 2017	Yes	Not reported	Not reported	Aerosol Penetration: Objective Airflow Resistance: Objective Physical State: Not blinded
Lin, 2018	Yes	Not reported	Not reported	Germicidal: Not blinded
Lore, 2012	Yes	Not reported*	Not reported	Aerosol Penetration: Objective Germicidal: Not blinded
Viscusi, 2007	Yes	Not reported	Yes	Aerosol Penetration: Objective Physical State: Not blinded
Viscusi, 2009	Yes	Yes	Yes	Aerosol Penetration: Objective Airflow Resistance: Objective Physical State: Not blinded
Viscusi, 2011	Yes	Yes	Yes	Fit: Objective Physical State: Odour, comfort, donning ease – Blinded Physical examination - Not blinded

*Heimbuch (2011) and Lore (2012) specified constant conditions during aerosol application of virus to mask, but not during outcome measurement

APPENDIX D. Summary of reported outcomes. Green and red cells indicate outcome success and failure respectively; yellow indicates mixed results. Outcome successes are defined as aerosol penetration < 5%, airflow resistance < 25 mmH₂O, Fit Factor > 100, and no physical changes.

Inter-vention	Subtype	Studies	Outcomes				
			Aerosol Penetration	Airflow Resistance	Germicidal Effect	Fit	Physical State (mask model)
Microwave	Dry	Viscusi 2007 Viscusi 2009	No significant increase; Remained < 5%	No significant increase; Remained < 25mmH ₂ O	Not assessed	Not assessed	Melting of one model each at 120 sec (UNS) and 240 sec (UNS)
	MGS	Bergman 2010 Fisher 2009 Fisher 2011 Heimbuch 2011 Lore 2012 Viscusi 2011	No significant increase; Remained < 5%	No significant increase; Remained < 25mmH ₂ O	Effective decontamination at durations > 30 sec; Log reduction > 3	Maintained fit; FF ≥ 100 for ≥ 90% of masks.	Slight separation of nose cushion from mask (3M 1870, UNS) or melting of strap (KC PFR95, UNS)
	Dry	Lin 2017 Viscusi 2007 Viscusi 2009	No significant increase; Remained < 5%	No significant increase; Remained < 25mmH ₂ O	Effective decontamination; Log reduction > 2	Not assessed	Melting of some models at temperatures ≥ 100°C (UNS)
	MHI	Bergman 2010 Bergman 2011 Heimbuch 2011 Lore 2012 Viscusi 2011	No significant increase; Remained < 5%	No significant increase; Remained < 25mmH ₂ O	Effective decontamination; Log reduction > 4	Maintained fit; Mean FF > 100 for all models.	Slight separation of nose cushion from mask in certain models (3M 1870, UNS)
Heat	AC	Lin 2017 Lin 2018 Viscusi 2007	Mixed results; Large increase (> 5%) reported in one study	No significant increase; Remained < 25mmH ₂ O	Effective decontamination; Log reduction > 4	Not assessed	Masks deformed, shrunken and stiff (3M 8210, UNS)

Abbreviations: MGS – Microwave-generated steam; MHI – Moist heat incubation; AC – Autoclave; FF – Fit Factor; UNS – Unspecified mask model(s)