DECONTAMINATION INTERVENTIONS FOR THE REUSE OF SURGICAL MASK PERSONAL PROTECTIVE EQUIPMENT: A SYSTEMATIC REVIEW

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Running Title: Surgical Mask Decontamination

ABSTRACT

Background: The high demand for personal protective equipment (PPE) during the novel coronavirus outbreak has created global shortages and prompted the need to develop strategies to conserve supply. Surgical mask PPE have a broad application of use in a pandemic setting, but little is known regarding decontamination interventions to allow for their reuse. **Objective:** Identify and synthesize data from original published studies evaluating interventions to decontaminate surgical masks for the purpose of reuse. **Methods:** We searched MEDLINE, Embase, CENTRAL, Global Health, the WHO COVID-19 database, Google Scholar, DisasterLit, preprint servers, and prominent journals from inception to April 8, 2020 for prospective original research on decontamination interventions for surgical mask PPE. Citation screening was conducted independently in duplicate. Study characteristics, interventions, and outcomes were extracted from included studies by two independent reviewers. Outcomes of interest included impact of decontamination interventions on surgical mask performance and germicidal effects. **Results:** Seven studies met eligibility criteria: one evaluated the effects of heat and chemical decontamination interventions applied *after* mask use on mask performance, and six evaluated interventions applied *prior* to mask use to enhance antimicrobial properties and/or mask performance. Mask performance and germicidal effects were both evaluated in heterogeneous test conditions across a variety of mask samples (whole masks and pieces or individual mask layers). Safety outcomes were infrequently evaluated. Mask performance was best preserved with dry heat decontamination. Germicidal effects were best in salt-, N-halamine- and nanoparticle-coated masks. **Conclusion:** There is limited evidence on the safety or efficacy of surgical mask decontamination. Given the heterogeneous methods used in the studies to date, we are unable to draw conclusions on the most appropriate, safest intervention(s) for decontaminating surgical masks for the purpose of reuse.

Keywords: COVID-19, SARS-CoV-2, PPE, decontamination, masks, surgical masks, systematic review

PRE-PRINT

Background & Rationale

As the global spread of novel coronavirus (SARS-CoV-2) continues to escalate, so has the demand for personal protective equipment (PPE), creating global shortages in the supply of N95 filtering face respirators (FFRs) and surgical masks. N95 FFRs are recommended by the World Health Organization (WHO) and the Centers for Disease Control and Prevention (CDC) for use by healthcare providers (HCPs) caring for coronavirus disease (COVID-19) patients requiring airborne precautions and during aerosol-generating procedures [1, 2]. Therefore, N95 FFRs are most commonly needed for HCPs in acute care and inpatient settings.

In contrast, surgical masks are recommended for use by HCPs to protect against the risk of droplet transmission in a broader range of inpatient healthcare settings, as well as outpatient settings (e.g. COVID-19 assessment centres, long-term care facilities, and community care settings) [2-4]. Surgical masks are also recommended for use by patients with suspected or confirmed COVID-19 to prevent potential spread in a variety of healthcare settings [2, 4]. PPE recommendations are dynamic and continue to broaden in response to the spread and our growing understanding of SARS-CoV-2 [4, 5]. Several institutions now recommend that everyone entering the hospital setting wear a surgical mask, regardless of whether they will have patient contact [6]. Furthermore, as the supply of N95 FFRs is threatened, healthcare professionals may resort to use of surgical masks for airborne precautions [3, 7-9].

These practices have created an unprecedented demand for surgical masks; unfortunately, the capacity for surge production of PPE is not sustainable in the long-term [7-9]. As most facemask PPE are designed for single-use, mask rationing and conservation is now a top priority globally [10]. Reusing these disposable masks is now suggested as a crisis capacity strategy to conserve available supplies during a pandemic [2, 10-12]. Subsequently, much attention has now turned to reprocessing and decontamination of facemask PPE. Several strategies such as

ultraviolet germicidal irradiation (UVGI), chemical disinfectants (e.g. hydrogen peroxide vapour, ethanol), and microwave- and heat-based methods have been evaluated; however, most of this literature has focussed on the decontamination of N95 FFRs [13-15].

The evidence on the efficacy and safety of decontamination and reuse of surgical masks is unclear. The objective of this systematic review was to evaluate and synthesize the evidence on decontamination or sterilization interventions for the purpose of surgical mask PPE reuse.

Methods

This systematic review protocol was designed *a priori*, registered on PROSPERO (April 15th, 2020; CRD42020178290), and uploaded as a pre-print on Open Science Framework (April 8th, 2020; <https://osf.io/8wt37/>) [16]. The reporting of this systematic review is in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Appendix A) [17].

Eligibility Criteria

Studies published in English or French were eligible for inclusion if the following criteria were met: 1) The study was original research, including systematic reviews; 2) The study evaluated surgical facemask PPE or their components; 3) The study evaluated any intervention(s) to decontaminate, sterilize or treat surgical masks (applied either before or after their use) for the purposes of reuse as PPE; 4) At least one of the following efficacy or safety outcomes of interest was reported: a) mask filtration performance (i.e. filtration efficiency and airflow resistance); b) reduction in pathogen load; c) clinical infection rates following use of the decontaminated masks; d) changes in physical state (i.e. mask appearance or physical degradation); e) adverse effects experienced by the wearer (e.g. skin irritation); or f) feasibility of the intervention (e.g. time, cost,

resource utilization). We excluded editorials, case reports, narrative reviews, study protocols, clinical practice guidelines, grey literature, book chapters, and patents.

Database Search & Study Selection

Two health sciences librarians (LS, MS) searched the following electronic databases from their dates of inception to April 8th, 2020: Medline and Medline in Process via OVID, Embase Classic + Embase via OVID, Cochrane CENTRAL (February 2020 issue) and Global Health via CAB Direct. A search strategy was developed in Medline, and then translated into the other databases, as appropriate (Appendix B). Language was restricted to English or French, with no other publication restrictions.

Three journals were also hand-searched, as they were particularly relevant to the review but are not indexed in any of the electronic databases: Journal of the International Society for Respiratory Protection, Aerosol Science and Technology, and the Journal of Engineered Fibers and Fabrics. A search of Google Scholar (April 8th, 2020) through Publish or Perish was screened until 50 consecutive apparently irrelevant citations 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 as of April 7th, 2020 was downloaded and searched within Reference Manager. Disaster Lit: Database for Disaster Medicine and Public Health, MedRxiv, and OSF Preprints were searched on April 8th, 2020 and citations pertaining to decontamination were selected and downloaded. All citations were entered into an Endnote file and duplicates were removed.

Citation Screening & Data Extraction

Citations were uploaded to insightScope (www.insightscope.ca) for title/abstract screening and full text review. Citation screening for title/abstract and full text review stages was conducted

independently and in duplicate by a team of 11 reviewers recruited from McMaster University, the University of Ottawa, and the University of Manitoba. Prior to gaining access to the full set of citations, each reviewer read the systematic review protocol and was required to achieve a sensitivity of at least 80% when screening a test set of 50 citations (containing 5 true positives and 45 true negatives). Reviewers achieving less than 80% sensitivity on the test set were provided with additional training prior to gaining access to the full set of citations. At both title/abstract and full text review, citations were excluded only if both reviewers agreed to exclude; disagreements were reviewed and resolved by the study leads where necessary (DZ, KC). Upon completion of full text review, the study co-lead (DZ) reviewed all retained citations to identify potential duplicates and confirm eligibility. The reference lists of all citations included for full text review were searched for potential eligible citations that may have evaded the initial database search.

Data were collected using electronic data extraction forms (Microsoft Excel) modified from previous systematic reviews [13, 14] for this protocol and piloted by two investigators (DZ, SG) on two eligible studies. Data was extracted from the full text publication and any related publications, referenced published protocols, or supplementary materials. Data extraction was completed in duplicate by two independent reviewers. Where necessary, graphical data was extracted using SourceForge Plot Digitizer (<http://plotdigitizer.sourceforge.net>) and checked by the second reviewer for accuracy. Disagreements were resolved by reviewer consensus and discussion with the study leads (DZ, KC), where necessary.

Risk of Bias Assessment

We planned to use recommended risk of bias tools where appropriate [18]; however, in the absence of a standard risk of bias tool for laboratory studies, we applied objective assessment

criteria developed for this purpose [15]. Risk of bias was assessed by two reviewers independently and in duplicate at the study level by outcome in the following domains: study design, methodological consistency, population heterogeneity, sampling bias, outcome evaluation, and selective reporting (Appendix C).

Outcomes

The primary outcome for this study was efficacy and safety of the decontamination intervention, as determined by any of the following: mask performance (filtration efficiency [FE] and airflow resistance); reduction in pathogen load; clinical infection rates following use of treated masks; mask appearance or physical degradation; or adverse effects experienced by the wearer (e.g. skin irritation). FE refers to the percentage of particles filtered at a specified particle size, which may be 0.1 μ m or 3 μ m depending on the testing agent and standard used [19]. For this systematic review, we converted study results reporting percentage particle penetration, to FE units (i.e. $FE\% = 100 - \text{particle penetration}$) for comparability [19]. Airflow resistance is measured as the pressure drop across the mask, quantifying initial resistance to airflow in millimetres of water column height pressure per square centimeter (mmH₂O/cm²) [20]. Greater airflow resistance indicates less breathability of the mask. Reduction in pathogen load/titers was reported as the log reduction from a time zero post-inoculation to a subsequently measured time point. If log reductions were not reported by the study, we calculated them using the pathogen load data provided (e.g. colony counts), where possible. A log reduction ≥ 3 was used as a reference indicating good germicidal effect [21]. The secondary outcome was feasibility of the intervention, such as the time, cost and resources required to implement the intervention.

Where series of results were presented for multiple experimental conditions, we report the summary of results conducted at the harshest testing conditions, to allow a conservative interpretation of the outcomes evaluated [19].

Statistical Analysis

Primary outcome data was analysed descriptively and presented using absolute values and as a percent change where possible. No three studies evaluated the same intervention, nor applied similar test agents or conditions when evaluating outcomes. This precluded pooling of data and planned quantitative analysis of outcomes [16]; therefore, selected results from included studies were summarized descriptively.

Results

Study Identification

Nine of 11 reviewers achieved the 80% sensitivity threshold on the test set. The two reviewers who did not achieve the 80% threshold were provided additional training regarding the screening protocol prior to citation screening. The review team achieved kappa values of 0.44 and 0.45 for title/abstract and full text screening respectively. Study leads resolved conflicts in 3.0% title/abstract and 12.1% full text screening citations.

A total of 2191 records were identified through the initial database search, of which 1874 unique citations were reviewed and 33 full-texts were retained and assessed for eligibility.

Twenty-six full texts were excluded for not meeting eligibility criteria, leaving seven unique studies for inclusion in our analysis (PRISMA diagram, Figure 1). No additional citations were identified on review of reference lists.

Study Characteristics

Characteristics of included studies are summarized in Table 1. Only one of the seven included studies specifically evaluated decontamination interventions applied *after* surgical mask wear, for the purpose of reuse [22]. The remaining six studies evaluated interventions applied to masks or mask components *prior* to use to enhance antimicrobial properties and/or FE for potential reuse or extended use (i.e. pre-contamination interventions) [23-28]. Interventions in these studies were tested on coated and control (uncoated) whole masks, pieces of whole masks (referred hereafter as mask pieces) or pieces of individual mask layers (referred hereafter as mask layer pieces). Risk of bias assessments for the included studies are described in Appendix D.

Decontamination Interventions for Surgical Mask Reuse

Lin *et al.* [22] evaluated five decontamination interventions on two surgical mask types commonly used in Taiwanese hospitals (gauze double-layer electret masks and Oimo spunlace non-woven masks; models unspecified): dry heat (via rice cooker), high-pressure moist heat (i.e. autoclave), and three chemical agents (70% ethanol, 100% isopropanol, and 0.5% sodium hypochlorite [i.e. bleach])[22]. The methods and findings of this study are summarized in Table 2. Mask pieces were assessed for FE, airflow resistance, and physical characteristics after each intervention was applied. FE was presented graphically for a range of particle sizes (0.0146 μ m to 0.594 μ m); we summarized the results for FE at 0.1 μ m, a standard particle size for viral FE testing [19]. At baseline, gauze and spunlace masks had FEs of approximately 87% and 45%, respectively. FE for both masks decreased after each of the five decontamination interventions, but the smallest change was observed following dry heat treatment of the gauze mask (absolute reduction of 1.3% FE). Moist heat and chemical decontamination interventions all resulted in greater FE decreases in both mask types, with absolute reductions ranging from 12% to 36%.

Bleach was the most damaging method, resulting in an absolute FE reduction of 15.3% in the spunlace mask and destruction of the gauze mask.

Airflow resistance was assessed at a flow rate of 5.95 L/min [22]. Statistically significant changes in pressure drop were reported following all decontamination interventions, except for dry heat and ethanol on gauze mask pieces. Airflow resistance results were not reported for bleach on gauze masks (mask destroyed), or isopropanol for either mask type. Physical appearance changes were reported only for gauze masks; the autoclave deformed and caused observable folds in the mask filter, and bleach destroyed the mask. Physical characteristics following decontamination with other interventions, or in spunlace masks, were not reported. This study did not assess the germicidal effects of any of the five decontamination methods.

Pre-Contamination Interventions

Six studies evaluated five unique pre-contamination methods applied prior to mask use: four were antimicrobial interventions (nanoparticle emulsion [24, 25], quaternary ammonium agent [28], monochlorinated N-halamine [23], sodium chloride [NaCl] salt [26]), and one was a fluorochemical repellent [27] (Table 1).

These interventions have a variety of proposed mechanisms of action. Quan *et al.* [26] evaluated multiple concentrations of “salt-functionalized filters”—a NaCl salt coating applied to the polypropylene middle layer of a three-ply surgical mask, which inactivates viruses by hyperosmotic stress upon the viral envelope. Tseng *et al.* [28] tested a quaternary ammonium agent (Goldshield 5 [GS5], AP Goldshield LLC, USA), a disinfectant commonly used in medical, commercial and household settings. Demir *et al.* [23] applied a monochlorinated N-halamine coating onto the polypropylene layer of a surgical mask, which inactivates Gram-negative and Gram-positive bacteria through direct transfer of oxidative halogens to the cell membrane. Li *et*

al. [24, 25] conducted two studies evaluating a silver nitrate and titanium dioxide nanoparticle emulsion coating of the outer layer of a surgical mask. Silver inactivates bacteria by interacting with the thiol groups of proteins and enzymes, and titanium oxide creates microbicidal hydroxyl radicals [24]. Finally, Shen *et al.* [27] applied a fluorochemical finish (Zonyl® PPR Protector, Ciba Specialty Chemicals, Switzerland) to the outer layer of surgical masks to enhance resistance to fluid penetration.

Filtration Efficiency and Airflow Resistance Following Pre-Contamination

Five studies evaluated the effects of their intervention on FE, airflow resistance, or both, applying different testing techniques (Table 3). Quan *et al.* used aerosolised H1N1 influenza virus (2.5µm to 4µm particle diameter) to evaluate FE on polypropylene mask filter pieces and found that increasing concentrations of the salt coating increased filter FE (54.4%, 69% and 83.9% for 3, 11 and 19 mg NaCl/cm², respectively) [26]. Airflow resistance was not assessed in this study. Tseng *et al.* evaluated FE of GS5-coated mask layer pieces using aerosolized bacteria (0.5µm to 2.1µm particle diameter) and GS5-coated masks using NaCl (0.075µm particle diameter), respectively, compared to uncoated controls. They found no statistically significant change in FE in the GS5-coated masks or mask layer pieces (0.6% to 1.8% FE increase in polypropylene filter layer, 1.8% FE reduction in mask; p=NS) [28]. Airflow resistance was also not significantly affected (pressure drop change of 1.0 mmH₂O; p=NS). Demir *et al.* only assessed airflow resistance and found similar results in N-halamine-treated polypropylene filters compared to untreated filters (26.7 ml/s/cm²; p=NS) [23].

Li *et al.* [25] used a potassium-fluorescein solution (particle size not reported) to test nanoparticle-coated full masks and expressed their results in FE as: 1) the percentage potassium content of each mask layer relative to the potassium content of the whole mask; and 2) a seven

point scale rating fluorescent stains on the face of mask users. They found that the percentage potassium content of each mask layer was similar compared to uncoated masks (+2%, -3% and +1.5% absolute difference from control for outer, middle and interior mask layers, respectively), and similar ratings of fluorescent stains. Airflow resistance was non-significantly increased (+1.4 ml/s/cm²; p=NS). Shen *et al.* [27] used an aerosolized pathogen simulant (1.0µm particle diameter) and also quantified FE as the percentage particle content of each mask layer to the particle content of the whole mask. They reported significant decreases in particle content on the repellent-coated outer mask layer coated with repellent (p<0.0001), but no changes to particle content on mask layers distal to the filter layer (suggesting no changes to FE of the mask as a whole). Airflow resistance was not assessed.

Germicidal Effects of Pre-Contamination Interventions

Four studies evaluated germicidal effects using a variety of aerosolized pathogens [23, 26, 28] or bacterial suspensions [23, 24], and assessed the change in pathogen load upon the mask or mask component(s) tested after different incubation periods (Table 3). All three tested concentrations of salt-treated polypropylene mask filters exhibited reductions in bacterial colony counts at 5 and 15 minutes post-incubation, and were below detection limit (BDL) by 60 minutes [26].

Germicidal effect was strongest in the 19 mg NaCl/cm² salt-coated mask filter (log reduction ≥ 3 at 5 and 15 minutes, and BDL at 60 minutes). Colony counts demonstrated a greater than 3 log reduction in N-halamine-coated mask filters when evaluated 10 minutes after a 3-hour bacterial aerosol test [23], and in the nanoparticle-coated mask outer layer at 24 hours post-incubation with bacterial suspensions [24]. GS5-coated mask layers did not appear to achieve adequate reduction in pathogen load (log reduction ≤ 1 in all experiments) [28].

In vivo infection was evaluated by Quan *et al.*, where 16-day survival of mice was assessed following exposure to aerosolized influenza viruses through a salt-treated mask filter barrier compared to an uncoated filter barrier. Mice sheltered by uncoated filter barriers were euthanized after losing more than 25% of their body weight (a surrogate outcome for mortality) by day 16, while none of the mice sheltered by the salt-coated mask filter irrespective of salt coating concentration, met this endpoint (i.e. 100% survival rate) [26]. Lung viral titers were also assessed; titers were lower, but still detectable, in lungs of mice sheltered by the salt-coated mask filters compared to those sheltered by uncoated filter barriers.

Physical Characteristics and Adverse Events following Pre-Contamination

Two studies assessed physical characteristics of nanoparticle-coated masks and/or adverse effects after their use in human subjects [24, 25]. A survey of blinded users of nanoparticle-coated and uncoated masks demonstrated no differences in perceived heat, humidity, odour, breathability, itchiness, or user comfort between the two groups ($p=NS$ in each survey domain) [25]. Symptom inquiry and physical examination of the facial skin in users of nanoparticle-coated and uncoated masks demonstrated no signs or symptoms of skin irritation between the two groups [24].

Discussion

This systematic review on the evidence for decontamination interventions for surgical mask PPE reveals the following key findings. First, there is a paucity of research evaluating decontamination interventions on surgical masks; there is only one study evaluating methods intended for decontaminating masks following use, and six studies evaluating pre-contamination methods to enhance the antimicrobial and/or filtration performance of surgical masks. Second, included studies evaluated different interventions, using heterogenous and non-standardized test

conditions, and assessed a variety of outcomes using inconsistent methods. This limits our ability to make comparisons between interventions and conclusions regarding their efficacy or safety. Furthermore, no studies provided explicit information on the feasibility, resource requirements, or applicability of these decontamination methods in institutional or hospital settings, making it challenging to determine if any of the interventions evaluated could be easily implemented during situations of high PPE demand.

Each decontamination intervention used in the included studies is founded in evidence-based scientific rationale. Heat is known to inactivate pathogens, including coronaviruses [29-31]; moist heat is a standard intervention for sterilization in healthcare facilities [32, 33]. The chemical disinfectants evaluated in the included studies are also widely used in household, commercial, healthcare, and food industry settings [32, 34]. Based on the limited evidence in this review, dry heat may alter surgical mask performance less than high-pressure moist heat or chemical interventions; however, the germicidal effect of dry heat in surgical masks is unclear. Bleach is not a safe method of decontaminating surgical masks; surgical mask performance is significantly altered and safety data from N95 FFR studies suggest potential health risks associated with off-gassing [15]. With respect to pre-contamination interventions, masks coated with salt films, GS5, nanoparticle emulsion and N-halamines were reported not to significantly alter mask performance. Of the interventions tested, N-halamine and nanoparticle emulsion showed strong germicidal effects in masks (log reductions ≥ 3), which is consistent with their application in medical devices [35], and food and water treatment [36]. Salt films also demonstrated strong germicidal effects in masks, but their application has been experimental to date [26]. An important consideration is that pathogen load was evaluated at different post-inoculation incubation time points in each study (i.e. five minutes to 24 hours) and it is well-established that viral load reductions can occur by virtue of time [37].

Ideal PPE decontamination methods should not only demonstrate effective reductions in pathogen burden, but also preserve the structural and functional integrity of the mask without causing any residual chemical hazard to the wearer [38]. The evidence that we have collated in this systematic review is therefore important and essential. However, we advise caution when interpreting some of the results of included studies for the following reasons: 1) some of the mask types used in these experiments appear to have baseline filtration efficiencies below reference standards which may have affected the results observed [19]; 2) experiments and test conditions applied to mask pieces or individual layers cannot necessarily be extrapolated to whole masks; and 3) the testing conditions and methods of reporting results were heterogenous. In contrast to N95 FFRs, surgical masks are not certified under the National Institute for Occupational Safety and Health regulations. The Food and Drug Administration recommends that several standards (ASTM F2101, ASTM 2299, Mil-M369454C, or modified Greene and Vesley method) may be applied to surgical masks, complicating the evaluation of mask performance in this study [19].

This systematic review reveals that the body of evidence on decontamination interventions for surgical masks is scant compared to N95 FFRs. Three recent systematic reviews have revealed 22 unique studies evaluating interventions such as microwave irradiation, heat, chemical disinfectants, and ultraviolet germicidal irradiation (UVGI) for decontamination of N95 FFRs [13-15]. UVGI and vaporous hydrogen peroxide were the most commonly evaluated and showed favourable evidence for germicidal effects without significant harm to mask performance; however, we were not able to find any publications evaluating these methods in surgical masks. The lack of research on surgical masks may stem from assumptions that methods effective in N95 FFRs can be extrapolated to surgical masks; some institutions are already applying the same decontamination methods to both N95 FFR as well as surgical masks [39]. Considering this systematic review demonstrates that different mask types can perform

differently after decontamination, and that surgical masks and N95 FFRs perform differently with aerosol challenges [22, 40], we cannot conclude that the same decontamination methods can be effectively or safely applied to all mask PPE types. Furthermore, there is limited data evaluating the effectiveness of any decontamination intervention against SARS-CoV-2 on PPE [39, 41], although more studies are underway. Independent research on surgical masks is therefore critical in order to inform clinicians, infection control experts, and public health administrators on how best to advise safe decontamination and reuse practices.

Strengths & Limitations

Our systematic review has several important strengths. To our knowledge, this is the first systematic review of decontamination interventions for the reuse of surgical mask PPE and provides important information describing the nature of interventions and outcomes evaluated to date. Our review highlights the variability in methodology and reporting of evaluated outcomes. As a result, we identified the following core outcomes to consider when conducting research in this field, to encourage more consistency in methodology and transparency of reporting: mask performance (FE, airflow resistance), decontamination effects (germicidal effects, *in vivo* infection rates), physical characteristics of decontaminated masks, adverse effects to mask users, and feasibility of the intervention. We also developed a systematic tool with which to assess risk of bias in this body of literature.

Our review also has limitations. We were unable to conduct any meta-analyses due to the paucity of studies and their heterogeneous methodologies and outcome assessments. Outcomes described in this systematic review required summarizing study results from multiple experiments; we rationalized the selective reporting of results in our methods to encourage conservative interpretation of the findings. Given the rapidly evolving landscape of PPE literature during the

SARS-CoV-2 pandemic, we plan to update this systematic review at regular intervals for new relevant evidence as it becomes available (i.e. living systematic review) [42].

Conclusion

There is inadequate evidence on the safety or efficacy of any decontamination intervention for extended use or reuse of surgical masks in the clinical setting. Further research should therefore be conducted specifically in surgical masks, that include decontamination interventions demonstrating promise in N95 FFRs (e.g. UVGI, vaporized hydrogen peroxide). To ensure the safety of HCPs and all end users, the same rigorous standard of research should be applied to surgical masks as with N95 FFRs, given its much broader applications as PPE. We recommend that future studies in this area consider applying core outcomes and test conditions that are in accordance with acceptable industry standards in their design, to enable transparency of reporting, interpretation of result in context of a particular setting or pathogen in question, and to enable future comparisons of efficacy between interventions.

Abbreviations: BDL, below detection limit; CDC, Centers for Disease Control and Prevention; COVID-19, coronavirus disease; FE, filtration efficiency; FFR, filtering face respirators; GS5, Goldshield 5 quaternary ammonium agent; HCP, healthcare provider; NaCl, sodium chloride; NS, not statistically significant; PPE, personal protective equipment; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; SARS-CoV-2, novel coronavirus; UVGI, ultraviolet germicidal irradiation; WHO, World Health Organization.

Acknowledgements: The authors are grateful to the following people for their contributions to citation screening (in alphabetical order): Anirudh Agarwal, Kwame Agyei, Jess Gibson, Hendrick Guerra, Ronish Gupta, Manvinder Kaur, Rhiannon Ng, Emiliyan Staykov.

Conflict of Interest: None to declare.

Source of Funding: This research did not receive any specific funding.

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Figure 1. PRISMA Flow Diagram

Table 1. Characteristics of included studies

Author (Year)	Intervention	Procedure				Mask/Component Tested	Testing Agent	Control
		Duration	Cycles	Temperature	Other			
Decontamination Interventions								
Lin (2017) [19]	Dry heat (rice cooker)	3 min	1	149-164°C	-	Mask pieces: 1. Gauze double-layer electret mask 2. Oimo spunlace nonwoven masks (models not specified)	Potassium sodium tartrate tetrahydrate solution (polydispersed droplets)	Untreated mask piece
	Moist heat (autoclave)	15 min	1	121°C	Pressure 1.06 kg/cm ²			
	Ethanol, 70%	10 min submersion	1	Room	Air dried overnight			
	Isopropanol, 100%	10 min submersion	1	Room	Air dried overnight			
	Sodium hypochlorite solution, 0.5%	10 min submersion	1	Room	Air dried overnight			
Pre-Contamination Interventions								
Quan (2017) [23]	Salt (NaCl) coating: 3, 7, 11, 14, and 19 mg NaCl/cm ²	Solution 1: Overnight ^a Solution 2: 1-day ^a	1	Room	Oven-dried 37°C × 1 day	Salt-coated pieces of polypropylene mask filter (mask model not specified)	Aerosolized virus: H1N1 CA/09 H1N1 PR/34 H5N1 VN/04	Uncoated mask filter
Tseng (2016) [25]	Quaternary ammonium agent (Goldshield 5; GS5), 1% in sterile water	Applied with common spray bottle (4 sprays = 1mL)		Room	Air dried × 24 hours	GS5-coated pieces of 3 mask layers and GS5-coated full mask (AERO PRO, Taiwan; model not specified)	Aerosolized bacteria: A. baumannii ATCC17978 E. faecalis ATCC29212 S. aureus ATCC29213	Sterile water coated mask
Demir (2015) [20]	N-halamine (1-chloro- 2,2,5,5- tetramethyl-4- imidazolidinone), 1 wt % in ethanol	10 min submersion Padded through laboratory wringer	1	Room	Air dried × 24 hours	N-halamine-coated pieces of polypropylene mask filter (Hollingsworth & Vose Company, USA; model not specified)	Aerosolized bacteria: S. aureus ATCC6538 E. coli 0157:H7 ATCC43895	Uncoated mask filter
Li (2006-A) [22]	Silver nitrate and titanium dioxide nanoparticle emulsion, 0.4 mg/cm ²	Coated to desired concentration with textile-finishing machine (China patent 03142467)				Full masks with nanoparticle-coated outermost mask layer (Winner Medical Group, China; model not specified)	Aerosolized pathogen simulant: KCl-fluorescein	Uncoated mask layer
Li (2006-B) [21]						Nanoparticle-coated pieces of outermost mask layer (Winner Medical Group, China; model not specified)	Bacterial suspensions: E. coli ATCC25922 S. aureus ATCC25923	Uncoated fabric
Shen (2005) [24]	Fluorochemical repellent (Zonyl® PPR Protector), 6% and 12%	Unspecified submersion time Padded through laboratory wringer	2	Room	Dried at 176°F × 2 min Cured at 250°F × 2 min	3 full masks made of nonwoven mask components with repellent applied to cover layer (models not specified)	Aerosolized pathogen simulant: Latex micro- spheres + synthetic blood	Uncoated mask

ATCC, American Type Culture Collection; GS5, Goldshield 5 quaternary ammonium agent; H1N1 CA/09, H1N1 influenza virus (A/California/04/2009); H1N1 PR/34, H1N1 influenza virus (A/Puerto Rico/08/2934); H5N1 VN/04, H5N1 influenza virus (A/Vietnam/1203/2004); KCl, potassium chloride; NaCl, sodium chloride.

^a Incubated in 600μL of salt-coating solution overnight at room temperature, then immersed and oven-dried for one day in a second salt-coating solution (0, 100, 300, 600, 900 or 1200μL) to achieve different salt-coating (sodium chloride, in mg) on filter per unit area.

Table 2. Decontamination methods and summary of results by outcome (Lin et al., 2017)^[19]

Test Agent & Conditions	Intervention	Mask/ Component	Findings	Comments
Filtration Efficiency ^a			FE% (absolute difference from control)	
Polydispersed potassium sodium tartrate tetrahydrate droplets (results for 0.1µm particle diameter) 5.95 L/min flow rate over mask pieces (stated to be equivalent to 85 L/min on full mask)	Dry heat	Gauze	85.6 (-1.3)	Dry heat caused the least reduction in FE; <i>p</i> -values not reported for this particle size.
		Spunlace	40.6 (-4.3)	
	Autoclave	Gauze	74.2 (-12.8)	
		Spunlace	43.7 (-12.1)	
	Ethanol	Gauze	70.5 (-16.5)	
		Spunlace	31.0 (-13.8)	
	Isopropanol	Gauze	50.8 (-36.1)	
		Spunlace	Not reported	
	Bleach	Gauze	Not assessable (mask destroyed)	
		Spunlace	29.6 (-15.3)	
Airflow Resistance ^b			Pressure drop in mmH ₂ O (absolute difference from control)	
Applied: 5.95 L/min flow rate over mask pieces (stated to be equivalent to 85 L/min on full mask)	Dry heat	Gauze	3.9 (+0.1), <i>p</i> =NS	No significant changes in airflow resistance following dry heat and ethanol decontamination (gauze mask only).
		Spunlace	1.4 (+0.1), <i>p</i> <0.05	
	Autoclave	Gauze	3.1 (-0.7), <i>p</i> <0.05	
		Spunlace	1.6 (+0.3), <i>p</i> <0.05	
	Ethanol	Gauze	3.9 (+0.2), <i>p</i> =NS	
		Spunlace	1.7 (+0.4), <i>p</i> <0.05	
	Isopropanol	Gauze	Not reported	
		Spunlace	Not reported	
	Bleach	Gauze	Not assessable (mask destroyed)	
		Spunlace	1.6 (+0.3), <i>p</i> <0.05	

FE, filtration efficiency; NS, not statistically significant.

^a FE to testing agent used, expressed as a percentage. A higher percentage filtration efficiency indicates better mask performance. Results in study were presented as percentage particle penetration, and converted to filtration efficiency (FE % = 100 – particle penetration) for consistency of reporting in this systematic review.

^b Airflow resistance assessed the “breathability” of the mask at tidal breathing. A lower airflow resistance means better breathability.

Table 3. Pre-contamination methods and summary of results by outcome

Author (Year)	Test Agent & Conditions	Intervention	Mask/Component	Findings				Comments
Filtration Efficiency ^a				FE% (absolute difference from control)				
Quan (2017) ^[23]	Aerosolized virus (H1N1 CA/09; 2.5-4µm diameter) at 17 kPa vacuum	Salt coating	Polypropylene Filter	Uncoated: 0.8 3 mg/cm2: 54.3 (+53.6) 11 mg/cm2: 69.0 (+68.2) 19 mg/cm2: 83.9 (+83.1)				Increasing FE observed with increasing salt coating concentrations; <i>p</i> -values not reported for comparisons with control.
Tseng (2016) ^[25]	Aerosolized bacteria (10 ⁴ CFU/m3 experiment, 0.5-2.1µm diameter) at 46 L/min flow rate (stated as equivalent to 95 L/min on full mask)	GS5	Outer Layer	60.7 (+6.3)	55 (+12.3)	69.3 (+18.2)	0.005	No significant increase in FE of mask filter layer with GS5 coating.
			Polypropylene Filter	99.3 (+1.8)	99.8 (+1.1)	99.9 (+0.6)	NS	
			Interior Layer	65.4 (+8.9)	59.5 (+10.0)	62.8 (+6.5)	0.02	
	NaCl aerosol (0.075µm particle diameter) at 85 L/min flow rate	GS5	Full Mask	77.6 (-1.8), <i>p</i> =NS				No significant change in FE with GS5 coating.
Li (2006-A) ^[22]	Aerosolized KCl-fluorescein solution sprayed onto full mask worn by exercising human subjects (flow rate and particle size not reported)	Nanoparticle emulsion	Outer Layer	82.0 (+2.0)				Results presented as percentage of total KCl particles found in each layer, respectively; KCl not reported for subject's face (i.e. cannot determine penetration <i>through</i> mask). <i>p</i> -values not reported for comparisons with control.
			Polypropylene Filter	13.0 (-3.0)				
			Interior Layer	4.5 (+1.5)				
Shen (2005) ^[24]	Aerosolized latex microspheres + synthetic blood (pathogen simulant; average particle size 1.0µm). Flow rate not reported. Each layer tested 3 times, in 3 individual masks.	Repellant		<i>Uncoated</i> (0% Repellant)	6% <i>Repellant</i>	12% <i>Repellant</i>	<i>p</i> -value	Results presented as percentage of total particles found on each mask layer respectively in the 3 masks tested. 0% found in inner layers of all masks, suggesting FE of native mask filter was unchanged by presence of repellant-coated outer layer. Outcome evaluated with laser scanning confocal microscope.
			Outer Layer	36.2%	25.8%	27.4%	<0.0001	
				37.7%	26.8%	27.4%		
				40.6%	29.2%	29.4%		
			Polypropylene Filter	63.4%	74.2%	72.0%	0.032	
				62.2%	73.2%	72.0%	0.043	
				55.3%	56.5%	57.2%	NS	
Interior Layer	0.0%	0.0%	0.0%	Not reported				
	0.0%	0.0%	0.0%					
Airflow Resistance ^b				Measured Variable (absolute difference from control)				
Tseng (2016) ^[25]	Applied: flow rate (85 L/min) over full mask	GS5	Full mask	Pressure drop: 16.8 (+ 1.0) mmH ₂ O, <i>p</i> =NS				No significant changes in airflow resistance.
Demir (2015) ^[20]	Applied: pressure drop (12.7 mmH ₂ O) over mask filter pieces ^c	N-halamine	Polypropylene Filter	Flow rate: 26.7 (−0.6) ml/s/cm2, <i>p</i> = not reported				
Li (2006-A) ^[22]	Applied: pressure drop (10 mmH ₂ O) over full mask	Nanoparticle emulsion	Full mask	Flow rate: 18.4 (−1.4) ml/s/cm2, <i>p</i> =NS				
Germicidal Effect				Pathogen Load (Log Reduction)				
Quan (2017) ^[23]	Aerosolized influenza virus (strain not reported) with post-	Salt coating	Polypropylene filter	Log reduction at 5, 15, 60 minutes post exposure ^{d, e} Uncoated: 0.0 (No), 1.7, 2.0 3 mg/cm2: 2.7, 2.8, BDL, <i>p</i> < 0.001				Good germicidal effect (log reduction > 3 in pathogen load) after

	inoculation incubation of 5-60 minutes			11 mg/cm ² : 2.9, 3.0, BDL, p < 0.001 19 mg/cm ² : 3.0, 3.0, BDL, p < 0.001	60 minutes incubation in all concentrations of salt coating.
	No = Viral load on untreated filter at 5 minutes incubation				
Tseng (2016) [25]	Aerosolized bacteria (10 ⁴ CFU/m ³ experiment) with post-inoculation incubation of 0 minutes	GS5	Polypropylene Filter	Log reduction immediately post exposure ^f	Inadequate germicidal effect (log reduction << 3 in pathogen load) on all GS5-coated mask layers.
				<i>A. baumannii</i> <i>E. faecalis</i> <i>S. aureus</i> <i>p-value</i>	
				Outer Layer 0.8 0.9 0.8 Not reported	
				Polypropylene Filter 1.0 0.8 0.8 Not reported	
	No = Sterile water-coated mask pathogen load immediately post-exposure		Interior Layer	0.8 0.9 0.9 Not reported	
Demir (2015) [20]	Aerosolized bacteria with post-inoculation incubation of 10 minutes	N-halamine	Polypropylene Filter	Log reduction at 10 minutes post exposure ^d	Good germicidal effect (log reduction > 3 in pathogen load) by 10 minutes.
				<i>S. aureus</i> <i>E. coli</i> <i>p-value</i>	
	No = Uncoated mask at 10 minutes post-exposure			4.4 3.2 Not reported	
Li (2006-B) [21]	Bacterial suspensions (10 ⁵ CFU/mL) with post-inoculation incubation of 0 and 24 hours	Nanoparticle emulsion	Outer Layer	Log reduction at 0, 24 hours post-exposure ^d	Good germicidal effect (log reduction > 3 in pathogen load) by 24 hours.
				<i>S. aureus</i> <i>E. coli</i> <i>p-value</i>	
				Uncoated: 0.0 (No), -0.3 Uncoated: 0.0 (No), 0.1 Not reported	
				Nanoparticle-coated: -0.2, 5.7 Nanoparticle-coated: 1.4, 5.9	
	No = Uncoated mask at 0 hours				
In Vivo Infection Prevention				Measured Variable	
Quan (2017) [23]	Aerosolized virus (H1N1 CA/09, H1N1 PR/34, or H5N1 VN/04)	Salt coating	Polypropylene Filter	16-day survival (%)	All mice protected by salt-coated filter barriers survived after exposure to lethal dose of aerosolized virus. (surrogate mortality endpoint of >25% loss in body weight). Full data across all viruses available only for 11 mg/cm ² salt-coated filter
				<i>H1N1 CA/09</i> <i>H1N1 PR/34</i> <i>H5N1 VN/04</i>	
				Uncoated: 0% Uncoated: 0% Uncoated: 0%	
				3 mg/cm ² : 100% 11 mg/cm ² : 100% 11 mg/cm ² : 100%	
				11 mg/cm ² : 100%	All surviving mice had reduced, but detectable, lung viral titers.
				19 mg/cm ² : 100%	
				Log reduction in lung viral titer ^g	
				Uncoated: 0.0 (No) 3 mg/cm ² : 0.6, p < 0.005 11 mg/cm ² : 1.1, p < 0.005 19 mg/cm ² : 1.3, p < 0.005	

BDL, below detection limit; CFU, colony forming units; FE, filtration efficiency; GS5, Goldshield 5 quaternary ammonium agent; H1N1 CA/09, H1N1 influenza virus (A/California/04/2009); H1N1 PR/34, H1N1 influenza virus (A/Puerto Rico/08/2934); H5N1 VN/04, H5N1 influenza virus (A/Vietnam/1203/2004); KCl, potassium chloride; No, time zero from which log reduction was calculated; NaCl, sodium chloride; NS, not statistically significant.

^a FE to testing agent used, expressed as a percentage. A higher percentage filtration efficiency indicates better mask performance.

^b Airflow resistance assessed the "breathability" of the mask at tidal breathing. A lower airflow resistance means better breathability.

^c Study reported pressure drop and flow rate in inches of water and cubic feet per minute per square foot, respectively. Results converted to SI units.

^d Colony-forming units or plaque-forming units reported in study, as applicable. Results converted to log reductions.

^e Plaque-forming units below detectable limit. Detection limit of assay not reported; log reduction cannot be calculated.

^f Colony-forming unit reduction percentages reported in study. Results converted to log reductions.

^g Absolute values for lung viral titers reported in study. Results converted to log reductions.