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Mask shortage during epidemics and pandemics: a scoping review of interventions to overcome limited supply

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ABSTRACT

Objective To characterise published evidence regarding preclinical and clinical interventions to overcome mask shortages during epidemics and pandemics.

Design Systematic scoping review.

Settings All healthcare settings relevant to epidemics and pandemics.

Search strategy English peer-reviewed studies published from January 1995 to June 2020 were included. Literature was identified using four databases (Medline-OVID, EMBASE, CINAHL, Cochrane Library), forwards-and-backwards searching through Scopus and an extensive grey literature search. Assessment of study eligibility, data extraction and evidence appraisal were performed in duplicate by two independent reviewers.

Results Of the 11 220 database citations, a total of 47 articles were included. These studies encompassed six broad categories of conservation strategies: decontamination, reusability of disposable masks and/or extended wear, layering, reusable respirators, non-traditional replacements or modifications and stockpiled masks. Promising strategies for mask conservation in the context of pandemics and epidemics include use of stockpiled masks, extended wear of disposable masks and decontamination.

Conclusion There are promising strategies for overcoming face mask shortages during epidemics and pandemics. Further research specific to practical considerations is required before implementation during the COVID-19 pandemic.

Strengths and limitations of this study

- This is the first scoping review of the literature that has evaluated the evidence behind overcoming mask shortages during pandemics and epidemics, which is increasingly relevant during the COVID-19 pandemic.
- Strengths of design include the robust search strategy, thorough grey literature search, registration of protocol, multiple evidence appraisals and completion of all steps in duplicate with two reviewers.
- Limitations include the limits of the evidence base and limitation to the English language.

INTRODUCTION

Face masks, including surgical masks and N95 respirators (table 1), are integral components of personal protective equipment (PPE) to protect healthcare workers (HCWs) from transmission of viral and bacterial pathogens.[1] They are essential for the prevention of nosocomial infection of the current COVID-19 pandemic.[2] The Centers for Disease Control and Prevention (CDC), WHO and expert bodies have highlighted the importance of appropriate PPE to prevent nosocomial infection of HCWs, as well as to limit the global spread of the virus.[3–5] While there is controversy regarding whether community members should wear masks in public, there is a consensus that healthcare providers have greater risk of exposure and require protection.[6 7] The consequences of limited or inappropriate use of PPE for healthcare providers has been demonstrated in previous epidemics and pandemics, including SARS, Ebolavirus and H1N1 influenza A.[8–10]

Recently, WHO has called attention to shortages in face masks during the COVID-19 pandemic.[11] The causes of these shortages are multifactorial, including increased demand for masks both by HCWs worldwide, and disruptions in the global supply chain through a large reduction in exports from China, a major producer of medical grade masks.[12] Hoarding and misuse by lay people further compromises supply in times of mass panic.[2] Given the currently high rate of infection of providers with COVID-19,[13 14] maintaining an adequate supply for them is a matter of urgency.

Strategies for overcoming the limited supply of masks in this time of public health crisis are being prioritised by medical bodies. The CDC has released a document outlining

Table 1 Types of face masks

Mask	Description	Intended use and purpose	Limitations	Fit testing required?
Non-medical face mask[103]	Covering over the mouth and nose with loose fitting; typically one layer, very thin.	Capturing large particles, such as dust.	Designed primarily to protect those exposed to user; does not protect against small airborne bacterial and viral particles; leakage occurs around the sides of the mask.	No
Surgical mask[104]	Disposable covering over the mouth and nose, often has malleable nose piece but does not form a face seal; typically three layers. Approved by the FDA in the USA, Health Canada in Canada.	Capturing large particle droplets from both user and patients.	Does not reliably protect against smaller airborne bacterial and viral particles; leakage occurs around the sides of the mask.	No
Respirator[104–106]	Tight fit covering over the mask and nose; evaluated and approved by the NIOSH. Respirators may or may not have exhalation valves, depending on the specific model and manufacturer. Exhalation valves are generally not optimal for healthcare settings as they expose others to infection from the wearer, although the mask is still protective for the wearer. *FFP1*: filters at least 80% of airborne particles with <22% inward leakage; may or may not have valve, depending on model. *N95 respirator (standard):* filters out at least 95% of airborne particles (equivalent to FFP2); may or may not have valve, depending on model. *N95 respirator (surgical):* filters at least 95% of airborne particles; designed for surgical settings and those involving high pressured streams of bodily fluid. *N99 respirator:* tested to filter at least 99% of airborne particles (equivalent to FFP3); may or may not have valve, depending on model. *Elastomeric respirator (includes half facepiece and full facepiece):* reusable device with replaceable cartridge filters that covers the nose and mouth; tight-fitting and requires fit-testing. *Powered air purifying respirators:* negative pressure air-purifying particulate respirators; may be tight-fitting (requires mask fit) or loose-fitting.	Filters out majority of airborne particles including large and small particles.	Varying levels of filtration depending on the model with minimal leakage around the sides of the mask. More complex to produce and costly than other disposable masks.	Yes

FDA, Food and Drug Administration; FFP, filtering face piece; NIOSH, National Institute for Occupational Safety and Health.

potential organisational methods, reuse of disposable products, non-traditional mask sources and novel approaches for fabrication.[15] The *Journal of the American Medical Association (JAMA)* recently issued a Call for Ideas for unconventional pitches related to increasing the PPE supply.[16] While numerous editorials and news articles address this topic, we are unaware of a systematic search of the published research to date.[17 18]

The objective of this scoping review is to characterise the research outcomes for preclinical and clinical interventions for overcoming limited supply of masks during pandemics and epidemics. We hope to inform best practices for addressing the current and potential future shortage of PPE supply while still maintaining both patient and provider safety.

METHODS

The scoping review was conducted according to the standards and guidelines established in the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) with the associated extension for Scoping Reviews, in addition to the fourth edition of the Joanna Briggs Institute Reviewer's Manual.[19 20] We registered an iterative protocol through the Open Science Forum.[21 22] Changes to the protocol were minimal, including one change to the search criteria to broaden the search by adding keyword searches.

Search strategy

We conducted a systematic literature search of Medline-OVID, EMBASE, CINAHL and Cochrane Library. Databases were examined from 1995 until the date of our literature searches (4 June 2020). The cut-off of 1995 was designated in order to balance relevance to newer mask models and infection control guidelines, while still including major epidemics such as SARS in 2003. A copy of the search strategy is provided in the online supplemental appendix 1.

To ensure completeness, we also searched the references of our full-text articles, as well as the citing articles via Scopus. We also screened the references of identified relevant reviews.

Non-database sources were systematically searched to examine grey literature as well as to identify further peer-reviewed articles that may have been missed in the search. To identify relevant peer-reviewed articles, we hand-searched GoogleFoam,[23] COVID-19 Expert,[24] relevant guidelines,[4 5 25–29] preprint databases[28 29] and specialised evidence collections that were specific to the current COVID-19 pandemic.[30–36] Sources of grey literature included DuckDuckGo,[30] Google News,[31] the JAMA Call to Ideas forum[16] and LexisNexis.[32] Details of the grey literature sources are listed in table 2. The sources of grey literature were selected by two frontline clinicians and senior authors (JMB, SMF) on the basis of relevance to the field.

Articles were excluded if they did not report outcomes, were not specific to pandemics or epidemics, did not include English translations or were only relevant for a community setting. Details of the eligibility criteria are provided in box 1.

Study selection

Each title/abstract identified from the database search underwent two rounds of screening by two independent reviewers. A total of four independent reviewers (AK, SK, TG, MY) participated in the screening process, with each reviewer reviewing half of the yield. A pilot test of the title/abstract screening was completed among the four reviewers for the first 200 search results to ensure sufficient inter-rater agreement. Afterwards, two reviewers (AK, SK) examined full-texts to assess for eligibility. Any disagreements between the two reviewers was resolved through discussion and consultation with the two senior authors (JMB, SMF).

Data extraction

To facilitate data extraction, a standardised form was developed and piloted on five studies. The data extraction template was modified in an iterative process until the research team was satisfied with its state. Two reviewers (AK, SK) piloted extraction for five studies with each other for the purpose of improving the extraction process.

Following the pilot, the full data extraction was completed by the four reviewers (AK, SK, TG, MY) working in parallel. Any disagreements in data extraction were resolved through discussion and consultation with the content experts (JMB, SMF). Summary and synthesis were completed descriptively.

Quality assessment and risk of bias

The quality rating of all studies was also graded in duplicate by two reviewers (AK, SK) using a rating scale adapted from the Oxford Centre for Evidence-based Medicine.[37]

The risk of bias of the included studies was then systematically assessed by at least two independent reviewers (AK, SK, JMB). Non-randomised trials were evaluated using the RoBANS tool, while randomised controlled trials (RCTs) were evaluated using the Cochrane risk of bias tool. To our knowledge, there is no widely accepted measure of quality for preclinical studies. As such, we adapted approaches previously reported in the literature to select five markers of quality for our included preclinical studies.[38–42]

Patient and public involvement

Patients and members of the public were not involved in the conduction of this scoping review.

However, this review was conducted under the supervision of two academic emergency physicians who serve on the frontlines during the COVID-19 pandemic. The relevance of the research question and outcome measures were thus informed by their priorities, experiences, l and preferences as HCWs.

Table 2 Sources hand-searched for peer-reviewed literature

Source	Details of source and methodology
Evidence collections ► Evidence Aid[33] ► BMC[34] ► *NEJM*[35] ► Springer[36] ► *Lancet*[13] ► Elsevier[107] ► *BMJ*[108]	These are curated evidence collections, editorials, guidelines and news pieces available from major publishers and evidence groups. Collections were hand-searched for all articles until 6 April 2020.
Google Foam[23]	Google Foam is a search engine of Free Open Access Medical Education, including blogs, podcasts, journal articles and social media posts. Google Foam was searched for relevant articles until 8 April 2020.
COVID-19 Expert application[24]	This is a digital application that is used by clinicians, which collects articles, guidelines and hospital policies related to COVID-19. COVID-19 Expert application was searched for relevant articles until 8 April 2020.
Preprint databases ► Channel: COVID-19 SARS-CoV-2 preprints from medRxiv and bioRxiv[28] ► Open Science Forum: Preprint Archive Search for COVID-19 or 2019-ncov[29]	Preprint databases are advanced sharing platforms to provide open access to articles prior to publication. Their articles are not yet peer reviewed. The references from the first 100 articles on each preprint database were hand-searched to identify relevant peer-reviewed articles on 8 April 2020.
Published guidelines[4 5 25–29] ► CDC recommendations ► National Personal Protective Technology Laboratory Personal Protective Equipment Conformity Assessment Studies and Evaluations ► JAMA Clinical Guidelines Synopsis ► Public Health Agency of Canada guidelines[29] ► Infection Prevention and Control Canada guidelines[28] ► American College of Emergency Physicians position paper[4] ► Canadian Association of Emergency Physician PPE position paper[5]	These guidelines include clinical care guidelines for patients with COVID-19, position papers on PPE as well as recommendations for extended use and limited reuse of N95 filtering facepiece respirators in healthcare settings. The references from the cited guidelines were hand-searched to identify relevant peer-reviewed articles.

BMC, BioMed Central; *BMJ*, *British Medical Journal*; CDC, Centers for Disease Control and Prevention; JAMA, Journal of the American Medical Association; *NEJM*, *New England Journal of Medicine*; PPE, personal protective equipment.

RESULTS

Search yield

Results of the study screening process are available in the PRISMA diagram in figure 1. Of the 11 220 imported titles and database citations, 5038 remained after duplicates were removed. After title and abstract screening, 71 were eligible for full-text evaluation. Of the 71 full-text articles, a total of 47 met inclusion criteria for this scoping review.

Article characteristics

Full details of the included articles are available in the online supplemental appendix 2.

All 47 studies were full-text articles. Of the 47 studies, 27 were laboratory-based. The remainder were user acceptance studies (n=5) or clinical designs (n=15). Of the 15 clinical studies, 7 were RCTs and the remainder were non-randomised/observational (n=8).

The majority of studies were conducted in the USA (n=39), with the remainder located in Asia (n=4), South America (n=1), Africa (n=1) or a combination of countries (n=2).

There were 25 studies that were specific to N95 respirators, with the remainder evaluating cloth masks (n=2), surgical masks (n=2), reusable elastomeric respirators (n=6) or multiple types of masks (n=12).

Twenty studies reported no conflict of interest. One study[43] noted that an author had a previous financial relationship with 3M.[43] This same study reported receiving support from 3M for mask testing. Two other studies[44 45] reported receiving support from industry partners.[44 45] Of these, one stated the authors had no conflicts of interest,

Box 1 Eligibility criteria

Population:
Relevant to healthcare providers/hospital staff/medical institutions/long-term care homes/dental offices/paramedics and prehospital care workers/military medical services/refugee health workers or any medical institutions that use face masks for medical purposes. Face masks include surgical masks and non-powered respirators.

Intervention:
Any intervention with the purpose of conserving/rationing masks relevant to pandemics/epidemics; any intervention with the purpose of increasing the supply of masks through procurement from other sources relevant to pandemics/epidemics.

Comparator:
Not available (any identified from literature).

Outcomes:
Any outcome reported in the literature (can be qualitative or quantitative, may include patient outcomes/provider outcomes, may include increases to supply, may include other markers of clinical quality of performance).

and one did not include any statement of potential conflicts of interest. The remaining 24 studies did not provide a disclosure statement.

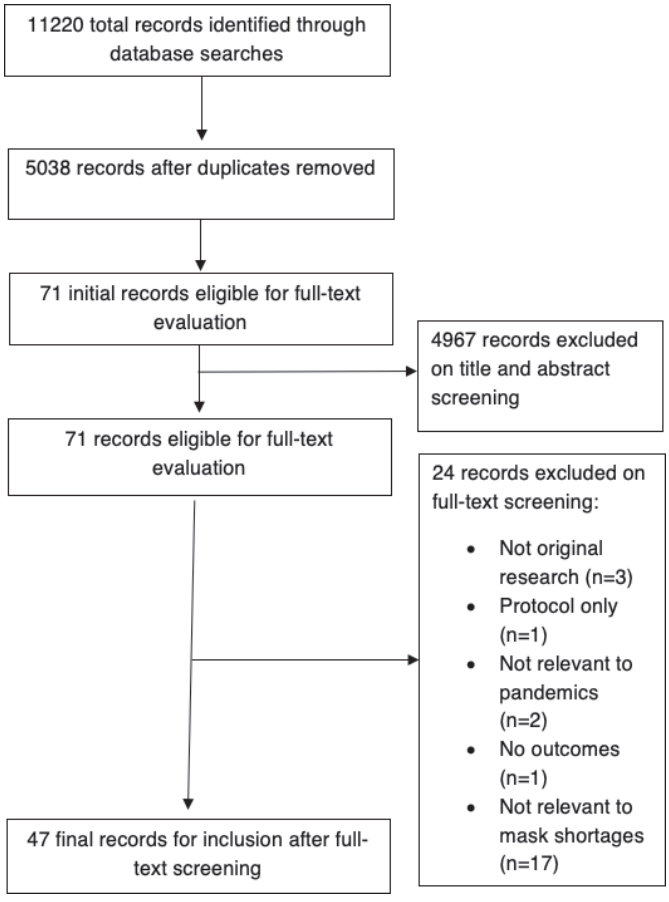

Figure 1 Preferred Reporting Items for Systematic Reviews and Meta-Analysis diagram.

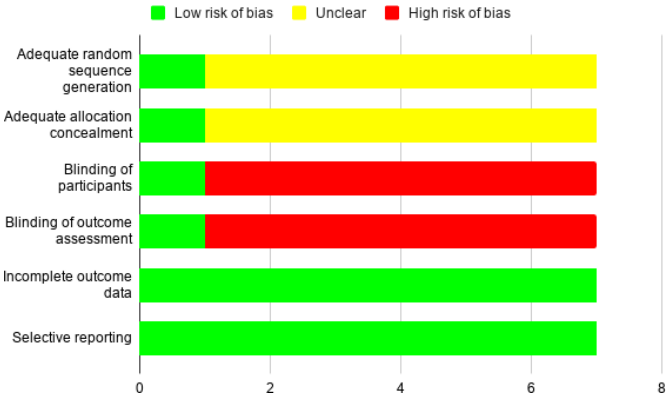

Figure 2 Cochrane risk of bias tool. Seven randomised controlled trials were evaluated using the Cochrane risk of bias tool. The majority (n=6) were noted to be intermediate risk, with one study graded as low risk.

Details of the evidence grading and risk of bias assessment are available in the online supplemental appendix 2 as well as in figures 2–4.

Strategies for overcoming limited supply

The research literature revealed numerous strategies evaluated for overcoming a limited supply of PPE during pandemics or epidemics. These strategies can be grouped into six main categories (table 3): decontamination of disposable masks, reuse and/or extended wear of disposable masks, layering of masks, introduction of reusable respirators, use of non-traditional replacements or modifications to masks, and use of stockpiled or expired masks.

Decontamination of disposable masks

Eighteen of the included studies evaluated decontamination methods of disposable masks in order to facilitate reuse. There were multiple methods of decontamination including: ultraviolet (UV) germicidal irradiation, pasteurisation, dry heat and chemical disinfectants (including ethylene oxide, ammonia, hydrogen peroxide, bleach, isopropyl alcohol, mixed disinfectants and commercially available cleaning wipes). A full summary

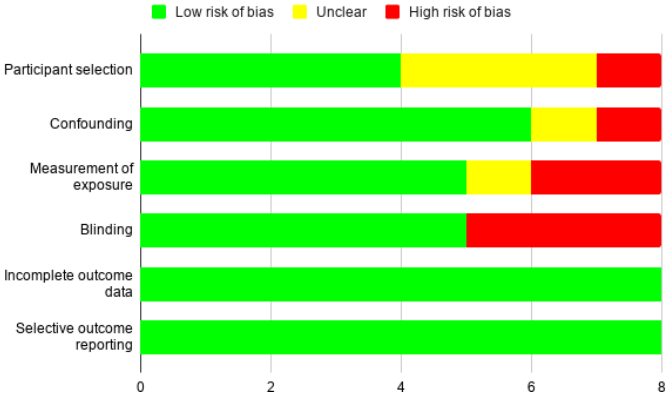

Figure 3 RoBANS risk of bias tool. Eight non-randomised studies were evaluated with the RoBANS tool. Seven studies were graded as low risk, with one study graded as intermediate risk to high risk.

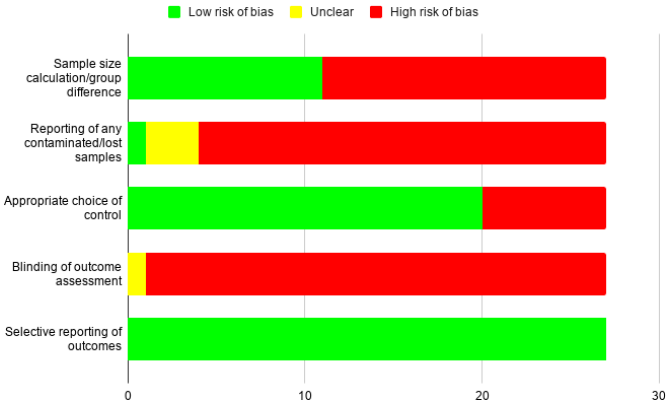

Figure 4 Preclinical risk of bias grading. Twenty-seven preclinical studies were evaluated using markers previously described in literature (see 'Methods' section). All studies were ranked as medium to high risk for bias.

of decontamination methods and assessment using the Health Canada criteria for mask decontamination is included in table 4.[46]

Studies of mask decontamination incorporated one or more of four outcome measures: (1) decontamination efficacy, (2) filtration performance after decontamination, (3) complications of decontamination, (4) user experience/acceptance of decontamination. Fifteen studies evaluated the efficacy of methods for decontamination of filtering facepiece respirators, including N95s and P100s. These were conducted in controlled laboratory settings, where primary outcomes included changes in viability of live pathogens and filtration performance on decontamination. Evaluated pathogens included strains of H1N1 (n=3), MS2 bacteriophage (n=4), *Escherichia coli* (n=1), *Bacillus subtilis* (n=1), *Geobacillus stearothermophilus* (n=1) and *Staphylococcus aureus* (n=1).[47–51] All studies noted some degree of reduced virus viability with UV, chemical or heat-based decontamination methods. The most studied method of decontamination was UV radiation, with 13 studies evaluating either UVA or UVC radiation at varying doses and exposure times (details in table 5). While most studies found most decontamination methods to be effective, UVC radiation (15 W 254 nm bulbs for 15 min) was noted as the most effective method by Lore *et al*[50] in comparison to microwave-generated steam or moist heat. In addition, decontamination using non-medical commercially available wipes and ethanol was notably ineffective.[52 53] In the only available comparison of UVC and UVA, UVA was found ineffective compared with UVC.[53]

There were contrasting results regarding filtration performance and decontamination methods. Several

Table 3 Description of strategies

Strategies	Description of methods	Evaluatingstudies
(1) Decontamination of disposable masks[47–50 52–56 59–62 109–111]	Sterilisation or cleaning of masks in order to reuse masks that are typically meant to be disposed of after use. Methods of decontamination included ultraviolet germicidal irradiation, pasteurisation, dry heat and chemical disinfectants (including ethylene oxide, ammonia, hydrogen peroxide, bleach, isopropyl alcohol, mixed disinfectants, cleaning wipes, see table 4).	Fisher *et al*,[47] Fisher and Shaffer,[109] Heimbuch *et al*,[52] Lin *et al*,[54] Mills *et al*,[48] Nemeth *et al*,[61] Bergman *et al*,[56] Lin *et al*,[53] Lindsley *et al*,[60] Lore *et al*,[50] Richter *et al*,[51] Salter *et al*,[55] Viscusi *et al*,[55] Viscusi *et al*,[57] Viscusi *et al*,[62] Vo *et al*,[111] Woo *et al*,[110] Heimbuch *et al*[49]
(2) Reuse of disposable masks[63–65 70–72]	Reuse of disposable masks without decontamination or disinfection.	Bergman *et al*,[70] Coulliette *et al*,[63] Fisher *et al*,[64] Fisher *et al*,[65] Pillai *et al*,[72] Vuma *et al*[71]
(3) Extended wear of disposable masks[63–72]	Use of disposable masks for longer than standard practice.	Bergman *et al*,[70] Brady *et al*,[67] Coulliette *et al*,[63] Duarte *et al*,[66] Fisher *et al*,[64] Fisher *et al*,[65] Pillai *et al*,[72] Radonovich *et al*,[68] Shenal *et al*,[69] Vuma *et al*[71]
(4) Layering of masks[69 73–76]	Layering of multiple masks or overlay of different types of masks.	Derrick *et al*,[73] Rebmann *et al*,[74] Roberge *et al*,[75] Sinkule *et al*,[76] Shenal *et al*[69]
(5) Reusable respirators[77–83]	Fabrication or testing of reusable respirators that are meant to be decontaminated between uses.	Bessesen *et al*,[79] Hines *et al*,[81] Hines *et al*,[82] Hines *et al*,[83] Lawrence *et al*,[77] Pompeii *et al*,[80] Subhash *et al*[78]
(6) Unconventional mask replacements or modifications[43–45 84]	Assessment of cloth masks, new mask types, modifications of existing mask designs and use of non-medical equipment as masks.	MacIntyre *et al*,[43] Quan *et al*,[84] Rengasamy *et al*,[44] Au *et al*[45]
(7) Stockpiled or expired masks[57 85–87]	Use of masks in long-term storage or stockpile facilities, potentially after expiry date.	Bergman *et al*,[86] Greenawald *et al*,[85] Rottach *et al*,[87] Viscusi *et al*[57]

Table 4 Summary of decontamination methods

Method	Description	Evaluated pathogens	Types of mask	Was pathogen viability reduced?	Was mask fit maintained?	Were there residual chemical hazards?	Limitations	Evaluating studies
Bleach[53 54 56 57 77 78 111]	Submersion of total 4–30 min in 0.1%–0.75% aqueous sodium hypochlorite	H1N1, MS2 coliphage	N95 models Reusable respirators P100 FFR	Yes	Not assessed	No, residual chemicals were below permissible exposure limit (Salter *et al*[58])	Contamination via aerosol route can lead to hard-to-access potentially contaminated surfaces. Physical damage to the filter and corrosion of metal nosepieces. Discernable odour after use.	Bergman *et al*,[56] Lawrence *et al*,[77] Lin *et al*,[54] Lin *et al*,[53] Subhash *et al*,[78] Viscusi *et al*,[55] Viscusi *et al*,[57] Vo *et al*[111]
Cleaning wipes[52]	Commercially available wipe products with primary active ingredients ranging from BAC, 0.9% hypochlorite, 70% isopropyl alcohol, 0.28% quaternary ammonium chloride, sodium hypochlorite dissolved in detergent or inert	*Staphylococcus aureus*, influenza	N95 models Surgical N95 models	Yes	Not assessed	Not assessed	BAC induced filter degradation. Hypochlorite blemished FFR, oxidised parts, imparted odour.	Heimbuch *et al*[52]
Dry heat[53–55]	FFR placed in an oven or rice cooker at 149°C–164°C for 3 min to 1 hour	MS2 coliphage, *Bacillus subtilis*	N95 models P100 FFR	Yes	Not assessed	Not assessed	FFRs melted at heats above maximum operating temperature.	Lin *et al*,[53] Lin *et al*,[54] Viscusi *et al*[55]
Ethanol[53 54]	10 min submersion in 70% ethanol solution	*B. subtilis*	N95 models	Yes	Not assessed	Not assessed	Increased penetration of particles. Limited bactericidal activity.	Lin *et al*,[53] Lin *et al*[54]
Ethylene oxide[55–58]	100% EtO gas exposure ranging from 724 to 883 mg/L on a single cycle for 1 hour	MS2 coliphage	N95 models P100 FFR	Yes	Not assessed	Yes, two toxic residues noted after decontamination of FFR rubber stamps (Salter *et al*[54])	Toxic residues (diacetone acetone and 2-hydroxyethyl acetate formed post-treatment.	Bergman *et al*,[56] Salter *et al*,[58] Viscusi *et al*,[57] VIscusi *et al*[59]

Continued

Table 4 Continued

Method	Description	Evaluated pathogens	Types of mask	Was pathogen viability reduced?	Was mask fit maintained?	Were there residual chemical hazards?	Limitations	Evaluating studies
Hydrogen peroxide[51 55–58]	Treatment modalities included ranged from gas plasma, vapourised (58% for 28–55 min) and liquid (3%–6% for 30 min)	MS2 coliphage	N95 models P100 FFR	Yes	Strap degradation was noted after 30 cycles of decontamination (Richter[51])	No, residual chemicals were below permissible exposure limit (Salter *et al*[54])	Vaporised hydrogen peroxide could be absorbed by cellulose in cotton-containing FFR models and cause compromised sterilisation due to low vapour concentration. Mean penetration levels are above 5% for FFRs treated with hydrogen peroxide gas plasma.	Bergman *et al*,[56] Richter,[51] Salter *et al*,[58] Viscusi *et al*,[55] Viscusi *et al*[57]
Isopropyl alcohol[54 55]	Submerged in 70% solution for 30 s or 1 min	MS2 coliphage	N95 models P100 FFR	Yes	Not assessed	Not assessed	Increased particle penetration, possibly due to degradation of electret filter media.	Lin *et al*,[54] Viscusi *et al*[55]
Microwave oven-generated steam[55 56 62 77]	Ranged from total exposure time of 90 s to 2 min at maximum power to 1100–1250 W with 50 mL tap water Commercially available microwavable steam bags	MS2 coliphage, H1N1, H5N1	N95 models Surgical N95 models P100 FFR Elastomeric respirators (half-masks) Powered air-purifying respirator	Yes	Yes (Viscusi *et al*[62])	Not assessed	Residual sporadic viable H1N1 virus detected, likely due to non-uniform steam distribution.	Bergman *et al*,[56] Heimbuch *et al*,[49] Lawrence *et al*,[77] Viscusi *et al*,[55] Viscusi *et al*[62]
Mixed disinfectant fluid[58]	Combinations included mixed oxidants (oxone, sodium chloride, sodium bicarbonate), dimethyl dioxirane (oxone, acetone, sodium bicarbonate)	N/A	N95 models	Yes	Not assessed	No, residual chemicals were below permissible exposure limit[58]	Initial survey, unable to endorse methods for decontamination Potential hazardous by-products.	Salter *et al*[58]

Continued

Table 4 Continued

Method	Description	Evaluated pathogens	Types of mask	Was pathogen viability reduced?	Was mask fit maintained?	Were there residual chemical hazards?	Limitations	Evaluating studies
Pasteurisation, autoclave, moist heat[53–56 62 77]	Method of non-chemical decontamination using moist heat Treatment time ranged from 20 to 30 min incubation at intensity of 60°C–65°C	H1N1, H5N1, MS2 coliphage	N95 models Surgical N95 models Elastomeric respirators (half-masks) Powered air-purifying respirators	Yes	Unclear: maintained for 4/6 FFR models, but reduced for 2/6 (Viscusi *et al*[62])	Not assessed	Exposure to high heats may affect filter performance.	Bergman *et al*,[56] Heimbuch *et al*,[49] Lawrence *et al*,[77] Lin *et al*,[54] Lin *et al*,[53] Viscusi *et al*,[62] Viscusi *et al*[55]
Soap and water[55]	20 min submersion	MS2 coliphage	N95 models P100 FFR	Yes	Not assessed	Not assessed	Increased particle penetration, possibly due to altered charge of filter materials.	Viscusi *et al*[55]
Ultraviolet germicidal irradiation[47 48 50 53 55–60 62 110]	UVC or UVA transmittance using various doses	*Escherichia coli*, bacteriophage MS2 (ATCC 15597-B1), H1N1 influenza A/PR/8/34 VR-1469 (ATCC VR-95H1N1), influenza A/H5N1 (VNH5N1)	N95 models, Surgical N95 models, P100 FFR	Yes	Yes (Viscusi *et al*[62])	No, residual chemicals were below permissible exposure limit (Salter *et al*[54])	Studies completed in controlled laboratory settings; may not be applicable to all mask types. May impact mask fit.	Bergman *et al*,[56] Fisher *et al*,[65] Heimbuch *et al*,[49] Lin *et al*,[53] Lindsley *et al*,[60] Lore *et al*,[50] Mills *et al*,[48] Salter *et al*,[58] Woo *et al*,[110] Viscusi *et al*,[55] Viscusi *et al*,[57] Viscusi *et al*,[62] Vo *et al*[111]

BAC, benzalkonium chloride; EtO, ethylene oxide; FFR, filtration facepiece respirator; N/A, not available; UVA, ultraviolet A; UVC, ultraviolet C.

Table 5 Summary of studies evaluating UVC decontamination

Citation	Details of UVC	Evaluated pathogens	Mask type	Sample size, control group	Key findings
Bergman *et al*[56]	Type: UV Bench Lamp (UVC, 254 nm, 40 W) Model: XX-40S, UVP, USA Conditions: continuous exposure of mask exteriors for 45 min at intensity of 1.8 mW/cm^2 from 25 cm height	N/A	N95 models Surgical N95 models (SN95-D, SN95-E and SN95-F)	Intervention arm: 6 models, 180 masks. Control group: 3 masks of each model were submerged in deionised water for 4 hours then dried for 16 hours.	Mask filtration preserved.
Fisher and Shaffer[109]	Type: UVC, 254 nm, 40 W Model: TUV 36T5 40 W, Philips, USA Conditions: masks were cut and separated by layer into coupons, then exposed for 1–10 min either bidirectionally or only on the exterior at intensity of 25 mW/m^2	*Escherichia coli*, bacteriophage MS2 (ATCC 15597-B1)	N95 models (Cardinal N95-ML, Wilson SAF-T-FIT Plus, 8210, 1860, 1870, PFR95-174)	Intervention arm: 6 models, 24 coupons. Control group: 2 coupons of each model were protected with a plastic layer when exposed to the UV, then challenged with virus.	When challenged with aerosolised NaCl and MS2 virus in droplet form, masks had varied responses based on exposure times and UV doses.
Heimbuch *et al*[49]	Type: 120 cm, 80 W UVC (254 nm) lamp Model: Ultraviolet Products, USA Conditions: continuous exposure of mask exterior for 15 min at intensity of 1.6–2.2 mW/cm^2 from 25 cm height	H1N1 influenza A/PR/8/34 VR-1469 (ATCC VR-95H1N1)	N95 models Surgical N95 models (SN95-D, SN95-E and SN95-F)	Intervention arm: 6 models, 36 masks. Control group: 3 masks of each model were left at room temperature.	When challenged with aerosolised H1N1, all UV-treated masks were below detection levels. When challenged with H1N1 in droplet form, four out of six UV-treated masks were below detection.
Lindsley *et al*[60]	Type: two 15 W T-150 254 nm UVC lamps Model: ILT-1700, International Light Technologies, USA Conditions: masks were cut and separated by layer into coupons, then exposed along with straps at intensity of 0, 120, 240, 470 or 950 J/cm^2 from 6.2 cm height	N/A	N95 models (3M 1860, 3M 9210, GE 1730, KC 46727)	Intervention arm: 4 models, 80 coupons. Control group: 4 coupons of each model were untreated.	When challenged with aerosolised NaCl, there was an increase of up to 1.25% penetration. There was no impact on flow resistance. There was noticeable physical degradation of masks at higher doses.
Lore *et al*[50]	Type: 126 (L) 15.2 (W) 10.8 cm (H), dual-bulb, 15 W UVC (254 nm wavelength) lamp Model: Ultraviolet Products, USA Conditions: continuous exposure of mask exterior for 15 min at intensity of 1.6–2.2 mW/cm^2 from 25 cm height	Influenza A/H5N1 (VNH5N1)	N95 models (1860, 1870)	Intervention arm: 2 models, 18 masks. Control group: 2 models, 18 masks.	When challenged with H5N1 in droplet form, all UV-treated masks were below viral particle detection levels. UV-treated masks performed best compared with microwave stream treatment and moist heat treatment.

Continued

Table 5 Continued

Citation	Details of UVC	Evaluated pathogens	Mask type	Sample size, control group	Key findings
Mills *et al*[48]	Type: eight 32 inch 254 nm UVC bulbs Model: Alloy 6061-T6 and Alloy 2024-T3; OnlineMetals.com, USA Conditions: continuous exposure of mask exterior for 1 min at intensity of 0.39 W/cm^2 from 1 m height	H1N1 influenza A/PR/8/34	N95 models (3M 1860, 3M 1870, 3M VFlex 1805, Alpha Protech 695, Gerson 1730, Kimberly-Clark PFR, Moldex 1512 Cup, Moldex 1712, Moldex EZ-22, Precept 65–3295 Cup Prestige Ameritech RP88020, Sperian HC-NB095, Sperian HC-NB295F, US Safety AD2N95A, US Safety AD4N95)	Intervention arm: 15 models, 90 masks. Control group: 90 masks of each model. Controls held at room temperature without UV intervention.	When challenged with H1N1 in droplet form, 12 of the 15 mask models had significantly reduced virus viability. Only 7 of the 15 mask straps had significant viral viability reductions.
Salter *et al*[58]	Type: multiwavelength, 8 W lamp Model: Ultraviolet Products, USA Conditions: masks were cut and separated by layer into coupons, then exposed for 1 hour at intensity of 4 mW/cm^2 of UVB and 3.4 mW/cm^2 of UVC at a height of 1 inch	N/A	N95 models (P1, P2, P3) Surgical N95 models (S1, S2, S3)	Intervention arm: 6 models, 18 masks. Control group: 18 masks of each model were untreated.	When masks treated with UV were extracted with pentane to identify decontaminants, GC-MS analysis presented unique peaks, but they may have been related to the pentane solvent.
Viscusi *et al*[55]	Type: 40 W UVC light Model: SterilGARD III laminar flow cabinet, Baker Company, USA Conditions: continuous exposure of mask exterior for 30–480 min at intensity of 0.24 mW/cm^2	N/A	N95 model P100 model	Intervention arm: 2 models, 160 masks. Control group: 20 masks were untreated, and 8 masks were submerged in tap water for 30 min then air dried.	When challenged with aerosolised NaCl, masks treated with UV rays performed similarly to new masks. No physical changes were observed.
Viscusi *et al*[59]	Type: 40 W UVC light Model: SterilGARD III laminar flow cabinet, Baker Company, USA Conditions: continuous exposure of mask exterior for 15 min at intensity of 0.18–0.20 mW/cm^2 from 25 cm height	N/A	N95 models (N95-A, N95-B, N95-C) Surgical N95 models (SN95-D, SN95-E and SN95-F) P100 models (P100-G, P100-H and P100-I)	Intervention arm: 9 models, 135 masks. Control group: 3 masks of each model were untreated.	When challenged with NaCl aerosol, UV-treated masks had similar penetration compared with new masks. No physical changes were observed.

Continued

Table 5 Continued

Citation	Details of UVC	Evaluated pathogens	Mask type	Sample size, control group	Key findings
Viscusi *et al*[62]	Type: 40 W UVC light Model: SterilGARD III laminar flow cabinet, Baker Company, USA Conditions: continuous exposure of mask exterior for 30 min in total for interior and exterior of mask at intensity of 1.8 mW/cm^2	N/A	N95 models (3M 8210, 3M 8000, Moldex 2000) Surgical N85 models (KCPFR95-270, 3M 1870, 3M 1860)	Intervention arm: 6 models, 360 masks. Control group: 20 masks of each model were untreated.	While most masks treated with UV were received favourably by participants compared with control, there was one report of a broken strap and another of an odour with the Moldex 2200 after UV treatment.
Vo *et al*[111]	Type: low-pressure mercury arc lamp—5.5 mg Hg; lamp type, TUV 36TS 4P SE; lamp voltage, 94 V; lamp wattage, 40 W; wavelength, 253.7 nm Model: SterilGARD III model SG403A, Baker Company, USA Conditions: continuous exposure of mask exterior from 1 to 5 hours at intensity of 0.4 mW/cm^2 from 42 cm height	*E. coli* ATCC 15597, bacteriophage MS2 (ATCC 15597-B1)	N95 model (N1105)	Intervention arm: 1 model, number not reported. Control group: number not reported. Controls were treated with either sodium hypochlorite or purified water for 10 min, then dried for 2 min.	When challenged with MS2 virus in droplet form, UV-treated masks had a dose-dependent response. While masks treated for 1–4 hours had detectable levels of virus, masks treated for 5 hours did not. No physical changes were observed.
Lin *et al*[53]	Type: UVA 365 nm, UVC 254 nm Model: UVGL-58 VUP, Upland, California Conditions: both sides were exposed for different times—1, 2, 5, 10 or 20 min	*Bacillus subtilis* spores	N95 (8210 to 3 m, St. Paul, Minnesota)	Intervention arm: 3 masks, 15 samples Control arm: 3 masks, 3 samples.	UVA radiation had relative spore survival above 20% after decontamination, but the UVC radiation had 99%–100% biocidal efficacy.
Woo *et al*[110]	Type: UVC lamp (UVG-11; 254 nm, 230 V, 4 W Model: UV Products, Cambridge, UK Conditions: continuous exposure of for 0–2 hours at a height of 10 cm	MS2 bacteriophage	N95 model (3M 1870)	Sample sizes NR (triplicate tests for each condition were conducted)	The highest inactivation efficiency was at low relative humidity (30% humidity) after applying UV for 30 min.

GC-MS, gas chromatography-mass spectrometry; N/A, not available; NR, not reported; UV, ultraviolet.

studies found diminished filtration performance on decontamination with bleach, ethylene oxide, ethanol, autoclaves, rice cookers or microwave heat.[52 54 55] Viscusi *et al*[55] found that UV and hydrogen peroxide (liquid and vaporised) had the least effect on filter performance. However, Bergman *et al*[56] found that, with the exception of hydrogen peroxide gas plasma which performed poorly, all treatment and control groups had comparable impact on filtration performance. Similarly, Fisher *et al* noted that microwave steam bags were 99.9% effective in MS2 decontamination while maintaining filtration efficiency.[47]

There were several complications associated with decontamination. For example, microwave irradiation using dry heat was noted to melt several filtration facepiece respirator (FFR) models.[54 57] Decontamination using ethylene oxide created hazardous by-products that could be injurious to provider.[58] Bleach would often impart a discernible odour on the FFR as well as corrode metal parts, such as the nose clip of masks.[58 59] Physical degradation also occurred in a dose-dependent manner with UV treatment and after repeated hydrogen peroxide treatment.[51 60] However, most studies did not formally assess mask fit after decontamination (table 4).

Two studies analysed the determinants related to provider uptake of decontamination.[61 62] Nemeth *et al*[61] evaluated user acceptance of FFR decontamination, noting that perceived safety of UV decontamination was higher in comparison to wearing an FFR for an extended period of time without decontamination.[61] Viscusi *et al*[62] reported that decontamination with UV, moist heat or microwave steam did not significantly change the user experience. Their clinical study found that FFR users are not likely to experience clinically meaningful reduction in fit, or an increase in odour, discomfort or difficulty in donning after decontamination. However, the authors noted that their results may have limited generalisability, as participants only wore the masks for 30 min when assessing comfort.

Reusability and extended wear of disposable masks

Ten studies evaluated outcomes related to the reusability and extended wear of disposable masks. All 10 studies evaluated N95 respirators, while 2 studies additionally evaluated surgical masks. Details of the studies are provided in table 6.

Three studies were laboratory-based.[63–65] Coulliette *et al*[63] noted that H1N1 viruses remained infectious for 6 days when deposited on the respirators under several conditions. Similarly, Fisher *et al*[64] found that respirators have the potential to act as fomites, as MS2 bacteriophage were still detectable on the 10th day after deposition. Another study considered contamination with extended use, by quantifying the reaerosolisation of MS2 bacteriophage due to reverse airflow after simulated coughing. They found that <1% of viable virus was reaerosolised after a single cough.

Of the six clinical studies, two examined the performance of N95s after extended use in a healthcare setting. Duarte *et al* assessed the physical damage of N95 respirators over 1–30 days of consecutive use.[66] A total of 668 respirators worn by 167 nursing assistants were evaluated. Past the fifth day of consecutive use, the respirators were visibly contaminated and folded. However, this was a subjective assessment of mask damage and was limited to visual characteristics. In contrast, Brady *et al*[67] presented a more controlled clinical study that assessed pathogen transfer after reuse of N95s. Their results found that adequate doffing procedures had a greater impact in preventing contamination than whether a mask was reused. Specifically, MS2 bacteriophage contamination was lower with reuse and proper doffing in comparison to improper doffing.

Two studies analysed perceived discomfort and exertion of HCWs on extended wear of the masks. Radonovich *et al*[68] noted that participants discontinued N95 use before 8 hours in 59% of sessions, citing intolerance. Similarly, Shenal *et al*[69] noted that perceived discomfort increased over an 8-hour period, but exertion only marginally increased. In addition, two studies noted that fit testing scores of respirators dropped significantly with multiple wears. Specifically, fit factor consistently dropped after a maximum of five consecutive donnings and half of participants failed at least one fit test after repeated donning and doffing.[70 71]

Finally, Pillai *et al*[72] conducted a survey of physician preferences regarding conservation strategies in N95 shortages. They noted that extended and reuse of disposable N95s was the most preferred conservation strategy, in comparison to use of reusable respirators.[72]

Layering of multiple masks

Five studies evaluated outcomes related to layering multiple masks, including layering the same mask type (n=1) versus overlay of one mask model over another (n=4). Details of the included studies are outlined in table 7.

Derrick *et al*[73] evaluated combinations of one, two, three or five surgical masks overlayed on top of one another in a crossover study of six volunteers. They noted that while combining multiple surgical masks improved filtration, this was still well below that of N95 respirators.[73]

Three clinical studies evaluated user experience of surgical mask overlay over N95s.[69 74 75] Shenal *et al*[69] and Roberge *et al*[75] found no statistically significant differences between overlay versus N95 respirator on its own. In contrast, Rebmann *et al*[74] found that the overlay was perceived to be less comfortable and raised CO_2 levels significantly, but without clinically relevant outcomes.[74]

Finally, a laboratory study found that the effect of a surgical mask overlay had variable effects depending on the model of N95.[76] For cup models, this worsened respiratory gases, but for horizontal models it improved or did not change these values. The authors suggested that the

Table 6 Summary of studies involving the reusability or extended wear of disposable masks

Citation	Study design	Type of mask	Length of wear	Total sample size	Key findings	Limitations
Bergman *et al*[70]	Interventional, uncontrolled	N95	NR (five consecutive wears)	Intervention arm: 10 test subjects on 6 N95 models Control arm: N/A	Five consecutive donnings can be performed before fit factor consistently drops below 100 (standard), impact is model-dependent.	Controlled laboratory setting, small sample size, short test time (5 min), tested donnings only versus extended wear.
Brady *et al*[67]	Controlled interventional with randomised crossover, unblinded	N95	NR (multiple use)	Intervention arm: 13 test subjects	MS2 contamination was higher with improper doffing without reuse versus proper doffing and reuse.	Did not analyse proper doffing reuse which would be more useful for comparison, controlled environment, did not test aerosolised particles.
Coulliette *et al*[63]	Laboratory	N95	6 days	Intervention arm: 6–9 mask samples Control arm: N/A	The virus remained infectious for 6 days when deposited under the respirators under several conditions.	Controlled laboratory setting, did not account for humidity changes with the wearer's respiration, may be not be generalisable to other viruses.
Duarte *et al*[66]	Observational	N95	1, 5, 15, and 30 days of consecutive use	Intervention arm: 167 nursing assistants with 668 respirators Control arm: N/A	Re-use should not exceed 5 days due to contamination and folds.	Subjective assessment of mask damage, limited to visible damage, nursing assistants potential inconsistent mask use, inconsistent labelling of the masks with marking pens with variable damage to the masks.
Fisher and Shaffer[64]	Laboratory	N95	10 days	Intervention arm: 36 coupons (6 coupons per procedure per contamination method) Control arm: N/A	MS2 was detectable on the 10th day after deposition, indicating that FFRs can be potential fomites.	Controlled laboratory setting, limited to non-enveloped virus, virus survivability is impacted by multiple factors.
Fisher *et al*[65]	Observational (laboratory)	N95	NR	Intervention arm: N/A Control arm: N/A	A small amount (<1%) of viable virus was aerosolised from the FFR via reverse airflow after a single simulated cough.	Limited to single simulated cough versus naturalistic setting, single mask model was evaluated, may not be generalisable to other viruses (such as enveloped viruses), did not examine re-aerosolisation from normal breathing.

Continued

Table 6 Continued

Citation	Study design	Type of mask	Length of wear	Total sample size	Key findings	Limitations
Pillai *et al*[72]	Survey of clinician beliefs	Disposable N95, surgical mask	NR	Intervention arm: 686 responses from physicians Control arm: N/A	Extended and reuse of disposable N95 was the most preferred conservation strategy.	Survey of preferences, no laboratory or clinical data.
Radonovich *et al*[68]	Crossover RCT, unblinded	Air-purifying respirator, N95 (cup, cup+exhalation valve, duckbill, cup+exhalation valve+medical mask, cup+medical mask), medical mask, half-face elastomeric respirator	8 hours (used as a standard)	Intervention arm: 27 HCP volunteers, 7 respiratory ensembles or a medical mask Control arm: crossover design with same participants	Participants discontinued respirator before 8 hours in 59% of sessions, citing intolerance.	Small sample size, setting that only simulated pandemic scenario.
Shenal *et al*[69]	Crossover interventional	Surgical mask, N95, half-face elastomeric respirator powered air-purifying respirator, layered masks	8 hours	Intervention arm: 27 HCP volunteers, 7 respiratory ensembles or a medical mask Control arm: crossover design with same participants	Perceived discomfort increased over 8-hour period, but exertion only marginally increased.	Small sample size, limited to only simulated pandemic environment, participation bias (most common reason for HCWs declining to participate was unwillingness to wear equipment for prolonged period).
Vuma *et al*[71]	Interventional, uncontrolled	N95	NR (multiple donnings)	Intervention arm: 25 HCPs Control arm: N/A	Approximately half (48%) of participants failed at least one fit test after re-donning N95 FFR.	Fit failure may be due to unrealistic environment, limited models of N95 tested.

FFR, filtration facepiece respirator; HCP, healthcare provider; HCW, healthcare worker; N/A, not available; NR, not reported.

Table 7 Summary of studies involving the layering of multiple masks

Citation	Study design	Details of layering	Total sample size	Key findings	Limitations
Derrick and Gomersall[73]	Crossover interventional	Combinations of one, two, three or five surgical masks	Intervention arm: 6 volunteers Control arm: crossover design with same participants	Multiple surgical masks do not filter ambient particles adequately, in addition to reducing quality of fit.	The study measured dust particles that were small in size, rather than directly measuring the virus. If viruses are carried on larger particles, the masks may be useful.
Rebmann *et al*[74]	Randomised crossover interventional	Either N95 or N95 layered with surgical mask overlay	Intervention arm: 10 nurses Control arm: crossover design with same participants	Wearing an surgical mask overlay on the N95 was tolerated but less comfortable, CO_2 levels increased significantly with overlay but did not have clinically relevant outcomes.	Potential for selection bias, use of transcutaneous measurement of CO_2 versus arterial measurement.
Roberge *et al*[75]	Interventional	N95 or N95 with surgical mask overlay	Intervention arm: 10 HCPs Control arm: subjects from Roberge *et al*[75]	No significant difference in physiological variables, perceived exertion or comfort scores with overlay.	Small sample size, limited mask models, use of respiratory inductive plethysmography versus more accurate laboratory equipment.
Sinkule *et al*[76]	Laboratory design, observational	FFR models with surgical mask overlay	Intervention arm: 30 FFR models Control arm: 30 FFR masks without surgical overlay	The overlaid placement on cup models worsened gas levels, while overlaid placement had no effect or improved results with horizontal models. Effects were thought to be likely imperceptible at user levels.	Limitations of automated breathing simulator measurement, relevant to subset of body sizes, does not mimic fluctuations of human breathing patterns.
Shenal *et al*[69]	Crossover interventional	Surgical mask over N95	Intervention arm: 27 HCPs Control arm: crossover design with same participants	No significant different in exertion level between an N95 on its own for 8 hours versus layering with surgical mask.	Small sample size, limited to only simulated pandemic environment, participation bias (most common reason for HCWs declining to participate was unwillingness to wear equipment for prolonged period).

FFR, filtering facepiece respirator; HCP, healthcare provider; HCW, healthcare worker.

differences would likely be imperceptible at low levels of exertion, however, no clinical correlates were evaluated.

Introduction of reusable respirators

Seven studies evaluated the use of reusable respirators as a method of conservation for disposable masks (table 8).

Two laboratory-based studies evaluated the efficacy of decontamination of reusable respirators.[77 78] Both studies reported that chemical disinfectant wipes (combined isopropyl alcohol plus quaternary ammonium wipes) were effective against influenza, but Subhash *et al*[78] found that isopropyl alcohol alone was ineffective.

The remaining five studies analysed the logistics and feasibility of introducing reusable respirators. Bessesen *et al*[79] noted that creation of standard operating procedures for disinfection significantly reduced the number of errors made by HCW, in comparison to following manufacturer instructions.[79] In addition, Pompeii *et al*[80] found that HCWs can be rapidly fit tested and trained to use the reusable elastomers in an outbreak simulation. Reusable elastomers did not require significantly different fit times in comparison to N95 fit testing.

Finally, three studies by Hines *et al*[81–83] evaluated user preferences and driving factors behind reusable elastomer programmes via surveys, focus groups and interviews. Reasons for adoption included perception that elastomers are more protective and useful during N95 shortages. Concerns for adoption included lack of convenience, dissatisfaction with breathing when wearing the respirator and obstacles to access disinfection services. Other barriers to compliance and continued use were lack of availability, difficulties with storage, and difficulties changing filters.

Unconventional mask replacements or modifications

Three studies evaluated non-traditional reusable masks[43–45] (table 9). Au *et al*[45] tested a reusable plastic mask trimmed to the user's face via an unblinded RCT. They noted that N95s were more effective in reducing airborne particles than the reusable masks. Two studies evaluated reusable cloth masks. MacIntyre *et al*[43] conducted a multi-institute RCT in a low-resource setting, in which reusable cloth masks were provided to 569 HCWs. Five double-layer cotton masks were provided to each worker for the four consecutive weeks, to be washed with soap and water each day. The rate of wearer respiratory infection was significantly higher in the cloth mask arm versus the medical mask controls, with laboratory tests also noting higher penetration of particles through the cloth masks. Similarly, Rengasamy *et al*[44] conducted a laboratory investigation in which cloth masks made from sweatshirts, T-shirts, towels, scarves and cotton were evaluated. They noted a wide variation in penetration across different fabrics, with higher penetration in cloth masks versus N95 controls.[44]

Another preclinical study evaluated the creation of a reusable virus deactivation system built into surgical masks. The investigators coated the middle of the three-layer masks (the polypropylene microfiber filter layer) with a solution of 29.03 wt by volume% of NaCl.[84] They noted that salt-coated filters had higher filtration efficiency against influenza viruses, in comparison to bare filters. Mice who were protected against H1N1 by salt filters showed higher survival rate in comparison to mice who were unprotected. The authors additionally noted that the salt-coated filters were effective in a variety of storage conditions.

Stockpiled or expired masks

Four studies evaluated the performance of respirators after stockpiling or storage (table 10). All four studies had favourable results in quality testing of stockpiled masks.

Greenawald *et al*[85] evaluated almost 4000 masks at 10 stockpile facilities in the USA with varying humidity and temperature parameters. All masks were tested beyond their listed expiration date, which ranged from over 5 to 10 years old. They found that 98% of tested N95s met performance standards for filtration performance, with only 2% of respirators having visual inspection concerns. Similarly, Viscusi *et al*[57] determined that most models stored for up to 10 years in warehouses had adequate filtration performances.

Bergman *et al*[86] found that the majority of respirator models in storage had adequate fit for subjects. However, Rottach *et al*[87] found that strap strength across time of storage was model-dependent. While one model showed no clear difference with age, another manufacturer's strap decreased in tensile strength over time.

Summary of grey literature

There were numerous diverse suggestions in the grey literature for potential conservation strategies. However, we found no included evaluations or outcomes, and no peer-reviewed studies that had not already been captured in our review. Examples of the conservation strategies are listed in table 11.

DISCUSSION

We included 47 studies in our systematic scoping review to characterise interventions related to overcoming limited supply of masks during pandemics and epidemics. These studies encompassed six broad categories of conservation strategies: decontamination, reusability of disposable masks and/or extended wear, layering, reusable respirators, non-traditional replacements or modifications and stockpiled masks.

Almost half of the included studies were laboratory-based or preclinical, while the remainder were user acceptance studies or clinical designs. A number of promising strategies were identified, including the use of reusable respirators, extended wear of N95s, use of masks stockpiled beyond manufacturer's listed expiry date and decontamination. While numerous studies suggested that decontamination of masks is feasible, there were three potential caveats that require further study: (1) hazardous by-products, (2) physical degradation and (3)

Table 8 Summary of studies involving reusable respirators

Citation	Study design	Details of respirator	Total sample size	Key findings	Limitations
Bessesen *et al*[79]	Non-randomised trial with control, blinded	Reusable elastomeric respirators	Intervention arm: 21 HCW volunteers (6 subjects who tested manufacturer guidelines, 6 subjects who developed standard operating procedures, 9 subjects who tested final procedures)	Creation of standard operating procedures for disinfection reduced the number of errors made by HCW.	Small sample size, single-centre design, time constraints of disinfection of a single respirator at a time.
Hines *et al*[81]	Interview, focus group	Reusable elastomeric respirator	Intervention arm: 22 (11 HCW, 11 leadership key informants) Control arm: N/A	Reasons for adoption included perception that elastomers are more protective and useful during N95 shortages. Barriers to adoption included lack of convenience, dissatisfaction with breathing/communication and obstacles to access disinfection services.	Continued use was not in a pandemic/epidemic setting, self-selected participation, small sample size.
Hines *et al*[82]	User acceptance study	Elastomeric half-face respirators and powered air-purifying respirators	Intervention arm: 1152 HCPs Control arm: N/A	N95 users rated respirators more favourably for comfort and communication, but elastomers were rated higher for protection. Reusable elastomeric respirators were more likely to be preferred over N95s.	Survey of beliefs, low participation rate (12%).
Hines *et al*[83]	Survey of healthcare workers	Elastomeric half-face respirators	Intervention arm: 432 HCPs who used elastomerics Control arm: N/A	Barriers to compliance included lack of availability, difficulties with storage, difficulties changing filters.	Survey of beliefs, low participation rate (21%).
Lawrence *et al*[77]	Laboratory study	Elastomeric half-face respirators and three powered air-purifying respirator	Intervention arm: 8 models (5 for half-mask, 3 for powered air-purifying respirators), which included 41 surfaces Control arm: 45 HMER replicates with aseptic inoculations	Cleaning alone as well as cleaning plus disinfection are both effective methods for eliminating viable influenza virus on most surface tested.	Time constraints for disinfection, laborious process of cleaning, requirement of containment device to prevent contamination, need for better guidance for HCW.
Pompeii *et al*[80]	RCT	Elastomeric half-mask respirators	Intervention arm: 124 HCP who were assigned to elastomers Control arm: 29 HCP who were assigned to N95	HCWs can be rapidly fit tested and trained to use the reusable elastomers in an outbreak simulation.	Simulation of pandemic, small sample size, lack of data on actual use of elastomers.

Continued

Table 8 Continued

Citation	Study design	Details of respirator	Total sample size	Key findings	Limitations
Subhash *et al*[78]	Laboratory study	Reusable elastomeric respirator	Intervention arm: 32 respirators with influenza Control arm: 8 respirators with sterile media	Quaternary ammonium/isopropyl alcohol and bleach detergent wipes were effective in eliminating H1N1 live virus, but isopropyl alcohol alone was ineffective.	Small flat portion of respirator was decontaminated only, straps/clips and irregular surfaces were not tested, limited to the single virus, performed in controlled laboratory setting.

HCP, healthcare provider; HCW, healthcare worker; HMER, half-mask elastomeric respirator; N/A, not available; RCT, randomised control trial.

compromise of mask fit. Strategies that were found to be less effective included the use of cloth masks, layering multiple surgical masks or re-donning previously used masks that have not been sterilised. Barriers to mask conservation strategies included the time costs, necessary training and provider compliance. Strategies such as the creation of standardised operating procedures, physician education and user feedback were proposed to overcome these barriers.

However, the generalisability of these findings is limited. Minimum evidence requirements from regulatory agencies such as Health Canada include: demonstration that number of pathogens has been reduced, demonstration that respirator filter and fit performance are maintained, evidence that there is no residual chemical hazard and assurance of adequate labelling.[46] The available literature does not meet these standards given the relative paucity of clinical studies. Many of the preclinical studies did not evaluate practical logistical barriers towards usage. For example, many studies cut N95 respirators into smaller coupons in order to test various decontamination techniques, precluding any understanding of how masks would perform in a clinical setting in terms of fit and seal, and whether elastic straps or nose bridge would be damaged or decontaminated. Most decontamination studies did not assess mask fit. There were no decontamination studies that evaluated clinical outcomes, such as rate of infection among healthcare providers. In addition, even the more promising approaches remain theoretical, as none of the preclinical studies tested decontamination for the SARS-CoV-2 pathogen. Proxy measures such as MS2 bacteriophages and aerosolised sodium may not be generalisable to the SARS-CoV-2 pathogen.

None of the clinical research occurred during an actual pandemic/epidemic setting, and studies assessing user compliance and discomfort may not be generalisable to such scenarios. As interventions were tested in highly controlled environments, they may not be generalisable to an outbreak setting, in which there may be system-wide disorganisation, resource overload, extended use times and limited personnel.

Our findings align with the current research base. There has been significant interest in pandemic preparedness, including cost-benefit analyses of stockpiling, methods to conserve ventilators, infection control modelling and strategies to improve surge capacity.[88–91] In previous outbreaks such as Ebola and influenza, hospital leaders have noted the importance of rapid PPE acquisition in response to sudden spikes in demand.[92 93] However, such efforts can fail to meet demand in times of pandemic, such as with COVID-19. In addition, willingness of health providers to work during pandemics is associated with their perception of safety.[94–97] Absenteeism may cause reduction in surge capacity or even basic staffing if there are mask shortages for providers.[94–96 98] The need to conserve available PPE for healthcare providers during the COVID-19 pandemic has informed guidelines for PPE use in lower risk groups, such as asymptomatic community members,

Table 9 Summary of studies involving unconventional mask replacements or modifications

Citation	Study design	Details of mask	Total sample size	Key findings	Limitations
Au *et al*[45]	Randomised trial with control, unblinded	Totobobo masks (compact reusable mask made of plastic material trimmed to user's face, filtered by disposable high-efficiency particulate air filter)	Intervention arm: 22 healthy volunteers Control arm: crossover design with same participants	Median reduction in airborne particle counts was significantly higher for N95 than Totobo masks.	Potential conflicts of interest (study investigator was trained by inventor of mask), may not be generalisable to other face shapes, small sample size.
Quan *et al*[84]	Preclinical	Surgical masks with salt-infiltrated filter for virus deactivation system	NR	Salt-coated filters had high efficacy in deactivating H1N1/H5N1 viruses and higher filtration efficiency in comparison to untreated filters.	Limited to animal models, controlled laboratory settings, may not be comparable against other viruses
MacIntyre *et al*[43]	Randomised controlled trials	Reusable cloth masks (five masks total for four consecutive weeks, washed with soap and water each day)	Intervention arm: 1149 (580 medical masks, 569 cloth masks) Control arm: 458 HCPs/masks	Rate of infection was significantly higher in the cloth mask arm. Higher penetration of particles through cloth masks (97%).	Lack of no-mask control, no measure of compliance with hand hygiene, inability to measure asymptomatic infection.
Rengasamy *et al*[44]	Preclinical	Cloth masks (sweatshirts, T-shirts, towels, scarves and commercial cloth masks)	Intervention arm: three models of five types of cloth Control arm: one N95 model	There was a wide variation in penetration of common fabric materials and cloth masks. Penetration levels for aerosols was significantly higher for fabrics versus control N95s.	Limited samples tested, fabrics were not worn or laundered, face seal leakage was not measured, human subjects are necessary.

HCP, healthcare provider; NR, not reported.

and prompted research priorities regarding decision-making, such as whether surgical masks are as effective against COVID-19 as N95 respirators.[99–101]

Strengths of our systematic scoping review included a robust search of the literature after consultation with a research librarian. This included further hand search of citations of included articles and reviews, and a search of grey literature, including preprint databases. We undertook duplicate screening, extraction and evidence grading by at least two independent reviewers. Limitations include the restriction of examined studies to those published in English and to the last 25 years. Furthermore, we were limited to the quality of the evidence base in the search yield.

The US Food and Drug Administration (FDA) issued a guidance in May 2020 to provide recommendations for sponsors of decontamination and bioburden reduction systems about what information should be included in a pre-emergency use authorisation (pre-EUA) and/or EUA request to help facilitate FDA's efficient review of such request.[102] This policy was intended to remain in effect only for the duration of the COVID-19 pandemic. As this guidance was issued subsequent to design and execution of the studies we have reviewed, we did not seek to measure their published results retroactively against the FDA guidelines. Future studies aimed at respirator conservation (including decontamination, reuse and use beyond manufacturer's expiry date) should consider these guidelines during protocol design.

Ultimately, we recommend further clinical research on mask conservation strategies, both in the current COVID-19 context as well as in preparation for any future disease outbreaks. Higher quality research, especially RCTs, is necessary for determining whether mask conservation strategies are effective against the SARS-CoV-2 pathogen specifically. While deviations from standard of care may be necessary in times of PPE shortage, it is important that evidence-informed decisions are made for both patient and provider safety.

CONCLUSION

Promising strategies for mask conservation in the context of pandemics and epidemics include use of

Table 10 Summary of studies involving the stockpiling or use of expired masks

Citation	Study design	Mask type	Details of storage	Total sample size	Key findings	Limitations
Bergman *et al*[86]	Observational (clinical)	N95	The US CDC maintains PPE, including N95 FFRs, in its SNS in strategic locations as a contingency plan for large-scale emergencies; study used PPE from the SNS for a representative sample	Intervention arm: 229 subjects on 7 N95 models Control arm: N/A	The majority (6/7) of respirator models had adequate fit for subjects, and models supported a range of facial sizes.	Limited models tested, small sample size for failed respirator, did not describe storage conditions (humidity, temperature, duration) or analyse between options.
Greenawald *et al*[85]	Mixed methods (observational, clinical)	Particulate-only air-purifying respirators, including N95 FFRs and P95 particulate filter	Study used PPE from 10 US SNS facilities (1 federal, 6 state, 2 regional and 1 county)	Intervention arm: 12 models (3971 masks) Control arm: N/A	98% of tested N95 FFRs met performance standards for filtration performance, only 2% of respirators had visual inspection concerns.	Lot-specific considerations, not peer-reviewed, did not assess against live pathogens or consider mask fit.
Viscusi *et al*[57]	Observational (laboratory)	Disposable N95s, stored in original packaging for 6 years, ranging in temperature from 15°C to 32°C	Study used random sampling from N95s present in the US SNS	Intervention arm: 21 models Control arm: N/A	Most models stored for up to 10 years in warehouses are likely to have adequate filtration performance.	No before-and-after comparator, only 21 models were analysed, respirator manufacturers are routinely redesigning standards.
Rottach and Lei[87]	Laboratory	N95	Study used samples from sets of N95s that were purchased for testing and stored on-site for up to 10 years; storage location of the samples suffered an environmental control failure and was subjected to higher than normal temperature and humidity for over 1 year	Intervention arm: 51 samples Control arm: N/A	Strap strength over time was model-dependent. One manufacturer strap showed changes with age, while a polyisoprene strap showed no clear difference with age.	Only two manufacturer straps were tested, environmental controls were not monitored (including temperature controls), did not examine fit factor based on strap strength.

CDC, Centers for Disease Control and Prevention; FFR, filtering facepiece respirator; N/A, not available; PPE, personal protective equipment; SNS, strategic national stockpile.

Table 11 Results of non-peer-reviewed literature

Source	Details of source	Examples of identified strategies
DuckDuckGo[30]	First 200 search results on 8 April 2020, sorted by relevance	Homemade cloth masks, mask drives, outsource production to unconventional suppliers, use of bandanas as masks, use of gas masks instead of face masks.
JAMA Call to Action forum[16]	First 200 suggestions on the Call to Action forum, sorted by date	Supply drives, cancellation of elective/cosmetic surgeries to conserve supply, snorkel masks, buy back PPE from community sources, three-dimensional (3D) printing, homemade cloth masks, use of bandanas or shirts as masks, use of constructive company masks, use of gas masks, use of vacuum cleaner bags, home air conditioner filters, racquetball/sports glasses, use of spill containment pads, creation of face shields using a clear A4 page, recycled plastic bottles into face shields, rotation of worn masks.
Google News[31]	First 100 search results as of 8 April 2020, sorted by relevance	Cloth masks, 3D printing face shields, mask drives, use of garbage bags as PPE, use of T-shirts, rotation of worn masks, sports dryers.
LexisNexis Academic[32]	First 100 search results categorised as News, as of 8 April 2020	Cloth masks, mask drives, ski goggles or scuba diving gear as masks, masks made from coffee filters and cotton bandages, use of T-shirts as mask, 3D printing.

JAMA, Journal of the American Medical Association; PPE, personal protective equipment.

stockpiled masks, extended wear of disposable masks, and UV-based methods for decontamination. Strategies that were found to be less effective included the use of cloth masks, layering multiple surgical masks and re-donning previously used respirators. However, there remains uncertainty regarding the effectiveness of these strategies in a clinical setting, as well as their generalisability to COVID-19. Further research is needed prior to clinical implementation.

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