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Liquid-Immersion Reprocessing Effects on Filtration Efficiency of 'Single-Use' Commercial Medical Face Masks

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Abstract

Purpose: Medical masks have inferior filtration efficiency and fit to filtering facepiece respirators (FFRs) but are widely used in healthcare and the community. These masks are intended for disposal after use but in the event of mask shortage re-use after reprocessing may be an option. We investigated eight reprocessing methods that each involved washing or soaking in liquid, are likely to eliminate respiratory viruses, and are safe and available in most community and healthcare settings.

Methods: Three brands of EN 14683 standards-compliant commercial medical mask were each reprocessed 10 times by one of eight methods. We measured filtration efficiency for poly-dispersed sodium chloride particles and pressure differential.

Results: Compared with new medical masks, reprocessed masks had significantly reduced filtration efficiency. The reduction was mild-moderate (6.5–25.8%) after warm water wash, hot water soak or boiling water soak; and moderate-large (24.1–51.5%) after detergent, soap or laundry machine wash, or bleach soak. There were mixed and minor changes in pressure differential. Most reprocessed standards-compliant masks had better filtration efficiency than new non-standard commercial masks and then cotton and cotton-polyester mix fabric samples, even triple-layered fabrics.

What's Important About This Paper?

The results have potentially major implications for under-resourced country health services and domestic settings around the world where facemasks might be unavailable or unaffordable, especialy with the current COVID-19 pandemic. The results show, and confirm reports of others, that non-detergent reprocessing methods have only mild effects on filtration efficiency for EN14683-compliant commercial masks, and that such masks even reprocessed up to 10 times are more efficient at blocking sub-micron particles than most cheaper non-standard masks and fabric masks.

Conclusions: High-quality commercial medical masks reprocessed 10 times by water immersion methods had better filtration efficiency than new non-standard masks and washable fabrics. These findings have particular relevance for community and low-resource healthcare settings.

Keywords: coronavirus; COVID; disinfection; facemask; filtration; influenza; mask; reprocessing

Introduction

Although there is increasing evidence of aerosol transmission of many respiratory pathogens and of the potential advantages of very high filtration-efficiency and close-fitting filtering facepiece respirators (FFRs), medical masks are relatively economical and widely used in healthcare, especially in low-resource settings, and in the community. Commercial medical masks are probably effective for reducing respiratory virus transmission, by both source control and protection of the wearer (MacIntyre *et al.*, 2017; Offeddu *et al.*, 2017; MacIntyre and Chughtai, 2020). Medical masks manufactured to meet the highest international standards for healthcare use (EN 14683, ASTM F2100) have over 98% filtration efficiency for particles the size of bacteria and viruses and less than 60 Pa/cm^2 (EN 14683) or 49 Pa/cm^2 (ASTM F2100) pressure differential (ASTM, 2019; CEN, 2019), but other brands are manufactured to lower standards or sold without any claim of standards compliance. Most commercial medical masks are intended to be discarded after use, but this may not be possible in low-resource settings or when supply is limited, for example during a pandemic. In these circumstances, one option would be to re-use these 'single-use' masks.

Used face masks become visibly soiled (Duarte *et al.*, 2010) and contaminated with viruses and other microbes from the surrounding environment (Prospero *et al.*, 2003; Noti *et al.*, 2012; Luksamijarulkul *et al.*, 2014; Rule *et al.*, 2018; Chughtai *et al.*, 2019) and from the wearer (Huynh *et al.*, 2008; Williams *et al.*, 2014). Before re-use of a mask, especially by a different wearer, it should be 'reprocessed' to remove biological material (washing) and to eliminate or inactivate microbes (disinfection or decontamination). If biological material (e.g. sputum, saliva) is not removed this may increase the resistance of trapped microbes to disinfection or drying (Parker *et al.*, 1944; Ulrich, 1981; Rabenau *et al.*, 2005; Darnell and Taylor, 2006; Thomas *et al.*, 2008; Greatorex *et al.*, 2011; Hirose *et al.*, 2019; Fedorenko *et al.*, 2020), have negative effects on appearance and odor, or block the mask filter. Effective cleaning to remove biological material from fabrics generally involves immersion in liquid and is enhanced by increased water temperature, detergents or soap, and agitation (Bloomfield *et al.*, 2013). Disinfection options for microbes that might contaminate a face mask are many. Even drying alone kills respiratory viruses in hours to days, especially on a clean surface (Parker *et al.*, 1944; Brady *et al.*, 1990; Sizun *et al.*, 2000; Lai *et al.*, 2005; Rabenau *et al.*, 2005; Thomas et al., 2008, 2014; Sakaguchi *et al.*, 2010; Greatorex *et al.*, 2011; Coulliette *et al.*, 2013; Chin *et al.*, 2020; Fedorenko *et al.*, 2020; van Doremalen *et al.*, 2020). Unfortunately, commercial 'single-use' medical masks are not designed or intended to be reprocessed: the cleaning or disinfection procedure may reduce the mask's electrostatic activity or physically damage its structure. Previous studies of liquid immersion and mask filtration efficiency show marked damage with organic solvents (Biermann *et al.*, 1982; Viscusi *et al.*, 2007; Lin *et al.*, 2017; Liao *et al.*, 2020; Ou *et al.*, 2020; Ullah *et al.*, 2020) or soapy water (Viscusi *et al.*, 2007), mixed results with bleach (Viscusi et al., 2007, 2009; Bergman *et al.*, 2010; Heimbuch *et al.*, 2014; Lin *et al.*, 2017; Liao *et al.*, 2020) and a minor or no effect with water alone (Biermann *et al.*, 1982; Moyer and Bergman, 2000; Viscusi *et al.*, 2007; Bergman *et al.*, 2010; Wang *et al.*, 2020; Chen *et al.*, 2021). Most studies included FFRs; only a few have included medical masks (Lin *et al.*, 2017; Ou *et al.*, 2020; Wang *et al.*, 2020).

The aim of this current study was to assess the effects of multiple cycles of liquid immersion reprocessing on filtration efficiency and breathability of commercial medical masks. We used eight reprocessing methods that each involved a washing process to remove biological material, is likely to eliminate or inactivate respiratory viruses from medical masks and is safe to administer and achievable in community and low-resource healthcare settings, where re-use of masks is most likely to occur. We applied these eight methods to three EN 14683 standards-compliant commercial brands of medical mask commonly used in healthcare facilities in New Zealand.

Materials and methods

Masks and fabrics

Three brands of commercial medical face mask were tested in the reprocessing studies (see Table 1). All were single-use, 3-ply, polypropylene masks that were stated by the manufacturer to comply with EN 14683 Type IIR (brands 'P' and 'E') or II (brand 'C') test standards (CEN, 2019) and were being used by healthcare workers in New Zealand in 2020. The filtering middle layer of brand P masks was described as 75% spunbound and 25% meltblown, and of brands E and C masks was described as meltblown.

For comparison, we also tested two brands of commercial face mask that had no manufacturer claim of compliance to international standards (brands 'B' and 'G'). Both non-standard brands were single-use, 3-ply, ear-loop, nose-bar masks intended for medical or surgical use, and had been used by healthcare workers in New Zealand in 2019.

One brand of commercial single-use FFR mask was tested. This was a Fluidshield 3 N95 particulate filter respirator and surgical mask, manufactured by Halyard Health, Alpharetta, GA, USA. The batch tested was manufactured in April 2018, with an expiry date of 10 April 2023, and lot AM8100841.

Three fabrics were tested: a cotton T-shirt, a 400-threadcount 100% cotton pillowcase, and a 250-threadcount cotton-polyester mix pillowcase. These were purchased from a local retail store.

Reprocessing

Eight sets of masks, including five of each of the three standards-compliant commercial medical face mask brands, were each reprocessed 10 times using one of eight methods (see Table 2). Each individual mask was, therefore, reprocessed using only one method, tested only once, then discarded.

Table 1. Commercial medical masks used for reprocessing studies.

Brand	Mask name	Manufacturer	Manufacture date	Expiry date	Batch
P	Primagard 120, PM4-306 procedure mask	priMED Medical Products Inc., Edmonton, AB, Canada	February 2020	February 2023	0421BLP20
E	Ecoma procedure face mask	Xianning Eco Medical Articles Co., Ltd., Xianning City, Hubei Province, P. R. China	April 2020	March 2022	AK202004-018
C	Medical Surgical Mask	Henan Yubei Eisai Co., Ltd., Henan Province, P. R. China	February 2020	February 2022	04200213

Air-drying was undertaken indoors, without a heat source (e.g. we did not use a hairdryer). Masks were dried for >12 h and were completely dry before the next reprocessing cycle.

Each purchased piece of cotton or cotton-polyester mix fabric was initially cut into two pieces. One piece of each fabric was labelled 'new'. The other piece of each fabric was washed in a Fisher & Paykel Elba laundry washing machine, set to low water level, cold water, fast spin, regular cycle, and medium-duration wash and rinse. We added Persil laundry powder detergent ½ scoop (approx. 25 g) to each load. The fabric pieces were not washed with other items. The fabric pieces were then hung to dry. This was repeated 10 times. The new and washed fabric pieces were then cut into smaller samples for testing.

Five samples of new and five samples of washed pieces of each the three fabric types were tested individually. Separate samples of each of the new and washed fabric types were also tested as a triple layered stack.

Testing

We tested masks reprocessed by each of the eight methods and new masks of brands P, E, and C, new non-standard masks of brands B and G, one brand of FFR and samples of each fabric type, new and washed. Five masks or fabric samples were tested consecutively for each group, with a positive control (no filter) run before and after the five mask or fabric tests. Three extra samples of each of the new and washed fabric types were placed together in a triple-layer stack and tested, with a positive control run before and after the stack. Each individual mask or fabric piece was only tested once.

Mask testing was undertaken at Lanaco in Auckland on two days in December 2020 and one day in February 2021. During testing the laboratory room air temperature ranged from 23.6 to 26.8°C and room humidity ranged from 39 to 58%. Before filtration testing each individual mask was examined by eye for fabric damage and metal corrosion and assessed for ear-loop elastic damage by gentle traction. A circular area of 100 cm^2 (113 mm diameter) was used for testing medical masks and fabric samples; a circular area of 45.4 cm^2 (76 mm diameter) was used for testing FFRs. All commercial masks were tested with the outer (colored) side facing the sodium chloride challenge.

Testing of filtration efficiency and pressure differential was done on a PALAS Modular Filter Test System—MFP 1000 HEPA (Palas GmbH, Karlsruhe, Germany). Sodium chloride (2%) solution was used to generate a poly-dispersed aerosol with median particle diameter of approximately 70 nm and geometric standard deviation of 2.5 nm. For medical mask and fabric testing a flow rate of 32 l/min with a face velocity of 0.053 m/s were used; for FFRs a flow rate of 14.5 l/min with a face velocity of 0.053 m/s were used. We measured sodium chloride particles with sizes ranging from 0.1 to 2 µm (0.1–2 µm). The filtration efficiency was calculated from the number of particles detected downstream of the mask or fabric in a filtration test compared with the number detected during tests without a mask or fabric, as described in the equation below.

$$\textit{Filtration efficiency}\,(\,\%\,) = \left(1 - \frac{\text{Number of particles detected with a filter}}{\text{Number of particles detected without a filter}}\right) \times 100\ \%$$

Analysis of results

Masks and fabrics were compared by measurement of filtration efficiency for all particle sizes between 0.1 and 2 µm and by pressure differential. Statistical assessment of the results of testing of the three mask brands (P, E, and C) was undertaken using the Kruskal–Wallis test and comparison of results for masks and fabrics before and after reprocessing or between mask types (standards-compliant masks, new and reprocessed, compared to non-standard masks and single- and triple-layer fabrics) was undertaken using the Mann-Whitney test. All statistical analysis was carried out using Stata/SE 16.1. In Figs 1 and 2, the error bars are placed one standard deviation above and one standard deviation below the mean.

Results

The results of 0.1 to 2 µm (combined) particle filtration efficiency and pressure differential are presented in Table 3 (masks), Table 4 (fabrics) and Figs 1 and 2. The effects of reprocessing on filtration efficiency for individual particle sizes between 0.1 and 1.5 µm are presented in Fig. 3 for brand P; the results for brands E and C were similar.

All individual new commercial medical masks that were stated by the manufacturer to comply with EN 14683 Type II or IIR test standards (CEN, 2019) (brands P, E and C) demonstrated a filtration efficiency in this current study of 90% or higher for 0.1–2 µm particle sizes combined. The two non-standard brands of commercial mask had significantly poorer mean filtration efficiency (29.3% (SD 3.0%) for brand B and 44.3% (SD 12.4%) for brand G) than the new masks of each of the three standards-compliant brands ($P < 0.05$). All individual new commercial FFRs demonstrated a filtration efficiency of 99% or higher for 0.1–2 µm (combined) particle sizes.

There was a significant difference ($P < 0.05$) in the results of filtration efficiency and pressure differential

Table 2. Reprocessing methods.

Method	Detail
Warm water wash	Masks were immersed in warm tap water (45°C), with no detergent or soap, for 10 s. Throughout the 10 s, each mask was gently washed by hand rubbing. Masks were then rinsed in room-temperature tap water then hung to dry.
Hot water soak 5 min, after warm water wash	Masks were first washed in warm tap water as above. Tap water was boiled and poured into a large, pre-warmed metal container with a lid. Masks were immersed (held down) for 5 min in the hot water. The hot water temperature 30–60 s after adding the masks was a mean of 84.6°C (range 82.2–87°C) and at 5 min was a mean of 78°C (range 76.2–78.9°C). Masks were then removed from the hot water, rinsed in room-temperature tap water then hung to dry.
Boiling water soak 30 min	Masks were immersed (held down) for 30 min in actively boiling tap water. The water temperature was over 95°C throughout each 30-min process. Masks were removed from the boiling water, rinsed in room-temperature tap water then hung to dry. There was no manual wash but the masks moved gently in the actively boiling water.
Detergent and warm water wash	Masks were immersed in warm tap water (45°C) with kitchen detergent for 10 s. Throughout the 10 s, each mask was gently washed by hand rubbing. Masks were then rinsed in room-temperature tap water then hung to dry. For the detergent we used 5 ml Cussons Morning Fresh ultra concentrate in 2.5 l of water. Cussons Morning Fresh includes sodium laureth sulphate (detergent), cocamidopropyl betaine (surfactant), sodium xylene sulfonate (hydrotrope), poloxamer 188 (viscosity reducing agent), and other compounds.
Soap and cold water wash	Masks were immersed in room-temperature tap water with bar soap for 10 s. Throughout the 10 s, each mask was gently washed by hand rubbing with Palmolive Naturals Moisture Care bar soap. Masks were then rinsed in room-temperature tap water then hung to dry.
Laundry machine wash	Masks were washed in a Fisher & Paykel Elba laundry washing machine, set to low water level, cold water, fast spin, regular cycle, and medium-duration wash and rinse. We added Persil laundry powder detergent ½ scoop (approx. 25 g) to each load. The masks were not washed with other items. Masks were then hung to dry.
Bleach wash and soak 10 min	Masks were immersed in room-temperature tap water containing bleach (sodium hypochlorite 0.1%, 1000 ppm) for 10 min. At the start of the bleach soak, each mask was gently washed by hand rubbing for 10 s in the bleach solution. Masks were then rinsed in room-temperature tap water then hung to dry.
Bleach soak 10 min, after detergent and warm water wash	Masks were immersed in warm tap water (45°C) with kitchen detergent (5 ml Cussons Morning Fresh ultra concentrate in 2.5 l of water) for 10 s. Throughout the 10 s, each mask was gently washed by hand rubbing. Masks were then rinsed in room-temperature tap water then immersed in room-temperature tap water containing bleach (sodium hypochlorite 0.1%, 1000 ppm) for 10 min. Masks were then rinsed in room-temperature tap water then hung to dry.

between the three standards-compliant brands of medical mask (P, E, and C) when new, and following each reprocessing intervention.

All methods of reprocessing significantly reduced the mean filtration efficiency of each of the three brands of medical mask ($P < 0.05$). The effects of reprocessing on pressure differential were mixed and minor.

All new and reprocessed medical masks of brands P, E, and C had significantly better mean filtration efficiency than the new non-standard masks and the single and triple-layer fabric samples ($P < 0.05$), except that masks of brand E that had been reprocessed using soap and cold water wash, laundry machine wash, or bleach wash and soak for 10 min, and masks of brand P that had been reprocessed with soap and cold water wash did not have significantly better mean filtration efficiency than the non-standard brand G masks.

Two brand P medical masks had weak elastic ear loops after reprocessing, which snapped on handling – one mask in the detergent and warm water group and one in the bleach after detergent and warm water group. No polypropylene fabric damage or metal nose-band corrosion was seen. There was no bleach odor in masks that had been reprocessed with bleach soak (after rinsing and drying).

Single-layer T-shirt and pillowcase fabrics demonstrated poor mean filtration efficiency (10.6–15.3%). Triple-stacked T-shirt and pillowcase fabrics demonstrated better filtration efficiency than single layers, but with higher pressure differential. There was no significant difference in filtration efficiency or pressure differential between new and washed T-shirt or pillowcase fabrics ($P > 0.05$).

Discussion

In this study, all eight liquid immersion reprocessing methods applied 10 times significantly reduced the filtration efficiency of the three brands of commercial standards-compliant medical mask. The extent of damage differed between the three brands. No reprocessed mask would meet the EN 14683 or ASTM F2100 standard for filtration efficiency (ASTM, 2019; CEN, 2019). The adverse effects on filtration efficiency were mild to moderate (6.5–25.8% across the 0.1–2 µm particle size) for reprocessing methods that involved only water (warm water wash; hot water soak 5 min, after warm water wash; and boiling water soak 30 min) and moderate to large (24.1–51.5%) for methods that involved detergent, soap or bleach. Reprocessing methods that involved only water still resulted in masks with better filtration efficiency than non-standard medical masks, and all reprocessing methods resulted in masks with better filtration efficiency than the fabrics tested. In this study, reprocessing had mixed minor effects on pressure differential (breathability).

The results of other published studies on liquid immersion reprocessing and filtration efficiency of commercial masks are similar to this current study. For example, soaking FFRs in cold water (without soap, detergent or disinfectant) had a minor or no effect on filtration efficiency (Biermann *et al.*, 1982; Moyer and Bergman, 2000; Viscusi *et al.*, 2007; Bergman *et al.*, 2010). Wang *et al.* (2020) immersed medical masks and FFRs in hot water (56–90+°C) for 30 min for 10 cycles and found a 0–5% reduction in filtration efficiency for 0.075 ± 0.02 µm sodium chloride particles. Chen *et al.* (2021) immersed FFRs in boiling water for 10 min for 3 cycles and found no significant change in filtration efficiency for 0.3–10 µm sodium chloride particles and no increase in pressure drop. Soapy water immersion significantly reduced FFR filtration efficiency (Viscusi *et al.*, 2007). Several early studies showed no effect on FFR filtration efficiency after exposure to dilute bleach (Viscusi et al., 2007, 2009; Bergman *et al.*, 2010; Heimbuch *et al.*, 2014), but two recent studies showed substantial reduction for both FFRs and medical masks (Lin *et al.*, 2017; Liao *et al.*, 2020). Although we did not study moist heat or steam reprocessing, these treatments have some similarities to immersion in hot or boiling water. Other studies show the effects of moist heat on filtration efficiency of FFRs are not significant at temperatures under 90°C (Bergman et al., 2010, 2011; Viscusi *et al.*, 2011; Lore *et al.*, 2012; Anderegg *et al.*, 2020; Liao *et al.*, 2020), little to none for steam (Fisher *et al.*, 2011; Liao *et al.*, 2020; Ou *et al.*, 2020) and mixed at temperatures of 121–125°C (Viscusi *et al.*, 2007; Lin et al., 2017, 2020; Liao *et al.*, 2020; Wang *et al.*, 2020).

The current study shows the reduction in filtration efficiency as a result of reprocessing affected all particle sizes measured, but disproportionately the submicrometer particles (Fig. 3). This has also been noted after isopropanol (Chen and Huang, 1998) and steam (Ou *et al.*, 2020) reprocessing and has been attributed to loss of electrostatic attraction by the mask filter layer, not to mechanical fiber damage (Chen and Huang, 1998; Wang *et al.*, 2020). A proportion of high-quality commercial medical mask filter efficiency is due to electrostatic mechanisms, and these have their greatest effects on 0.1–1 µm particles (Biermann *et al.*, 1982). These adverse effects on sub-micrometer particle filtration are likely to be of clinical importance. Yang *et al.* (2007) showed that 82% of coughed droplets are from 0.74 to 2.12 µm diameter. Respiratory viruses have

been detected in droplets expelled from the mouth that are smaller than 1 µm (Lindsley *et al.*, 2010) or 5 µm (Leung *et al.*, 2020) and from indoor air samples in particles that are smaller than 1 µm (Yip *et al.*, 2019), 2.5 µm (Yang *et al.*, 2011), 4 µm (Blachere *et al.*, 2009), or 4.7 µm (Bischoff *et al.*, 2013). Tang *et al.* (2020) present strong evidence to support influenza, SARS-CoV-1 and COVID-19 transmission by small-droplet aerosol.

Reprocessing may have weakened the elastic ear loops of two brand P medical masks in the current study, but caused no other obvious visible damage. Other studies have examined reprocessed FFRs for physical damage and found no effect from water alone or soapy water (Viscusi *et al.*, 2007; Bergman *et al.*, 2010) and mixed effects from moist heat or steam (Bergman *et al.*, 2010; Viscusi *et al.*, 2011; Ou *et al.*, 2020). Bleach immersion, at least without rinsing afterwards, has caused physical damage in studies of FFRs and medical masks, including tarnishing or oxidizing of the metal nose bands, discoloration and a dryness or stiffening of the fabric, persistent odor, and destruction of gauze (Viscusi et al., 2007, 2009; Bergman *et al.*, 2010; Lin *et al.*, 2017). In the current study we did not measure the effects of reprocessing on mask fit. Most other studies have found little to no change in mask fit after moist heat or steam reprocessing (Bergman *et al.*, 2011; Viscusi *et al.*, 2011; Anderegg *et al.*, 2020), but Ou *et al.* (2020) found progressive loss of FFR fit with cycles of moist heat treatment. This raises the possibility that repeated boiling or hot water soaking of masks might also adversely affect fit.

In the current study we did not evaluate the impact of reprocessing on micro-organism inactivation. Based on other data, four of the reprocessing methods we studied (hot water soak, boiling water soak, and bleach soaks) will kill all viral and bacterial pathogens likely to contaminate a face mask, including respiratory viruses, *Staphylococcus aureus*, streptococci, meningococci and herpes simplex virus (HSV). For example, sodium hypochlorite at a concentration of 0.1% (1000 ppm) should eliminate or inactivate all relevant viral and bacterial pathogens in 10 min (CDC, 2008; WHO, 2020) and moist heat at a temperature of >75°C should kill respiratory viruses (including influenza and coronaviruses), HSV, and relevant bacteria in 5 min (Sullivan *et al.*, 1971; Groh *et al.*, 1996; Wardrip *et al.*, 2000; Kennedy *et al.*, 2005; Jeong *et al.*, 2010; Gamble *et al.*, 2020). The proof of efficacy of moist heat and sodium hypochlorite for inactivation of bacteria and viruses includes studies of mask fabric (Bergman *et al.*, 2020; O'Hearn *et al.*, 2020). This level of disinfection would be especially important if reprocessed masks are subsequently intended to be used by a different person. In contrast, the other

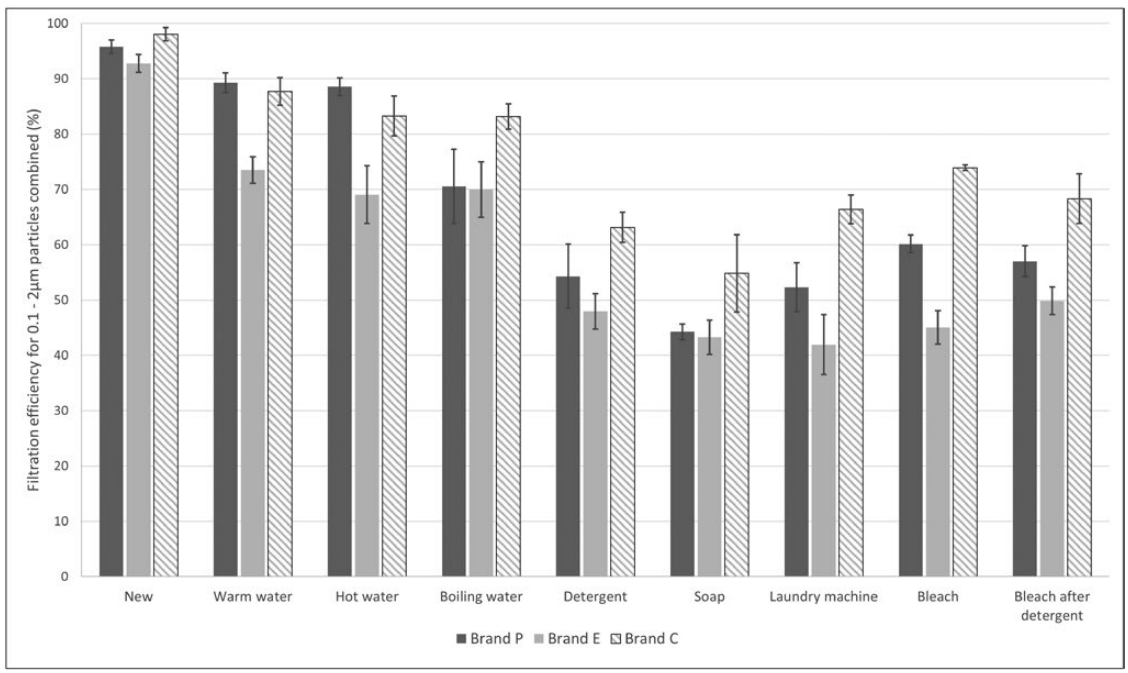

Figure 1. Filtration efficiency of new and reprocessed (10 cycles) standards-compliant commercial medical masks, brands P, E, and C.

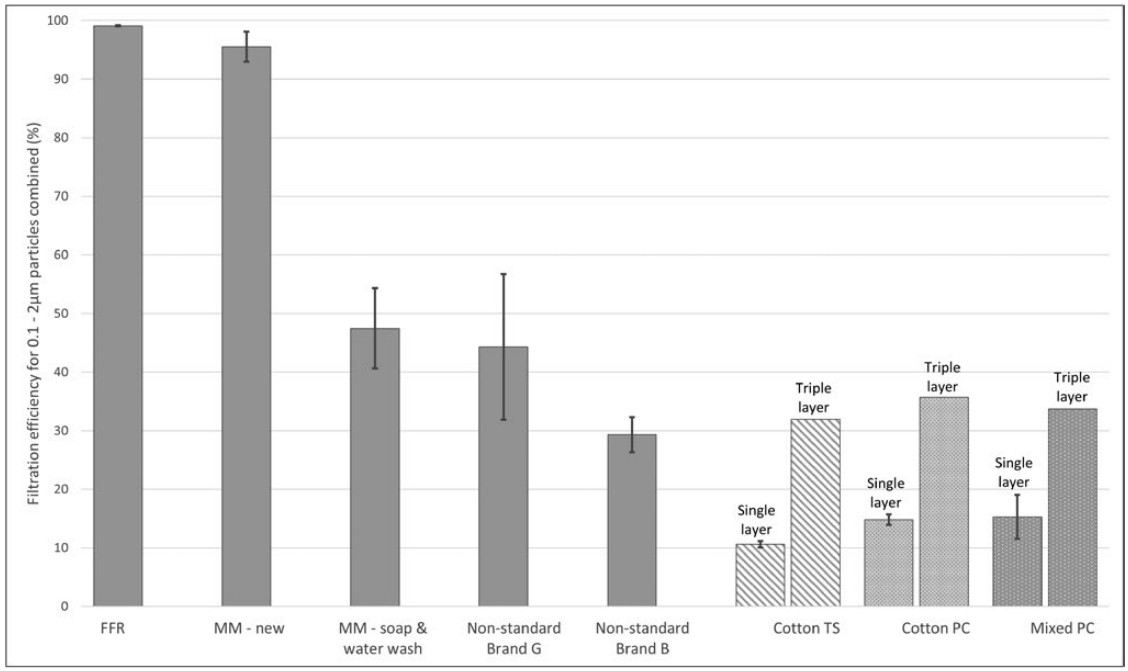

Figure 2. Filtration efficiency of masks and fabrics.

Note: this figure displays results only for new masks and fabrics (not reprocessed or washed), except for MM – soap and water wash (10 cycles).

FFR, filtering facepiece respirator; Mixed, mixed polyester and cotton; MM, medical masks (commercial, results combined for the three brands (P, E, and C) that comply with EN 14683 standard); PC, pillowcase; TS, T-shirt.

four reprocessing methods we studied (warm water wash, detergent and warm water wash, laundry machine wash, and soap and cold water wash) are not high-level disinfection methods but in combination with air-drying (e.g. at least 12 h) are likely to eliminate or inactivate respiratory viruses (e.g. influenza, coronaviruses) and reduce contamination with other relevant viruses and bacteria. Water alone (especially warm water) removes biological material and dilutes microbes on fabrics and masks (Lakdawala *et al.*, 2011; Bloomfield *et al.*, 2013; Wang *et al.*, 2020). Detergent and soap enhance removal of biological material and dilution of microbes and directly kill respiratory viruses (Sidwell and Dixon, 1969; Lai *et al.*, 2005; Greatorex *et al.*, 2010; Kawahara *et al.*, 2018). After washing with water (±detergent or soap) the absence of biological material (Parker *et al.*, 1944; Rabenau *et al.*, 2005; Thomas *et al.*, 2008; Greatorex *et al.*, 2011; Fedorenko *et al.*, 2020) and low microbial load (Parker *et al.*, 1944; Brady *et al.*, 1990; Lai *et al.*, 2005; Thomas et al., 2008, 2014) both predict rapid loss of respiratory virus viability during air-drying. The efficacy of washing and air-drying has been demonstrated in laundry washing machine studies, with or without detergent, leading to multi-log reduction in viral or bacterial loads (Sidwell and Dixon, 1969; Sidwell *et al.*, 1971; Bloomfield *et al.*, 2013). We included these four simple washing and detergent/soap methods in the current study because they may be the only options available in community and low-resource healthcare situations, and because elimination or inactivation of respiratory viruses is the primary goal when reprocessing masks to be re-used by the same person.

Dry-only reprocessing methods (e.g. dry heat, UV radiation) were not included in this study primarily because they do not remove biological material that might otherwise compromise the disinfection process. Cleaning is the necessary first step of any sterilization or disinfection process (CDC, 2003). We did not include methods that are alcohol- or solvent-based because they have previously and repeatedly been found to severely damage mask fabrics (Viscusi *et al.*, 2007; Liao *et al.*, 2020; Ullah *et al.*, 2020). We included some reprocessing methods that are likely to be available in community and low-resource healthcare settings, the latter which may only include water, bar soap and a kettle.

Table 3. Filtration efficiency and pressure differentials for new and reprocessed (10 cycles) masks.

	Filtration efficiency for 0.1 to 2 µm particles (%) (mean (STDEV))*			Pressure differential (Pa) (mean (STDEV))*		
FFR – new	99.1 (0.1)			99.3 (2.4)		
Standards-compliant medical masks	Brand P	Brand E	Brand C	Brand P	Brand E	Brand C
New	95.8 (1.2)	92.8 (1.6)	98.0 (1.2)	25.6 (0.4)	25.0 (0.6)	38.7 (0.6)
Reprocessed - warm water wash	**89.3 (1.8)**	**73.5 (2.4)**	**87.7 (2.5)**	**22.6 (0.9)**	**20.1 (0.5)**	**49.3 (1.5)**
Reprocessed - hot water soak 5 min, after warm water wash	**88.6 (1.6)**	**69.1 (5.2)**	**83.3 (3.6)**	**23.3 (0.7)**	**20.8 (0.6)**	**50.5 (1.7)**
Reprocessed - boiling water soak 30 min	**70.5 (6.7)**	**70 (5.0)**	**83.2 (2.3)**	**28.7 (0.3)**	**26.5 (0.4)**	**43.4 (1.4)**
Reprocessed - detergent and warm water	**54.3 (5.8)**	**47.9 (3.2)**	**63.1 (2.7)**	24.8 (0.7)	**23.5 (0.4)**	38.1 (1.4)
Reprocessed - soap and cold water	**44.3 (1.4)**	**43.3 (3.1)**	**54.8 (7.0)**	25.4 (1.0)	26.8 (1.6)	**40.9 (1.2)**
Reprocessed - laundry machine wash	**52.3 (4.4)**	**41.9 (5.4)**	**66.4 (2.6)**	**23.3 (1.1)**	**22.4 (0.5)**	**35.1 (1.0)**
Reprocessed - bleach wash and soak 10 min	**60.1 (1.6)**	**45.1 (3.0)**	**73.9 (0.5)**	**23.0 (0.5)**	**21.3 (0.6)**	**54.9 (2.7)**
Reprocessed - bleach soak 10 min, after detergent and warm water wash	**57.0 (2.8)**	**49.8 (2.5)**	**68.3 (4.5)**	**22.9 (0.8)**	**23.3 (0.1)**	**35.6 (0.5)**
Non-standard medical mask Brand B – new	29.3 (3.0)			19.2 (0.4)		
Non-standard medical mask Brand G - new	44.3 (12.4)			23.4 (2.5)		

*Each result based on testing 5 masks; Bold, significant ($p < 0.05$) difference in the mean compared with new masks of the same brand; FFR, filtering facepiece respirator; Pa, Pascals; STDEV, standard deviation

Table 4. Filtration efficiency and pressure differentials for fabrics.

	Filtration efficiency for 0.1 to 2 μm particles (%) (mean (STDEV))		Pressure differential (Pa) (mean (STDEV))	
	New (unwashed)	Washed (10 times)	New (unwashed)	Washed (10 times)
Single layer of fabric*				
•Cotton T-shirt	10.6 (0.6)	11.6 (1.1)	17.4 (0.8)	17.1 (0.4)
•Cotton 400-thread pillowcase	14.8 (0.9)	18.5 (2.3)	104 (11.8)	122.4 (10.5)
•Mixed 250-thread pillowcase	15.3 (3.7)	12.6 (1.8)	38.6 (1.4)	36.4 (2)
Triple layer of fabric				
•Cotton T-shirt	31.9	27.7	48.0	44.0
•Cotton 400-thread pillowcase	35.7	43.9	259.4	294.8
•Mixed 250-thread pillowcase	33.7	50.8	113.8	105.4

*Each result based on testing 5 samples; Pa, Pascals; STDEV, standard deviation

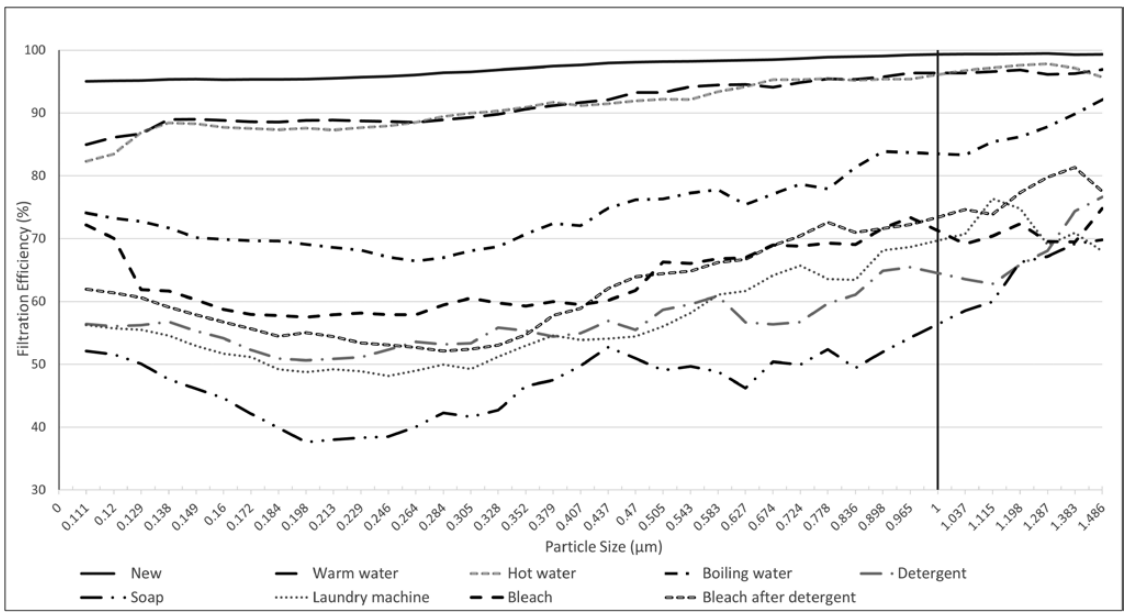

Figure 3. Filtration efficiency by particle size for brand P commercial standards-compliant medical mask, new and after reprocessing (10 cycles).

Major limitations of this study are that we have not assessed the effects of the eight liquid immersion reprocessing methods on microbial inactivation or mask fit. Poor fit significantly affects the inhalation of airborne particles by the wearer and is the major flaw in medical mask design (Lawrence *et al.*, 2006; Oberg and Brosseau, 2008; Noti *et al.*, 2012; Clapp *et al.*, 2021). It is possible that the hot or boiling water reprocessing methods in the current study will reduce mask fit, given the findings of moist heat affecting mask fit in one other study (Ou *et al.*, 2020). Another limitation of this study is that we have not taken into account the adverse effects of mask use between reprocessing cycles, although these are not expected to be substantial (van der Sande *et al.*, 2008).

Unfortunately, all reprocessing methods in this study damaged the filtration efficiency of medical masks, especially in the important sub-micrometer particle range. The magnitude of this damage for any brand of mask other than the three we tested is uncertain and the effects of these liquid immersion treatments on mask integrity and fit are uncertain. Moreover, reprocessing single-use items goes against manufacturers' and formal international guidelines and may create regulatory issues for healthcare

facilities. In a situation where no new standards-compliant commercial medical masks are available, however, the alternatives to reprocessing may be worse, especially the option of wearing no mask at all. Our results show that standards-compliant commercial medical masks, even after 10 cycles of liquid-immersion reprocessing, generally have better filtration efficacy than non-standard medical masks and triple-layer washable fabrics. Others studies have also shown non- and low-standard commercial medical masks to have poor filtration efficiency (Oberg and Brosseau, 2008), and washable fabrics to have poor filtration efficiency for sub-micrometer particles and poor breathability (Rengasamy *et al.*, 2010; Davies *et al.*, 2013; Mueller *et al.*, 2018; Konda *et al.*, 2020; Yan *et al.*, 2020). One randomized clinical trial of commercial medical masks versus simple rewashable cotton masks showed a markedly higher rate of influenza-like illness in those who wore fabric masks (MacIntyre *et al.*, 2015). In the future, improved washable fabric masks will hopefully be available (Konda *et al.*, 2020); these might be a reasonable alternative to disposable masks and solve the problems of supply and environmental disposal.

If reprocessing is necessary, we support the recommendations of others to protect staff handling used masks from exposure to microbes, to discard any mask that is visibly damaged or poorly fitting, and to measure and limit the number of cycles each mask is reprocessed.

Conclusions

New commercial medical masks that comply with international standards have excellent filtration efficiency and breathability. For situations where it is not possible to discard masks after each use, the current study shows that high-quality 'single-use' masks generally have better filtration efficiency after liquid immersion reprocessing, up to 10 times, than new non-standard medical masks or washable fabrics. Based on our and others' data, immersion in warm, hot or boiling water has less adverse effect on filtration efficiency than immersion in water with soap, detergent or bleach. The effect of liquid immersion reprocessing on mask fit is uncertain. These findings have particular relevance for community and low-resource healthcare settings.

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Conflicts of interest

Lanaco is a private company that manufactures filter media, respirators and masks. In this study, Lanaco staff provided technical assistance with mask testing and interpretation of the results, but did not influence the design of the study.

Author contributions

Richard Everts conceived of the study, led the design of the study, assisted with the mask testing, and wrote the manuscript.
Shadha Al Ghusaini had input into the design of the study, assisted with preliminary mask testing (unpublished), assisted with formal mask testing, and contributed to the manuscript.
Lucy Telfar-Barnard and Lance Jennings had input into the design of the study, analysis and interpretation of the results, and manuscript.
Shaun Tan and Sonja Jekel assisted with formal mask testing, data analysis and contributed to the manuscript.
Barbara Gibson had input into the interpretation of the results and manuscript.
Kevin Choi assisted with preliminary mask testing (unpublished) and contributed to the manuscript.
Ella Barclay and Dougal Hilson had input into the concept of the study, assisted with preliminary mask testing (unpublished), and contributed to the manuscript.

Ethics approval

Not required.

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Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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