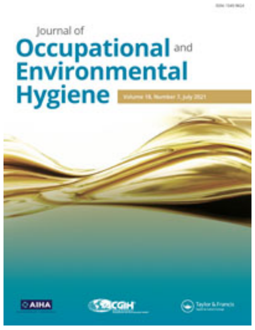

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Homemade facemasks: particle filtration, breathability, fit, and other performance characteristics

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ABSTRACT

Homemade cloth masks and other improvised face coverings have become widespread during the COVID-19 pandemic driven by severe shortages of personal protective equipment. In this study, various alternative (mostly common household) materials, which have not traditionally been used in respiratory protective devices, were tested for particle filtration performance and breathability. Most of these materials were found of some—but rather limited—utility in facemasks. At a breathing flow rate of 30 L min^{-1}, 17 out of 19 tested materials demonstrated collection efficiency below 50%; at 85 L min^{-1}, only one material featured particle collection efficiency above 50%. Pressure drop values were mostly below 4 mm w.g. (observed in 89% of cases for the two flow rates), which provides comfortable breathing. Only for one fabric material (silk) tested at 85 L min^{-1} did the pressure drop reach 11 mm w.g. Based on these results, a three-layer facemask prototype was designed and fabricated comprised of the best performing materials. Additional tests were conducted to examine possible particle detachment/shedding from the materials used in the newly developed facemask, but no such phenomenon was observed. The prototype was evaluated on 10 human subjects using the standard OSHA-approved quantitative fit testing protocol. The mask protection level, determined as an adopted fit factor, was found to lie between that of the two commercial surgical/medical masks tested for comparison. A 10-cycle washing of the mask prototype lowered its collection efficiency across the particle size range; however, washing did not substantially affect mask breathability. The study revealed that although homemade masks offer a certain level of protection to a wearer, one should not expect them to provide the same respiratory protection as high-end commercial surgical/medical masks or—by any means—NIOSH-certified N95 filtering facepieces.

KEYWORDS
Cloth mask; COVID-19; face covering; fit; particle collection efficiency

Introduction

In an early phase of the COVID-19 pandemic, a grass-roots movement was established to design, produce, and distribute homemade facemasks made of materials that had not been traditionally used for air filtration or respiratory protection. This movement became widespread in the U.S., driven by severe shortages of personal protective equipment. Homemade cloth masks have been predominantly used by the general population due to very limited access to clinical-grade respiratory protective devices. The cloth masks and face coverings have also been permitted in non-healthcare occupational settings. As source control devices, they are widely deployed to help protect "others" from exposure to the virus aerosolized by contagious mask wearers. Filtering facepiece respirators (FFRs) approved by the National Institute for Occupational Safety and Health (NIOSH) are designed to also protect a wearer. The U.S. Centers for Disease Control and Prevention (CDC) pointed to the need for additional research-based evidence on the efficacy of cloth mask materials for personal protection of a wearer, together with data on fit, durability, and other characteristics (Centers for Disease Control and Prevention, National Center for Immunization and Respiratory Diseases 2020).

Only a handful of published studies were available prior to the COVID-19 pandemic on the particle collection and fit of improvised facemask prototypes made of common household materials (Dato et al. 2006; Davies et al. 2013; Rengasamy et al. 2010; Shakya et al. 2017; Van der Sande et al. 2008). Since the beginning of COVID-19, attempts have been made to assess the collection (i.e., filtration) efficiency (E_c) and—to a lesser extent—breathability, which is

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linked to air pressure drop (Δp). Several household materials used to design facemasks as an alternative to commercially manufactured filtering devices have been evaluated (Aydin et al. 2020; Drewnick et al. 2021; Guha et al. 2021; Hao et al. 2021; Hill et al. 2020; Konda et al. 2020; Long et al. 2020; Lustig et al. 2020; O'Kelly et al. 2020; Rengasamy et al. 2010; Zangmeister et al. 2020; Zhao et al. 2020). Most studies identified one or more materials with E_c in excess of 20% combined with Δp of < 15 mm w.g., including cotton, polycotton, polyester, silk, polypropylene, and others. However, only a few of the studies reported a material with a collection efficiency threshold higher than 50% while exhibiting Δp lower than 5 mm w.g., which were achieved only for specific materials such as certain cotton quilt, cotton 600 thread count sheet, silk, chiffon, and polypropylene (Konda et al. 2020; Zhao et al. 2020). A consensus was reached that wearing such improvised masks is better for viral exposure reduction than being totally unprotected, although the studies suggested that common cloth fabrics, as well as less cloth-like materials, offer relatively low-filter collection efficiency as compared to commercial NIOSH-approved respirator filters (Chua et al. 2020; Garcia-Godoy et al. 2020; Lima et al. 2020). Limitations of cloth facemasks also include moisture retention and the need to clean/wash them regularly; detergent water may negatively impact the filtration efficiency of the mask material (Neupane et al. 2019).

While aerosol is filtered when drawn through the filter of a respiratory protective device, a poor fit permits some particles to penetrate through faceseal leakage. The latter pathway may be even more powerful than the former (Grinshpun et al. 2009). An Occupational Safety and Health Administration (OSHA)-approved quantitative fit test estimates the combined effect of the particle penetration through the filter and the faceseal leakage. The fit test is traditionally performed for NIOSH-approved respirators. For example, an N95 FFR is considered passing the fit test if its Fit Factor (FF), which is the time-integrated ratio of the aerosol concentrations measured outside and inside the respirator, exceeds 100 (OSHA, 2004). In contrast, surgical masks are not subjected to fit testing. They have conventionally been used for source control as well as for protecting a wearer from larger droplets, e.g., sprays and splashes, but not from the smaller particles. To our knowledge, the faceseal quality of homemade masks when worn by individuals conducting activities was assessed in only three relatively small studies (Dato et al. 2006; Davies et al. 2013; Van der Sande et al. 2008). Two studies quantitatively fit tested a facemask prototype made of 100% cotton T-shirt material. A median FF of 17 was reported for the first and most limited study ($N = 3$) (Dato et al. 2006), whereas the larger study ($N = 21$) revealed much lower FF medians of about 1 to 2 (Davies et al. 2013). An FF of 1 indicates no protection. The third study conducted with teacloth mask wearers ($N = 28$) reported a median protection factor (PF), a measure conceptually similar to FFs, from approximately 2 to 3 for various activities, whether measured after ≤ 15 min or 3 hr ($N = 22$) (Van der Sande et al. 2008). Median values of the fit/protection factors for medical-grade surgical masks as reported in two of these studies were somewhat higher, with medians ranging from about 3 to 7 (Davies et al. 2013; Van der Sande et al. 2008). More encouraging fit test results featuring FF of 15 to 79 were yielded by several other studies conducted using homemade or pre-made cloth masks on a mannequin or a single subject under varied test conditions (Clapp et al. 2020; Hill et al. 2020; Mueller et al. 2020; Shakya et al. 2017), calling for future replication by fit testing multiple subjects.

When utilizing a common household material, e.g., fabric, as an alternative to a commercial filter material, there is a risk that small pieces (e.g., fabric fibers) can be detached from the inner surface of the facemask and plausibly inhaled by the wearer. To our knowledge, currently no published data are available concerning this phenomenon for homemade facemasks.

To summarize, further research is needed on particle collection efficiency, breathability, and fit of homemade facemasks fabricated of various materials. The potential of non-conventional materials to shed inhalable particles during breathing should be examined. Finally, it is important to identify materials that can tolerate re-use and washing (O'Kelly et al. 2020). The main objectives of this pilot study were to (1) evaluate various materials that can be used for homemade facemasks for the general public and (2) design a homemade mask prototype comparable to high-end surgical masks by performance, including respiratory protection and breathability.

Methods

Materials and samples chosen for testing

We conducted an extensive review of a variety of household materials, which were not originally designed for respiratory protection against aerosol particles but have been (or could be) used for homemade facemasks. As a result, a pool of 19 individual material samples was established, including non-woven polyester, multiple brands of paper coffee filters, cloth (various 100% cotton fabrics, 200 and 400 thread count cotton sheeting, a polycotton fabric, polyester blend sheeting, silk, polyester fleece interfacing), cotton quilt batting, melt-blown polypropylene (MBPP), etc. Unlike the "improvised" filtering materials, MBPP is a manufactured filter used in commercially available surgical masks and respirators. Materials were cut into square samples of approximately 17.5 cm × 17.5 cm (7" × 7"), with a sample mounted within the testing frame being 16 cm × 16 cm = 256 cm^2. These dimensions were selected to mimic a fully unfolded commercial surgical mask.

Testing in the flow-through filter evaluation set-up

The first series of experiments was conducted in a conventional flow-through filter evaluation set-up. The set-up consists of a chamber housing an aerosol generator, an air supply unit, a square-shaped frame holding a sample of the material being tested with an exhaust plenum downstream of the frame, and two aerosol sampling ports located upstream and downstream of the frame. The filter holder assembly is leakage-proof as was confirmed through a validation test. The air temperature and relative humidity inside the chamber were 22–24 °C and 40–65%, respectively.

The particle collection efficiency of each tested material sample was obtained using an electrical low-pressure impactor (ELPI, Dekati, Inc., Kangasala, Finland), which particle-size-selectively measured the concentration of challenge aerosol upstream (C_{up}) and downstream (C_{down}) of the sample exposed to an aerosol flow simulating human inhalation. Two flow rates were chosen: 30 L min^{-1} (moderate workload) and 85 L min^{-1} (strenuous work, also the flow rate used by NIOSH in respirator certification testing protocol) (Janssen et al. 2005). The flow rates of 30 and 85 L min^{-1} generate respective face velocities of 1.95 and 5.53 cm/sec for a filter area of 256 cm^2. The challenge aerosol, dry sodium chloride (NaCl), was supplied by an aerosol generator (Model 8026, TSI Inc., Shoreview, Minnesota) and charge equilibrated by passing through a Kr^{85} source. The measured aerodynamic particle size range, approximately 0.04–3.2 µm, was represented by 10 size fractions spanning the size of a naked SARS-CoV-2 virus of approximately 0.1 µm as well as larger virus agglomerates and particle carriers. It is noted that the ELPI allowed for measuring particles above 3.2 µm; however, the NaCl size distribution was represented primarily by sub-micrometer particles and essentially died off at about 3 µm. The collection efficiency (E_c) was calculated for each particle size fraction (size-specific value) and for the total particles (size-integrated value) as follows:

$$E_c = 1 - \frac{C_{down}}{C_{up}}$$

The breathability was assessed in the same flow-through system by measuring the air pressure drop, Δp, across the tested material that was exposed to air flows of 30 and 85 L min^{-1} using a DigiMag differential digital pressure gauge (Model DM-1103, Dwyer Instruments, Michigan City, IN). The manufacturer-reported gauge reading range was 0–12.7 mm (0–0.5") w.g. with an accuracy of ± 2%. A quality factor (q_f) was calculated for each material and flow rate based on the measured size-integrated E_c and Δp as follows (Brown 1993):

$$q_f = \frac{ln\frac{1}{1-E_C}}{\Delta p}$$

Additionally, experiments were performed in the same flow-through set-up to identify whether there was any detachment/shedding of a tested material as the air flow was passing through. In the absence of the incoming challenge aerosol upstream (the aerosol generator was turned off and a HEPA-cleaned particle-free air was supplied), shedding would result in detectable aerosol particle count downstream. The ELPI lower limit of detection (LOD) is seven particles per cm^3 so that the instrument can detect a very low particle release level. The detachment/shedding examination was limited to the materials used in the face-mask prototype developed in the study (see below).

The flow-through set-up was also used for the performance evaluation of the multilayered prototype once it was developed. The outcomes such as E_c, Δp, and q_f were determined for the prototype in two scenarios: (1) unwashed and (2) washed via 10 machine cycles with detergent at a delicate, small load, warm water setting and then air dried.

Prototyping

The prototyping effort was based on an examination of all material evaluation data obtained in the flow-through set-up described above. The following criteria were established:

1. for the "central" filtering material, the highest E_c, with acceptably low Δp (allowing for easy breathing),

Table 1. Characteristics of masks under study.

	Mask type		
Physical features	Homemade mask prototype	Commercial high-end surgical mask A (Reference)	Commercial low-end surgical mask B (Reference)
Dimensions			
Unpleated (i.e., unfolded)	16 × 16 cm (6.3 × 6.3″)	18 × 18 cm (7.1 × 7.1″)	16 × 17.5 cm (6.3 × 6.9″)
Pleated, flattened	16 × 7 cm (6.3 × 2.8″)	18 × 8 cm (7.1 × 3.2″)	17.5 × 9.5 cm (6.9 × 3.7″)
Pleat folding pattern	Bidirectional	Bidirectional	Unidirectional
Fasteners			
Type	Tie-on, vertically attached	Tie-on, horizontally attached	Ear loops
Material	Folded interfacing	Unspecified	75% nylon & 25% spandex cord
Fastener length	42.5 ± 1.5 cm (16.7 ± 0.6″)	39 ± 1 cm (15.4 ± 0.4″)	18 cm (7.1″)
Fastener-to-mask attachment	Sewn (zig-zag stitch)	Non-sewn	Non-sewn
Materials by layer			
Outside	Polycotton	Unspecified	NWPP (unspecified)
Middle	MBPP[a]	NWPP[a] (unspecified) filter web	MBPP
Inside	Polycotton	"Soft" inner layer (unspecified)	NWPP (unspecified)
Other	NWPP layer: bacterial filtration efficiency (BFE): ≥ 95%	NWPP layer: particulate filtration efficiency ≥ 95%, BFE ≥ 98% Nosefoam	–

[a] NWPP = non-woven polypropylene; MBPP = melt-blown polypropylene.

and no detectable particle detachment (the latter concerns shed mask material particles that could potentially be inhaled);

2. for the outer layers, choice of a common, durable, and washable material selected from those which revealed the best E_c and Δp combinations, sans detected particle detachment; and
3. for the selected three-layered unwashed prototype, no abnormal Δp and no particle detachment identified. By "abnormal" Δp, we imply the situation when a pressure drop of the three-layer mask is appreciably greater than the sum of pressure drops of individual layers or exceeds the NIOSH N95 upper threshold of 35 mm w.g. (NIOSH, 2019).

Prototype mask material size, pleats, ties, and nose piece design decisions were informed by the configuration used in high-performance, clinical-grade surgical masks, with the constraint that it could be homemade (e.g., sewn).

Fit testing

The mask prototype was subjected to the OSHA-approved quantitative fit test (OSHA, 2004). This test is typically performed with NIOSH-certified respirators, e.g., N95, but not with lower-grade, poorly fit facemasks. At the same time, fit testing allowed assessing the total inward leakage derived from the penetration through both the filter and the peripheral faceseal leak. A Portacount Respirator Fit Tester (Model 8048, TSI Inc., Shoreview, MN) was deployed to generate a database on the total and exercise-specific fit factors. Since we adopted the standard respirator fit test protocol for the evaluation of lower-level facemasks, we call the quantitative outcome of this testing an "adopted" fit factor (aFF). Ten (N = 10) study subjects, including four females and six males, were recruited and fit tested in three replicates with the newly developed homemade mask prototype. The study protocol and informed consent for the subjects were approved by the University of Cincinnati IRB.

Additionally, two commercially available facemasks were tested for comparison. "Mask A" was a high-end mask made by a major U.S. manufacturer for surgical and other health procedures. The other, "Mask B" was a general purpose, low-end, "economy" mask made in China, available for purchase off-the-shelf from a large U.S. chain store. Both reference masks were flat, valve-free, and three-layered with the inclusion of non-woven polypropylene (NWPP). Both masks (as well as the newly developed homemade mask) had bendable nose clips. It is to note that the NWPP group is represented by different non-woven materials, including MBPP. Properties of the newly developed homemade mask prototype and the two reference masks are described in Table 1.

The fit tests were carried out with the NaCl particle generator operating in a room-size exposure chamber and the Portacount (in the N95 mode) that recorded the ratio of the ambient and in-mask aerosol concentrations while a subject performed a sequence of exercises/maneuvers (aiming at simulating work activities). These included normal breathing, deep breathing, turning head side to side, moving head up and down, talking, grimace, bending over, and repeated normal breathing. Exercise-specific aFF values were generated for each of these standard OSHA fit test exercises, except for the grimace. An overall aFF was calculated

Table 2. Filtration efficiencies, pressure drops, and quality factors determined for 19 unwashed, single-layer materials at 30 and 85 L min^{-1}.[a]

	30 L min^{-1}			85 L min^{-1}		
Material	E_c, %	Δp (mm w.g.)	q_f (mm w.g.)$^{-1}$	E_c, %	Δp (mm w.g.)	q_f (mm w.g.)$^{-1}$
Air Conditioner Filter (Unspecified Non-woven Polyester)	12.8	0.03	4.58	11.3	0.08	1.50
Coffee Filter (6), Paper	14.5	0.84	0.19	10.8	2.84	0.04
T-Shirt, Men's Crew Neck 100% Cotton	14.8	0.18	0.89	9.5	0.52	0.19
Coffee Filter (5), Paper	15.1	0.85	0.19	12.5	2.92	0.05
Pillowcase, Cotton 100% (200 Thread Count, Percale)	16.2	0.66	0.27	13.4	2.11	0.07
Coffee Filter (3), Paper CPF 200	17.8	0.71	0.28	19.7	2.31	0.09
Coffee Filter (4), Paper	19.6	1.66	0.13	18.6	6.25	0.03
Fabric, Quilter 100% Cotton	20.3	0.82	0.28	14.4	2.54	0.06
Pillowcase, Cotton 100% (400 Thread Count, Sateen)	20.3	0.80	0.28	17.1	2.52	0.07
Fabric, Flannel 100% Cotton	21.6	0.34	0.72	15.9	1.07	0.16
Interfacing, 100% Polyester Fleece (Sew-In)	22.7	0.07	3.68	15.7	0.14	1.22
Pillowcase, Polycotton Blend (200 Thread Count, Percale)	23.2	0.76	0.35	19.0	2.40	0.09
Fabric, Polycotton Blend Gingham	23.5	1.27	0.21	17.6	4.10	0.05
Pillowcase, Polycotton Blend (130 Thread Count, "B-Grade") (PC)	30.0	0.41	0.87	16.3	1.17	0.15
Fabric, Dupioni 100% Silk	30.5	3.22	0.11	20.6	11.08	0.02
Fabric, Batik 100% Cotton	31.5	1.84	0.21	21.7	5.68	0.04
Coffee Filter (1), Paper	32.5	0.79	0.50	20.9	2.87	0.08
Batting, 100% Cotton	50.7	0.27	2.62	28.6	0.79	0.43
Melt-Blown Polypropylene (MBPP)	84.5	0.49	3.81	78.1	1.67	0.91

[a] *Note:* For an area of $16 \times 16\,\text{cm} = 256\,\text{cm}^2$ the flow rate of 30 L min^{-1} creates the face velocity of 1.95 cm/sec and flow rate of 85 L min^{-1} creates the face velocity of 5.53 cm/sec.

as the harmonic mean of exercise-specific aFF values. The Portacount truncates aFF results exceeding 200. To follow a conservative approach, it was decided to denote aFFs = 201 in any instance when the measured overall aFF was truncated. The order in which the three masks were tested was randomized for each subject and replicate.

Data analysis methods

For each material, distributions of particle-size integrated means of E_c were examined graphically for each of the tested flow rates. Similarly, we examined the distributions of the air pressure drop values (Δp) and the calculated quality factors (q_f). To look for evidence of detectable particle detachment/shedding, the aerosol concentration measured downstream of the material exposed to particle-free airflow was compared to the lower limit of detection of the ELPI as described above. A repeated measures ANOVA via SPSS Statistics, Version 27 (IBM, Armonk, NY) general linear model repeated measures procedure was conducted to test the newly developed three-layer prototype for differences between 10 mean E_c values calculated for each particle size fraction pre- and post-washing (two ordinal categories) with simultaneous adjustment for air flow rate (two ordinal categories) and the interaction term.

The replicated experimental design was used with the overall aFFs being the outcome and mask type being the main effect. Distributions of overall aFF obtained from the mask wearers were examined graphically and summarized by mask type using descriptive statistics such as non-pooled and pooled means, standard deviations (SDs), and medians. Potential differences in overall aFF means between mask types (three nominal categories) with simultaneous adjustment for replicate (three ordinal categories) were tested for statistical significance. A two-way, repeated measure analysis of variance (ANOVA) general linear model repeated measures procedure was also applied to conduct the fit test analysis. Power estimates for the aFF analysis were calculated with $\alpha = 0.05$ for detection of a range of differences between factor-level aFF means anticipated *a priori*. With 10 subjects, estimated power was ≥ 0.79 for both mean aFF differences of 5 (with SD ≤ 2) and 10 (with SD ≤ 4).

Results

Testing of single-layer materials: particle collection and breathability

Results of the single-layer material testing at two flow rates are presented in Table 2 as the size-integrated E_c, the pressure drop Δp, and the quality factor q_f. The materials are listed in order from low to high E_c obtained at 30 L min^{-1}. Most of the tested common household materials featured a relatively low E_c compared to the 95% N95 filtration benchmark ($E_c \geq 95\%$). For all the tested materials, except MBPP, the overall collection efficiency was less than or approximately equal to 50% at 30 L min^{-1} and below 30% at

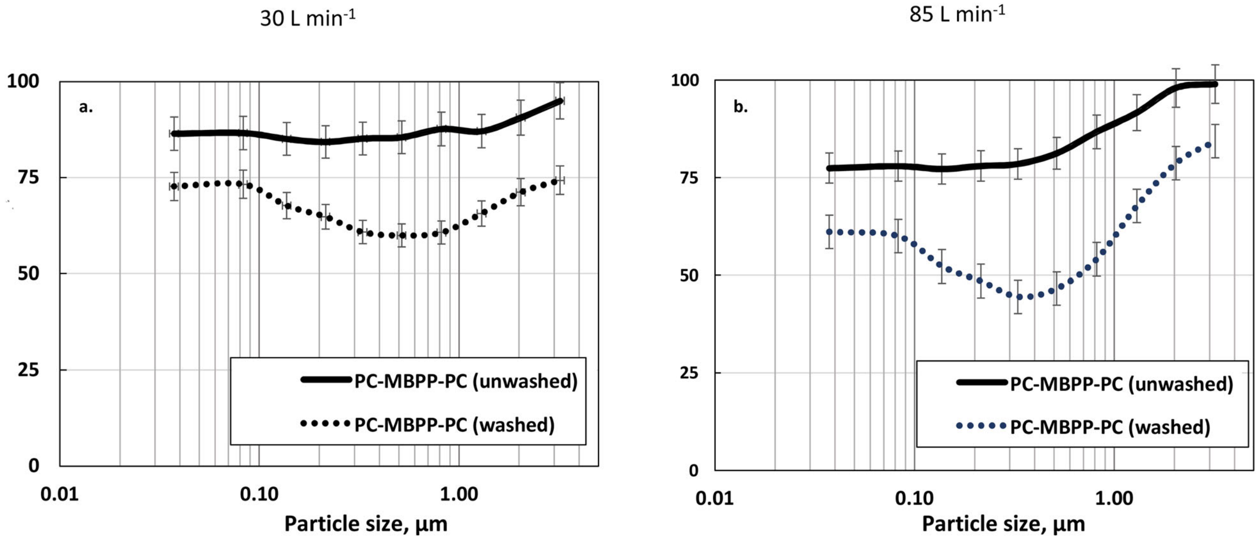

Figure 1. Particle size-specific collection efficiency of the multilayered PC-MBPP-PC material—unwashed and washed—at (a) 30 L min^{-1} and (b) 85 L min^{-1}.

85 L min^{-1}. The only exception, MBPP, featured E_c = 84.5% at 30 L min^{-1} and E_c = 78.1% at 85 L min^{-1}, which made it a very good candidate for a homemade facemask. The particle size-integrated collection efficiencies obtained for MBPP were consistent with the respective size-specific results (data not shown). The breathability of MBPP was very good with Δp being 0.49 and 1.67 mm w.g. at the respective flow rates (considered to be low relative to that reported for filters used for respiratory protection). The q_f value calculated for MBPP was the second best among the 19 materials tested at 30 L min^{-1} and the third best among those tested at 85 L min^{-1}. We acknowledge that MBPP is actually a commercial filter material rather than a common household material. Besides, the use of MBPP in a single layer appeared potentially problematic because such a facemask may not meet the durability/washability criteria. The pillowcase polycotton (PC) with a 130 thread count showed a size-integrated E_c of 30.0% and 16.3% at 30 and 85 L min^{-1}, respectively. While this level of protection is much lower than the one featured by the filters of N95 FFRs or high-end medical masks, PC was found to be among the best materials at 30 L min^{-1} (# 6 of 19 in the list) and in the middle of the list at 85 L min^{-1} by E_c. The size-specific collection efficiency results for PC agreed with the size-integrated data (data not shown). This material also featured good breathability with Δp of 0.41 and 1.17 mm w.g. at 30 and 85 L min^{-1}, respectively, one of the best among the 19 tested. Its relatively high q_f (Han 2000; Zangmeister et al. 2020), together with durability and comfort provided by this pillowcase fabric, made PC a good candidate for the homemade facemask, especially if used in a multilayer design.

Design of the mask prototype

The prospect of further improving the particle collection characteristic of the best-performing material and, more importantly, shielding it to better withstand repeated wear and washing led us to a three-layer design in which MBPP—the material which was found most efficient in the single-layer configuration—is “bracketed” by two outer layers of a more durable fabric (PC) so that in the prototype (PC-MBPP-PC), the middle MBPP layer is sewn-in around the periphery of the two outer PC layers. The flat, valve-free design chosen for the facemask prototype was similar to that of commonly used, commercial surgical masks. Material squares were pleated laterally to permit sufficient expansion, thus allowing for accommodating a variety of facial dimensions and shapes. Supple ties of folded, thinly layered, zigzag stitched, ¾” interfacing strips were used as fasteners for the mask prototype. This allowed for safe doffing and helped improve the faceseal. Elastic ties were not used because of potential latex allergies among wearers. A bendable aluminum bracket nose piece was inserted in a fabric tube sewn under the top mask border.

Assessment of detachment

No measurable shedding was observed at both tested air flow rates for either of the two materials used in the three-layer prototype. While the ELPI reading showed zero particles downstream of either single-layer material or the three-layer prototype when a HEPA-filtered air was supplied, we report the concentration of released particles as $< \mathrm{LOD}$ (LOD $\approx 7\,\mathrm{cm}^{-3}$).

Effect of washing on the mask prototype performance

Particle size-integrated E_c

A 10-cycle washing of the mask prototype three-layer material substantially reduced its particle size-integrated collection efficiency: from 85.8 to 69.3% for $30\,\mathrm{L\ min}^{-1}$ and from 78.1 to 55.9% for $85\,\mathrm{L\ min}^{-1}$. In conjunction, the 10 particle size-specific mean E_c values were significantly ($p < 0.001$) lower after machine washing in the repeated measures ANOVA model with simultaneous adjustment for air flow rate ($p = 0.078$) and the two-way interaction ($p = 0.019$). The significant interaction reflects that the difference in mean E_c between washed vs. unwashed samples was a function of air flow rate, it being greater when measured at the higher flow rate. Washing, however, did not appreciably affect mask breathability, causing a negligibly small increase (as low as 1–3%) of the pressure drop from the levels recorded for an unwashed material (0.88 and 3.54 mm w.g. at $30\,\mathrm{L\ min}^{-1}$ and $85\,\mathrm{L\ min}^{-1}$, respectively). The mask quality factor q_f decreased almost twice for both tested flow rates because of washing.

Particle size-specific E_c

Figure 1 presents the particle size-specific collection efficiency values obtained at both flow rates for the unwashed prototype and the one subjected to a 10-cycle washing. While decreased post-washing, the collection efficiency tested at $30\,\mathrm{L\ min}^{-1}$ remained above 50% across the submicrometer particle size. At $85\,\mathrm{L\ min}^{-1}$, the particle size-specific E_c values measured for the unwashed material were between 75 and 100%, depending on the particle size; however, after washing, they significantly dropped for all particle sizes dipping beneath 50% in the most penetrating particle size range. The non-monotonic curves in Figure 1 are consistent with the theory of particle filtration and reflect the diffusional deposition mechanism, which is predominant for smaller particles, as well as inertia and interception, which are predominant for larger particles. At $30\,\mathrm{L\ min}^{-1}$, the curve for the unwashed mask is almost flat for sub-micrometer particles but then E_c increases with the particle size increase reaching almost 100% for 3-µm particles. At $85\,\mathrm{L\ min}^{-1}$, the unwashed mask curve is essentially flat for particles <0.3–0.4 µm, but then E_c increases with a particle size reaching 100% for 2-µm particles. The collection efficiency pattern obtained after the mask material was washed appeared more pronouncedly non-monotonic. The particle sizes yielding the lowest collection (the most penetrating particle sizes) were approximately in a range of 0.3 to 1 µm for $30\,\mathrm{L\ min}^{-1}$ and between 0.2 and 0.6 µm for $85\,\mathrm{L\ min}^{-1}$.

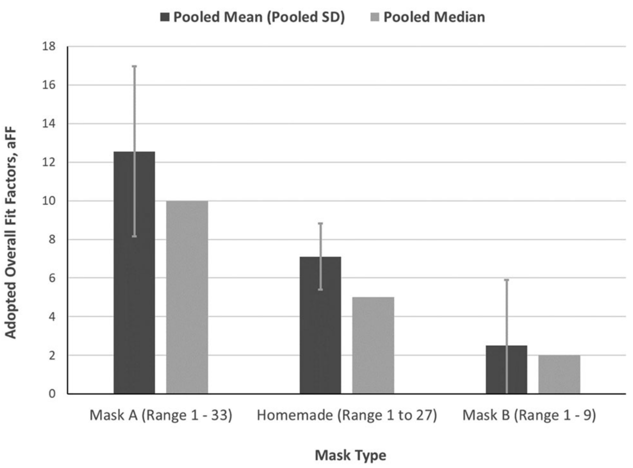

Figure 2. Pooled mean (black bars), standard deviation (error bars), and median (grey bars) values as well as non-pooled ranges for overall aFFs by mask type. The data represent three aFF replicates per subjects pooled across N subjects: $N = 9$ for the high-end surgical Mask A (Subject 10 is excluded) and $N = 10$ for two other masks.

Fit testing results

Accounting for three masks (our three-layer prototype and two commercial surgical masks tested for comparison), 10 subjects and three replicates, altogether 90 quantitative fit tests were conducted, generating a variety of aFF values covering two orders of magnitude. Pooled overall aFF means (also known as grand means), standard deviations, and medians, were calculated for each mask. Both pooled mean and median overall aFF values for the homemade mask fell between those obtained for the low- and high-end surgical masks. Overall, aFF ranges were 1 to 27 for the homemade mask, 2 to 196 for Mask A, and 1 to 9 for Mask B. The lower limits of the overall aFF ranges across replicates and subjects were essentially the same for the three masks (aFF = 1 means no protection) while the upper limit observed for the high-end surgical Mask A was outstandingly high, apparently due to an extreme outlier of 196 recorded for the third replicate of one subject (labeled as "Subject 10"). The latter generated a very large standard deviation for the high-end surgical Mask A. To acknowledge this abnormality, we also generated pooled overall aFF summary statistics with Subject 10 excluded for surgical Mask A ($N = 9$) while retaining the original number of subjects ($N = 10$) for the two other masks. Additionally, statistical analysis of repeated measures ANOVA was conducted twice, including the Subject 10 data for Mask A (referred as "in" [$N = 10$]) and excluding it (referred as "out" [$N = 9$]) from the analysis.

Figure 2 presents the pooled summary statistics of the fit test data with $N = 9$ for the commercial surgical Mask A and $N = 10$ for both the homemade mask and the commercial surgical Mask B. It is seen that the level of protection offered by the homemade mask prototype developed in this effort (overall aFF $= 7.1 \pm 1.6$, median $= 5$) is not as high as the one determined for Mask A, the high-end commercial protection device (overall aFF $= 12.6 \pm 4.4$, median $= 10$) but greater than the one found for Mask B, the low-end device (overall aFF $= 2.5 \pm 3.2$, median $= 2$).

The overall aFF was log transformed for the analysis to address sphericity. There was a highly significant difference in overall aFF between the mask types ($p < 0.001$), controlling for potential effects of replicate (non-significant) in the repeated measures ANOVA model, regardless of whether Subject 10 was "in" or "out." Pairwise mask comparisons were also performed to test which specific pairs of masks, if any, were significantly different. Overall, aFF values were significantly higher for the homemade mask than for the low-end Mask B ($p = 0.002$ for "in" and $p = 0.003$ for "out"). However, the homemade mask showed lower aFF values as compared to the high-end Mask A; the difference was significant with Subject 10 included ($p = 0.039$), and borderline significant with Subject 10 excluded ($p = 0.082$). The difference between the Masks A and B was found significant in both analyses ($p < 0.001$ for "in" and "out"). Between-subject aFF effect was highly significant ($p < 0.001$ for "in" and for "out"). It was concluded that differences in overall aFF between subjects and within subjects for a mask type persisted regardless of whether the analysis was conducted with or without the data from Subject 10.

Discussion

This study generated the performance data on a variety of materials that are either available or under consideration for utilization in homemade facemasks, which have become an essential component of public and occupational health infection mitigation programs during COVID-19. The findings of this study are generally in line with those reported by other investigators with respect to the material filtration performance and breathability of single-layer materials (Clapp et al. 2020; Drewnick et al. 2021; Hao et al. 2021; Hill et al. 2020; Konda et al. 2020; Long et al. 2020; O'Kelly et al. 2020; Rengasamy et al. 2010; Zangmeister et al. 2020; Zhao et al. 2020). For some material types, however, other investigations, e.g., Konda et al. (2020), reported most E_c values exceeding ours. It is acknowledged that it is often challenging to adequately compare the performance of the same materials reported in different studies because the material's collection efficiency depends on the linear face velocity and the particle size distribution, which both differ from one study to the other. The face velocity, which is a ratio of the flow rate to the filtration area, is sometimes not specified by the investigators. Different reports on improvised facemasks quote different flow rates and areas of the test samples with the latter ranging from 2.5 cm diameter (O'Kelly et al. 2020) to 100 cm^2 (Drewnick et al. 2021; Konda et al. 2020; Rengasamy et al. 2010) and greater (this study). Additionally, sample materials of the same type (e.g., 100% cotton) may vary in terms of layers, thread count, weave, density, electric charge, or pretest washing. For instance, in the current study, within candidate filter materials of the same general type, e.g., coffee filters or 100% cotton, the best material had an E_c about twice that of the worst one, and the most breathable 100% cotton had Δp an order of magnitude lower than that of the least breathable. Our results are consistent with the finding published by of Clapp and colleagues who reported a five-fold difference in E_c and nearly four-fold difference in Δp among three MBPP mask samples (Clapp et al. 2020).

The negative effect of washing on the particle collection efficiency observed in this study was not surprising although this finding suggests a limitation for the facemask re-use. One study (Neupane et al. 2019) identified a linear decrease in E_c after each hand-wash and air-dry cycle with an approximately 20% decline after the fourth cycle, which is consistent with our findings for the multiple washing that demonstrated 19% and 28% decay in size-integrated E_c at low and high flow rates, respectively. Substantial degradation of the synthetic clothing fabric after repeated machine washings has been documented in the marine microplastic pollution literature. In one such study, fibers in the waste water drained from a washing machine were enumerated and the fiber size was characterized using scanning electron microscopy (SEM) for acrylic, polyester, and PC after each of the five washing cycles (Napper and Thompson 2016). Estimated detached PC fiber counts were consistently lower (by several folds) than acrylic and polyester counts and remained lower across different treatments conditions involving the fabric detergent, conditioner, and water temperature. Shed PC fibers were also reportedly shorter and wider than fibers from the other materials. The type of washing is a variable to be considered when comparing findings from different studies, e.g., the self-washing and washing in the hospital laundry generated different outcomes in terms of the effect of washing on the risk of infection of mask wearers (MacIntyre et al. 2020).

In addition, invariably low overall aFFs obtained for the low-end commercial surgical Mask B raises questions about ear loops as a mask fastening method. A poor faceseal associated with insufficient tightening plausibly contributed to the particle penetration more heavily than the mask materials. Other investigators who have measured fit for both ear loop and tie-on masks also found lower-fit performance for ear loop masks (Clapp et al. 2020; Sickbert-Bennett et al. 2020). Two studies found that mask fit measured on a mannequin and on one individual was improved after adding a hosiery, tube-shaped overlayer (Clapp et al. 2020; Mueller et al. 2020). More research-based evidence is needed to assess how a homemade mask fastening method impacts on faceseal, acceptability, and safe doffing practices for tube-shaped devices.

Limitations

The collection efficiency and breathability testing in the flow-through set-up covered multiple materials. At the same time, the fit testing was performed only with one three-layer mask prototype that used a specific combination of materials (plus two commercial masks for comparison). The number of subjects fit tested was limited to 10 which generated a relatively high data variability for aFF. Furthermore, although we intended to recruit subjects representing a robust range of facial features/dimensions, we did not aim at targeting the NIOSH 25-subject bi-variate face size panel.

The automatic truncation of aFF > 200 by the Portacount is a limiting factor for any analysis of fit testing data because, generally speaking, it lowers the aFF means and standard deviations. However, this limitation does not appear to affect the overall aFF findings of this study since none of the overall aFFs actually approached 200.

The effect of washing on the facemask prototype performance was assessed for E_c and Δp, but not for aFF. While the visual inspection of the prototype did not reveal any changes after the 10^{th} cycle, washing could impact its fit if its integrity (e.g., cloth edge fraying or shrinkage) or other characteristics were altered. Besides, different washing procedures may impact the mask performance in a different way—the effect was not investigated in this study.

It is noted that factors such as the homemade mask maker skills, equipment, and settings (e.g., sewing machine stitch type or tension), as well as adherence to a specific fabrication protocol are likely to vary. For example, according to our fabrication protocol, the middle layer of the newly developed prototype was annealed (i.e., sewn down) to the outer layers around the entire mask periphery only to limit potential leaks from needle punctures. Other homemade mask makers may not necessarily follow this approach. The question how the above factors may impact the performance characteristics of a homemade facemask was not considered in this investigation.

Future research is needed to address the above limitations and expand the testing. While this study adopted the standard OSHA fit test with a specific series of exercises for assessing the protection of the mask wearer, engaging the subjects in alternative activities/maneuvers and using different approaches to measuring the in-mask and ambient aerosol will allow generating potentially impactful information on the performance of homemade facemasks. Evaluating the masks' workplace protection factor (or a simulated workplace protection factor) by a real-time monitoring of the in-mask and ambient aerosol concentrations would be relevant for assessing their performance in occupational environments. The other area of future studies is the assessment of double masking for maximizing the effectiveness of respiratory protection. In this context, the CDC has recently initiated a laboratory research effort to improve the fit of a medical procedure mask by fitting a cloth mask over it (Brooks et al. 2021).

Conclusions

Alternative (mostly common household) materials that have not been previously used in respiratory protective devices were tested with respect to the particle filtration performance and breathability. Most of these materials were found of certain (although limited) utilization in homemade/improvised facemasks. At a breathing flow rate of 30 L $\min^{-1}$, 17 out of 19 materials tested in this study showed the collection efficiency below 50%; at 85 L $\min^{-1}$, only 1 material allowed collecting more than 50% of particles. The pressure drop was mostly below 4 mm w.g. (observed in 89% of cases), which provides comfortable breathing, although at 85 L $\min^{-1}$ Δp was as high as 11 mm w.g. for one fabric material (silk). Based on the results of material performance evaluation, a three-layer facemask prototype was designed and fabricated with the middle layer made of MBPP and two outer layers made of PC. The materials used in the prototype were tested for particle detachment and a zero-shedding was observed downstream. Performance evaluation of the facemask prototype on 10 human subjects utilizing the standard OSHA-approved quantitative fit testing protocol demonstrated that its protection level, determined as an adopted fit factor (aFF) is between that of the commercial low-end Mask B and high-end commercial surgical/medical Mask A. Finally, the 10-cycle washing of the mask prototype significantly reduced its collection efficiency across the particle size range tested; however, washing did not significantly affect the mask breathability. Overall, the study revealed limitations of homemade masks. Although they offer a certain level of protection to a wearer, one should not expect them to provide the same respiratory protection as high-grade commercial surgical/medical masks or—by any means—the NIOSH-certified N95 FFRs.

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