

BMJ Open Ability of fabric face mask materials to filter ultrafine particles at coughing velocity

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ABSTRACT

Objective We examined the ability of fabrics which might be used to create home-made face masks to filter out ultrafine (0.02–0.1 µm) particles at the velocity of adult human coughing.

Methods Twenty commonly available fabrics and materials were evaluated for their ability to reduce air concentrations of ultrafine particles at coughing face velocities. Further assessment was made on the filtration ability of selected fabrics while damp and of fabric combinations which might be used to construct home-made masks.

Results Single fabric layers blocked a range of ultrafine particles. When fabrics were layered, a higher percentage of ultrafine particles were filtered. The average filtration efficiency of single layer fabrics and of layered combination was found to be 35% and 45%, respectively. Non-woven fusible interfacing, when combined with other fabrics, could add up to 11% additional filtration efficiency. However, fabric and fabric combinations were more difficult to breathe through than N95 masks.

Conclusions The current coronavirus pandemic has left many communities without access to N95 face masks. Our findings suggest that face masks made from layered common fabric can help filter ultrafine particles and provide some protection for the wearer when commercial face masks are unavailable.

INTRODUCTION

The current SARS-CoV-2 outbreak has left many communities without sufficient quantities of face masks for the protection of medical staff and first responders, let alone sufficient quantities of masks for the general population's use. Policies requiring or requesting individuals to wear face masks when they leave their homes have been implemented in most governmental regions throughout the world, with over 180 countries specifically recommending wearing face masks at the time this article was written.¹

Home-made face masks have now become a necessity for many to both meet the demands that cannot be met by supply chains and/or to provide more affordable options. Although widespread online resources are available to help home sewers and makers create masks,

Strengths and limitations of this study

- The study tested a large number of potential face mask materials, including materials currently in common use such as Lycra which have not been previously tested.
- Filtration efficiency at coughing velocities was evaluated, more closely mimicking use-case of masks worn for community protection than previous studies.
- Data from prior published work and current study were assessed, creating a picture of filtration efficiency and the impact of velocity.
- The study did not discriminate between pathogenic and non-pathogenic particles.
- Breathing resistance was estimated based on qualitative feedback.

scientific guidance on the most suitable materials is currently limited.

Although not as effective as surgical masks or respirators, home-made face masks have been shown to provide benefit in filtering viral and bacterial particles.^{2–4} The primary purpose of face masks worn by the general public is to limit the spread of viral particles from respiratory activity, rather than blocking the inhalation of any contagious particles.⁵ For the protection of the face mask wearer, the Centers for Disease Control and Prevention specifically recommends fabric face masks for the purpose of limiting viral spread through respiratory droplet.^{5 6} Face masks worn for the protection of others must efficiently filter particles emitted while coughing, when large amounts of potentially infectious respiratory droplets are produced.

Prior studies evaluating the efficacy of fabric face masks have tested their filtration ability under velocities representative of normal to active breathing.^{2–4} Significantly more potentially infectious particles are generated and spread by coughing, which occurs at velocities up to 100 times greater than those tested in previous experiments.^{7 8} This study evaluates the effectiveness of fabrics to filter ultrafine



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particles at velocities representative of adult coughing. Although no previous studies have evaluated the ability of face masks to filter particles at high velocities, evidence suggested high velocities may significantly decrease the efficacy of face mask materials.^{9,10}

Furthermore, past studies have tested a limited set of similar materials, namely T-shirts, sweatshirts, scarves and tea towels.²⁻⁴ Communicating with the international community of home sewers and small businesses seeking to design face masks, we determined a need for the assessment of a much wider range of fabric types, including stretch fabrics, felts, wool and nylon. Some fabrics, such as stretch Lycra and nylon, are in frequent use in commercial and home-made face masks but have not been evaluated for filtration efficiency. Conversations with material scientists and sewers highlighted the need to consider the possible benefits of non-woven interfacing, a material not previously tested for filtration.

Finally, our study assesses the impact of moisture, an effect of respiration, on filtration efficiency. A selection of fabrics were tested when damp to simulate dampness from sweat or heavy respiration. Furthermore, as fabric face masks are often washed and reworn, we tested all materials after subjecting them to one cycle in a home laundry machine. The literature evaluating the impact of washing and drying of fabric face masks is limited. One study on one fabric face mask showed a decrease in filtration efficiency with washing.¹¹ All fabric materials were tested after one wash and dry in a home machine.

Both individual materials and material combinations were tested with the goal of increasing particle filtration of home-made masks.

METHODS

This study was conducted in response to the rapidly growing SARS-CoV-2 outbreak. As such, priority was given to developing a test apparatus which could be constructed and provide usable results in a short amount of time.

Patient and public involvement

The research team communicated closely with home sewers, small businesses branching out to include fabric face mask manufactures, and physicians interested in protecting at-risk patients when masks were not available. Our conversations highlighted a need for filtration information on a wider variety of materials than those assessed in previous studies. We studied a range of materials that were previously unexamined in the literature, but of high interest to the aforementioned communities. These included Lycra, felts, washable vacuum bags and quilt batting/wadding. Materials for investigation were selected based on those that home sewers reported as being readily available. Responding to home sewers' understanding of fabric categories and the success of cotton in prior research,²⁻⁴ we also tested various weaves of cotton commonly available, including quilting cotton, shirting cotton and cotton jersey knit.

The physician and home sewing communities raised concerns regarding the risks of infection by reusing masks. In response to this, preference was given to materials which could be cleaned in a home washing machine and/or dryer at its hottest setting. All materials were washed and dried before testing. This caused significant shrinkage of wool felt. In response to further concerns about efficacy when damp, top-performing materials were subjected to five additional tests when damp.

Testing apparatus

Tests were conducted as described by Hutten.¹² An airtight apparatus allowed simultaneous testing of unfiltered and filtered air. The aerosol particles were generated by nebulising NaCl with a nebuliser (Pari Pro Plus, Vios, USA, 312F83-LC+) at the total output rate of 590 mg/min.

A 2.5 cm diameter tube provided access to two ultrafine particle counters (P-Trak, TSI, USA, Model 8525) which measured concentrations of particles between 0.02 and 0.1 µm. Most respiratory viruses of concern fall in this size range, including influenza, severe acute respiratory syndrome and SARS-CoV-2. Indeed, analysis of viral particle sizes in individuals with respiratory infections suggests transmission through small particle aerosols, rather than through large droplets, is the rule rather than the exception.¹³

The testing apparatus held a 2.5 cm diameter sample of the filter material. The material was allowed to relax on a flat surface and the testing mount placed on top, with excess material secured by an adjustable clip. See [figure 1](#) for an illustration of the testing apparatus.

After mounting a new specimen, a minimum of 3 min loading time at high velocity was given. At least 30 s between sequential tests on a previously loaded material was given.

Probes for the velocity metre and particle counters were inserted halfway into the tube. Flexible sealant was

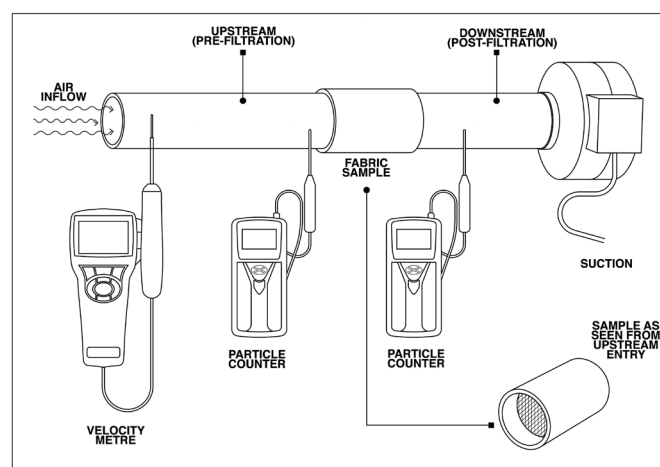


Figure 1 Diagram of experimental apparatus using two P-Trak Ultrafine Particle 8525 counters for simultaneous measurement and a TSI 9565 VelociCalc to measure face velocity.

used around the entry points of the probes to prevent air leakage.

Airflow was controlled through suction, which pulled air through the filter medium at a rate of approximately 16.5 m/s. This target number was chosen as a median between the average face velocity (11.2 m/s) and the greatest face velocity (22 m/s) recorded in a study on saliva droplet transport by adult coughing.⁷ Face velocity represents the speed of the particles when leaving the mouth. The chosen velocity was also in line with the 15.3 m/s average initial coughing velocity of an adult male measured in a 2012 study.¹⁴ Velocity was measured with VelociCalc Ventilation Meter (TSI, USA, Model 9565).

Prior to conducting high velocity tests, calibration tests were performed to validate the testing apparatus at lower velocities. Five control tests at lower velocity (face velocity between 5.5 and 7.5 m/s) showed the N95 performance averaging 89% with a high of 93%. A high-quality fine particulate matter (PM) 2.5 filter showed an average filtration efficiency of 89% and a high of 90%.

Calculating filtration efficiency

Filtration efficiency represents the per cent of particles a filter medium can block. Hutten's¹² formula was used to assess filtration efficiency (FE).

$$FE = \frac{(\text{Upstream Particle Count} - \text{Downstream Particle Count}) \times 100}{\text{Upstream Particle Count}}$$

For each material or material combination, 10 sets of readings were collected. Readings were collected using two P-Trak Ultrafine Particle Counters (Model 8525). Each reading was collected as a 10 s average of ultrafine air particle concentrations. The average filtration efficiency for each material was calculated. Due to the number of readings collected, the 95% CI for error bars was calculated using the appropriate t distribution critical value.

Breathing resistance

To estimate the breathing resistance of each material, and thus their suitability for use in a face mask, two members of the team tested the breathing resistance of each material. The sample holder (see [figure 1](#)), which allowed airflow only through a 1" diameter of the selected material, was held tightly to the mouth so all respiration occurred through the sample. Before evaluating materials, testers first breathed through an empty sample holder to feel a lack of resistance.

Testers then breathed for 20–40 s through each held sample first while breathing normally and then while breathing quickly and heavily. Each fabric was scored on a 0–3 scale, where 3 represented a great difficulty in drawing breath, 2 represented that there was noticeable resistance but breath could be drawn, 1 represented minor limitation but relative ease of breathing, and 0 represented no noticeable hindrance. There was very high agreement between the two testers (over 97%) and any disagreement was easily settled by discussion. Combining and layering fabric was not found to significantly increase breathing difficulty. All face mask fabric combinations scored 1 or 2.

Damp testing

Dampness was achieved by applying 7 mL of filtered water, the approximate amount of water exhaled by an adult during an hour of respiration,¹⁵ to the 5 cm² section of the material.

Study design and limitations

It should be noted that, due to the limitations imposed by this outbreak, this study was done with available materials. Data from this study should be treated as preliminary and used to inform decisions about filtration media only in relation to existing studies which assess viral filtration through the collection of viral cultures.

Ten readings were taken for each material, although one reading for the disposable High Efficiency Particulate Arrestance (HEPA) vacuum bag had to be later discarded due to a data transfer error. At least two different sections of each type of fabric were tested to ensure accurate representation of the material. Zero readings were taken on the particle testers regularly to ensure proper functioning.

RESULTS

Materials

All materials blocked some ultrafine particles (see [figure 2](#)). A 3M N95 mask and hospital-grade surgical mask were tested for the sake of comparison. Two types of vacuum bag, a disposable HEPA vacuum bag and a washable HEPA vacuum bag, were evaluated due to the number of people attempting to use these materials as face mask filters. Eighteen fabrics were tested as a single layer. Lastly, fabrics were layered to represent potential mask designs. For this test, fusible interfacing was heat-bonded to another layer.

HEPA vacuum bags blocked the most ultrafine particles, with the N95 mask from 3M blocking the second greatest percentage of particles.

Repurposing HEPA filters holds great promise for emergency face masks; however, great care should be taken that the component materials within the filter do not pose dangers to those making or wearing the face mask. While the single-use HEPA vacuum bag tested showed the greatest ability to filter ultrafine particles, the layers fell apart when the material was cut, exposing the inner layers of the fabric. Vacuum bags may have component materials which are effective at filtering particles but which are unsafe to inhale or come into close contact with the face. The reusable, washable HEPA bags had a construction more suitable to creating emergency face masks as the material held together well and did not expose the inner fibres, but the safety of the materials used is also unknown.

The filtration efficiencies of select materials were tested when damp ([table 1](#)). Only minor differences in filtration efficiency were noted for quilting cotton, cotton flannel and craft felt. Denim showed a significant decrease in efficiency, while the HEPA single-use vacuum bags showed an increase in efficiency when damp.

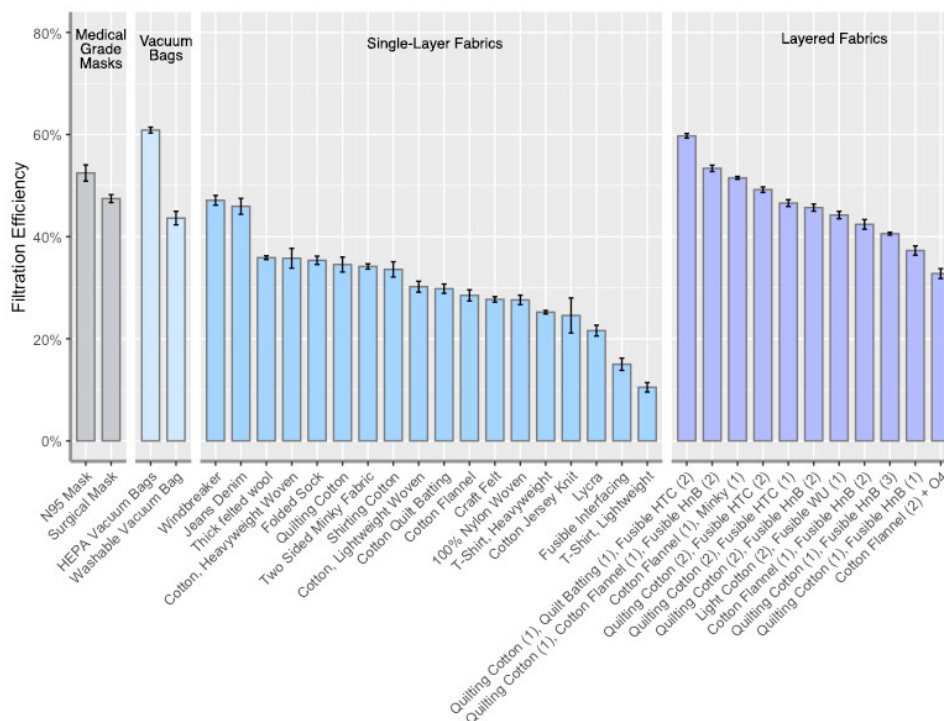


Figure 2 The filtration efficiency of tested fabrics and fabric combinations with error bars showing 95% confidence. Heat-n-Bond (HnB); Wonder Under (WU).

Table 1 also provides breathing resistance, fabric composition, filtration efficiency and SD. The most suitable fabrics for face masks are those with a high filtration efficiency but low breathing resistance. Denim jeans and windbreaker fabric blocked a high proportion of ultrafine particles but were extremely difficult to breathe through (see table 1). The windbreaker fabric may be suited to a loose-fitting face mask which protects the wearer from liquid droplets or splashes but is unsuitable for filtration.

Suitable materials which showed high filtration efficiency and low breathing resistance included felted wool, quilting cotton and cotton flannel. A single sock held flat compared well with the quilting cotton and, when pressed tight against the nose and mouth, may provide emergency protection.

Non-woven fusible interfacing

Non-woven fusible interfacing, the kind used for stiffening collars and other areas in garments, was able to significantly improve the ability of the fabrics to filter ultrafine particles without increasing breathing resistance. Of particular note, we found that brands exhibited significant differences in filtering performance. HTC brand lightweight interfacing was more effective than Heat-n-Bond brand lightweight interfacing. Applying two layers of the Heat-n-Bond achieved similar improvements to filtration efficiency as the HTC brand. Wonder Under, a double-sided, heavyweight fusible interfacing for constructing bags and craft projects, showed similar filtration ability to the HTC brand but may be too stiff to be suitable for face mask design.

Material combinations

When layered to create potential face mask configurations, common fabrics were able to achieve much higher levels of ultrafine particle filtration (see figure 2). Some material combinations were able to filter out higher percentages of ultrafine particles than the surgical or N95 masks tested, although this should not be taken to mean they provide higher levels of protection from viruses. All fabric combinations scored between 2 and 3 on the breathing resistance test, indicating they were more difficult to breathe through than an N95 mask.

DISCUSSION

Our data suggest that, in times of severe supply shortage, common fabrics can be layered to create face masks which protect wearers and others from a significant percentage of ultrafine particles. It should not be inferred that these layered fabrics can protect wearers from more viral particles than N95 masks or surgical masks as our study did not discriminate between viral particles and other ultrafine particles. Many viruses are carried on droplets or other particles significantly larger than those tested here. Furthermore, these results do not incorporate the challenges of achieving fit, a critical factor of face mask design. The benefit of using materials which offer high filtration efficiency is likely to be significantly reduced or negated if the mask is worn with a poor fit.

Many viruses are carried on droplets or other particles significantly larger than those tested here. Previous

Table 1 Chart of materials' composition (if available), breathing resistance, mean filtration efficiency (FE), SD of FE, and where available, FE when damp.

Fabric	Brand	Fibre Composition	Ease of Breathing Through Material	Dry		Damp	
				Mean % FE	SD	Mean % FE	SD
N95 Mask	3M	N/A	1	52.47	2.222	45.68	1.247
Surgical Mask		N/A	2	47.46	1.087	42.73	1.664
Disposable HEPA Vacuum Bags	Kenmore	N/A	2	60.86	0.761	71.93	4.407
Windbreaker		100% Polyester	3	47.12	1.332	45.55	3.535
Jeans Denim		100% Cotton	3	45.94	2.176	30.69	5.314
Washable Vacuum Bag HEPA	CanineCoddler	N/A	2	43.64	1.852	44.97	2.267
Thick felted wool	Weir Crafts	100% Merino Wool	0	35.87	0.502		
Cotton, Heavyweight Woven		100% Cotton	2	35.77	2.707		
Folded Sock		Cotton, Lycra	2	35.36	1.146		
Quilting Cotton		100% Cotton	1	34.54	2.047	31.88	1.406
Two Sided Minky Fabric		N/A	1	34.17	0.716		
Shirting Cotton		100% Cotton	1	33.59	2.097		
Cotton, Lightweight Woven		100% Cotton	0	30.2	1.499		
Cotton Quilt Batting		100% Cotton	0	29.81	1.27		
Cotton Flannel		100% Cotton	1	28.5	1.529	30.14	1.196
Craft Felt	Misscrafts	Rayon, Acrylic, Polyester	0	27.72	0.748		
100% Nylon Woven		100% Nylon	3	27.61	1.303		
T-Shirt, Heavyweight	Gildan	100% Cotton	1	25.21	0.471		
Cotton Jersey Knit		100% Cotton	0	24.56	4.8		
Lycra		82% Nylon, 18% Spandex	0	21.6	1.477		
Fusible Interfacing	HTC	N/A	0	15	1.672		
T-Shirt, Lightweight	Retro Brant	50% Polyester, 50% Cotton	0	10.5	1.293		

studies have shown that large particles are more readily filtered^{3,4} than smaller particles, indicating that a study of ultrafine particles will lead to a low 'baseline', on which filtration efficiency of larger particles will increase. Moreover, ultrafine particles tend to pose high risks during other emergency situations when fabric face masks are needed, such as forest fire outbreaks and times of high, concentrated pollution.

The effect of velocity on filtration efficiency

The flow rate of air used in this study represents the velocity of air expelled during human coughing⁷ and is the first such study to evaluate fabric filtration under high velocities. A velocity of 16.5 m/s or 1650 cm/s was chosen to represent the face velocity of an adult coughing.⁷ N95 filtration efficiency of NaCl was seen to decrease with velocity in prior filtration studies, from 99% in Rengasamy *et al's* evaluation at 0.165 m/s⁴ to 85% in Konda *et al's*³ evaluation at 0.26 m/s. As the velocity was up to 100 times greater than Rengasamy *et al's*⁴ and 63 times greater than Konda *et al's*,³ filtration efficiency was expected to be significantly lower if velocity impacts filtration efficiency.

Our results support the idea that velocity has a significant impact on filtration efficiency.

Popular mask filtration which specifies a face velocity include U.S. Food and Drug Administration, Particle Filtration Efficiency test (FDA-PFE) and American Society for Testing and Materials, Particle Filtration Efficiency test (ASTM-PFE) and use velocities ranging from 0.5 to 25 cm/s. Several testing methods do not specify a face velocity but instead provide flow rate for particle generation. While face velocity cannot be derived from flow rate, the flow rates used in these methods of 85L/min in the National Institute for Occupational Safety and Health (NIOSH) NaCl test and 28.3L/min in the American Society for Testing and Materials, Bacteria and Viral Filtration Efficiency test (ASTM-BFE) are lower than Konda *et al's*³ upper flow rate of 90L/min, which corresponded to a face velocity of 0.26 m/s.

No prior studies have evaluated the ability of N95 face masks to filter particles at such high face velocities which can be used as a direct comparison. Rengasamy *et al's*¹⁰ 2015 study on synthetic blood penetration of N95 masks

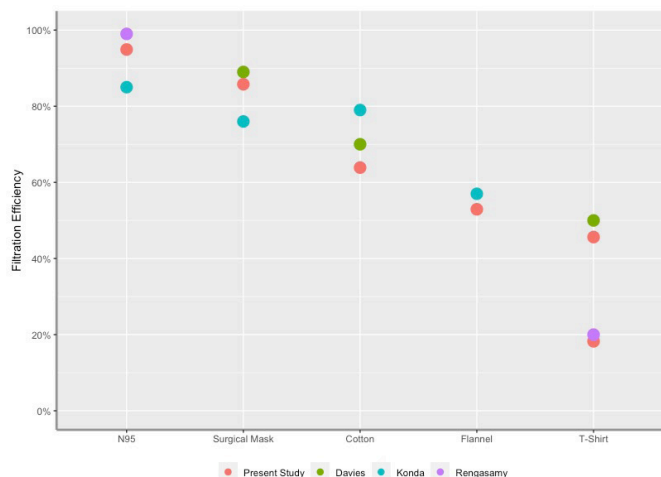


Figure 3 A comparison of existing data on fabric ultrafine filtration. Data chosen represent the highest velocity for each study. Data from this study were adjusted to proportionally represent a velocity of 0.2 m/s for this comparison. Data from Rengasamy *et al*⁴ are estimated from the included graphs, as statistical information about the data was not provided.

found that the number of respirator samples which failed the blood penetration test increased with increasing test velocities. This, along with our findings, indicates a strong need to further evaluate mask filtration at high velocities. While a leak around the downstream testing port could lead to a lowered particle count, the possibility of low performance at high velocities should be eliminated through further study.

Comparing fabric filtration efficiency

Although the results from higher velocity tests are significantly lower than previous tests, the relationship between the efficiency of the tested materials remains highly consistent with prior studies. The average velocity used in prior studies is 0.20 m/s, which is 82.5% of the velocity used in the prior study. When the values for high velocity filtration are increased by 82.5%, the data compare closely with data from previous research. [figure 3](#) compares data from studies which examine fabric filtration. Where applicable, the data chosen represented similar particle size filtration and the highest velocities offered. It should be noted that each test uses different methods of testing filtration efficiency and different brands of materials. Konda *et al*³ applied a maximum face velocity of 0.26 m/s using NaCl aerosol (approximately 0.74 µm). Rengasamy *et al* similarly used aerosolised NaCl at the lowest face velocity of 0.165 m/s⁴. Davies *et al*² assessed the filtration of Bacteriophage MS2 (0.023 µm) at a face velocity of 0.2 m/s. Despite the differences in testing method, velocities used and differences in product brands, the compiled data show close groupings of filtration efficiency. Data on T-shirt filtration in the present study are presented for both lightweight and heavyweight T-shirts.

A comparison showed that no one study method consistently produced the highest results. Konda *et al*,³ who recorded the highest fabric filtration efficiency,

also recorded the lowest filtration efficiency for N95 and surgical masks. Surprisingly, Rengasamy *et al*'s data⁴ do not closely resemble Konda *et al*'s,³ although both studies compared NaCl filtration. This may be a factor of the Konda *et al*'s³ filtration studied at a greater velocity than Rengasamy *et al*,⁴ another indication of the importance of velocity on filtration. Our filtration efficiency for fabric was frequently lower than others, a fact which may be accounted for with our single wash of the material before testing¹¹ and provides further evidence that washing fabric masks reduces their filtration efficiency.

Safety considerations

It is suggested home-made face masks should not be used in place of other protective measures such as self-isolation or social distancing. Rather, our results suggest home-made face masks may be a viable protective measure for those who cannot remain isolated and cannot obtain commercial face masks.

Repurposing material for home-made face masks comes with its own risks. Consideration should be given to respiratory hazards which may arise from the material used to construct a home-made face mask. For example, concern has been expressed that certain HEPA vacuum bags include fibres which, if inhaled, can cause lung injury. Lint and fibres from fabric, when inhaled in large quantities, are known to contribute to multiple lung problems, including asthma, byssinosis and bronchitis. For this reason, we would caution those needing to create home-made face masks to ensure all materials are safe, non-toxic and lint-free. Fabrics which readily shed fibres may not be suited for face mask design. The risks associated with such materials are an important area of further study, as large numbers of people are currently creating, wearing, washing, distributing and selling home-made face masks. Further research should evaluate the ability of these materials and material combinations to filter specific viruses, pollutants and other harmful airborne particles. Additional research on home-made face mask fit and fit testing is also critical at this time.

It is our hope that this study can assist home sewers and makers to create the best face mask possible when standardised commercial personal protective equipment is unavailable. Our study shows face masks can be created from common fabrics to provide wearers with significant protection from ultrafine particles. Until further research can establish the safety and viral filtration of fabric face masks, we suggest the use of approved respiratory protection whenever possible and the use of home-made face masks only when these products are unavailable.

It should be noted that the results of this study may also inform emergency mask creation in response to environmental emergencies where ultrafine particle levels are particularly dangerous, such as in the case of smoke or smog. Repeated face mask shortages during the California wildfires over the past few years have illustrated the recurring need for scientific data to guide the design of

home-made face masks when commercial supply chains are unable to meet demand.

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Contributors EOK conceived of the study, developed the study methodology, obtained the study materials and testing apparatus, collected study data, and wrote the manuscript. SP obtained the study materials, analysed the data and performed calculations, designed the graphs, and edited the manuscript. JW and JC developed the study methodology, reviewed the data, edited the manuscript and supervised the study.

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