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Original Research

Home-made masks with filtration efficiency for nano-aerosols for community mitigation of COVID-19 pandemic

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ABSTRACT

Objectives: The novel coronavirus disease 2019 (COVID-19) epidemic that emerged in December 2019 has rapidly evolved in recent months to become a worldwide and ongoing pandemic. Shortage of medical masks remains an unresolved problem. This study aims to investigate the filtration efficiency (FE) of home-made masks that could be used as alternatives for community mitigation of COVID-19.

Study design: Experimental observational analytic study.

Methods: The FE of home-made masks and medical masks (as the control) were tested under laminar flow within a scaled air duct system using nebulised NaCl aerosols sized 6–220 nm. The size-resolved NaCl aerosol count was measured using a scanning mobility particle-sizer spectrometer. Home-made masks with an external plastic face shield also underwent a splash test. In addition, the fibre structures of medical masks were studied under an electron microscope after treatment with either 75% alcohol or soap and water at 60 °C.

Results: The FE of the home-made masks at 6–200 nm were non-inferior to that of medical masks (84.54% vs 86.94%, $P = 0.102$). Both types of masks achieved an FE of 90% at 6–89 nm. A significantly higher FE was achieved when one piece of tissue paper was added adjacent to the inner surface of the medical mask than medical mask alone (6–200 nm: 91.64% vs 86.94%, $P < 0.0001$; 6–89 nm: 94.27% vs 90.54%, $P < 0.0001$; 90–200 nm: 82.69% vs 73.81%, $P < 0.0001$). The plastic face shield prevented the home-made mask from fluid splash. The fibre structures of the external surface of medical masks were damaged after treatment with either 75% alcohol or soap and water at 60 °C.

Conclusions: The home-made masks in this study, which were made of one piece of tissue paper and two pieces of kitchen towels, layered from face to external, had an FE at 6–200 nm non-inferior to that of medical mask materials, which had a certified FE of $\geq 95\%$ at 3 μm . In the current COVID-19 pandemic with the shortage of medical masks, these home-made masks combined with an external plastic shield could be used as an alternative to medical masks for community mitigation. In addition, one piece of tissue paper could be placed adjacent to the inner surface of a medical mask to prolong effective lifespan of the medical mask. These demand reduction strategies could be used to reserve medical masks for use in healthcare and certain high-risk community settings, such as symptomatic persons, caregivers and attendees to healthcare institutions.

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Introduction

The emerging severe acute respiratory syndrome (SARS) epidemic associated with the novel coronavirus (initially named

2019-nCoV) was first reported in Wuhan, Hubei, the People's Republic of China on December 30, 2019.¹ Rapid identification and genetic characterisation of 2019-nCoV showed its close relationship to bat SARS-related coronaviruses; thus, the virus could have potentially originated from bats.² The epidemic had been going on for more than 3 months (as of writing) globally. The World Health Organisation renamed 2019-nCoV as SARS-CoV-2 and characterised the coronavirus disease 2019 (COVID-19) as a controllable pandemic.^{3,4} This public health emergency has imposed enormous

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physical, mental health and economic burdens on the global population.³

The rapid spread of COVID-19 saw a panic-driven desire for medical masks,⁵ alcohol-based hand gels, household disinfectants, foods and other items in affected communities. The raw materials for production of personal protective equipment were reported to be running low. Doubt surrounded the effectiveness of medical masks in conferring respiratory protection and respirators that could sufficiently filter aerosols of the size at least comparable to SARS-CoV-2 viral particles with a diameter of ~50–200 nm were in high demand;^{6,7} this is much smaller than the 3 µm (measurement conversion 1000 nm = 1 µm) test and certification level of bacterial filtration efficiency (BFE) for medical mask materials.^{8,9} Previous studies have also shown that SARS-CoV and the influenza virus are highly penetrable through medical masks and respirators.^{10,11} Export restrictions on medical masks from certain COVID-19-affected countries for domestic use resulted in further average prices increases; thus, resource inequality in low-resource settings was further aggravated.³

Under these circumstances of medical mask shortages, community dwellers attempted unofficial methods to decontaminate and reuse disposable not-for-reuse medical masks and respirators, and made their own masks by referring to unofficial online videos using materials with uncertain filtration efficiency (FE) and no apparent water-resistant functions.^{5,6,12} Inappropriate reuse of disposable items by the public will increase the risks of cross- and environmental contamination, and infection.^{5,6,13,14}

Medical masks have been proven to be much more effective in source control or outward protection (i.e. reducing droplet dispersion and environmental contamination from coughing or sneezing) than inward protection (i.e. preventing the wearer from exposure to microorganism-laden droplets); thus, medical masks are normally advised for symptomatic patients.^{5,10,13,15} Under the current (as of writing) situation of the COVID-19 pandemic, the majority of the global population are uninfected and susceptible. Significant impacts on healthcare systems are expected before achieving population immunity by natural infection or vaccines (the effectiveness of any immunity also remains uncertain). To date, no effective specific antivirals, chemoprophylaxis or vaccines are available, and asymptomatic- and presymptomatic-infected individuals could shed virus and be responsible for transmission and spreading of COVID-19 in communities.^{16,17} With continued implementation of other infection control measures,^{5,10,13,15,19,20} medical masks and non-medical face masks (face masks) could serve to prevent transmission by limiting virus-laden droplets being spread from infected individuals in communities.

The global need for medical masks in healthcare settings during pandemics is extremely high.¹² Even after boosted global mass production, supply remains an unresolved issue,¹² which is widened further when the demand for community use is taken in to account.

Home-made masks that are made of readily accessible materials with FEs at nano-aerosol levels and are affordable and simple to make are urgently needed, especially in low-resource settings as last-resort alternatives to medical masks for community use. The present study examined the FE of home-made masks at 6–220 nm. A splash test was performed on an external plastic shield combined with the home-made mask on a manikin model. The effect of decontamination of medical masks with either 75% alcohol or soap and water was also examined.

Methods

Test materials

Commercially available pocket-sized 4-ply tissue paper (Neutral Tempo® Petit 4-ply pocket tissue, SCA Hygiene Products GmbH)

and kitchen towels (Vinda kitchen towel 9", Vinda Paper) and medical masks (Bloomsoms, BFE ≥95%)⁹ were selected for analysis. A transparent stationery plastic folder was used to create a plastic face shield.

Examination under scanning electron microscopy

Untreated tissue paper and kitchen towels, and medical masks untreated and treated with 75% alcohol, and soap and water of 60 °C, respectively, were examined under scanning electron microscopy (SEM) for fibre analysis. From the initial findings (Fig. 1), two pieces of kitchen towels were used and overlaid at a 90° rotation to increase the intercalation by overlapping and reduce inter-spaces for testing FE.

Testing FE

The test system was built to be similar to that of the American Society for Testing and Materials (ASTM) standard test method for determining particulate filtration efficiency (PFE) in medical masks and has been described previously (Fig. 2 and Supplementary text S1).^{9,21–23}

Combinations of test materials were tested for FE at 6–220 nm (Fig. 3). Two measurements were taken as follows: (i) at point B, the air flow to the external surface to the test material (upstream aerosol count); and (ii) at point C, the air flow and subsequent penetration of aerosols to the inner surface of the test materials (downstream aerosol count) (Fig. 2; Supplementary Tables S1 and S2). FE of different

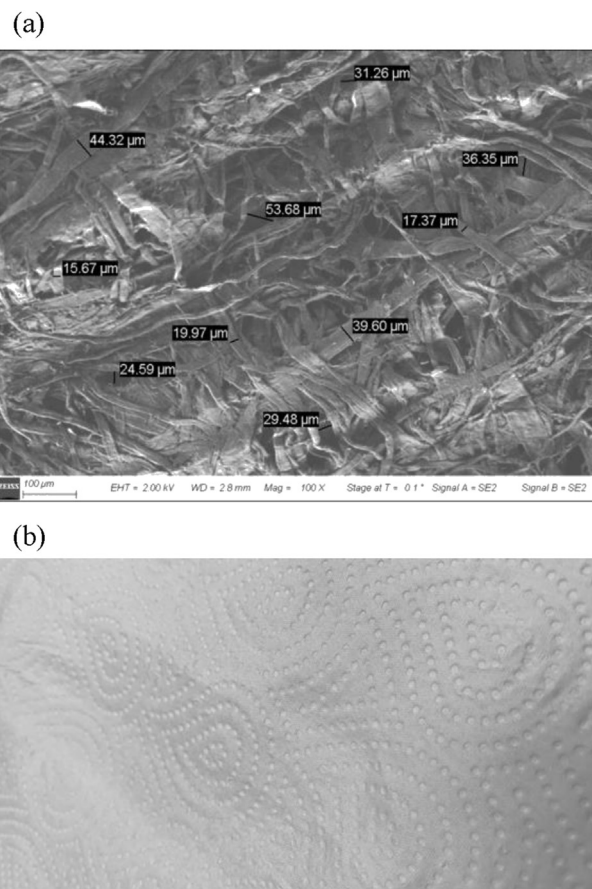


Fig. 1. Scanning electron microscopy (SEM) (100×) images of (a) the widest inter-fibre spaces of kitchen towel corresponding to (b) the embossing pattern on the actual kitchen towel.

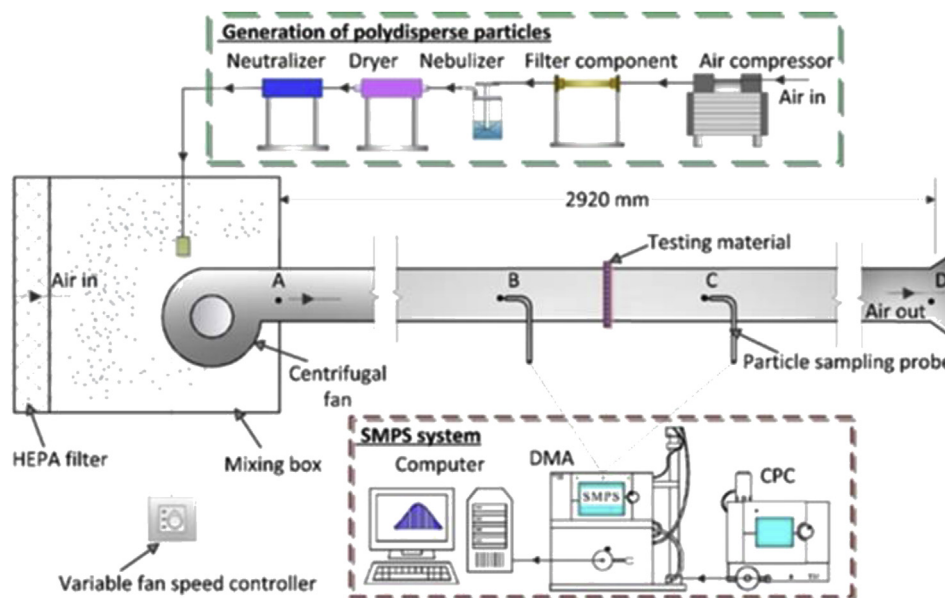


Fig. 2. Schematic diagram of the system for testing filtration efficiency: set-up, aerosol generation, aerosol neutraliser, aerosol dilution and humidity control, material specimen holder, airflow metering, aerosol concentration counting and measurements. HEPA: high-efficiency particulate air; DMA: differential mobility analyzer; SMPS: scanning mobility particle-sizer; CPC: condensation particle counter.

test materials at aerosols of different diameters (d) was calculated and shown (Fig. 3).⁹ Simulated airflows tested air flowing from the external air, through the masks' layers, to and behind the inner surface of the mask (i.e. the surface that would be touching the face). The highest FE of the home-made masks was seen with one layer of tissue paper, followed by two layers of kitchen towels; this combination was selected to be tested against medical masks for FE at $3\ \mu\text{m}$, and with an external plastic face shield for a splash test (Supplementary text S2).

Preparation of home-made masks and plastic face shield

Preparation of the home-made masks

Firstly, hand hygiene was performed.^{5,7,15,19,20} One piece of kitchen towel was put on top of another at 90° . A piece of 4-ply tissue paper (as innermost water absorbent layer of the mask) was placed on top of the kitchen towels; the three-layered stack was folded and cut at its longest edge into two. Four sides of this three-layered material (as 1 mask) were sealed by adhesive tape (2 inch-width). Two holes per side were punched on the left and right sides of the mask by a hole puncher. Plastic-coated wire was attached to the upper edge of the mask by adhesive tape. Alternatively, a pair of glasses could be used to fix the mask on the wearer's nose bridge if no such wire is available. Rubber bands or strings were threaded through the holes (one for each) on the mask; and their lengths were adjusted accordingly to cover the breathing zone to below the chin.

Preparation of plastic face shield

A transparent stationary plastic folder was cut at its closed edge into half. One piece was attached to the edge of the pair of glasses with binder clips, to serve as a water-proof shield to the face mask.

See Supplementary Video S1 to view preparation of the masks and shield.

Supplementary data related to this article can be found online at <https://doi.org/10.1016/j.puhe.2020.08.018>

Statistical analyses

Descriptive statistics were recorded. FE of materials at aerosols sized in diameter (d) was calculated as $FE(d) = [\text{Upstream aerosol count}(d) - \text{Downstream aerosol count}(d)] / \text{Upstream aerosol count}(d) \times 100\%$. Student's paired t -test was used for comparing means between groups. A P -value < 0.05 was considered to be statistically significant. IBM® SPSS® Statistics for Windows, version 24.0 (IBM Corp., Armonk, NY) was used for statistics analyses.

Results

The mean, median, geometric standard deviation (GSD) of aerosol sizes and total concentrations of aerosols in the upstream and downstream measurements are shown (Supplementary Tables S1 and S2). The FE of different materials at 25–200 nm showed concave-up curves, all indicating their lowest FE at 100–125 nm, which represents the most penetrating particle size, and highest FE at smaller- (25 nm) and larger- (200 nm) sized aerosols (Fig. 3).

The highest FE of the home-made masks was seen with one layer of tissue paper, followed by two layers of kitchen towels (sample D in Fig. 3), which achieved an FE across 6–200 nm and was non-inferior to that of a medical mask (sample F in Fig. 3) (6–200 nm: 84.54% vs 86.94%, $P = 0.102$; 90–200 nm: 72.89% vs 73.81%, $P = 0.109$) (see Figs. 3 and 4; Table 1). Both the selected home-made mask combination (sample D) and the medical mask (sample F) achieved an FE of $>99.9\%$ at $3\ \mu\text{m}$ (Table 1). The FE of using a medical mask in combination with tissue paper (sample E in Fig. 3) was significantly higher than that of the medical mask alone (sample F) (6–200 nm: 91.64% vs 86.94%, $P < 0.0001$; 6–89 nm: 94.27% vs 90.54%, $P < 0.001$; 90–200 nm: 82.69% vs 73.81%, $P < 0.0001$) (Fig. 4).

The external plastic face shield was shown to prevent splash droplets from contaminating the home-made mask (sample D; Supplementary Fig. S1).

Fibre structures on the external surfaces of surgical masks were damaged after treatment with either 75% alcohol or soap and water at 60 °C (Fig. 5). Images of untreated and treated medical masks (Fig. 5) and untreated test materials (Supplementary Fig. S2) under the SEM are shown.

Discussion

To the best of the authors' knowledge, this is the first study of FE of home-made masks at 6–200 nm-sized aerosols during the initial phase of the COVID-19 pandemic. Crisis/alternate strategies for safe extended use and limited reuse of respirators in healthcare settings has been implemented both during this time of medical mask shortage in the COVID-19 pandemic and previously.^{15,19,24} Based on available data (as of writing) on transmissibility and clinical severity of COVID-19, the use of face masks in community settings for high-risk groups is recommended.^{13,15,16,18,19} Moreover, there are asymptomatic- and presymptomatic-infected individuals who carry and shed SARS-CoV-2 from their upper respiratory tract, with viral loads at almost peak levels just before they become symptomatic.^{16–18} The risk of spreading COVID-19 in communities is further increased in those with prolonged asymptomatic phases and those with very high viral loads.^{16,17}

When the majority of the global population was susceptible to SARS-CoV-2 infection, during the initial 100 days of COVID-19 pandemic, the incidence of COVID-19 in Hong Kong (HK) where early and community-wide (>95% population) face mask use was implemented was significantly less (129.0 per million population) than that of other comparative countries where face mask usage was not adopted in the community (e.g. Spain 2983.2, Italy 2250.8, Germany 1241.5, France 1151.6, US 1102.8, UK 831.5, Singapore 259.8 and South Korea 200.5 per million population); other multifaceted control and administrative interventions had been similarly implemented.^{15,19,20,25} Epidemiological investigations in HK also showed significantly more clusters of COVID-19 patients had engaged in recreational settings where masks were not worn

(11 clusters) compared with settings where masks had been worn (3 clusters).²⁵ It was suggested that community-wide mask wearing might contribute to epidemic control of COVID-19 by reducing the spread of SARS-CoV-2 from infected patients with no or mild symptoms, and it is advocated as an adjunctive measure in densely populated regions to mitigate the COVID-19 pandemic.²⁵

A recent review also showed that face mask use for those in contact with the emerging coronaviruses (including SARS and SARS-CoV-2)-infected patients was associated with a large reduction in infection risk, in both healthcare and community settings. Such inward protection (i.e. self-protection from being infected) remained significant, even after accounting for the differential respirator use between healthcare and community settings. Inward protection was also shown when use of face masks (including reusable gauze or multilayered cotton masks) was compared to wearing no masks. These findings support face mask use, irrespective of settings during the COVID-19 pandemic. Face shield use could confer additional benefits that might result in a further large reduction in viral infection.²⁶

An animal experiment showed that medical masks were effective for inward protection in reducing infection risk of uninfected hamsters from SARS-CoV-2-infected hamsters via non-contact modes, and even more effective for source control (i.e. limiting the spread of infection).²⁷ Moreover, another recent study has shown that home-made masks (made of 4-layers of kitchen towels and 1-layer of polyester cloth) had a comparable efficacy (95.15%) to N95 respirators (99.98%) and medical masks (97.14%) in preventing nebulised live low-pathogenic avian influenza virus-laden aerosols (median *d* 3.9 μm; 65% < 5.0 μm), as surrogates of coronaviruses, from penetrating the masks under an experimental system simulating human breathing. It was suggested that such home-made masks might be efficacious to slow the spread of SARS-CoV-2 in communities.²⁸

The global success in combating the pandemic can only be achieved when there is no active community transmission. With variable and fluctuated levels of transmission activities in different localities over time, and before effective specific antivirals,

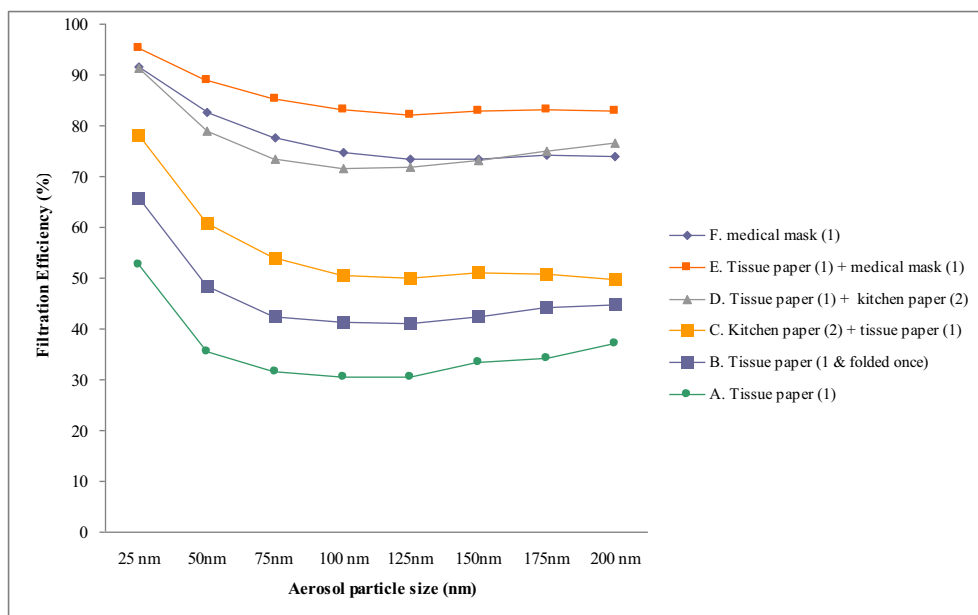


Fig. 3. Mean filtration efficiency (%) of different combinations of test materials at respective aerosol sizes. The key is written in layering order as if simulating wearing a mask from face to external area (number of pieces used are given in parentheses). Materials were tested with aerosols as follows: (i) at point B, the air flow to the external surface of the test material (upstream aerosol count); and (ii) at point C, the air flow and subsequent penetration of aerosols to the inner surface of the test materials (downstream aerosol count) (Fig. 2). FE of different test materials at aerosols of different diameters (d) was calculated and shown.

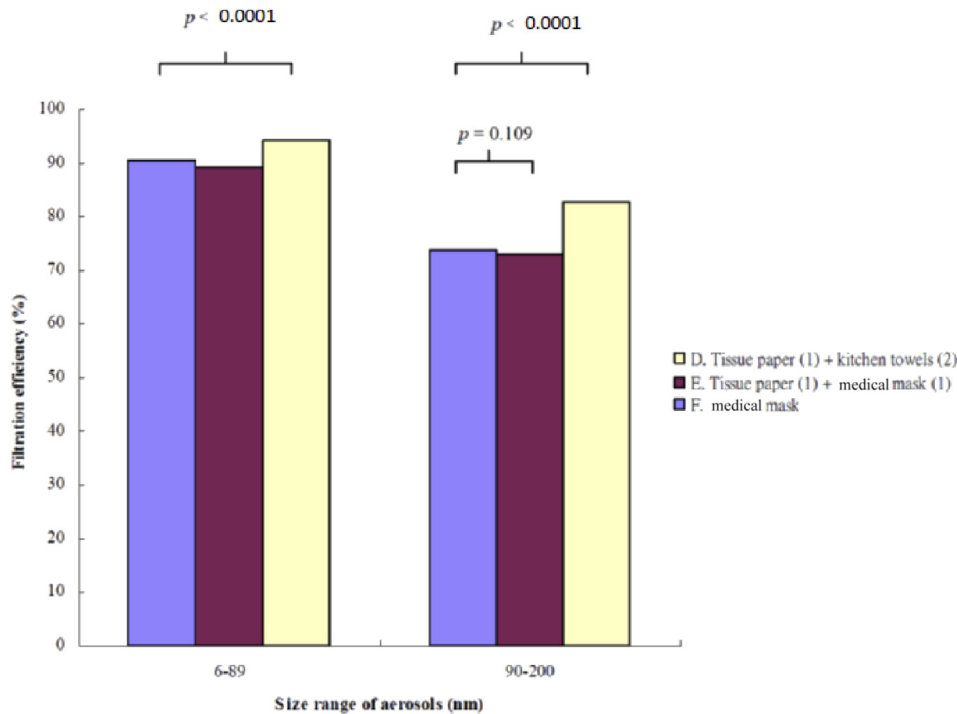


Fig. 4. Filtration efficiency of samples D, E and F (combination D = one piece of tissue paper and two pieces of kitchen towels; E = tissue paper and medical mask; and F = medical mask) at 6–89 nm and 90–200 nm. The key is written in layering order as if simulating wearing a mask from face to external (number of pieces used are given in parentheses). Materials were tested with aerosols as follows: (i) at point B, the air flow to the external surface of the test material (upstream aerosol count); and (ii) at point C, the air flow and subsequent penetration of aerosols to the inner surface of the test materials (downstream aerosol count). (Fig. 2). FE of different test materials at aerosols of different diameters (d) was calculated, compared and shown.

Table 1
Mean filtration efficiency (%) ± standard deviation (SD) of different test materials at respective aerosol sizes.

Test materials ^a	Mean filtration efficiency (%) ± SD								
	25 nm	50 nm	75 nm	100 nm	125 nm	150 nm	175 nm	200 nm	3 μm (3000 nm)
A. Tissue paper (1)	52.56 ± 1.36	35.62 ± 0.53	31.61 ± 1.14	30.45 ± 0.50	30.47 ± 1.54	33.49 ± 1.33	34.20 ± 0.61	36.99 ± 1.15	Not done
B. Tissue paper (1 & folded)	65.81 ± 0.47	48.40 ± 0.21	42.39 ± 0.46	41.21 ± 0.47	41.15 ± 1.31	42.41 ± 1.26	44.31 ± 2.21	44.64 ± 0.76	Not done
C. Kitchen towel (2) + tissue paper (1)	78.16 ± 0.30	60.67 ± 0.51	53.85 ± 0.55	50.63 ± 0.06	50.04 ± 0.41	50.99 ± 0.48	50.89 ± 0.27	49.86 ± 0.37	Not done
D. Tissue paper (1) + kitchen towel (2)	91.20 ± 0.26	78.82 ± 0.30	73.46 ± 0.58	71.53 ± 0.53	71.79 ± 0.37	73.24 ± 0.34	74.93 ± 1.17	76.54 ± 0.94	99.99 ± 0.01
E. Tissue paper (1) + medical mask (1)	95.28 ± 0.11	89.00 ± 0.20	85.21 ± 0.60	83.22 ± 0.53	82.21 ± 0.32	82.88 ± 0.26	83.23 ± 0.96	82.87 ± 0.80	Not done
F. Medical mask (1)	91.54 ± 0.23	82.63 ± 0.24	77.59 ± 0.11	74.78 ± 1.21	73.33 ± 0.25	73.31 ± 0.21	74.21 ± 0.44	73.85 ± 1.27	99.87 ± 0.16

^a In layering order as if simulating wearing a mask from face to external (number of pieces used are given in parentheses). Materials were tested with aerosols as follows: (i) at point B, the air flow to the external surface of the test material (upstream aerosol count); and (ii) at point C, the air flow and subsequent penetration of aerosols to the inner surface of the test materials (downstream aerosol count) (Fig. 2). FE of different test materials at aerosols of different diameters (d) was calculated and shown.

chemoprophylaxis and vaccines being available, the global challenge is to identify asymptomatic- and presymptomatic-infected individuals from whom the pandemic could be self-sustaining. In addition, it is important to be prepared for a resurgence of travel-related confirmed cases in those areas/countries without active transmission, especially after people gradually resume movements and economic activities, both locally and internationally. Vigilant mandatory surveillance for border control should be implemented in all areas/countries in an ideal situation; however, the feasibility of this is not guaranteed. Hence, community-wide face mask use is likely to be needed as a community mitigation strategy to prevent viral shedding from infected individuals, especially those who are asymptomatic.

Although medical mask shortage in healthcare settings remains unresolved, home-made masks with FE at the nano-aerosol level

could be used as alternatives for certain lower-risk community settings, thus enabling to reallocation and prioritisation of medical masks for healthcare settings and high-risk community settings, such as for caregivers, attendees to healthcare and institutional facilities.

An external plastic face shield could also be used as personal protective equipment from droplets when social distancing is not possible and/or masks are not feasible (e.g. for toddlers or when eating/drinking). Such practices might also limit the spread of future droplet-transmitted epidemics and help prevent overwhelming the already stretched healthcare systems and associated excess mortality. Moreover, unprotected healthcare workers in the community could acquire infection that could then result in nosocomial outbreaks. Subsequent quarantine and isolation of healthcare workers would further overwhelm the already stretched healthcare system.

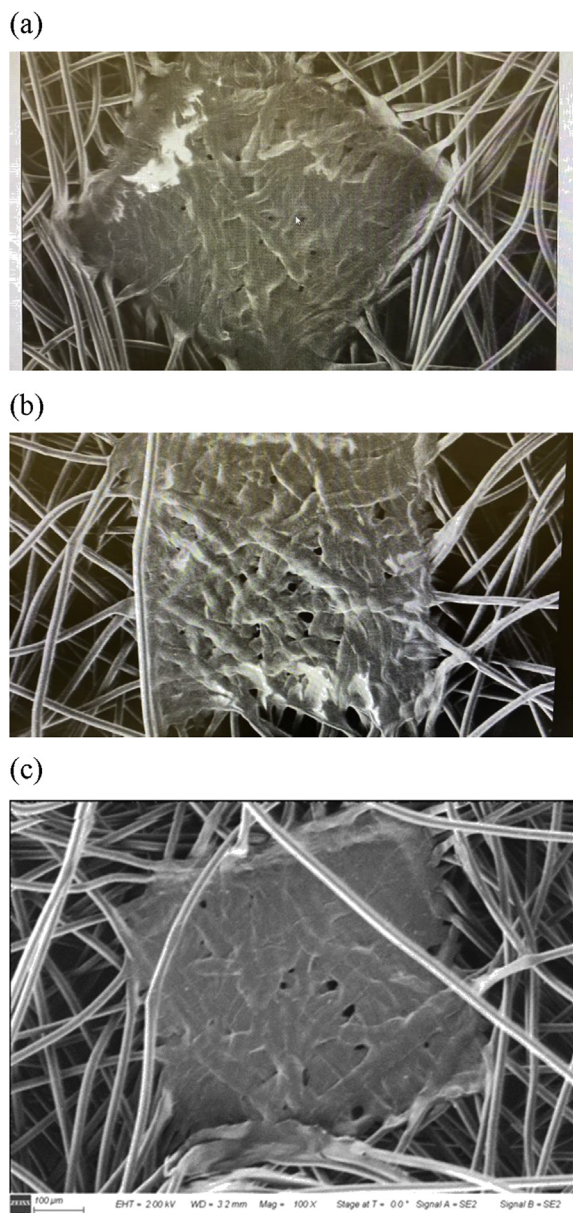


Fig. 5. Images of the external surfaces of medical masks shown under SEM (100 \times). (a) Untreated, (b) damaged fibre structure after treatment with 75% alcohol, and (c) damaged fibre structure after treatment with soap and water at 60 °C.

FE certification of home-made mask materials is not available locally, and there is insufficient time to wait for overseas-certified FE results. Unlike mass production of commercially available medical masks using the same FE-certified materials, there could be slight, but minimal, heterogeneity in the materials used for the home-made masks in this study when prepared by individuals from different communities. Nevertheless, the tissue paper and kitchen towels complied with international standards for tissue paper and tissue products, and food safety management systems accordingly, with purposes of use directly on users' skin and breathing zones, and foods, respectively. Today, individuals may experience difficulty selecting an appropriate cloth/fabric face mask as there is great heterogeneity in the products available and little information on their effectiveness, although cotton-gauze home-made masks were shown to be protective in military barracks and healthcare settings during the pneumonic plague

epidemic a century ago.²⁹ Variably low FE (9–40%) at 20–1000 nm in cloth/fabric home-made masks conferred marginal respiratory protection.³⁰ Various materials, including cotton or water-resistant breathable fabrics and dust wipe papers, were considered when creating the home-made masks for this study. After balancing many factors, including safety, breathability, accessibility, availability, costs and affordability for low-resource settings, tissue paper and kitchen towels were selected. The home-made masks were easy-to-create by hand, unlike the 100% cotton-made masks, requiring sewing machines to speed-up construction and the material (e.g. an unworn T-shirt) could better be used for wearing.³¹ In addition, certified FE results were specified for materials only, not for overall effectiveness of the whole mask in protection nor defining any acceptable level of FE.^{5,23}

This study examined FE of home-made masks in a timely manner. They were tested by methods similar to ASTM for PFE and under stringent conditions adapted from standard methods.^{9,20,21} The nano-sized NaCl aerosols used in this study fulfilled requirements for certification of air-purifying respirators: GSD <1.86; mean d $0.075 \pm 0.02 \mu\text{m}$, which was even smaller than required in BFE ($3.0 \pm 0.3 \mu\text{m}$) and PFE ($0.1 \mu\text{m}$) of medical masks.^{9,22,23} Rapid real-time detection of aerosol counts was used, rather than requiring further incubation time necessary for total bacterial counts in testing BFE.^{9,22,23} The flow rate and exposure time, which simulated cough velocity and coughing time, respectively, also fulfilled those required in standard tests.^{9,22,23,32}

Nano-sized aerosols were used because technology advancement has made submicron measurements feasible for droplets ranging from <100 nm to 5–10 μm , which have previously not been able to be detected in cough clouds.^{32,33} The most prevalent aerosols were sized <100 nm and 100–300 nm, each quantified at least 10^6 , among the expelled particles (ranging from <100 nm to 10,000 nm) generated from coughing patients with a respiratory infection.³³ The majority of exhaled particles (70%) from influenza-infected coughing patients ranged from 300 to <500 nm, followed by 500 nm to 1 μm (17%).³⁴ The least protection that medical masks conferred was found to be in the 40–320 nm range.¹¹ Under certain conditions, appropriately sized aerosols with viable viral droplet nuclei could theoretically be suspended in the air for extended durations and recirculated for long travel distances; although, clinically, this remains controversial.^{11,34} Influenza viral RNA load was found to be highest in aerosols sized <4 μm (42% in <1 μm ; 23% in 1–4 μm) in coughs from influenza A-infected patients; and 18% (2 of 11) of these patients had viable virus detected in cough aerosols.³⁴ The FE of medical masks at nano-sizes has not been certified previously. Our study provides FE of home-made masks and medical masks for nano-aerosols. This might reduce doubts on using home-made masks in certain community settings as a last-resort for community mitigations in the current pandemic.

The concave-up FE curves (Fig. 3) can be explained by the classical fibrous filtration theory that smaller particles are transported predominated by diffusion (Brownian motion), larger particles mainly by inertial impaction and interception, and intermediate-sized particles are transported by both mechanisms without any predominance.^{22,31} Medical masks and the home-made mask materials used in this study worked as a fibrous filter, comprising of abundant randomly oriented fibres forming a dense mat to capture and retain particles throughout its depth or thickness.^{22,31} Aerosol transport and filtration through fibrous filters involves different mechanisms, including impaction, interception, diffusion and electrostatic attraction.^{22,31}

FE of test materials for larger-sized aerosols was not tested in the present study because the plastic shield was designed to serve as an external physical barrier preventing conjunctiva mucosa, mask–face interface (face-seal leak) at different edges of the home-

made mask, and the breathing zone, from direct exposure to larger-sized aerosols and fluid splash at low to moderate amounts, to counter-balance the limitations of the home-made masks.

At 25 nm, FE was 91.20% for the home-made masks (sample D, Fig. 3), which is better than a vacuum cleaner bag (86%), tea towel (72.5%), cotton mix (70%), antimicrobial pillow case (68.9%) and 100% cotton T-shirt (50.9%) at 23 nm.³¹ FE of medical masks (sample F, Fig. 3) at 25 nm (91.54%) concurred the previously reported 89.5% at 23 nm;³¹ but no comparison should be made with its certified BFE, which was tested at 3 μm .^{22,23}

The higher FE in sample D than sample C (see Fig. 3) could be explained by the different layering order. The overlapped kitchen towels facing externally might reduce the inter-fibre spaces, increasing obstruction and aerosol travelling time during the initial path of aerosol penetrating of the home-made mask. The fluffy alternate raised flat areas of kitchen towels might also increase the surface areas to trap incoming particles. The higher FE in sample E (tissue paper plus medical mask) than sample F (medical mask alone) is likely to be related to increased aerosol travel distance.

There are limitations to the present study. The set-up was similar to that in ASTM methods for PFE, and the testing parameters were stringent and referenced to standard protocols using nano-aerosols.^{9,22,23} The FE of medical masks (99.87% at 3 μm) illustrated that the current test method was able to test and achieve a comparable FE as certified by ASTM method.^{9,22,23} At 75 nm, FE was 77.6%, which concurred with previous findings of medical masks FE 54.74–88.4%.^{22,23} The area of the test materials was smaller than required in BFE/PFE tests;^{9,22} however, the materials adequately covered the highest (and the usually constant) area of mouth opening during coughing and the initial cough-cloud width.³² The overall effectiveness of home-made masks for protection was not tested, which was out of the study's scope. Nevertheless, the in-use plastic face shield would cover any face-seal leak, preventing larger

droplet dispersion from sources or exposure to receivers. Virus-laden droplets, if any, in incoming airflow from the front and sides, would have highly likely been impacted to the external surface of the face shield and the droplet speed would then be largely retarded before they could penetrate the face shield (if possible) and contact the breathing zone. Airflows heading up from below the chin and entering the shield-mask (external surface) interspaces might be prevented by the properly worn home-made mask, which covered the breathing zone to below the chin.

The home-made masks in this study need to be changed once wet as this impacts the absorbency of the materials. Disposable masks have lower risks of cross-contamination than reused items.⁶ The acceptance of home-made masks regarding comfortability and breathability (assessed by pressure drop across materials) were not assessed. Nevertheless, the authors of the study and associated members of the working group who tried and used the home-made masks in community settings, perceived the masks to be acceptable for general use as suggested. The home-made masks in this study had fewer layers (3 layers; 2 were kitchen towels) and might be more breathable than the other home-made masks (e.g. 5 layers; 4 were kitchen towels) whose breathability was also perceived as acceptable and more breathable than N95 respirators by their authors.^{26,28} A meta-analysis, which included studies in non-healthcare settings during COVID-19 and other previous epidemics, found that use of face masks and face shields were acceptable, feasible and reassuring.²⁶

At times when limited medical masks are available, the home-made masks in this study provide a suitable alternative with a non-inferior FE to medical masks. However, other home-made masks with variable or unknown FE, and the reuse of disposable not-for-reuse face masks may provide false protection, although inward (self-) protection has been shown, even with home-made masks, which is better than no protection.^{26,31} Hence, if people cannot get hold of medical masks, they may consider home-made masks to protect their breathing-zone in the current COVID-19 pandemic.



Fig. 6. Home-made mask combined with hat/visor with plastic face-shield. (Biophysical measurements of the human model: body height 160 cm; hairline to tip of the chin 20 cm; left ear lobe to tip of the nose 13 cm; tip of the nose to right ear lobe 13 cm)

Conclusions

Home-made masks with FE in the nano-sized range are urgently needed for community mitigation of COVID-19 and as alternatives to medical masks because of their current shortage. In this study, the FE of medical masks at 3 μm was comparable to the certified BFE at 3 μm .^{9,22,23} The FE of home-made masks using one layer of tissue paper and two layers of kitchen towels (sample D) was non-inferior to that of medical masks for 6–200 nm aerosols, and the FE of medical masks with tissue paper (sample E) was higher than for medical masks alone (sample F). In times of medical mask shortage, one piece of tissue paper might be put adjacent to the inner surface of the medical mask to reduce contamination and prolong the effective lifespan of the medical mask. The current home-made masks, combined with plastic face shields (Supplementary Video S1), could be used as alternatives to medical masks for low-risk community settings to reserve medical masks for healthcare use and certain community settings, to mitigate the spread of COVID-19 until chemoprophylaxis and/or vaccines are available. Decontamination of medical masks damaged their fibre structures and is not recommended; reuse of such masks would give a false sense of protection. Commercially available hats/visors with plastic face shields could be alternatives to the plastic face shield in the current study (Fig. 6).

Nanotechnology incorporation in masks/fabrics, with or without copper-impregnated for antimicrobial effects, are available.^{35,36} Further research is needed to develop effective materials, reusability and decontamination methods, if feasible, of medical masks for respiratory protection^{7,17,30,35,36}; and further quality and

effectiveness improvement of home-made masks should be investigated as an alternative.

Collaboration from interdisciplinary and cross-specialty expertise were used in this study to achieve evidence-based applications for timely and constructive responses to mitigate damage control during the COVID-19 pandemic.

Author statements

Ethical approval

Not required. No human participants, patients or patient-related information was involved in the study.

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Competing interests

None declared.

Author contributions

All authors contributed equally. IWSL and ACKL: study methods; experiment design, set-up, technical and expertise support with knowledge and intellectual input; full access to all the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis; revision of the manuscript for technical intellectual content. IWSL: statistical analysis; data interpretation; manuscript writing; critical revision of the manuscript for important intellectual content. JKMF and CML: concept and design; administrative support; CML: supervision.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.puhe.2020.08.018>.

References

- Huang C, Wang Y, Li X, Ren L, Zhao J, Hu Y, et al. Clinical features of patients infected with 2019 novel coronavirus in Wuhan, China. *Lancet* 2020; **395**(10223):497–506. [https://doi.org/10.1016/S0140-6736\(20\)30183-5](https://doi.org/10.1016/S0140-6736(20)30183-5).
- Zhou P, Yang XL, Wang XG, Hu B, Zhang L, Zhang W, et al. A pneumonia outbreak associated with a new coronavirus of probable bat origin. *Nature* 2020; **579**(7798):270–3. <https://doi.org/10.1038/d41586-020-2012-7>.
- WHO Director. *General's opening remarks at the media briefing on COVID-19*. World Health Organization; 11 March 2020. <https://www.who.int/dg/speeches/detail/who-director-general-s-opening-remarks-at-the-media-briefing-on-covid-19-11-March-2020>. [Accessed 18 May 2020].
- Naming the coronavirus disease (COVID-2019) and the virus that causes it. World Health Organization. [https://www.who.int/emergencies/diseases/novel-coronavirus-2019/technical-guidance/naming-the-coronavirus-disease-\(covid-2019\)-and-the-virus-that-causes-it](https://www.who.int/emergencies/diseases/novel-coronavirus-2019/technical-guidance/naming-the-coronavirus-disease-(covid-2019)-and-the-virus-that-causes-it) [accessed 18 Sept 2020].
- WHO Team Health Emergencies Preparedness and Response. *Advice on the use of masks in the community, during home care and in health care settings in the context of the novel coronavirus (2019-nCoV) outbreak*. World Health Organization; January 29 2020. [https://www.who.int/publications-detail/advice-on-the-use-of-masks-in-the-community-during-home-care-and-in-healthcaresettings-in-the-context-of-the-novel-coronavirus-\(2019-ncov\)-outbreak](https://www.who.int/publications-detail/advice-on-the-use-of-masks-in-the-community-during-home-care-and-in-healthcaresettings-in-the-context-of-the-novel-coronavirus-(2019-ncov)-outbreak). [Accessed 18 May 2020].
- Reusability of facemasks during an influenza pandemic: facing the flu*. Washington, DC: The National Academies Press, Institute of Medicine; 2006. <https://doi.org/10.17226/11637> <http://www8.nationalacademies.org/onpinews/news-item.aspx?RecordID=11637>. [Accessed 18 May 2020].
- Modes of transmission of virus causing COVID-19: implications for IPC precaution recommendation. World Health Organization; 29 March 2020. <https://www.who.int/news-room/commentaries/detail/modes-of-transmission-of-virus-causing-covid-19-implications-for-ipc-precaution-recommendations> [accessed 18 Sept 2020].
- Zhu N, Zhang D, Wang W, Li X, Yang B, Song J, et al. China novel coronavirus investigating and research team. A novel coronavirus from patients with pneumonia in China, 2019. *N Engl J Med* 2020; **382**(8):727–33. <https://doi.org/10.1056/NEJMoa2001017>.
- ASTM & COVID-19. ASTM F2100-19 standard specification for performance of materials used in medical face masks. ASTM F2101-19 standard test method for evaluating the bacterial filtration efficiency (BFE) of medical face mask materials, using a biological aerosol of *Staphylococcus aureus*. ASTM F2299/F2299m-03(2017) standard test method for determining the initial efficiency of materials used in medical face masks to penetration by particulates using latex spheres. <https://www.astm.org/COVID-19/> [accessed on 18 Sept 2020].
- Patel RB, Skaria SD, Mansour MM, Smaldone GC. Respiratory source control using a surgical mask: an in vitro study. *J Occup Environ Hyg* 2016; **13**(7): 569–76. <https://doi.org/10.1080/15459624.2015.1043050>.
- Lee SA, Grinshpun SA, Reponen T. Respiratory performance offered by N95 respirators and surgical masks: human subject evaluation with NaCl aerosol representing bacterial and viral particle size range. *Ann Occup Hyg* 2008; **52**(3): 177–85. <https://doi.org/10.1093/annhyg/men005>.
- Carias C, Rainisch G, Shankar M, Adhikari BB, Swerdlow DL, Bower WA, et al. Potential demand for respirators and surgical masks during a hypothetical influenza pandemic in the United States. *Clin Infect Dis* 2015; **60**(Suppl 1): S42–51. <https://doi.org/10.1093/cid/civ141>.
- Qualls N, Levitt A, Kanade N, Wright-Jegede N, Dopson S, Biggerstaff M, et al. CDC Community Mitigation Guidelines Work Group. Community mitigation guidelines to prevent pandemic influenza - United States, 2017. *MMWR Recomm Rep (Morb Mortal Wkly Rep)* 2017; **66**(1):1–34. <https://doi.org/10.15585/mmwr.r6601a1>.
- Fisher EM, Shaffer RE. Commentary considerations for recommending extended use and limited reuse of filtering facepiece respirators healthcare settings. *J Occup Environ Hyg* 2014; **11**(8):D115–28. <https://doi.org/10.1080/15459624.2014.902954>.
- Coronavirus (COVID-19). Centers for Disease Prevention and Control. U.S Department of Health and Human Services. <https://www.cdc.gov/coronavirus/2019-ncov/index.html> [accessed 18 Sept 2020].
- Bai Y, Yao L, Wei T, Tian F, Jin DY, Chen L, et al. Presumed asymptomatic carrier transmission of COVID-19. *J Am Med Assoc* 2020 Feb 21. <https://doi.org/10.1001/jama.2020.2565>.
- To KKW, Tsang OTY, Leung WS, Tam AR, Wu TC, Lung DC, et al. Temporal profiles of viral load in posterior oropharyngeal saliva samples and serum antibody responses during infection by SARS-CoV-2: an observation cohort study. *Lancet* March 23, 2020. [https://doi.org/10.1016/S1473-3099\(20\)30196-1](https://doi.org/10.1016/S1473-3099(20)30196-1).
- Zhang J, Litvinova M, Wang W, Wang Y, Deng X, Chen X, et al. Evolving epidemiology and transmission dynamics of coronavirus disease 2019 outside Hubei province, China: a descriptive and modelling study. *Lancet Infect Dis* 2020; **20**(7):793–802. [https://doi.org/10.1016/S1473-3099\(20\)30230-9](https://doi.org/10.1016/S1473-3099(20)30230-9).
- COVID-19 pandemic. European centre for disease prevention and control (ECDC). <https://www.ecdc.europa.eu/en/covid-19-pandemic> [accessed 18 Sept 2020].
- Coronavirus disease 2019 (COVID-19) in Hong Kong. The Government of the Hong Kong Special Administrative Region. <https://www.coronavirus.gov.hk/eng/index.html> [accessed 18 Sept 2020].
- Zhang HH, Jin X, Nunayon SS, Lai ACK. Hydraulic performance and deposition enhancement of ultrafine particles for in-duct twisted tapes under stationary and rotating conditions. *Appl Therm Eng* 2020; **165**:114519. <https://doi.org/10.1016/j.applthermaleng.2019.114519>.
- Wang J, Tronville P. Towards standardized test methods to determine the effectiveness of filtration media against airborne nanoparticles. *J Nanoparticle Res* 2014; **16**:2417. <https://doi.org/10.1007/s11051-014-2417-z>.
- Rengasamy S, Shaffer R, Williams B, Smit S. A comparison of facemask and respirator filtration test methods. *J Occup Environ Hyg* 2017; **14**(2):92–103. <https://doi.org/10.1080/15459624.2016.1225157>. Erratum in: *J Occup Environ Hyg* 2017; **14**(4):D64.
- Recommended guidance of extended use and limited reuse of N95 filtering facepiece respirators in healthcare. Centers for Disease Control and Prevention, the U.S Department of Health and Human Services; 27 March 2020. <https://www.cdc.gov/niosh/topics/hcwcontrols/recommendedguidanceextuse.html> [accessed 18 Sept 2020].
- Cheng VCC, Wong SC, Chuang VWM, So SYC, Chen JHK, Sridhar S, et al. The role of community-wide wearing of face mask for control of coronavirus disease 2019 (COVID-19) epidemic due to SARS-CoV-2. *J Infect* 2020; **81**(1):107–14. <https://doi.org/10.1016/j.jinf.2020.04.024>.
- Chu DK, Akl EA, Duda S, Solo K, Yaacoub S, Schünemann HJ. COVID-19 Systematic Urgent Review Group Effort (SURGE) study authors. Physical distancing, face masks, and eye protection to prevent person-to-person transmission of SARS-CoV-2 and COVID-19: a systematic review and meta-analysis. *Lancet* 2020; **395**(10242):1973–87. [https://doi.org/10.1016/S0140-6736\(20\)31142-9](https://doi.org/10.1016/S0140-6736(20)31142-9).
- HKU hamster research shows masks effective in preventing Covid-19 transmission. May 18, 2020. The University of Hong Kong Fight COVID-19, <https://fightcovid19.hku.hk/hku-hamster-research-shows-masks-effective-in-preventing-covid-19-transmission/>. [Accessed 18 May 2020].
- Ma Q-X, Shan H, Zhang H-L, Li G-M, Yang R-M, Chen J-M. Potential utilities of mask-wearing and instant hand hygiene for fighting SARS-CoV-2. *J Med Virol* 2020. <https://doi.org/10.1002/jmv.25805>. 10.1002/jmv.25805.

29. Dato VM, Hostler D, Hahn ME. Simple respiratory mask. *Emerg Infect Dis* 2006;**12**(6):1033–4. <https://doi.org/10.3201/eid1206.051468>.
30. Rengasamy S, Eimer B, Shaffer RE. Simple respiratory protection—evaluation of the filtration performance of cloth masks and common fabric materials against 20–1000 nm size particles. *Ann Occup Hyg* 2010;**54**(7):789–98. <https://doi.org/10.1093/annhyg/meq044>.
31. Davies A, Thompson KA, Giri K, Kafatos G, Walker J, Bennett A. Testing the efficacy of homemade masks: would they protect in an influenza pandemic? *Disaster Med Public Health Prep* 2013;**7**(4):413–8. <https://doi.org/10.1017/dmp.2013.43>.
32. Gupta JK, Lin CH, Chen Q. Flow dynamics and characterization of a cough. *Indoor Air* 2009;**19**(6):517–25. <https://doi.org/10.1111/j.1600-0668.2009.00619.x>.
33. Lee J, Yoo D, Ryu S, Ham S, Lee K, Yeo M, et al. Quantity, size distribution, and characteristics of cough-generated aerosol produced by patients with an upper respiratory tract infection. *Aerosol Air Qual Res* 2019;**19**(4):840–53. <https://doi.org/10.4209/aaqr.2018.01.0031>.
34. Lindsley WG, Blachere FM, Thewlis RE, Vishnu A, Davis KA, Cao G, et al. Measurements of airborne influenza virus in aerosol particles from human coughs. *PLoS One* 2010;**5**(11). <https://doi.org/10.1371/journal.pone.0015100>. e15100.
35. Skaria SD, Smaldone GC. Respiratory source control using surgical masks with nanofiber media. *Ann Occup Hyg* 2014;**58**(6):771–81. <https://doi.org/10.1093/annhyg/meu023>.
36. Czech company develops “revolutionary” facemask that could help limit spread of coronavirus. Radio Prague Radio Broadcast in English, Czech Radio. 30 Jan 2020. <https://english.radio.cz/czech-company-develops-revolutionary-facemask-could-help-limit-spread-8109303> [accessed 18 Sept 2020].