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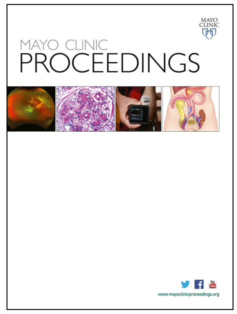

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Forgotten Technology in the COVID-19 Pandemic. Filtration Properties of Cloth and Cloth Masks: A Narrative Review

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Abstract

We searched Medline and Embase, and used Google, including articles reporting the filtration properties of flat cloth, or cloth masks. We reviewed the reference lists of relevant articles and review articles, and identified articles the press. We found 25 articles. Study of protection for the wearer often used a manikin wearing a mask, with airflow to simulate different breathing rates. Studies of protection of the environment, also known as source control, used convenience samples of healthy volunteers. The design and execution of the studies was generally rigorously described. Many descriptions of cloth lacked the detail required for reproducibility; no study gave all the expected details of material, thread count, weave, and weight. Some of the homemade mask designs were reproducible.

Successful masks were muslin at 100 threads per inch (TPI) in 3-4 layers (4-layer muslin or a muslin-flannel-muslin sandwich); tea towels (also known as dish towels), studied as one-layer, and two-layer expected to be better; and good-quality cotton T shirts in 2 layers (with a stitched edge to prevent stretching). In flat-cloth experiments, tea towel, cotton 600 TPI in two layers, and cotton 600 TPI with flannel 90 TPI, performed well, but two-layer cotton 80 TPI did not. Multiple layers should be used, at least two, and preferably three or four; however there is a trade-off in that this increases the resistance to breathing.

This is not a systematic review; however, we included all the articles that we identified in an unbiased way. We did not include grey literature or preprints.

Abbreviations

ASTM: American Society for Testing and Materials; AFNOR: Association française de normalisation; COVID-19: coronavirus disease 2019; NIOSH: National Institute for Occupational Safety and Health; PPE: personal protective equipment; RCT: randomized controlled trial; SARS-CoV-2: severe acute respiratory syndrome coronavirus 2; TPI: threads per inch, the sum of the warp plus weft thread count per inch; WHO: World Health Organisation

Introduction

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) resulting in coronavirus disease 2019 (COVID-19) has, at the time of writing, claimed at least 600,000 lives.[1] The management of this global crisis requires detailed appraisal of evidence to support clear, actionable, and consistent public health messaging. The use of cloth masks for general public use is being debated, and is in flux: in April 2020, the World Health Organisation (WHO) changed its position from 'not recommended under any circumstance'[2] to 'there is no current evidence to make a recommendation for or against their use,'[3] recognizing that, 'decision makers may be moving ahead with advising the use of non-medical masks', as was indeed occurring.[4-8] On June 5, 2020, the WHO updated its guidance further 'to advise that to prevent COVID-19 transmission effectively in areas of community transmission, governments should encourage the general public to wear masks in specific situations and settings as part of a comprehensive approach to suppress SARS-CoV-2 transmission.'[9]

In early March, the WHO estimated that 89 million masks would be needed each month, globally, for medical purposes alone,[10] highlighting the importance of directing the supply of medical masks amd respirator-type masks (e.g., N95s) to medical use. Non-medical masks will be needed for the other purposes outlined. Cloth masks potentially offer a reusable, sustainable and environmentally-friendly solution.

This review summarizes a century of evidence on the efficiency of cloth and cloth masks to reduce transmission of droplets and aerosols (**Box, supplementary table**).[11-36] We argue that this body of work should inform decisions in the context of reducing the transmissibility of COVID-19. Physical distancing, hand washing and disinfection of surfaces remain the cornerstones of policy, and we stress that we are not discussing cloth masks as a means of relaxing these interventions, or as a replacement for formal personal protective equipment (PPE) for high-risk workers.

What are the standards in this literature?

When we breathe, eat, speak, sing, cough or sneeze, particles are released into the environment. The size distribution of these particles varies with the activity, as does their velocity and their trajectory. Though technically all these particles of liquid (respiratory secretions) suspended in gas (air) are aerosols, we recognize a useful distinction between coarse particles, sometimes called droplets, which are usually defined as > 5µm aerodynamic diameter, and aerosols, which are particles of < 5 µm aerodynamic diameter. Virus particles are nanoparticles, much less than 1 µm; exhaled secretions may contain virus particles.

Filtration efficiency is the proportion of particles blocked by a filter, usually expressed as a percentage, and assessed using surrogate markers, not directly with transmissible pathogens (**figure 1, supplementary figure 1**). Some surrogates are non-biological, such as ambient particles, or aerosols of diesel combustion or saline; others are bioaerosols, usually bacterial. Filtration standards specify detail for testing of mask materials (equipment, surface area tested, air flow, particle type and size). Medical masks (also known as dental masks and surgical masks) are certified according to the standards set by the American Society for Testing and Materials (ASTM) standards.[37] Canada uses these US standards for mask materials, which define 3 levels (1-3) of mask according to particle filtration efficiency, greater than 95%, 98% and 98% for the flat material, respectively. Increasing resistance to splashing with synthetic blood further distinguishes level 2 and level 3 masks. Particle filtration efficiency of the flat mask material is assessed using latex spheres at 0.1 µm; bacterial filtration efficiency using aerosolised *Staphylococcus aureus* at a mean particle size of 3 µm.[37] The material for respirator-type masks, in North America called N95s, is certified according to standards set by the US National Institute for Occupational Safety and Health (NIOSH).[38] The relationship between particle size and filtration efficiency is not linear, with small particles having consistently lower efficiency, but U-shaped, with the lowest filtration efficiency usually around 0.3 µm, which is sometimes called the most-penetrating-particle size.[23, 38] Mask material for respirators is therefore tested at 0.3 µm, and particle filtration efficiency greater than 95% is required.[38] The US Occupational Safety and Health Administration and Canadian Standards Association standard Z94.4 further require that N95 masks be fitted to the individual who will wear them.[39, 40] Fit assesses both penetration through the mask material and leak around the mask edge. A quantitative fit testing device, the Portacount (TSI, Auburn, IL, US), measures saline particles in the 0.02 – 1 µm range, inside and outside the mask. A ratio of 100 particles outside the mask to 1 particle inside, known as a fit factor, is required: this is equivalent to filtration efficiency of 99%. A non-quantitative alternative standard is to test with a hood and a strong-tasting aerosol such as saccharin. [39] No fit testing is required for medical masks.

The diameter of SARS-CoV-2 virus has been reported as between 0.065 and 0.140 µm.[41] In contrast, the space between threads in many woven cloths are visible to the naked eye, and even in high-thread count fabric, the gaps between fibres are of the order of magnitude of 5 to 15 µm.[23] In lower thread-count fabric, gaps as large as 50 to 200 µm are expected and observed.[23, 42, 43] It is counterintuitive that cloth stops particles smaller than 5 µm; however, particles of this size encounter cloth fibres and are filtered through the three physical principles of impaction, sedimentation and diffusion.[44]

Transmission of virus is usually not as isolated virions, but in larger particles combined with respiratory secretions. Though the literature describing the size distribution of particles generated by activities such as breathing, coughing and sneezing is not completely consistent, it appears that even for the less explosive activities, a proportion of particles are >1 µm, and for coughing and sneezing, particles in the 10 µm and even 100 µm range have been observed[45] though other reports suggest peak particle size around 1 – 5 µm[46]; the reasons for these large differences between studies are not apparent. The particle size used for testing medical masks is 0.1 µm.[37] If individual particles contain more than one virion, and larger particles contain more virions than smaller particles, filtration efficiency for virions reaching the environment may exceed expectations based on testing using nano latex test particles.

Cloth is woven (crossing threads, known as warp and weft), knitted (interlocking loops of fibre) or felted (compressed disorganized fibres). Woven cloth is further described by its weave. In plain weave, fibres cross at 90 degrees. Twisted weave gives a diagonal stripe to the finish, and is known as twill weave: a common example is denim. When the warp and the weft are different numbers of threads in a given distance (conventionally, an inch), thread count may be expressed by two numbers, e.g., 20x14. Thread count expressed as a single number, threads per inch (TPI), is the sum of the warp plus weft thread count per inch. The finish may be plain or raised to fuzziness, which is called a nap. Some fabrics, called terry, have projecting loops of fibre to increase absorbance. The overall heaviness is described by its weight per surface area. Very high thread counts (>300) are usually obtained by using very thin fibre and the resulting material may be very fine (light-weight, such as some bed-linen).

Surgical gauze, plain woven cotton or linen (such as most dish-towels [US] or tea-towels [UK], i.e., flat cloths used for drying dishes), muslin and buttercloth (a cloth used for straining in the manufacture of butter), and some bed-linen, are plain-weave unnapped cloth. Flannel, commonly used for nightwear and some bed linen, is a plain-weave napped cloth, often of cotton. T-shirt material is usually knitted jersey; the proportion of cotton to man-made fibre, and the weight, varies. Terry is used for most bath and hand-towels.

Commercial disposable masks are made from non-woven synthetic fibres in bonded layers. These are unsystematically called medical masks, face masks, surgical masks, dental masks and procedure masks. We use the term medical masks.

Can fabric block coarse and fine particles?

The increasing effectiveness of multiple layers of cloth to reduce transmission was demonstrated in 1919, in a series of experiments using controlled sprays and real coughing to create bioaerosols.[34] Bacterial counts were used as the surrogate marker. Filtration efficiency increased with thread count and layers, and was consistently greater, at any given total thread count, the fewer the layers (e.g., one layer with mean thread count 42 provided greater filtration than two layers with thread count 22, total thread count 44) (**supplementary figures 2-4**). At all distances, total thread counts above ~300 TPI were associated with >80% filtration efficiency. Others confirmed these observations using similar designs[16, 19, 22, 24], one study observing that twill weave cotton was associated with 94% filtration efficiency, compared with 98 and 99% for material from two medical masks.[16]

Filtration efficiencies of 28-73% were reported for single layers of bath towel and cotton shirt tested with 2 μm bacterial particles.[18] For tea towel fabric, filtration efficiency for bacteria was 83% with one layer and 97% at two layers, compared with medical mask material at 96%.[14] For virus, one layer of tea towel had 72% efficiency, and one layer of T-shirt fabric 50%, compared with 89% for mask material.[14]

Results are dependent on the type of cloth studied. For NaCl aerosol, three commercially-available cloth masks, and single layers of scarfs, most sweatshirts, T-shirts and towel were associated with filtration efficiency of 10-40%.[29] The cloth from the mask studied in the single randomized controlled trial (RCT) was tested using a TSI filter tester, according to Australian and New Zealand standards for respirators.[26] Filtration efficiency for the cloth was 3%, compared to the medical mask, which tested at 56%. The trial is described in detail below.

Table 1 summarizes studies that use modern methodology **(supplementary figure 1A)** to test the filtration efficiency of flat cloth, organized by fabric type, and includes information on medical-mask-material and respirator-material comparators.[14, 16, 20, 21, 23, 26, 29, 35, 47] Few of these studies used standardized methodology and their results are not directly comparable. Collectively, they show that even at low thread counts and layers, and for aerosols, some kinds of cloth block substantial percentages of transmission. Filtration efficacy >50% has been observed for single layers of high-thread-count cotton, for linen and cotton tea towels, for some T shirt materials, and some towels; efficiency increases with layers, and efficiency for virus is of the same order of magnitude as that for bacteria.

An important variable is airflow; in general, other experimental conditions being constant, lower filtration efficiencies would be expected with higher airflows, though this is not consistently observed, perhaps because of random error.[23, 29] Most testing of flat materials aims to simulate breathing through a mask, sometimes at high minute ventilation to simulate exertion.[14, 21, 23, 35, 37, 38] Lower flow rates, as observed in some studies,[23] and flow rates as velocities,[29] require consideration in interpretation. Peak flow rates of 200 – 1300 L/min, and peak velocities of 29 m/s have been observed for human coughs[46]. None of the experiments that we identified on flat cloth aimed to simulate these conditions.

Does wearing a cloth mask prevent coarse and fine particles from reaching the environment (outward protection, or source control; supplementary figure 1C and D)?

In a design in which volunteers, talking or coughing, sat at a table on which agar plates were arranged, masks of 3-8 layers of buttercloth (TPI ~90), blocked 100% of bacteria at all distances.[15] Similar results were obtained by others.[27, 48]

A 3-layer 46x46 gauze mask (i.e., TPI 92 in each layer), compared with no mask, reduced bacterial counts by 64% in the zone immediately in front of healthy volunteers, who were talking.[31] In a controlled box experiment, using volunteers talking, a mask made of a sandwich of thin muslin and 4oz flannel (136 g/m^2) reduced bacteria recovered on sedimentation plates by >99%, compared with the recovery from unmasked volunteers.[17] Total airborne microorganisms were reduced by >99%, and bacteria recovered from aerosols (<4 µm) by 88-99%, compared with those recovered from unmasked volunteers. Another controlled-box experiment with talking volunteers compared 4 medical masks and one commercially produced four-layer cotton muslin (92 TPI[49]) reusable mask.[28] Filtration efficiency, assessed by bacterial counts, was 96-99% for the commercial disposable masks and 99% for the commercial 4-layer muslin mask. For aerosols (<3.3 µm) filtration efficiencies were 72-89%, and 89% respectively.

Using a pattern based on a pleated medical mask, but without assistance, volunteers made 2-layer T-shirt masks with over-the-head elastic.[14, 50] Wearing the mask they had made, volunteers coughed twice into a box: at each particle size, homemade and medical masks were similar, with 79% and 85% efficiency respectively at the smallest particle size measured, 0.65 – 1 µm, P=0.24 (**table 2**).

We identified one disconfirming report: studied using a Portacount (0.02-1 µm) on a manikin, the efficiency of a one-layer tea-towel mask in reducing aerosols reaching the environment was 17% (**table 3**).[32]

These studies show that some multilayered cloth masks can show remarkable filtration efficiency in the outward direction, reducing all particles by 64-99% and aerosols by 72-99% emitted by the wearer: for some designs comparable or better than commercial medical masks.

Does wearing a cloth mask prevent inhalation of coarse and fine particles (inward protection, or personal protection)?

Table 4 summarizes studies of cloth masks worn by volunteers or on a manikin (**supplementary figure 1B**). Three authors made personalized cloth mask from heavy-duty T-shirt material, including three sets of ties and 8 layers of material at the front.[13] Filtration efficiency, measured using a Portacount (0.02-1 µm), was 97%, 92% and 94% for the three individuals tested. (On this test, a respirator performing at 99% or above would be considered a good fit.)

In a study using healthy volunteers and a Portacount (0.02-1 µm), a 2-layer home-made T-shirt mask provided 50% inward filtration efficiency during a range of activities, compared with 80-86% from a medical mask[14, 50].

Three cloth masks and one medical mask purchased from street vendors in Kathmandu, Nepal, and two N95 masks, were tested using a manikin.[30] Test particles were polystyrene latex and diesel combustion particles. Cloth mask 1, which had a conical shape and an exhalation valve, performed as well as the two N95 masks: all three masks had ≈80% filtration efficiency for polystyrene latex particles across the range of particle sizes, from 30 nm to 2.5 µm. Cloth masks 2 and 3, simple rectangles with ear-loops, had filtration efficiency of 15-65% for 30 nm particles and 65-75% efficiency for 2.5 µm particles. For diesel particles between 30-500 nm in diameter, filtration efficiency was 25-85%, 10-70%, and 10-25% for cloth masks 1, 2, and 3 respectively; and 55-85% for the surgical mask.

Similar results, filtration efficiencies of 55 to 77%, tested with aerosols 0.2-1.0 µm, were reported for a one-layer tea towel mask (table 3).[32]

In experiments using a manikin to identify leakage around the interface between mask and face, leakage was reduced by taping, or by holding material in place with pantyhose.[12]

These studies show that one specific cloth mask performed as well as an N95 in excluding aerosols from the wearer,[30] that complex, multi-layer homemade masks can perform above 90%,[13] and that simple one-layer masks can perform similarly to medical masks.[32] The poorest-performing masks showed some inward filtration efficacy for aerosols.

Does wearing a cloth mask prevent disease in animal experiments?

In rabbits, exposed to aerosolised tubercle bacilli, tightly-fitting 3- or 6-layer 40x44 (84 TPI) gauze masks reduced the number of tubercles per rabbit from 28.5 in unmasked and 1.4 in masked, representing filtration efficacy of 95%, p=0.003 (our calculations).[25] This controlled animal experiment shows significant reduction in aerosol transmission of tuberculosis, usually considered an airborne organism, by multilayered cloth masks.

Have RCTs on the effectiveness of cloth masks in any setting been conducted?

We identified a single RCT that compared continuous wear of a cloth mask with continuous and with as-needed wear of medical masks.[26] The cloth masks used were tested on an industry-standard TSI device, according to the standards used for N95-type mask material, and were found to be unusually inefficient at 3%. Though data are not exactly comparable between studies, the observed filtration efficiency of 3% for this particular cloth mask material is the lowest we identified in any study (table 1).[13, 14, 26, 50] The medical mask comparator, assessed at 56% filtration efficiency (as flat material), performed substantially better.[37] Unsurprisingly, given these properties, continuous cloth mask use, compared with continuous medical mask use, was associated with increased incidence of influenza-like illness, relative risk (RR) 13.3 (95% CI 1.74-101). Participants in this study were healthcare workers on high-risk medical wards. The comparator groups were continuous medical mask use and medical mask use where indicated by the patient's isolation status. The use of a cloth mask continuously meant that health care workers caring for patients requiring respiratory isolation wore a cloth mask in this context instead of a medical mask. This study has been widely discussed in the press, and has not always been accurately represented. One report summarizes it as "actually increased the rate of infections among health care workers compared to those who wore surgical masks," which could be interpreted as cloth masks actually causing harm.[51] A 2015 article on this study carries the title "Cloth masks: Dangerous to your health?" and refers to "harm caused by cloth masks."[52] The study leaves us unable to draw conclusions about the efficacy or harms of wearing a cloth mask, compared with no mask, because there is no 'no mask' comparison group. What we can infer from this study, however, is that in a healthcare setting, a device with 56% filtration efficiency prevents clinical illness compared with one with 3% filtration efficiency.

There is absence of evidence, then, rather than evidence of absence, or evidence of harm, on whether cloth masks prevent transmission of clinical illness.

Does wearing a medical mask in a community context protect oneself or others?

Greenhalgh and coworkers, on 9 April 2020, identified five peer-reviewed systematic reviews on public mask wearing to prevent transmission of a wide range of respiratory pathogens, and summarized them as absence of evidence; citing the precautionary principle, the authors advocated for public mask wearing.[53] Using the framework of evidence-based medicine and the concept of risk-based decision making under uncertainty (i.e., the absence of clear clinical evidence of benefit), we supported this position.[54] Subsequently, in a meta-analysis of observational studies of risk of infection from the coronaviruses SARS-CoV-1, MERS and SARS-CoV-2, use of masks (respirators, medical masks, or 12-16 layer cloth masks) compared with no mask, was protective in both health-care settings (RR 0.30, 95% CI 0.22-0.41; I^2 50%) and non-health-care settings (RR 0.56, 95% CI 0.40-0.79; I^2 48%).[55]

Does wearing a cloth mask in a community context protect oneself or others?

The meta-analysis identified three observational studies of mask use in the community.[55] The primary studies, reports of of SARS-C0V-1 transmission in Hong Kong, Beijing, and Vietnam, did not identify the mask type used.[56-58] One of these reports includes only nine participants wearing masks.[56] In another of these reports, compared with not visiting the index case, the odds ratio (OR) for infection associated with a visit with a mask was 1.8 (95% confidence interval [CI] 0.8-4.0) for one person wearing a mask, 1.9 (0.9-4.0) for both persons wearing a mask, and 4.2 (2.4-7.3) for neither wearing a mask.[57] The third study reports OR for infection of 0.5 (0.2-0.9) for sometimes wearing a mask when going out, and 0.3 (0.2-0.5) for always wearing a mask when going out, compared with the referent of never wearing a mask when going out.[56, 58]

The meta-analysis and detailed review of the primary studies advance our understanding from 'absence of evidence' to the point where we have somewhat-consistent observational evidence of a protective effect from mask wearing in the community, with a large effect size. It is plausible that masks protect people and there is coherence between the data on community mask wearing and mask wearing in health care.[59] However, the evidence is somewhat indirect: SARS-CoV-1 transmission may differ from SARS-CoV-2. RCTs have not been conducted.

Symptomatic people should follow public health guidance and self-isolate. The point of community mask wearing is to prevent presymptomatic and asymptomatic transmission. Though asymptomatic transmission undoubtedly occurs,[60-63] the proportion of transmission that occurs from asymptomatic individuals is the subject of controversy.[64, 65] However, evidence from transmission pairs suggests that in individuals who will eventually develop symptoms, peak infectivity may occur before the onset of symptoms, and that the highest levels of viral shdding may occur in a period 2-3 days before the appearance of symptoms and 1 day after.[66] Data on viral load in the days after symptom onset are congruent with this,[67] and presymptomatic transmission has been documented.[63, 68] Modeling studies show that facemask use depresses the effective basic reproductive rate over a range of plausible values for mask use and cloth mask effectiveness, and that in conjunction with periods of lockdown, even 50% adherence to a 50% effective cloth mask dramatically alters the total numbers affected.[69]

What materials and designs should be used? An evidence-informed cloth mask.

A pleated mask design based on the common pleated design for ASTM level 1 masks results in a mask with subjectively good fit that is relatively simple to make. Paper fasteners, florists' or electricians' wire, or pipecleaner can be inserted across the top to improve fit at the nose. Though data are not available that conform with any modern standard method, from the studies available, cotton, muslin (a type of unfinished cotton), and flannel are the best supported and are our suggestions for an evidence-informed cloth mask. Successful masks have used muslin at TPI of ~100 in 3-4 layers (4-layer muslin[28] or a muslin-flannel-muslin sandwich[17]), tea towels (also known as dish towels), studied as one-layer,[14, 32, 50, 70] and two-layer expected to be better,[12, 14, 15, 18-24, 27, 34] and good-quality cotton T shirts in 2 layers[14, 47, 50]; in flat-cloth experiments cotton 600 TPI in two layers,[23] or cotton 600 TPI with flannel 90 TPI,[23] performed well. (Two-layer cotton 80 TPI did not perform well.[23]) Multiple layers should be used, at least two, and preferably three or four. With fabric that stretches, such as T shirt fabric, it may be important to use a design with edge stitching to prevent transmission of tension to the cloth, which will increase the size of gaps in the material and affect filtration. There is a trade-off with increased layers: they provide increased filtration efficiency, but also increase the resistance to breathing, which increases the work of breathing, and may lead to discomfort and even to reduced adherence. Increased resistance with increased layers also leads to increased edge leak, decreasing the efficiency of the mask. People making masks for sale should specify the materials (composition, weave, weight, thread count) for each layer and the number of layers (e.g., cotton 100%, plain weave, 150 g/m^2, 300 TPI; 3 layers). People making their own masks or choosing a mask should consider these same factors, and also their planned activities while wearing a mask. It might be sensible, for example, to choose a higher number of layers for quietly sitting at a desk in a shared workspace for the duration of a working day, than for grocery shopping in a ventilated environment with physical distancing. WHO guidance, 5 June 2020,[9] based on expert opinion, recommends a three-layer mask, the outer layer and middle layers hydrophobic (e.g., polypropylene, polyester and their blends) and the inner layer hydrophilic (e.g., cotton or cotton blends).

Our recommendations for materials, above, are the same if using a bandana or scarf-type design, though we would anticipate that this would be less efficient. Optimally, this will include a prefolded shape, and a clear differentiation of outside and inside, such as this multi-layered suggestion.[71] Evidence on household filters is limited. The one included study of tissue paper and paper towel did not report high efficiencies[35]: we think a third or fourth layer of cloth is preferable to a disposable filter.

The information above, intended for the general public and for mask manufacturers, on materials, designs, and correct use, can be found at clothmasks.ca. We will update this site as new information is published.

What are the research priorities? An evidence-based cloth mask.

Reproducibly-described cloth and cloth masks should be tested in aerosol laboratories. The effects of activity, time, and moisture[18, 24] on effectiveness should be studied. The trade-off between increased protection on the one hand, and decreased tolerability and increased leak on the other, with higher thread counts and additional layers, should be explicitly explored.[72] Women, children, and people who wear glasses require special consideration. Optimal methods of laundering (home and industrial) and the effect of laundering on mask properties should be studied.

Human trials should focus on best-performing cloth masks, should include healthcare workers, other essential workers, and clients of essential services who can tolerate mask wearing, and should study both inward and outward protection. Considerations are multi-faceted educational interventions, measures of unintended consequences (e.g., incorrect mask use; complacency about physical distancing and hand hygiene; mitigation of effects on people who do not hear well); and address the impact of adherence on outcomes.

If reproducible designs of cloth mask that meet ASTM standards can be identified, this will have direct and immediate impact in low- and middle-income countries. Widespread adoption in any setting, including high-income countries, of reusable evidence-based cloth masks that meet the standards of PPE would reduce the environmental impact of PPE, and mitigate supply problems in this and future pandemics.

Standards for cloth masks have been developed in by the French standardization association, Association française de normalisation (AFNOR): testing flat cloth using 3 µm particles, 70-<90% filtration efficiency is designated category 2 (for use by the general public in a group of mask-wearers) and 90-<95% category 1 (for use by non-health-care professionals, e.g., police, in contact with the public).[73-75] At the time of writing, a database of >1200 tested mask-material combinations (many of them including non-woven synthetic materials such spunbond and meltbond, that are used in formal PPE) has been compiled.[75, 76]

Businesses and academics in textiles, design and fashion are critical in embracing evolving information on evidence-informed and evidence-based masks, and in using their specific knowledge and skills to create a variety of masks that are not only functional, but comfortable and stylish, to maximize the acceptability of mask wearing, particularly for young people.

Conclusions

Cloth masks can offer substantial filtration, in some cases equivalent to some medical masks. This knowledge on hand can be used to create evidence-informed cloth masks to mitigate transmissibility of viruses such as COVID-19. Aerosol laboratory testing of these masks may lead to the design of evidence-based cloth masks, reproducibly-described so as to be manufactured in diverse settings. No direct data with clinically-important outcomes are available.

Advocating for the public to wear cloth masks shifts the cost of a public health intervention from society to the individual. In low-resource areas and for people living in poverty this may be unacceptable and could be mitigated by public health interventions, with local manufacture and distribution of evidence-informed and evidence-based cloth masks.

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Author contributions

The concept for the manuscript originated with C.M.C., M.J.J., J.F.E.M., R.P-F, W.C.W. and J.J.C.; C.M.C. and E.L.F. performed the original literature review; and C.M.C. wrote the first draft. E.L.F., A.A., I.A.C., G.K., and M.J. reviewed citations and performed data extraction; J.J.C. and E.L.F. collated discrepancies, and with C.M.C., resolved them by consensus. E.L.F. performed statistical analysis on reported data, and created graphs and tables. M.B.D. provided input on aerosol science and R.C.L.B. on virology and relevance to COVID-19. All authors contributed references and important revisions of content and meaning. C.M.C. is the guarantor for the work.

Disclosures

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Box

We searched Medline and Embase, and used Google, using search terms 'cloth', 'fabric', 'gauze', 'cotton', 'mask' and 'filtration' and synonyms for articles on the filtration properties of flat cloth or cloth masks or face coverings. We reviewed the reference lists of relevant articles and review articles to identify further articles. Our selection of articles for this review was unbiased; i.e., it did not depend on the direction of the results. We did not conduct a systematic review or search grey literature. We identified 25 articles that described filtration properties of cloth or cloth masks, some of which included medical masks and N95 respirators as comparators. Most studies used surrogates for filtration, sometimes graded by particle size. Some studies used bioaerosols, usually bacterial. A minority of papers used virus; one study used SARS-CoV2. Studies of the filtration properties of flat cloth used a variety of methods, few of which were the equivalent to the standard methods used by the American Society for Testing and Materials. Study of protection for the wearer often used a manikin wearing a mask, with airflow to simulate different breathing rates. Studies of protection of the environment, also known as source control, used convenience samples of healthy volunteers, often the investigators themselves; the volunteers are rarely characterized in any way. The design and execution of the studies was generally rigorously described; the number of replicates and variance of estimates less well described, and it was unusual to find statistical comparisons between different types of cloth or types of mask. Many descriptions of cloth were lacking in the detail required for reproducibility; no study gave all the expected details of material, thread count, weave, and weight. Some of the homemade mask designs were reproducible.

Table 1. Summary of filtration efficiency for flat cloth, including details of methodology: aerosol used, aerosol size and flow rate.

Composition	Weight, Weave, Thread Count	1 layer	2 layer	Aerosol	Measured Aerosol Size	Flow rate (L/min)	Standard	
Cotton								
'Quilters' cotton'	80 TPI	4%	32%	NaCl solution	75-100 nm	~ 3.5‡	No	Konda 2020[23, 36]
	80 TPI	3%		NaCl solution	75-100 nm	~ 9‡	No	Konda 2020
	80 TPI	6%	50%	NaCl solution	2-3 µm	~ 3.5‡	No	Konda 2020
	80 TPI	34%		NaCl solution	2-3 µm	~ 9‡	No	Konda 2020
Cotton 600 TPI (#1 in hybrids, below)	600 TPI	76%	85%	NaCl solution	75-100 nm	~ 3.5‡	No	Konda 2020
	600 TPI	98%	99.5%	NaCl solution	2-3 µm	~ 3.5‡	No	Konda 2020
Gauze, cotton	NA	1%	1% 4 layer 4%	NaCl solution	75 nm§	85	NIOSH	Jung 2014[21]
T shirt: 100% cotton	Knit	69%	71%	*B atrophaeus*	NA	30	No	Davies 2013[14]
	Knit	51%		*Bacteriophage MS2*	NA	30	No	Davies 2013
T shirt, Hanes: 100% cotton	Knit	9%		NaCl solution	1 µm	5.5 cm/s	No	Rengasamy 2010[29]
		12%		NaCl solution	1 µm	17 cm/s	No	Rengasamy 2010
T shirt, cotton	Knit 157 g/m^2	22%		NaCl solution	75 nm§	32	No	Zhao 2020[35]
Sweater, cotton	Knit 360 g/m^2	26%		NaCl solution	75 nm§	32	No	Zhao 2020
Towel, Pem America: 100% cotton	NA	23%		NaCl solution	1 µm	5.5 cm/s	No	Rengasamy 2010[29]
		49%		NaCl solution	1 µm	17 cm/s	No	Rengasamy 2010
Towel, Pinzon: 100% cotton	NA	30%		NaCl solution	1 µm	5.5 cm/s	No	Rengasamy 2010
		58%		NaCl solution	1 µm	17 cm/s	No	Rengasamy 2010
Towel, Aquis: 100% cotton	NA	33%		NaCl solution	1 µm	5.5 cm/s	No	Rengasamy 2010
		0%		NaCl solution	1 µm	17 cm/s	No	Rengasamy 2010
Scarf: cotton	NA	62%	71%	*B atrophaeus*	NA	30	No	Davies 2013[14]
	NA	49%		*Bacteriophage MS2*	NA	30	No	Davies 2013
Scarf, Pocket Square: 100% cotton	NA	0%		NaCl solution	1 µm	5.5 cm/s	No	Rengasamy 2010[29]
		0%		NaCl solution	1 µm	17 cm/s	No	Rengasamy 2010

Scarf, Seed Supply: 100% cotton	NA	1%		NaCl solution	1 µm	5.5 cm/s	No	Rengasamy 2010
		7%		NaCl solution	1 µm	17 cm/s	No	Rengasamy 2010
Pillowcase	NA	61%	62%	*B atrophaeus*	NA	30	No	Davies 2013[14]
	NA	57%		*Bacteriophage MS2*	NA	30	No	Davies 2013
Pillowcase: 100% cotton	116 g/m[2]	5%		NaCl solution	75 nm[§]	32	No	Zhao 2020[35]
Handkerchief, cotton	NA	1%	2% 4 layer 4%	NaCl solution	75 nm[§]	85	NIOSH	Jung 2014[21]
Linen								
Tea towel	NA	83%	97%	*B atrophaeus*	NA	30	No	Davies 2013[14]
	NA	72%		*Bacteriophage MS2*	NA	30	No	Davies 2013
Linen	NA	60%		*B atrophaeus*	NA	30	No	Davies 2013
	NA	62%		*Bacteriophage MS2*	NA	30	No	Davies 2013
Silk								
Silk	NA	58%		*B atrophaeus*	NA	30	No	Davies 2013
	NA	54%		*Bacteriophage MS2*	NA	30	No	Davies 2013
Silk 100% (#2 in hybrids, below)	39 g/m[2] 145 TPI[†]	54%	65% 4 layers: 84%	NaCl solution	75-100 nm	~ 3.5[‡]	No	Konda 2020[23]
	39 g/m2 145 TPI[†]	55%	66% 4 layers: 89%	NaCl solution	2-3 µm	~ 3.5[‡]	No	Konda 2020
Napkin: Silk	Woven 84 g/m[2]	5%		NaCl solution	75 nm[§]	32	No	Zhao 2020[35]
Manmade								
Chiffon: 90% polyester, 10% spandex (#3 in hybrids, below)	195 TPI[†]	58%	86%	NaCl solution	75-100 nm	~ 3.5[‡]	No	Konda 2020[23]
	195 TPI[†]	24%		NaCl solution	75-100 nm	~ 9[‡]	No	Konda 2020
	195 TPI[†]	73%	90%	NaCl solution	2-3 µm	~ 3.5[‡]	No	Konda 2020
	195 TPI[†]	53%		NaCl solution	2-3 µm	~ 9[‡]	No	Konda 2020
Interfacing material: polypropylene	Spunbond 30 g/m[2]	6%		NaCl solution	75 nm§	32	No	Zhao 2020
Scarf, Walmart Fleece: 100% polyester	NA	25%		NaCl solution	1 µm	5.5 cm/s	No	Rengasamy 2010[29]
		14%		NaCl solution	1 µm	17 cm/s	No	Rengasamy 2010
Toddler wrap: polyester	Knit 200 g/m[2]	18%		NaCl solution	75 nm[§]	32	No	Zhao 2020[35]
Exercise pants: nylon	Woven	23%		NaCl solution	75 nm[§]	32	No	Zhao 2020

	164 g/m^2							
Composites								
Cotton mix	NA	75%		*B atrophaeus*	NA	30	No	Davies 2013[14]
	NA	70%		*Bacteriophage MS2*	NA	30	No	Davies 2013
Flannel: 65% cotton, 35% polyester (#4 in hybrids, below)	90 TPI[†]	55%		NaCl solution	75-100 nm	~ 3.5[‡]	No	Konda 2020[23]
	90 TPI[†]	13%		NaCl solution	75-100 nm	~ 9[‡]	No	Konda 2020
	90 TPI[†]	44%		NaCl solution	2-3 µm	~ 3.5[‡]	No	Konda 2020
	90 TPI[†]	46%		NaCl solution	2-3 µm	~ 9[‡]	No	Konda 2020
Norma Kamali sweatshirt: 85% cotton, 15% polyester	NA	8%		NaCl solution	1 µm	5.5 cm/s	No	Rengasamy 2010[29]
	NA	26%		NaCl solution	1 µm	17 cm/s	No	Rengasamy 2010
Hanes sweatshirt: 70% cotton, 30% polyester	NA	19%		NaCl solution	1 µm	5.5 cm/s	No	Rengasamy 2010
	NA	15%		NaCl solution	1 µm	17 cm/s	No	Rengasamy 2010
Faded Glory sweatshirt: 60% cotton, 40% polyester	NA	6%		NaCl solution	1 µm	5.5 cm/s	No	Rengasamy 2010
	NA	12%		NaCl solution	1 µm	17 cm/s	No	Rengasamy 2010
Dickies T shirt: 99% cotton, 1% polyester	NA	8%		NaCl solution	1 µm	5.5 cm/s	No	Rengasamy 2010
	NA	20%		NaCl solution	1 µm	17 cm/s	No	Rengasamy 2010
Faded Glory T shirt: 60% cotton, 40% polyester	NA	0%		NaCl solution	1 µm	5.5 cm/s	No	Rengasamy 2010
	NA	15%		NaCl solution	1 µm	17 cm/s	No	Rengasamy 2010
Paper								
Paper towel: cellulose	Bonded 43 g/m^2	10%		NaCl solution	75 nm[§]	32	No	Zhao 2020[35]
Tissue paper: cellulose	Bonded 33 g/m2	20%		NaCl solution	75 nm[§]	32	No	Zhao 2020
Copy paper: cellulose[*]	Bonded 73 g/m2	99.9%		NaCl solution	75 nm[§]	32	No	Zhao 2020
Hybrids								
Cotton/Silk (1 layer of #1 above[**], 1 layer of #2 above)		96%		NaCl solution	75-100 nm	~ 3.5[‡]	No	Konda 2020[23]
		97%		NaCl solution	2-3 µm	~ 3.5[‡]	No	Konda 2020
Cotton/Chiffon (1 layer of #1 above[**], 1 layer of #3 above)		97%		NaCl solution	75-100 nm	~ 3.5[‡]	No	Konda 2020
		99.5%		NaCl solution	2-3 µm	~ 3.5[‡]	No	Konda 2020
Cotton/Flannel (1 layer of #1 above[**], 1 layer of #4 above)		95%		NaCl solution	75-100 nm	~ 3.5[‡]	No	Konda 2020
		96%		NaCl solution	2-3 µm	~ 3.5[‡]	No	Konda 2020
Cloth mask material								
Commercial mask fabric A, bleached cotton	96 TPI	69%		*Staph aureus*	NA	8	US military standard,	Furuhashi 1978[16]

							1978	
Commercial mask fabric D, bleached cotton	86 TPI	43%		*Staph aureus*	NA	8	US military standard, 1978	Furuhashi 1978
Commercial mask fabric B, calico	160 TPI	73%		*Staph aureus*	NA	8	US military standard, 1978	Furuhashi 1978
Commercial mask fabric C, twill weave	NA	94%		*Staph aureus*	NA	8	US military standard, 1978	Furuhashi 1978
Cloth mask A: 50% nylon, 40% polypropylene, 10% polyurethane	1.22 mm thick	29%	59%, 4 layer 75%	NaCl solution	0.3-0.5 µm	NA	No	Jang 2015[20]
	1.22 mm thick	60%	70%, 4 layer 94%	NaCl solution	2-5 µm	NA	No	Jang 2015
Cloth mask B: 84% nylon, 12% polyester, 4% spandex	0.62 mm thick	28%	32% 4 layer 67%	NaCl solution	0.3-0.5 µm	NA	No	Jang 2015
	0.62 mm thick	63%	71% 4 layer 77%	NaCl solution	2-5 µm	NA	No	Jang 2015
Cloth mask C: 100% polyester	0.29 mm thick	18%	50%, 4 layer 55%	NaCl solution	0.3-0.5 µm	NA	No	Jang 2015
	0.29 mm thick	45%	78%, 4 layer 81%	NaCl solution	2-5 µm	NA	No	Jang 2015
Cloth mask D: 100% polyester microfibre	0.30 mm thick	9%	45% 4 layer 62%	NaCl solution	0.3-0.5 µm	NA	No	Jang 2015
	0.30 mm thick	45%	59% 4 layer 99%	NaCl solution	2-5 µm	NA	No	Jang 2015

Cloth mask E: 100% polyester microfibre	2.77 mm thick	27%		NaCl solution	0.3-0.5 µm	NA	No	Jang 2015
	2.77 mm thick	80%		NaCl solution	2-5 µm	NA	No	Jang 2015
Cotton mask: surgical type, 4 distinct masks	NA	23% SD 27		NaCl solution	75 nm[§]	85	NIOSH	Jung 2014
Cloth mask	NA	3%		NaCl solution	75 nm[§]	NA	AS/ NZS1716	MacIntyre 2015[26]
Respro Bandit	NA	22%		NaCl solution	1 µm	5.5 cm/s	No	Rengasamy 2010[29]
	NA	34%		NaCl solution	1 µm	17 cm/s	No	Rengasamy 2010
Breath Health	NA	13%		NaCl solution	1 µm	5.5 cm/s	No	Rengasamy 2010
	NA	44%		NaCl solution	1 µm	17 cm/s	No	Rengasamy 2010
Breath Health Fleece	NA	22%		NaCl solution	1 µm	5.5 cm/s	No	Rengasamy 2010
	NA	13%		NaCl solution	1 µm	17 cm/s	No	Rengasamy 2010
Medical mask material								
Mölnlycke Health Care Barrier 4239		96%		*B atrophaeus*	NA	30	No	Davies 2013[14]
		90%		*Bacteriophage MS2*	NA	30	No	Davies 2013
Hopes	Fine glass fiber with non-woven fabric	98%		*Staph aureus*	NA	8	"US military standard" 1978	Furuhashi 1978[16]
Medispo	Fine glass fiber with non-woven fabric	99%		*Staph aureus*	NA	8	"US military standard" 1978	Furuhashi 1978
Medical mask material	NA	56%		NaCl solution	75 nm[§]		AS/NZS1716	MacIntyre 2015[26]
R class respirator material	1.81 mm thick	91%		NaCl solution	0.3-0.5 µm	NA	No	Jang 2015[20]
		100%		NaCl solution	2-5 µm	NA	No	Jang 2015
Medical mask: surgical type, 4 distinct masks	NA	41% SD 38		NaCl solution	75 nm[§]	85	NIOSH	Jung 2014[21]
Medical mask: dental type, 5 distinct masks	NA	71% SD 12		NaCl solution	75 nm[§]	85	NIOSH	Jung 2014

For experimental details and additional studies, see supplementary table

We extracted information on weight, weave, thread count and thickness for each material when available.

NA not available; TPI threads per inch (number of threads in warp plus number of threads in weft); SD standard deviation

§TSI filter tester generates NaCl aerosol with count mean diameter 75 nm and geometric standard deviation 1.75

* this is writing paper, and obviously not breathable

** The 600 TPI cotton was used in the hybrid experiments (personal communication, Supratik Guha)

†calculated from pitch, the distance between the centre of one thread and the next

‡Konda et al[23] measured cloth using a system that produced initial flow rates of 35 L/min and 90 L/min respectively; however, when cloth was inserted, increasing the resistance, the flow rate fell, probably by an order of magnitude (personal communication, Supratik Guha), and erratum.[36] We have reflected this by reporting a flow rate that is the initial divided by 10, and by indicating that it is approximate (~); we thought this preferable to giving no indication. The experiments in this paper include some readings done with a gap past the filter, to simulate edge leak. We have extracted these data in the supplementary material but here present the results of flat cloth with no gap.

When multiple data points were available, we extracted data closest to 100 nm (used for testing particle filtration efficiency for medical masks, according to ASTM standards) and 3000 nm (3 µm) (used for testing bioaerosol filtration efficiency for medical masks, according to ASTM standards). To be conservative, we selected the closest point below the target particle size.

Many original papers provided a measure of error variance. We have not extracted these data to this table for readability. They are often wide, in the 10 – 30% range. We report the SD for Jung et al 2014 because it reflects the differences in properties of a number of distinct masks of different materials (4 surgical, 3 dental and 5 cotton; tested in triplicate for each design) that are not reported separately, not the error variance of a single mask.

We did not extract data for N95 mask material and medical mask material from Konda et al,[23] because the methodology used for testing fabric by them were under conditions different than are those used for specifying fitted protective equipment such as the N95 respirators, which are tested under higher differential pressures and flows (personal communication, Supratik Guha).

Table 2. Filtration efficiency for homemade 2-layer T shirt, and disposable commercial medical masks according to particle diameter from 21 volunteers coughing, recalculated from Davies and colleagues[14]; P values are our calculations, difference between two proportions, using R (R foundation, Vienna, Austria).

Particle Diameter (µm)	2-layer T Shirt Mask	Medical Mask	P
>7	67%	44%	0.14
4.7-7	61%	61%	1.00
3.3-4.7	20%	20%	1.00
2.1-3.3	85%	89%	0.70
1.1-2.1	84%	94%	0.31
0.65-1.1	71%	86%	0.24
Total	**79%**	**85%**	**0.62**

Bacterial filtration efficiency was calculated as (*Bacterial counts without mask - Bacterial counts with mask*)/*Bacterial counts without mask*.

Table 3. Protection factor and filtration efficiency for homemade and medical masks according to particle diameter from 28 volunteers (inward, immediate), 22 volunteers (inward, after 3 hours), and data from a manikin wearing a mask (outward), recalculated from van der Sande and colleagues.[32]

	Filtration efficiency		
	Inward		Outward
	Immediate	After 3 hours	Immediate
1-layer Tea-Towel Mask	55 – 69%	63 - 77%	17%
Medical Mask	76 – 81%	74 – 83%	58%

Filtration efficiency is calculated as *1- (1/Protection factor).* Both adults and children were studied in short term, with somewhat lower performance in children; we have extracted the adult data for consistency with the rest of the literature. For each experimental condition, we have extracted the highest and lowest median efficiencies from the data provided. Outward data were read from graphs. Because medians were reported, statistical testing was not possible.

Table 4. Summary of filtration efficiency for cloth masks, inward protection (protecting the wearer), assessed at < 1µm particle size. From the paper by Shakya and colleagues, we excluded cloth mask 1 because it had an exhalation valve that may have improved its performance; we included the latex particle data because they are comparable with other experiments, but not the data obtained with diesel combustion particles. (These data are shown in the supplementary table.) When a medical mask was included as a comparator, we have also shown the data for the medical mask.

First Author, Year	Cloth Mask Detailed Description	Testing	Device and Particle Size	Details	Cloth Mask Filtration Efficiency		Medical Mask Filtration Efficiency	
Dato 2006[13]	T-shirt mask made by the authors to fit their own faces; 8-layer high quality preshrunk cotton T-shirt fabric (Hanes Heavweight T-shirt) with 3 sets of ties	The authors as volunteers	Portacount 0.02-1 µm	Author 1	99%			
				Author 2	92%			
				Author 3	94%			
					Cloth Mask		Medical Mask	
					Initial	After the other exercises	Initial	After the other exercises
Davies 2013[14]	T-shirt mask by unskilled volunteers, to a pattern, without assistance; 2-layer T-shirt fabric, pleated design	Volunteers	Portacount 0.02-1 µm	Normal breathing	50%	50%	83%	80%
				Heavy breathing	50%		86%	
				Shaking head	50%		80%	
				Nodding	50%		80%	
				Bending over	0%		67%	
				Talking	50%		83%	
				Overall	50%		80%	
					Cloth Mask Flow rate		Medical Mask Flow rate	
					8L/min	19L/min	8L/min	19L/min
Shakya 2017[30]	Purchased from street vendor, Kathmandu Nepal in 2014; simple cloth rectangles (layers unknown) with ear loop,	Manikin	Particle counter 30 nm	Cloth mask 2	89%	15%	91%	62%
				Cloth mask 3	54%	26%		
			100 nm	Cloth mask 2	57%	32%	94%	70%
				Cloth mask 3	57%	27%		
			500 nm	Cloth mask 2	47%	57%	92%	65%
				Cloth mask	45%	31%		

	cloth not specified			3				
			1 µm	Cloth mask 2	69%	54%	99%	96%
				Cloth mask 3	85%	49%		
					Cloth Mask		Medical Mask	
					Short term	After 3 hours	Short term	After 3 hours
Van der Sande 2008[32]	Cloth mask, homemade, made of TD Cerise Multi teacloths (tea-towel), Blokker; one layer mask	Volunteers	Portacount 0.02-1 µm	Sitting quietly	60%	69%	76%	77%
				Nodding	55%	63%	79%	78%
				Shaking head	55%	66%	80%	76%
				Reading	69%	77%	81%	83%
				Walking	58%	66%	76%	74%

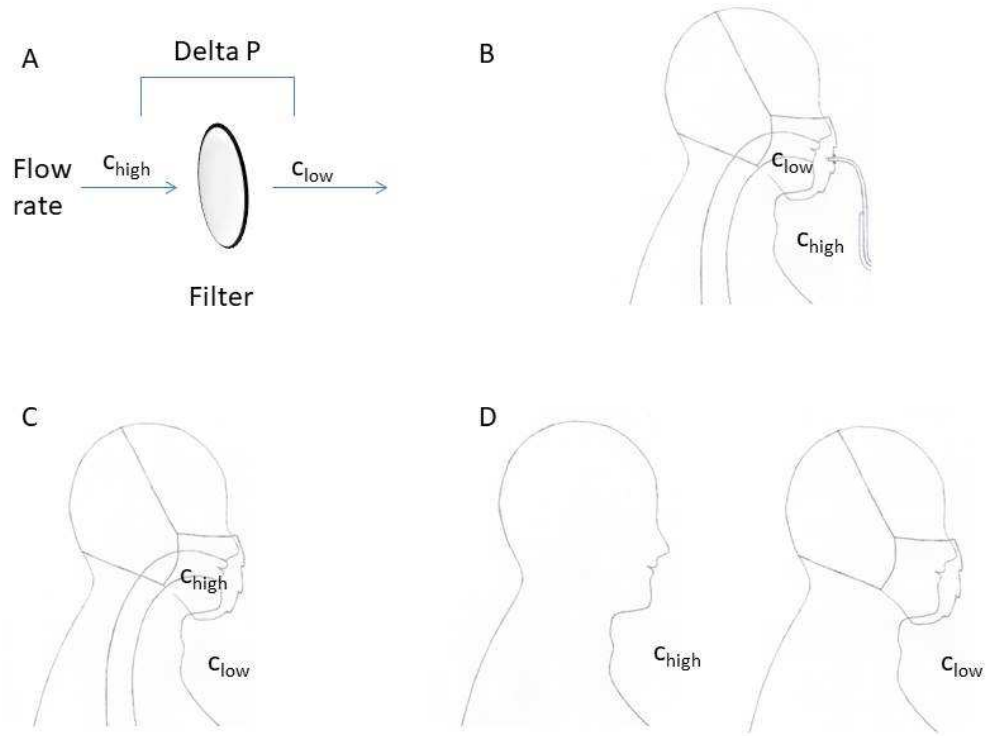
Figure 1. Schematic showing different types of filtration experiments.

A: an experiment on a flat cloth sample or mask material sample (the filter). The surface area of the sample tested, the particle size, particle composition and the flow rate should be defined. The pressure drop across the filter under these or other, specified, conditions can be measured. There is no edge leak. All the particles that contribute to the concentration on the protected side of the filter have penetrated the material. The TSI 8130 filter tester (TSI, Auburn, IL, US) is an example of such a system. Using this type of experiment, the American Society for Testing and Materials (ASTM) defines the standards for testing material for medical masks, and the National Institute for Occupational Safety and Health (NIOSH) the standards for testing material for respirators (N95-type masks).

B: an inward protection experiment on a mask using a human volunteer or a manikin. For human volunteers, the concentration inside the mask is measured using a thin-walled tube, called a probe, that fits across the mask material. For a manikin, a pump will simulate breathing and the concentration inside the mask can be measured at any point in the circuit. The concentration outside the mask is measured from the surrounding air. The TSI Portacount (TSI, Auburn, IL, US) is an example of such a system, and can be used with human volunteers or with a manikin. When the particles to be measured are inert and harmless, such as the saline aerosol typically used with the Portacount, the experiment can be conducted in an ordinary room without special conditions. The concentration of particles on the protected side (the inside) is a combination of penetration of the mask (through the material) and edge leak (around the material); it measures both the material and the fit. In experiments using human volunteers, a variety of activities can be undertaken to further challenge the mask (e.g., deep breathing, head movement, bending). In experiments using manikins, the flow rate can be adjusted to simulate different levels of minute respiration, corresponding to different activity levels. For medical masks, no relevant standards have been defined. For respirators (N95-type masks), the Occupational Safety and Health Administration requires that N95 masks be fitted to the individual who will wear them. This can be done quantitatively using a device such as the Portacount, or non-quantitatively, using a strong-tasting substance such as saccharin.

C: an outward protection experiment on a mask using a manikin. The aerosol is generated and passed through the manikin into the mask. The concentration of the aerosol on the source side can be measured at any point in the circuit. The concentration of the aerosol on the protected side is measured from the environment. The apparatus is protected in a chamber filled with filtered air, to ensure that all particles outside the mask have come from the manikin. The concentration of particles on the protected side (the outside) is a combination of penetration of the mask (through the material) and edge leak (around the material). There are no standards that relate to this design.

D: an outward protection experiment using human volunteers. The aerosol is generated through human activity – breathing, talking, or coughing. Usually these are bioaerosol experiments, measuring normal human mouth flora, or pathogens from volunteers who are unwell. (In some experiments, to standardize the experiment and to increase the concentration of bacteria in the aerosol, volunteer-investigators contaminated their mouths with non-pathogenic bacteria and studied transmission specifically of that species.) There are no standards that relate to this design.



c_{high} particle concentration on the source side of the filter; c_{low} particle concentration on the protected side of the filter; Delta P pressure drop across the filter