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Review of the Breathability and Filtration Efficiency of Common Household Materials for Face Masks

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Abstract

The World Health Organization and the U.S. Centers for Disease Control have recommended universal face masking by the general public to slow the spread of COVID-19. A number of recent studies have evaluated the filtration efficiency and pressure differential (an indicator of breathability) of various, widely available materials that the general public can use to make face masks at home. In this manuscript, we summarize those studies to provide guidance for both the public to select the best materials for face masks and for future researchers to rigorously evaluate and report on mask material testing. Of the tested fabric materials and material combinations with adequate breathability, most single and multi-layer combinations had a filtration efficiency of less than 30%. Most studies evaluating commonly available mask materials did not follow standard methods that would facilitate comparison across studies, and materials were often described with too few details to allow consumers to purchase equivalent materials to make their own masks. To improve the usability of future study results, researchers should use standard methods and report material characteristics in detail.

Graphical Abstract

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Supporting Information
The supporting information is available free of charge at [website].
Terms used for combining measurements of pressure differential and filtration efficiency; effect of face velocity and layers on pressure differential; detailed summaries of studies that assessed the penetration of bacteria and other non-standard particles.

Vocabulary

Face velocity: The volumetric flow per unit area or flow velocity; common units are cm/s or m/s.

Filtration efficiency: The proportion of particles filtered by the evaluated material. The filtration efficiency of a fabric or filter is determined by challenging the material with particles carried in air moving at a specific velocity.

Breathability: The ease of breathing through a material. Breathability is typically measured by the pressure differential (also called "pressure drop") between the two sides of a mask as air flows through it at a rate similar to that during breathing and should be tested at a specified face velocity perpendicular to the plane of the tested material or at a specific flow rate across a specified material surface area.

Non-woven material: Material made from short, staple fibers and long fibers that are bonded together by chemical, mechanical, heat or solvent treatment (rather than knit or woven together).

Darcy's Law: The difference between the pressure on the upstream side of a porous material (the side that is first impacted by particles in the flow) and the pressure on the downstream side (the reverse side) is proportional to the face velocity of air through the material.

Keywords

face mask; cloth mask; homemade mask; filtration efficiency; breathability; pressure differential; COVID-19; SARS-CoV-2

The COVID-19 pandemic has led the U.S. CDC to recommend universal face masking among the general public.[1] Limited supplies of surgical masks and N95 filtering facepiece respirators are prioritized for healthcare workers, and the general public has been advised to wear homemade or purchased cloth face coverings. Many materials can block large droplets, and a recent meta-analysis indicates that mask-wearing is effective at reducing transmission rates for SARS-CoV-2.[2] Beyond reduction in droplet-based transmission, a second concern is the ability of cloth masks to filter smaller droplets and aerosols. A mask's ability to protect against aerosols is dependent on both the choice of mask fabric and the mask's design – specifically how well it fits the wearer's face. A number of recent published and pre-print studies have evaluated the filtration efficiency and differential pressure (an indicator of breathability) of various materials. In this report, we provide a synthesis of those studies with the goal to recommend specific materials that can be used to make masks at home and to provide guidance for future research.

A major limitation of the studies that evaluated common household materials for face masks was that the materials tested were often not specified with adequate detail to evaluate the experimental results. This lack of detail prevents not only further sourcing of the tested materials but also the replication of the experiments. For example, we found that a number of materials were referred to as "cotton T-shirt", yet the fabrics used for cotton t-shirts have a wide range of thread counts, densities, and textures. The lack of characterization of the material also limits opportunities to understand which material properties are most important for filtration and/or breathability or to extrapolate from materials used in published results to similar materials that may be widely available.

To enable experiment replicability, fabric characterization could include, at a minimum, the composition of materials (*e.g.*, 100% cotton), weight (grams per square meter), production technique (woven, knit, or non-woven) and if applicable, threads per inch. Additional details on thread thickness would also be beneficial to ensure that appropriate comparisons are made. Since it is not fully understood which material properties most affect filtration efficiency and pressure differentials, there may be additional fabric characteristics that are important to report to ensure that experiments can be repeated and experimental results can be effectively utilized.

Our ability to recommend specific materials was also limited by various filtration efficiency measurement methodologies employed. Methods used to assess the filtration efficiency of common materials vary widely in key parameters, including the type of particles used to assess efficiency and the volumetric flow of air per unit area mask (also called "face velocity" and "flow velocity"). Recent papers have often failed to report the details of measurement techniques, such as face velocity or the area of the material under test, which are needed to compare against other studies. Moreover, without better understanding of the expected relationship between face velocity and pressure differential or filtration efficiency, it is a challenge to compare one study to another.

In addition to the material used to make a mask, the efficacy of a face mask depends on how well the mask fits on the face and prevents leakage. Mask fit is an active topic of research and beyond the scope of this review. In brief, leakage primarily occurs along the outer edges that touch the face and is especially high during a high pressure expiratory event like a cough.[3] Masks with the lowest peripheral leakage should have a consistently close and well-tensioned fit around the entire perimeter of the mask. One preliminary study found that cone-shaped cloth community masks had less leakage than flat, surgical-style community masks.[4] In addition to a close-fitting shape, leakage can be minimized by increasing the tension on head straps [5-7] and localized sealing of crucial leakage points along the faceseal.[8,9] The studies reviewed tested the filtration efficiency of materials that were tightly affixed to the testing apparatus to eliminate leakage. The filtration efficiency of the material determined in this near-zero leakage condition does not represent the actual filtration efficiency of a cloth mask during use due to edge leakage. We report the results of our review of the literature that examined different materials that could be used to make cloth masks. Our goals were to (1) summarize both the quantitative and qualitative findings related to different materials considered for homemade masks and (2) identify gaps in the scientific literature for future study.

Fabric characterization

Various characteristics of fabrics may influence their filtration efficiency and breathability. If a study finds that a fabric has excellent filtration and breathability, this information is not useful to consumers or researchers if the characteristics of the fabric are not reported such that the consumer or researcher can obtain the fabric. It is currently unclear which characteristics are the most influential for filtration efficiency or breathability. As such, it is important to characterize and report the characteristics of tested fabric with as much detail as possible. Fabric characteristics that are likely to be important include fiber content, the process used to combine threads, weight/density, and thread characteristics.

Fabrics can be made from one or more natural or synthetic fibers. Cotton, linen, silk, and wool are examples of natural materials. Nylon, polyester, polyurethane, and polypropylene are examples of synthetic materials. Materials may be hydrophobic (repel water) or hydrophilic (absorb water). Polyester is naturally hydrophobic while cotton is naturally hydrophilic. More hydrophobic materials in a mask will increase the relative humidity in the breathing space between the mask and the face. Walking briskly for 1 hour while wearing a surgical mask, which has a hydrophobic outer layer, was found to increase the relative humidity and temperature in the mask breathing space from approximately 55% to 90% and from 32 to 33.5 °C, respectively; in the same study, 7% of participants reported significant facial warmth and 11% reported moisture buildup on the inside of the mask.[10] The study found no clinically significantly physiological impact or substantial changes in subjective perceptions of exertion or heat.[11]

Materials may also be naturally electrically charged or hold an artificially induced charge that improves filtration. Filters used in respirators, including N95 filtering facepiece respirators and most surgical masks, contain a layer of charged/electrostatic fabric that greatly enhances particle filtration.[12] All synthetic fabrics hold an electrostatic charge that is reduced if the fabric composition includes a natural fiber. It has been suggested that some fabrics can temporarily hold an electrostatic charge and can be recharged by mask wearer (*e.g.*, by rubbing mask with latex glove) periodically.[13] Whether this is practical for face masks has not been determined. When a filter material is stripped of its electrical charge, the filtration efficiency will decline.

Fabrics are also characterized by whether the threads are knitted or woven together or whether the fabric itself is composed of non-woven fibers (*e.g.*, meltblown polypropylene used in N95 filtering facepiece respirators and surgical masks). Some fabrics, including spandex and other knit fabrics, are inherently stretchable or may stretch with wear, resulting in an increase in pores size and a reduced ability to filter particles.[13] Within manufacturing methods, some weave patterns can be more effective at filtering than others. For example, one study found that twill weave filters particles more effectively than satin weave.[14] Even after the threads are attached to each other, the fabric can be altered through post-processing, for example by cutting loops (*e.g.*, fleece, velvet, and corduroy) or leaving them intact (*e.g.*, terrycloth).

Thread characteristics include diameter, pitch, and process by which the thread was manufactured. For example, twisting a thread of a fabric reduces the effective surface area of the thread by hiding some fibers behind other fibers, making them less likely to interact with the air flowing through the fabric. The process by which threads are combined and thread characteristics both influence fabric density, which is typically described by threads per square inch (TPI) or grams per square meter (gsm).

The fiber content, the process by which threads are combined, and the thread characteristics strongly influence the size of pores between individual fibers. Assuming other characteristics are constant, small pore size is associated with higher filtration efficiency.[13] Crudely, relative pore size of two materials can be determined by holding each material directly over the eye and up to a bright light (Figure 1). For multiple layers of material, the pore size of a single layer does not necessarily indicate the pore size of the stacked layers because the pores may be aligned or misaligned (Figure 2).

Pressure differential

Measurements of pressure differential

To be effective, a mask needs to both filter out particles and allow a person to breathe easily. The ease of breathing through a respirator, surgical mask, or cloth mask is typically measured by the pressure differential between the two sides of a mask as air flows through it at a rate similar to that during breathing. The pressure differential should be tested at a specified face velocity perpendicular to the plane of the tested material or at a specific flow rate across a specified material surface area. For materials that are homogenous (non-directional), the pressure differential measured when passing air from side A to side B is the same as the pressure differential measured when air flows from side B to side A. For a mask that is asymmetric or made of heterogeneous layers, the air pressure differential could be directionally-dependent (that is, air pressure from side A to side B could be different than from side B to side A).

The pressure differential across a fabric or mask under a given face velocity is an indicator of how much the material impedes air flow. This is directly related to the breathability of a material: higher values of pressure differential indicate that the fabric or mask is harder to breathe through and lower values mean that it is more breathable. Darcy's Law states that the difference between the pressure on the upstream side of a porous material (the side that is first impacted by particles in the flow) and the pressure on the downstream side (the reverse side) is proportional to the face velocity of air through the material.[15] Darcy's law serves as a basis for the following general relationships:

- For a fixed volumetric flow rate, an increase in area of the tested material will decrease the face velocity and pressure differential. A near-linear relationship has been experimentally demonstrated for microfiber cloth.[15]
- For a fixed face velocity, a larger area of a given material is not expected to substantially change the pressure differential, as both face velocity and pressure are already normalized by area (pressure is force per unit area). Inhomogeneities in flow and in the material could make small differences in the pressure differential when the area under test changes. Moreover, as there is always a boundary layer, the face velocity, even under laminar, unidirectional flow, is not exactly the same across the tested area and this will create a small difference in pressure differential when the tested area is varied.
- For a fixed face velocity, it is expected that pressure differential will increase with multiple layers of the same material because molecules will have to move through more of the material that has a given impedance and the pores of one layer are not expected to align perfectly with the pores in another layer.

However, the linear relationship between pressure differential and face velocity assumed by Darcy's law does not always hold,[16] so measurements of pressure differentials obtained in experiments with widely varying face velocities should not be compared; the face velocity used for tests should be within the normal breathing range (3.3—27.2 cm/s).[17]

Standards for measuring pressure differential

There are a number of standards that define measurement methods and performance criteria for N95 filtering facepiece respirators and surgical masks.[17] Some of these methods have been adapted to measure pressure across fabrics. In 2020, the EU established a standard for fabrics meant to be used as face coverings or masks (CWA 17553). In general, testing methods specify the cross-sectional area of fabric to be tested and the volumetric flow rate across the fabric (the 'face velocity'), as well as the method for measuring pressure differential. The use of a standard face velocity is required to compare measured pressure differential across different materials and different areas under test. Table 1 lists the maximum pressure differentials specified in the standards for face mask materials.

Filtration Efficiency

Measurement of Filtration Efficiency

The filtration efficiency (FE) is the proportion of particles filtered by the evaluated material. The filtration efficiency of a fabric or filter is determined by challenging the material with particles carried in air moving at a specific velocity. The particle concentration is measured before (upstream from) the fabric and after (downstream from) the fabric. The difference between these two concentrations is used to determine their filtration efficiency, FE = (1 - C_i/C_o)* 100, where C_i and C_o are the concentration of particles inside (downstream) and outside (upstream) of the mask), or filter penetration rate, P_{filter} = 100 – FE. Filtration efficiency depends on the material/fabric, but also on particle size and shape, particle charge, face velocity, and how the particles are measured (*e.g.*, mass *vs*. count). This same measure can be used for a whole mask or a sample of material. Filtration efficiency is considered to be the same no matter which direction the particles penetrate through the fabric or filter. An FE of 95% means that 95% of particles (of a specified size) are filtered, and would not be either inhaled by the wearer or expelled by the wearer into the air outside the mask.

Filtration efficiency is also dependent on the size of the particles used to challenge the material. Larger droplets (>20 μm in aerodynamic droplet diameter) move in a trajectory determined by inertia and gravity and tend to drop to the ground within seconds to minutes after being expelled.[18] Small droplets (<5—10 μm, often called aerosols), are light enough to be buffeted by air currents so they tend to float in the air like smoke and can linger in the air for many minutes or hours.[19-21] Droplets between 10—20 μm in diameter show a mixture of the two behaviors.[18] Coughing, talking, and breathing produce millions of microdroplets, which have distinct particle size distribution modes associated with the lower respiratory tract, larynx, and upper respiratory tract. Particles from the lower respiratory tract and larynx have a median particles size of 1.6—2.5 μm while particles from processes in the upper respiratory tract have a median particle size of 123—145 μm.[22] While the SARS-CoV-2 virus is 0.06—0.15 μm in diameter,[23] respiratory viruses are not emitted from the respiratory tract as free viruses; instead, they are released attached to droplets in respiratory secretions.[24] Thus, SARS-CoV-2, like other respiratory viruses, is present in particles with a variety of size ranges.[25]

Particles are blocked by filters according to different mechanisms, such as straining, inertial impaction, interception, diffusion and electrostatic attraction.[26]Given all of these processes, particles with a diameter close to 0.3 μm tend to be the most difficult to capture for masks manufactured with non-electrostatic materials such as cloth:[13] Smaller particles are readily captured through diffusion and larger particles through interception and inertia. This aligns with the 0.3 μm particle diameter used in the most conservative (protective) filtration efficiency tests.[27] N95 filtering facepiece respirators and surgical masks rely on electrostatic attraction for their high filtration efficiencies. Similarly, addition of charge to fabrics has been shown to improve their filtration efficiency, as they can capture particles through electrostatic attraction in addition to filtration. However, electret filters can lose their charge upon exposure to solvents such as isopropyl alcohol, resulting in reduction of their filtration efficiency. For filters that have an electrostatic charge, the most penetrating particle size is 0.05–0.1 μm.[1]

We recognize that the filtration efficiency of particles 0.3 μm in diameter does not necessarily correlate with their filtration efficiency of particles of smaller or larger size and thus the relative ranking of material's filtration efficiency at 0.3 μm does not necessarily indicate their relative rank at filtering the particle sizes that may carry SARS-CoV-2. However, given that 0.3 μm is close to the most penetrating particle size and the currently accepted standard for mask filtration tests, we compared filtration efficiencies of particles 0.3 μm in size when such data is available. If filtration efficiency data on monodispersed particles 0.2—0.4 μm particles was not available, we used the filtration efficiency data from challenging materials with particles <0.3 μm in size. If filtration efficiency data on polydispersed particles <0.3 μm in size was not available, we used the filtration efficiency data from challenging materials with polydispered particles >0.3 μm in size. We preferentially examined filtration efficiencies on particles <0.3 um in size compared to particles >0.3 um because the former range is bounded while the latter range is not and some studies tested very large particle sizes, which are relatively easy to filter out.

It has been observed that face velocity is inversely associated with filtration efficiency.[28,29] One reason for this may be that at higher flow rates, a particle has less time to diffuse away from the path of convection that would cause it to hit a fiber.[28,29] Another reason may be that a higher flow rate can results in enlargement of pores in a material, which allows more particles to pass through the material. Inhomogeneities in the air flow (at any face velocity) or inhomogeneities in quality of the tested material result in a range of filtration efficiencies for a given material. The error in characterizing materials due to these inhomogeneities may be larger for smaller test areas (because the sample size may not be representative of the material). Thus, filtration efficiency measurements are expected to be more accurate if multiple samples of each material, each with a test area similar in size to the area of a face mask, are tested.

For a discussion of indicators that combine pressure differential and filtration efficiency, see the Supporting Information.

Methods

We searched Pubmed and Google Scholar for studies online before 31 January 2021 evaluating filtration efficiency and differential pressure for fabrics and other materials that might be used to make homemade masks. Keywords for search were: ((“fabric” OR “cloth”) AND “mask”) AND “filtration efficiency” AND (“breathability” OR “pressure drop” OR “pressure differential”) AND ((“particle” OR “particulate”) OR (“virus” OR “viral”)). Article abstracts were reviewed and excluded if they mentioned materials that could not be easily procured by atypical US resident (such as activated carbon or nano-tubes, particles, fibers) or required an input of energy (such as a nanogenerator). One paper was excluded because it examined coating cloth with mangosteen extract, which is not widely available.[30] Only articles published in English were included in this review; one article in Korean[31] appeared to be appropriate for inclusion other than the language requirement. Studies that present filtration of objects other than particles (*e.g.*, bacteria and nanoparticles), are presented in the Supplementary Information.

Factors considered in evaluation of the quality of the studies and their limitations were whether the study was published in peer-reviewed scientific journal, whether standard methods were used for evaluation of filtration efficiency and pressure differential, whether methods for fabric evaluation were described in enough detail so that the study could be replicated, whether the fabric was described in adequate detail so that it could be acquired by others in order to replicate the study, and whether multiple samples were tested. We used the evaluation results to rank the studies and determine whether or not they should be included in the data analyzed in the discussion.

We report results from literature in terms of face velocity and pressure, both of which include the relevant quantities (force and volumetric flux) normalized by the area that is being measured. In this way, measurements can be more easily compared across experiments that use different areas of materials. Such a comparison, when the face velocity is the same across experiments, assumes that measurements are made with laminar flow that is perpendicular to the plane of the material being tested and negligible edge effects, flow imperfections, and material inhomogeneities.

Results

The methods used in each study are described along with the primary findings and the limitations of the study; studies are arranged in alphabetical order. Two-dimensional graphs of the findings from each study on filtration efficiency (%) by differential pressure (ΔPa) were prepared for a single layer of fabric (Figure 3A) and multi-layered fabrics/fabric combinations (Figure 3B). The scales are the same for all graphs to facilitate comparisons. Filtration efficiency and pressure differential results within and across studies were highly variable, even for what are listed as the same materials. Studies that had a very limited number of data points or presented findings that could not be translated into standard measures of filtration efficiency (%) or differential pressure (Pa) were not included in the presented figures. In addition, studies were not included in the presented figures if essential aspects of their methods were undefined,[32] highly inaccurate (*i.e.*, pressure differentials from [33]), or entirely incomparable to other studies (*i.e.*, very low or high face velocities used for testing [26,34,35]). Studies that tested bacteria[36,37] or non-standard particles such as human-generated droplets[38] or water[39] are not included in the results section and are instead discussed in the Supporting Information.

Detailed summaries of each study

Aydin *et al*., 2020—In a peer-reviewed paper, Aydin *et al.*[26] reported blocking efficiency of high-velocity droplets and pressure differential on 11 different fabrics. Fabrics were characterized by material type, weight, hydrophilicity, thread count, and porosity. Results were compared to a single medical mask of unspecified make and model.

The paper reports a protocol proposed to mimic high-velocity, high-momentum droplets that would be produced by coughing or sneezing. The study is intended to complement existing studies which look at filtration of the smaller, lower velocity aerosols generated by talking or breathing. Droplet blocking efficiency was tested by using an inhaler to launch H_2O droplets into the test fabric. The droplets had a size range of 100—1000 µm and a measured velocity of 17.1 m/s or 2.7 m/s. These H_2O droplets contain a homogeneous suspension of 0.100 µm diameter fluorescent beads. Any beads which penetrated the mask were counted. High-speed videography was used to determine particle velocity and to image how particles were caught or passed through single or double layers of fabric. Pressure differential was estimated by mounting the fabric across a tube of area 78.5 cm^2 with air moving through at five measured face velocities ranging from less than 10 cm/s to more than 300 cm/s while pressure was measured.

The primary limitation of this study was that it is unclear if high velocity droplets coming out of an inhaler with a puff of air is a realistic simulation of a cough or a sneeze inside a mask. During a cough or sneeze the droplets are both high velocity and simultaneously being forced through the fabric by a blast of several liters of air.

Since the droplet velocity was about 100 times higher and the droplet size is over 100 times larger than those of other filter efficiency experiments, the results from this study are not presented in the discussion section.

Drewnick *et al*., 2020—In a peer-reviewed paper, Drewnick *et al.*[40] reported filtration efficiency and pressure drop for 48 sample materials, including twelve cotton fabrics, five cotton-synthetic blends, eleven synthetic fibers, four paper-like materials, four natural fiber materials, eight synthetic household materials, and three commercially available surgical masks and one FFP2 mask. Full details of sample materials utilized in their experiments are included in Table S1 of their supplementary information, including specifics like thread count, material area density, and material composition. Drewnick *el al.* also experimentally evaluated the impact of leaks on filtration efficiency by introducing holes into a selection of filtered materials; they additionally evaluated mathematical models for estimating filtration efficiency and pressure drop of multiple layers of filtering materials.

Filtration tests were performed with two experimental setups. The first utilized Condensation Particle Counter and NaCl aerosol generated by a differential mobility analyzer and nebulizer. Aerosols were evaluated directly from the nebulizer or after passing through an aerosol neutralizer. Material samples were placed in a filter holder with an internal diameter of 65 mm (surface area = 33.2 cm^2). Measurements were performed with 0.030, 0.050, 0.100, 0.250 and 0.500 μm diameter for both charged and neutralized states at two flow rates, which corresponded to flow velocities at the filter of 5.3 cm/s and 12.9 cm/s. Measurements were taken 9 times for each material-particle size-flow combination. Pressure drop was measured three times after stabilization between pressure gauges up and downstream of the sample with a 1 Pa uncertainty. For particles 0.250—10 μm in diameter, a Scanning Mobility Particle Sizer/Optical Particle Counter (SMPS/OPC) setup was utilized. Ambient aerosol entered the room through an open air gage and was drawn through the material sample, which fixed onto a flange with internal diameter 70 mm.

Across evaluated materials, a wide range of filtration efficiencies were observed across particle sizes. A filtration efficiency minimum was found for particles between 0.05—0.5 μm. Increasing face velocity led to decreased filtration efficiency for small particles and an increase in filtration efficiency for large particles due to different loss mechanisms involved for small and large particles. The authors found that they could reasonably estimate the FE of layers of the same materials following power law equations they describe in the text. Strengths of this study include very thorough evaluation of each material, including replicates, various testing conditions (*e.g.*, charged and charge-neutralized particles; different face velocities; different size bins). Methods and results are presented clearly, including thorough details of evaluated materials.

Authors note their paper did not include humidification of particles or consideration of the impact of washing materials on filtration efficiency and breathability. Additionally, given the large number of materials evaluated, the numerous evaluation conditions, and the number of replicates, additional information—perhaps in the form of tabular data stored in an online data repository—would be tremendously helpful for replication and further evaluation. We note that the authors shared a comprehensive dataset willingly upon request.

Hao *et al*., 2020—Hao and colleagues evaluated the filtration efficiency and pressure differential of a wide range of materials and reported the results in a publicly available dataset (https://yangwangpmtl.wordpress.com/) and in a peer reviewed article.[33] For the first 169 samples, the pressure differential was measured by a scanning mobility particle sizer (TSI SMPS) with a resolution of 100 Pa and an assumed accuracy of ±500 Pa; for the later tests a digital manometer with a 0.001 psi (6.9 Pa) resolution and accuracy of ±0.3% accuracy was used (personal communication, Wang Y, 14 June 2020). Test aerosols (NaCl) were generated by a constant output atomizer (TSI 3076) and filtration efficiency was measured at 0.3 μm with a scanning mobility particle sizer (SMPS, TSI 3936). The filtration efficiency and pressure differential were tested at face velocities of 9.2 cm/s, 15.3 cm/s, 23.2 cm/s, which correspond to flow rates of 6 L/min, 10 L/min and 15 L/min through a test material diameter of 37 mm (area: 10.75 cm^2).

Air filters had the highest filtration efficiencies and relatively low pressure differentials compared to the other materials tested in this study. Microfiber materials had filtration efficiencies >50% but relatively high pressure differentials. The filtration efficiency of knit and woven cottons was less than 40%. An interesting finding was that lack of a consistent effect of face velocity on filtration efficiency (Figure 4).

A primary limitation of this study was that the pressure differentials were an order of magnitude higher than in other studies, for the same materials. The methods for pressure differential measurement were not described in detail and the pressure measurement device had poor resolution. Given this limitation, pressure differentials for this study are not reported here.

Hao *et al*., 2021—This paper[41] examined the size-dependent filtration performances of five types of paper materials and 16 types of fabric materials. The test aerosols were generated by a constant output atomizer (Model 3076, TSI Inc. Shoreview, MN) nebulizing a NaCl-water solution with a mass concentration of 0.1%. The atomizer generated aerosols at a flow rate of 3.0 liters per minute (1pm) over 43 cm^2 of material for a face velocity of 9.2 cm/s. The weight of the tested materials ranged from 28 gsm (silk) to 372 gsm (lycra cloth) and were compared against a surgical mask weighing 71 gsm. The study also examined material structure and the effects of washing and drying cycles on microfiber, flannel, bamboo, velvet, jersey, silk, cotton, and muslin.

In general, fabric materials with higher gsm showed higher particle filtration efficiency. Four out of 21 materias, microfiber, shop towel, coffee filter paper, and lycra cloth, were found to have a filtration efficiency above 20% at 0.3 μm. Non-woven and tightly knit materials were identified to have the best filtration efficiency. Better filtration efficiency and reusability generally correlates to higher gsm but a heavier weight is also correlated to lower breathability. The integrity of materials tested was not compromised after washing and drying, yet the filtration efficiency of medical masks and respirator materials degraded due to a loss of static charge. However, after several cycles of cleaning, the filtration efficiency of N95 respirator and surgical mask materials was still higher than all of the fabric materials except the microfiber cloth.

The brand and weight of most materials tested was given, but several materials had missing brand information, which would make it difficult for consumers or researchers to procure these materials. Materials were not pre-conditioned, as recommended in the NIOSH protocol.

Jung *et al*. 2014—In this peer-reviewed study, Jung *et al.*[42] evaluated the particle filtration efficiency of 44 different models of masks, including so-called yellow sand (dust storm protection) masks, "quarantine masks", "medical masks", and handkerchiefs (made of either cotton or gauze of unspecified material). All adult yellow sand masks tested in this study met KF80 regulatory standards as filtering facepiece respirators; all quarantine masks either met KF94 or NIOSH N95 regulatory standards as filtering facepiece respirators. The authors used the TSI 8130 Automatic Filter Tester and conducted tests according to NIOSH procedures and, separately, the procedures from the Korean Food and Drug Administration. Since 314 cm^2 of fabric was tested rather than ~150 cm^2 tested in the NIOSH protocol, but the flow rate was the same, the face velocity in this study was 4.5 cm/s instead of 9.4 cm/s as in the NIOSH protocol. Additionally materials in this study were not preconditioned as specified in NIOSH standard TEB-APR-STP-0003/0007/00059. The Korean Food and Drug (KDFA) method was similar to the NIOSH method except that the NaCl concentration was 1%, the filtration flow rate was 95 L/min, and the pressure differential flow rate was 30 L/min. The authors also examined whether penetration changes as load of particles on the mask increases. Results of filtration efficiency were similar when the materials were tested with the two protocols ($p = 0.12$), so only the results obtained with the modified NIOSH protocol are reported here.

The primary finding of this study was that handkerchiefs had a very low average filtration efficiency, 13%, even when four layers were used. The results from the other, non-cloth masks are not described here.

The primary limitation of this study was that the characteristics of some of the masks tested were not presented in enough detail to allow for comparisons with other studies or for the experiments to be replicated.

Konda *et al*., 2020—In a peer-reviewed study, Konda *et al.*[32] studied filtration efficiency and pressure differential across materials including N95 filtering facepiece respirator and surgical-style mask materials, cotton (labeled with threads per inch), chiffon, and natural silk.

A fundamental limitation of the study was explained in a later correction:[43] Since flow rate was measured only without material impeding the flow, the actual flow rate at which tests were performed was lower than stated and varied with each material. Further errors were pointed out in a letter to the editor.[44-46] The flaws in the study make it impossible to compare filtration efficiency or pressure differential to the results of other studies. As such, results from[32] are not reflected in the results or discussed further.

Li *et al*., 2020—The peer-review article by Li *et al.* [47] examined the filtration efficiency of face masks made of one or more layers of paper towels and/or 4-ply sheets of tissue paper. The filtration efficiency of NaCl aerosols 0.006—0.22 μm in diameter was measured using a scanning mobility particle-size spectrometer and compared to that of a surgical-style mask. The authors also tested if a face shield could protect the mask during a splash test. In addition, the fiber structure of a medical mask was observed under an electron microscope after exposure to either 75% alcohol or soap and water at 60°C.

The primary finding was that the filtration efficiency of the paper mask was 85%, compared to the medical mask, which was 87% (0.006—0.2 μm particles). The fibers of the surgical-style face mask were damaged after treatment with either 75% or soap and water at 60°C, but the degree of damage of effect on filtration was not quantified.

The primary limitation was an inadequately described procedure and results that do not agree with theory. For example, two masks with the same materials layered in a different order had a filtration efficiency at 0.2 μm that differed by 25 percentage points.

Lustig *et al*., 2020—In this peer-reviewed study,[34] 37 unique combinations of fabrics were evaluated for a permeability index against nanoparticles 0.010—10 μm in size. The volumetric airflow through the material (0.785 cm^2) was 14 L/min at steady-state so the face velocity was 297 cm/s. Filtration was assessed by spraying an aqueous solution of fluorescent nanoparticles onto the material and the nanoparticles that passed through the material were captured on a glass slide. Results for each material were expressed as "fractional transmission" and compared to a reference 5-layer N95 filtering facepiece respirator (3M 1860S).

The primary limitation of this study was that the face velocities used when determining filtration efficiencies are 10—60 times higher than the face velocities used in other studies and should not be comparable since filtration efficiency is expected to drop substantially with a dramatic increase in face velocity. Additionally, the study did not test the pressure differential across the material combinations, so it is unclear whether material combinations with high filtration efficiency are useful for mask fabrication. Hence the results from this study are not presented in the discussion section.

MITTL (unpublished)—The MIT Lincoln Laboratory (MITLL) tests fabrics as part of a collaboration with The Advanced Functional Fabrics of America and the Massachusetts Emergency Response Team. The MITLL testing method is similar to NIOSH TEB-APR-STP-0003/0007/00059 method in that it uses charge-neutralized NaCl particles, a face velocity of 9.4 cm/s, and similar temperature and relative humidity preconditioning. Minor differences include that the NaCl aerosols used by MITLL range from 0.3—10 μm, with a count median diameter of 0.371 μm instead of 0.020 μm, and a geometric standard deviation of 2.38 instead of <1.86. However, MITLL is able to report results for particles 0.3—0.374 μm in diameter, which is approximately the range evaluated with the NIOSH method. Another difference is that MITLL uses an optical particle sizer rather than a photometer and that MITLL tests a disc of fabric rather than a full face mask. For this review, MITTL provided results from 7 cloth masks, 3 types of surgical-style masks (that were tested before and after washing with soap), and 2 types of KN95s.

The primary finding is that none of the cloth masks had a filtration efficiency of greater than 25% for particles 0.3—0.374 μm in diameter. Additionally, the filtration efficiency of surgical-style masks was greatly reduced after washing; the efficiency of one mask was reduced by 30% while the other masks were reduced by 50% and 70%. The filtration efficiency of the two KN95s was 42% and 98% for particles 0.3—0.374 μm in diameter.

The primary limitation of the results is that the characteristics of some of the masks tested were not presented in enough detail to allow for comparisons with other studies or for the experiments to be replicated.

O'Kelly *et al.*, 2020—In this published paper, O' Kelly *et al.*[35] performed an evaluation of twenty widely available fabrics and other materials (hereafter collectively referred to as "fabrics"). For each fabric, a total of ten measurements were taken from at least two sections of the fabric. Fabrics were washed and dried prior to assessment; exact details regarding the effect of this washing step were not reported but shrinkage was noted. Breathability was assessed using a qualitative test; two members of the research team held fabric 'tightly' over their mouth and inhaled through their mouth. Fabrics were scored from 0—3, where 0 represented no difficulty breathing and 3 represented great difficulty in breathing. Filtration efficiency was investigated using two TSI P–Trak 8525 ultrafine particle counters; the authors state that these count particles ≤0.1 μm and smaller. Fabric was held across a 2.5 cm diameter tube through which air flowed at 1650 cm/s. Additionally, the impact of dampness due to respiration was evaluated by applying 7 mL of filtered water to the 5 cm square section of material.

The primary finding from this study was that all tested fabrics are at least partially effective at filtering ultrafine particles at coughing velocity. Denim and a windbreaker fabric, while highest in filtration efficiency among single-layer fabrics, were harder to breathe through than N95 mask material. Layering fabrics increases filtration efficiency but reduces breathability. Adding non-woven fusible interfacing increases filtration efficiency without reducing breathability, but filtration performance varies by brand. The combinations with highest filtration efficiency included cotton quilting fabric with quilt batting and HTC brand lightweight fusible interfacing; cotton quilting fabric with cotton flannel, and Heat-n-Bond brand lightweight fusible interfacing; and cotton flannel with Minky. Dampness caused only minor changes in filtration efficiency for quilting cotton, and cotton flannel, while denim showed a large decrease in filtration efficiency when moist. Washing caused the wool felt to shrink but did not change the material's filtration efficiency.

The primary limitation of this study was the unclear particle size used to assess filtration efficiency. The researchers state that they measured all particles ≤0.1 μm in diameter, but the P-trak model 8525 measures particles 0.020—1 μm in diameter without further size selection. As a result, the filtration efficiency of particles 0.3 μm in diameter cannot be determined. Another limitation of the study was that breathability was measured subjectively, with investigators rating their breathing difficulty when the fabric was placed over their mouth; the amount of leakage was not measured. Using this rating system, for example, a N95 mask was rated more breathable than a surgical-style mask. Finally, although fiber content was reported, the details of most fabrics were insufficient to allow for the experiments to be replicated or for consumers to identify/purchase the same fabrics.

Pan *et al*., 2020—In Pan *et al*.,[48] a non-reviewed pre-print, ten materials were tested for filtration efficiency and pressure differential. Filtration efficiency testing followed a modified NIOSH process with additional testing of NaCl particles up to 5 μm diameter. Air flow was 3.0 L/min (face velocity 10 cm/s) and challenged the materials with charged NaCl particles. Pressure drop was measured using the same system. Tested materials included a vacuum bag, coffee filter, cotton fabric, and bandanas. Three tests were conducted on 25 mm diameter cutouts from different locations of the parent material. The researchers also measured the efficiency of masks on mannikins during mimicked inhalation and exhalation; we do not include those results here as the focus of this review is mask material rather than fit.

While the vacuum bag and microfiber cloth had filtration efficiencies close to 75%, the microfiber did not meet breathability standards. The filtration efficiency of other household materials were all below 50%, with the double-layer bandana at 39%, the pillowcase at 13% and cotton T-shirt at 10%.

This study used high quality methods but did not present enough information on the materials for consumers or other researchers to acquire the same materials.

Pei *et al*., 2020—In this peer-reviewed study, Pei *et al*.[49] evaluate filtration efficiency and pressure differential across commercial masks, furnace filters, vacuum filters, sterilization wraps, household fabrics, and paper products. From all materials, 40 mm-diameter discs were cut and evaluated in the measurement setup. Researchers referred to NIOSH testing protocols, using neutralized monodisperse NaCl particles 0.03, 0.05, 0.08, 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, and 1.0 μm in diameter with a flow rate of 85 ± 4 L/min (face velocity 10.5 cm/s).

Some of the commercial masks had filtration efficiencies that exceeded 50% but the composition of these masks was not provided so it is unclear if they were made from readily available materials or more specialized materials. The air filters also had >50% filtration efficiencies, although the more efficient filters had relatively high pressure differentials, indicating they would be relatively difficult to breathe through. The most efficient household materials (shop towels, 5 layers of a T-shirt, and 5 layers of a bedsheet) had similar breathability issues. The household materials that were more breathable had filtration efficiencies <50%.

Similar to other studies, a limitation of this study was that too little detail was provided on the generic household materials (*i.e*., T-shirt, bedsheet) and commercial masks tested making it difficult for consumers to obtain the same materials. The authors also note that they do not endorse the safety of the materials tested, citing concerns about possible fiber shedding.

Rengasamy *et al.*, 2010—Rengasamy *et al.*,[50] in a peer-reviewed paper, evaluated aerosol penetration and resistance across three brands each of cotton/polyester sweatshirts, T-shirts, towels, and scarves, as well as N95 filtering facepiece respirator filter media and three brands of purchased cloth masks. The pressure differential across materials was only evaluated at 5.5 cm/s (33 L/min); aerosol penetration was tested at face velocities of 5.5 cm/s and 16.5 cm/s over a test area of 100 cm^2. The lower flow rate is approximately the same as what was used in Zhao 2020, *et al.*,[13] Filtration efficiency was tested against polydisperse NaCl aerosols using a TSI 8130 Automated Filter Tester and against monodisperse NaCl aerosols using a TSI 3160 Fractional Efficiency Tester.

The primary study finding was that all the tested sweatshirt, T-shirt, towel, and scarf fabrics perform substantially worse than N95 filtering facepiece respirator material at filtering NaCl aerosols 0.020—1 μm in diameter. Filtration efficiencies ranged from 10—60% at 5.5 cm/s face velocity, with all three brands of towels and one brand of sweatshirt performing the best and T-shirts and scarves generally performing poorly. There was substantial variability in performance across sweatshirt brands. For polydisperse particles, increasing face velocity did not substantially affect filtration efficiency; penetration increased slightly at higher face velocity for monodisperse aerosols.

The primary limitation of the study was that the characteristics of materials were not described in adequate detail to allow for results to be understood in the context of fiber characteristics such as weight or weave. However, specific products were identified such that tests could be replicated and consumers could purchase identical materials. In addition, breathability was not directly assessed and fabrics were not laundered prior to testing.

Schempf, 2020—TSI, Inc. (Minneapolis, MN, USA) develops and sells several instruments commonly used for filtration (*e.g.*, TSI 8130a, also used by NIOSH) and fit testing (*e.g.*, Portacount) of respirators. Recently, they have used their facilities to test the filtration efficiency and pressure differential of more than 100 fabrics and fabric combinations that were selected, prepared, and sent to TSI by Schempf, a community mask-maker.[51] TSI conducted the fabric tests using the TSI 8130a instrument and generally followed the NIOSH procedure (42 CFR part 84) using polydisperse uncharged NaCl particles to challenge the material. They maintained a flow rate of 60 L/min across 100 cm^2 to produce a face velocity of 10 cm/s, similar to the NIOSH flow rate of 85 L/min over 150 cm^2 (face velocity = 9.4 cm/s). Many of the fabrics tested were described in adequate detail for replication. Multiple samples of some fabrics were also tested.

A primary study finding was that some non-woven materials had high filtration efficiencies. One layer of <u>Filti</u> material had a filtration efficiency of ~87% and was still relatively breathable (ΔP = 83 Pa, close to pressure drop obtained with atypical N95 mask); and ~98% for two layers, but the pressure differential was high (143 Pa). Similarly, one layer (the blue sheet) of Halyard H600 surgical instrument wrap had a filtration efficiency of ~63% while the blue and white sheets together had a filtration efficiency of ~85%. One layer of Evolon microfilament textile had 58% filtration efficiency and one layer of Pellon 360 interfacing had ~35% filtration efficiency while two layers had ~66% filtration efficiency. Materials with poor filtration efficiency included Jo-Ann Stores' stretch chiffon as well as samples of spandex, sports nylon, and quilter s cotton. One material, silky solid charmeuse, exceeded the NIOSH standard for pressure differential (245 Pa), indicating that it would be too difficult to breathe through to serve as mask material. Multilayer and mixed fabrics were also tested.

An important finding was the effect of washing on fabric filtration efficiency and pressure differential. In this study, material was washed using a front-loading washer, with a standard temperature setting, laundry detergent only (no bleach), and a standard dryer heat setting (personal communication, Schempf C, 14 July 2020). Washing DuckCanvas had little effect on filtration efficiency (14.7 to 15.0%) or pressure differential (90 to 101 Pa). However, washing two layers of Filti reduced filtration efficiency from 98% to 46% and the pressure differential dropped from 142 to 40 Pa. The effect of washing and drying the Pellon and Evolon was not examined.

The primary limitation of the study was that only one sample of each fabric type/condition was tested. This high-quality study used NIOSH methods and a thorough description of materials.

Teesing *et al*., 2020—In this peer-reviewed study, Teesing *et al.*[52] evaluated widely available mask materials for filtration efficacy (using a Solair 3100 Lighthouse instrument) and pressure differential (using an AccuFIT 9000 Respirator Fit Test instrument). They tested particles 0.3, 0.5, 1.0 and 5.0 μm in diameter with a flow rate of 28.3 L/min over a 4 cm-diameter cutout for a face velocity of 37.6 cm/s (personal communication, Teasing G, 1 March 2021). Their threshold for breathability was 70 Pa. They assessed top performers for hydrophobicity and fit across multiple design options. Materials tested included commercial air filters, household products (*e.g.*, coffee filter, paper towel), and filter fabric (ePM_1 85% [ISO 16890] or F9 [EN 779:2012]) alone or in combination with cotton quilt fabric. The authors also calculated the population-level mask-wearing compliance that would be required to sufficiently reduce the reproduction number (R_0) of SARS-CoV-2 for each mask material-design combination.

The authors found that leather had a filtration efficiency of 100% and the commercially manufactured filter material ePM1, 85% sandwiched between quilt fabric had a filtration efficiency of 94%. However, these materials and combinations failed breathability tests. ePM1, 85% by itself had a filtration efficiency of 90% and passed breathability tests. Of common materials that passed the breathability test, 1 layer of paper towels between two layers of quilt fabric had the highest filtration (42%), but breathability was near the maximum threshold. All other household materials that were breathable had filtration efficiencies of <34%. Fabric masks performed poorly in hydrophobicity tests in which standardized solutions with bacteria were sprayed onto the masks, with a membrane on the other side then cultured for bacterial growth.

This study tested commercial filter materials, which are not readily available. The commonly available materials that they tested were not described in enough detail to allow other researchers or consumers to source identical materials. Although authors tested the washability of the commercial filter options, they did not assess performance after washing, concluding only that washing caused malformation of all materials.

Wang *et al.*, 2020—In this non-peer-reviewed preprint, Wang *et al.*[53] evaluated 17 materials and 15 combinations of materials for pressure difference, resistance to surface wetting, particle filtration efficiency, and bacterial filtration efficiency. They followed the China standard for surgical masks (YY0469-2011) which requires a pressure differential of ≤49 Pa, resistance to surface wetting of ≥3 [unitless], particle filtration efficiency (PFE) of ≥30%, and bacterial filtration efficiency (bacterial filtration efficiency) of ≥95%. The 17 individual materials included materials from various clothing and household items, including a diaper, tea towels, medical non-woven material, and a non-woven shopping bag. They report the brand (*e.g.*, UNIQLO) and composition (*e.g.*, 100% cotton) of candidate materials. The particle filtration efficiency test process was similar to the NIOSH method but used a flow rate of 30 L/min instead of 85 L/min.

Pressure differential was evaluated first in order to exclude materials from further study with a pressure difference >49 Pa under a flow rate of 8 L/min through 4.9 cm^2 of material as measured with a Qingdao SRP ZR-1200. This corresponds to a face velocity of 27.2 cm/s. particle filtration efficiency was evaluated using the TSI 8130 Automated Filter Tester at 30 L/min through a cross-sectional area of 100 cm^2 using a NaCl aerosol (median diameter of particle count 0.075 ± 0.020 μm). Bacterial filtration efficiency was measured using *Staphylococcus aureus* in an airflow of 28.3 L/min.

Eleven of the 17 single-layer materials met the pressure differential criterion of ≤49 Pa. Some of the materials that failed the pressure differential test were jeans (denim), a diaper, and two pillowcases. Of the 11 that met the pressure differential criterion, only the medical non-woven material met the particle filtration efficiency standard of >30% (42 ± 2%). The other materials, such as the T-shirt, fleece, tea towel, and non-woven shopping bag, had particle filtration efficiency ranging from 6 to 14%. None of the materials met the high standard for bacterial filtration efficiency (≥95%). Of the 15 double-layer materials evaluated, 12 passed the pressure differential criterion and 7 of those 12 had a filtration efficiency >30%. The particle filtration efficiency of the fleece sweater plus a “hairy tea towel” was 56 ± 1%, roughly equivalent to that of the double-layer non-woven material (54 ± 1%).

This was the only study, among those reviewed in this document, that conducted both particle filtration efficiency and bacterial filtration efficiency tests on the same material combinations; particle filtration efficiency tests the filtration of particles <0.3 μm while bacterial filtration efficiency tests the filtration of bacteria of 3 μm in size. There was no consistent relationship between particle filtration efficiency and bacterial filtration efficiency. For four material combinations particle filtration efficiency ranged from 35—56% while bacterial filtration efficiency was less than half with values from 16—24%. For three other material combinations particle filtration efficiency ranged from 40—54% while the bacterial filtration efficiency ranged from 88 to 93%. Three double-layer materials including double-layer medical non-woven fabric, medical non-woven fabric plus non-woven shopping bag, and medical non-woven fabric plus a “granular tea towel” could meet all the standards of pressure difference, particle filtration efficiency, and resistance to surface wetting, and were close to the standard of the bacterial filtration efficiency.

Wilson (unpublished)—This study sought to determine the differential pressure across layers of fabric relative to that of a Halyard surgical mask. The apparatus involved pressing the fabrics against a 1 cm^2 aperture build of steel washers using an O-ring with 1 kg force. The differential pressure across a Halyard surgical mask was 2 inches H_2O (500 Pa), as assessed by an Hti HT-1890 manometer with resolution 0.01 inches H_2O (personal communication, Robert E Wilson, 2 July 2020).

The primary finding from this study was that every additional layer of material increases pressure differential (Figure S2), which supports intuition. For some materials (*e.g.*, cotton and polyester) this increase is approximately linear (*e.g.*, doubling the layers doubled the pressure differential). However, for other materials the effect of layer is not so precise and there may be large differences in the effect of layer for the same material (*e.g.*, chiffon, interfacing, microfiber).

The primary limitation of this study is that it was not clear to what extent the flow rate changed when materials were tested after the flow rate was set by the surgical mask. If the flow rate changed to a large degree then it may be difficult to compare the pressure differentials between materials.

Zangmeister *et al.*, 2020—Zangmeister *et al.*,[54] in a peer-reviewed report, evaluated 41 fabric materials and combinations of fabrics for filtration efficiency and pressure differential using EN 1822 and ISO 29463 methods (polydispersed charge neutralized NaCl particles, sized 0.050—0.825 μm). All but three of the fabrics were tested as two layers. The fabrics were also micro-imaged. The cross-sectional area of fabrics tested was 4.0 cm^2 and the face velocity was 6.3 cm/s, for a flow rate of 1.5 L/min. For each fabric, five pieces were tested. Filtration efficiency curves for each fabric were generated for 0.050—0.825 μm size particles, and the particle size with the lowest filtration efficiency (FE_{min}), was reported.

The primary finding from this study was that the filtration efficiency of the cotton fabrics tested was less than 35%, and the filtration efficiency of the polyester knit fabrics tested was less than 25%. The fabrics with the best filtration efficiency were woven cotton with a moderate to high thread count and woven synthetics with moderate thread count. Cotton material FE_{min} ranged from 7.1—33.6% (down proof ticking had the highest FE_{min}), with differential pressure ranging from 28—334 Pa (down proof ticking had highest Pa). Polyester knits and weaves FE_{min} ranged from 1.3—21.4% with differential pressure ranging from 13—217 Pa. One to 5 layers of lightweight flannel (cotton fiber poplin weave) were tested and filtration efficiency and pressure differential increased monotonically with the number of layers. The manuscript supplement has a detailed description of weave types.

The primary limitation of this study was that the FE_{min} was reported only for monodispered particles within range 0.146 to 0.437 μm, depending on the fabric tested. Therefore, the results are difficult to compare to most studies that reported filtration efficiency for all particles <0.3 μm.

Zhao *et al*., 2020—Zhao *et al*.,[13] in a peer-reviewed report, evaluated different materials for pressure differential and filtration efficiency using a modified NIOSH method. The modification was the use of 32 L/min volumetric flow rate over a surface area of 100 cm^2, yielding a face velocity of 5.3 cm/s. Materials were imaged using a scanning electron microscope. The materials were also tested for filtration efficiency after electrically charging them by rubbing them with latex or nitrile gloves.

The primary finding of this study was that materials with an electrostatic charge have higher filtration efficiency than uncharged materials. After rubbing the materials to create an electrostatic charge, all materials except for cotton showed increased filtration efficiency. However, this gain in filtration efficiency decayed rapidly. Polyester and silk lost almost all of the efficiency associated with the induced charge 30 minutes after the charge was induced; polypropylene lost >60% of the induced efficiency after 60 minutes and nylon lost >90% of the induced efficiency after 120 minutes. Data from this study was featured in WHO's guidance on community mask wearing.[55,56]

The filtration efficiency of meltblown polypropylene used in two surgical-style masks and an N95 filtering facepiece respirator were 19%, 33%, and 96%, respectively. The type of spunbond polypropylene tested in this study had a low pressure differential and a filtration efficiency of only 6%. Cotton, polyester, nylon and silk had filtration efficiency of 5—25% and polypropylene spunbond had filtration efficiency of 6—10%. The differences in filtration efficiency for cotton materials of different weights, based on this imaging, was attributed to pore size. Polyester had similar properties as cotton. With regard to pressure differential, nylon exhibited a pressure differential of 244 Pa, an order of magnitude or two higher than the other materials and higher than the tested surgical-style masks and filtering facepiece respirator material.

The primary limitation of this study was that the characteristics of materials were not presented in enough detail to allow for the experiments to be replicated or for consumers to identify/purchase the most effective fabrics/materials. Another limitation of this and several other studies is that the materials were not tested in the high humidity environment that represents the environment of a face mask.

Summary of studies using low-cost methods

In emergency and low-resource settings, the expensive, specialized equipment recommended by NIOSH for testing particle filtration at 0.3 μm (a TSI 8130) may not be available. Several researchers have attempted to develop alternative methods to quickly and qualitatively estimate if materials provide high or low filtration efficiency.

One study examined the ability of different masks to filter ambient particulate matter.[57] The number of particles larger than 0.6 μm that passed through the masks were counted using a bright-field microscope. Despite the cost of a microscope and calibration slide, this method is relatively low-cost. This method tests the filtration efficiency of particulate matter settling out of the air and thus does not account for the rate of airflow that may push a particle through a mask while inhaling or exhaling, which may influence the absolute and relative filtration efficiency.

In a slightly more expensive study, a sheet of laser light was passed through a slit in a box to visualize the particles emitted by a speaker repeating the phrase “Stay healthy, people” into the box while wearing different types of masks.[58] The light scattered by the particles was captured by a cell phone camera and the image was processed to determine the number and qualitative size of the particles. Materials that block almost all visible particles captured by the camera may also block 0.3 μm particles but this needs to be confirmed. The results confirmed that material combinations that include a non-woven material (such as polypropylene) may be more effective than materials that are composed only of cotton. To ensure that the filtration efficiency of the fabric is being tested (instead of testing the filtration efficiency and mask fit simultaneously, the mask should be sealed tightly on the participant’s face, for example by using a mask brace.

In a similar but more expensive study, a high-speed camera imaged particles passing through a mask during coughing.[59] The results were evaluated qualitatively (non-magnified visual analysis of the captured image) and showed that masks made from multiple layers of cloth were more effective than masks made from a single layer of cloth and that a surgical masks was more effective than masks made from multiple layers of cloth.

Validation of these methods against the TSI 8130 gold-standard may ultimately confirm that they can be used to separate materials with very low filtration efficiency from those with very high filtration efficiency, but they are unlikely to differentiate materials that are close in efficiency. An additional drawback is that none of these methods are able to determine the size of the particles that passed through the mask so their filtration efficiency of particles 0.3 μm in diameter (or other relevant sizes) cannot be determined.

Breathability may more easily be qualitatively assessed by holding fabric tightly over one's wide-open mouth and quickly inhaling. One should first conduct this test with a material that is known to be acceptable, such as material from an N95, KN95, or surgical mask and then attempt to inhale through candidate test material. It if takes more than approximately one second to inhale through the test material, it is likely not a good candidate for a mask that fits snugly over the mouth and nose and is still breathable. While this method is qualitative and subjective, it can provide an individual with some guidance on the suitability of common materials for use in face masks.

Discussion

Study quality

Studies varied in quality; many of the studies are not yet peer-reviewed. All but one study (Wilson, unpublished) tested filtration efficiency and most also tested pressure differential. There was a mix of standard testing methods with minor variations and non-standard test methods. The methods for assessing pressure differential varied from standard methods in the face velocity used and/or the cross-sectional area of material tested (or the cross-sectional area was not reported), making pressure differential difficult to compare across studies (Table 3). When measuring filtration efficiency, some studies used the NIOSH standard of polydisperse NaCl and reported filtration efficiency for particles <0.3 μm, while other studies used monodisperse particles or reported filtration efficiency at specific sizes (*e.g.*, 0.1 μm, 0.3 μm, or 1 μm). Some studies measured filtration efficiency using particles characterized by their mass median aerodynamic diameter (MMAD, the geometric median of the distribution of particle mass) while others used particles measured by their count median diameter (CMD, the geometric median of the distribution of particles diameters). Unfortunately, most studies did not characterize fabrics in enough detail to reproduce the experiments (Table 2). Only a few studies evaluated the impact of washing and drying.[57]

Effect of face velocity on filtration efficiency

Prior to the finding of prior studies,[28,29] we found that increasing face velocity was associated with little to no effect on filtration efficiency (Figure 4). Microfibers, non-wovens, bedsheets, and woven cotton demonstrated little change in filtration efficiency as face velocity increased. Some cotton knit fabrics declined in filtration efficiency while others appeared to be unaffected. In one study that compared face velocity of 5.5 cm/s to 16.5 cm/s, the higher face velocity was associated with slightly lower filtration for monodispersed particles but no significant difference in filtration for polydisperse particles.[50] An increasing face velocity is associated with a monotonic increase in pressure differential, but the slope varies depending on the material.[26]

Filtration efficiency of various materials

The combined filtration efficiencies across all studies for a single layer of material are presented in Figure 5A. For what are described as the same material types there is a wide range of values for filtration efficiency. These differences may be due to differences in fabric and differences between test methods. However, some trends emerge. Some microfiber and non-woven materials had markedly higher filtration efficiency than other materials. Single layer bandanas, interfacing, scarves (material unspecified), non-cotton clothing, cotton clothing, paper materials, towels, and quilt fabric all have median filtration efficiencies of less than 25%.

Washing led to a large decline in filtration efficiency for a non-woven material (Filti) but no decline in wool felt.[35,51] Dampening (7 mL water on 5 cm^2 material) on quilting cotton, cotton flannel, and dense polyester (“craft”) felt led to no change in filtration efficiency but caused a large decline in filter efficiency of denim.[35]

The effect of multiple layers or combined materials on filtration efficiency

There was a monotonic increase in filtration and pressure differential with increasing layers (Figure S2). However, there is a wide variability in slope for a given material, indicating significant inhomogeneity across the same material or differences between materials that are otherwise described identically.

The combined filtration efficiencies across all studies for multiple layers of the same material are presented in Figure 5B. Multiple layers of a single material type showed substantial variation across studies (*e.g.*, non-wovens and woven cotton) and within a single study (*e.g.*, woven cotton). The materials that had low filtration efficiency levels as single layers tended to also have low filtrations with two or more layers. Multiple layers of synthetic knits, knit and woven cottons, and quilt fabric generally had filtration rates of <25%.

The combined filtration efficiencies across all studies for combinations of materials are also presented in Figure 5B. However, very few of the same material combinations were tested in multiple studies. Given the interstudy variation in filtration efficiencies for single material types, results from combinations of materials that were tested in only one study should be interpreted with caution.

Hazards of materials

It is important that the mask be made of materials that are not impregnated with chemicals. For example, shop towels that contain latex binders[60] can cause an allergic reaction. Materials may also disintegrate into small toxic particles that could be inhaled into the lungs. This may be a problem with repeated washing and drying of some materials. For example, vacuum bags, if cut, are friable and could fall apart and generate fibers that could be harmful to the lungs; some vacuum bags also contain glass microfibers, nanofibers, or fiberglass that could pose a hazard if inhaled.[61] In addition, some vacuum bags are treated with biocides to inhibit bacterial or mold growth.[61] The material safety data sheet for a vacuum bag may not list all the additives. Shop-Vac has issued a statement that no one should make a mask from any filters that they sell.[62] Vacuum bags are not intended for use as a mask and should be avoided. In addition, some fabrics are impregnated with fire-retardants and should not be used for making masks.

Some fabrics contain substances that may cause an allergic reaction. For example, while blue shop towels have reasonable filtration efficiency,[51] they also can contain latex, which can cause an allergic reaction in some people.

Conclusions and Recommendations

In this review of studies that have tested readily available materials for production of homemade face masks, we find that researchers have used a wide range of testing methods, which limits comparison of results. Furthermore, only a few studies reported the characteristics of fabrics to the level of detail required to compare similar fabrics across studies or allow consumers to find and purchase the materials. As such, do-it-yourself mask makers, manufacturers of cloth masks, and scientists should consider the consensus results of a group of well-designed studies (such as those from [13,33,40,50,51,53,54]) and interpret with caution individual reports, which may not present results obtained using standard methods or may have drawn conclusions that are not generalizable.

The filtration efficiency of materials, even when tested under standard conditions with 0.3 μm, uncharged particles flowing towards the material at approximately 9 cm/s, does not necessarily represent the ability of a mask to filter SARS-CoV-2 because of the size and effects of the aerosol particles carrying the virus. Given that the precise dynamics of aerosolized SARS-CoV-2 are unknown, it is sensible to assume that materials that have higher filtration efficiencies under standard testing conditions may more effectively filter aerosolized SARS-CoV-2. With respect to specific materials, many non-woven and microfiber materials (*e.g.*, Filti, Halyard) had a filtration efficiency of >80%, although the filtration efficiency of some materials was <20%. Almost all tested samples of cotton (knit or woven), synthetic knit, chiffon, quilt fabric, quilt batting, flannel, fleece, and interfacing had filtration efficiencies of <25%, even when multiple layers were used. Using multiple layers of material can improve filtration efficiency but each layer also increases the pressure differential and reduces breathability (Figure S2). There was generally no substantial impact on filtration efficiency when materials became slightly damp, but damp materials may have reduced breathability.[35] It is possible to increase the filtration efficiency of some materials by inducing in them an electrostatic charge, for example by rubbing the material with latex.[13] However, the efficiency gained from the induced charge dissipates substantially within 30—120 min.[13] It is also possible to decrease the filtration efficiency of some materials. Meltblown polypropylene, a non-woven material often used in N95 filtering facepiece respirator and surgical masks, does not maintain its charge after washing with soap and water.[63] Since electrostatic attraction is one of the primary filtration mechanisms of non-woven materials, washing with soap reduces the filtration efficiency of these materials.[63]

Fabrics may contain chemicals or components that can cause adverse health effects and these should not be used for face masks. Additionally, some commercial and industrial filters, vacuum bags, and specialty fabrics are treated with fungicides, flame retardants, or other potentially unsafe additives. Consumers should carefully assess materials for these types of additives when selecting materials to use for face masks.

Recommendations for researchers

Given the wide variability in methods in the current literature, we strongly advise that future research on materials for masks focus on reproducible, replicable research, with clear and precise descriptions of both the materials assessed and methods used for assessments. Ideally, studies will all use the same standard methods for evaluating material characteristics (filtration efficiency, pressure differential, *etc.*) so that results can be directly compared with other studies. We suggest following the methods specified in EU CWA 17553 for testing homemade fabric face masks or adapting the methods specified in NIOSH TEB-APR-STP-0059 for testing N95 masks. If there is any deviation from standard methods, then both the methods and apparatuses used should be described clearly and completely, with pictures or diagrams to assist replication. Critical experimental factors to report include the face velocity (or air flow and cross-sectional area of materials tested), characteristics of the particles used for filtration efficiency tests, characteristics include the particle size and charge, the type of particle (NaCl, polystyrene, *etc.*), and whether the particles were monodispersed or polydispersed. While the most penetrating particle size is approximately 0.3 μm for materials with no electrostatic charge[13] and 0.05–0.1 μm[1] for materials with an electrostatic charge, a material's filtration efficiency of these particle sizes may not be a good representation of its filtration efficiency of particles more relevant to viral and bacterial respiratory infections. Future research could examine the most relevant sizes for viruses and bacteria either alone or as they would be transmitted *via* aerosols and droplets.

Studies on cloth mask materials should report enough detail on the materials tested and how the materials were acquired such that other researchers and consumers can obtain, test, and/or use comparable fabrics. Important details include the material (fiber) composition, the brand, product, and weight/density, and how the threads are combined to form the material (*e.g.*, non-woven, knit (with details), woven (with details)). Including a magnified image of the material with the scale may also help identify important characteristics of effective and ineffective materials.

Given the number of published studies with results that conflict with long-standing, well-supported theory, we suggest that researchers validate their findings against standard materials and commonly accepted theoretical frameworks. Testing a standardized material such as reference media sheets, a coupon of material used to make N95 filtering facepiece respirators, or Halyard sterilization wrap may help determine if the experimental methods for testing filtration efficiency are reasonable. It may be more appropriate to use Halyard H100 sterilization wrap as a standardized material than Halyard H500 or H600 sterilization wraps or N95 filtering facepiece respirators because Halyard H100 wrap has a filtration efficiency that is close to the filtration efficiency of commonly assessed woven and knit fabrics. Another way to assess the validity of study methods is to compare preliminary study findings to theory-based expectations. If they are contrary, it may be useful to re-examine the experimental methods that were used. For example, researchers should measure air flow before it passess through the test material rather than after it has passed through the material.[32,43]

Testing methods should account for inhomogeneities with the material and if the material is stretchy, the testing should be done within the expected ranges of stretch when used in a face mask. To address inhomogeneities, we suggest at least 5 coupons of the material should be tested (note, however, that official NIOSH testing requires 20 samples of masks or mask materials); each coupon should be taken from non-adjacent sections of the material. To address the potential for abnormal stretching, material should not be stretched during testing. This means that fabrics should be sealed tightly against a flat surface with a hole through which air flows instead of being stretched around the end of a tube.

Given that washing and other processes such as drying with hot air or coating with antimicrobial sprays can alter the material characteristics, the filtration efficiency and pressure differential of fabrics should be assessed after materials post-fabrication applications have been performed and the fabric has been washed ~10 times.

Important areas for future research include the effect on material filtration efficiency and pressure differential of (1) short- and long-term wear under realistic conditions; (2) a variety of washing and drying methods; (3) repeated high-expiration events such as coughing and sneezing; and (4) accumulated moisture due to breathing over an extended period of time. Long-term wear under realistic conditions could include wearing a mask for 10—30 days, repeatedly crumpling and folding a mask, storing a mask in a pocket or purse with keys, and stretching a mask by 10%. Washing techniques could include water only; bar, powdered, or liquid soap; and/or using a washing machine or hand washing. Drying techniques could include hang drying, drying flat, wringing dry, and hot-air drying.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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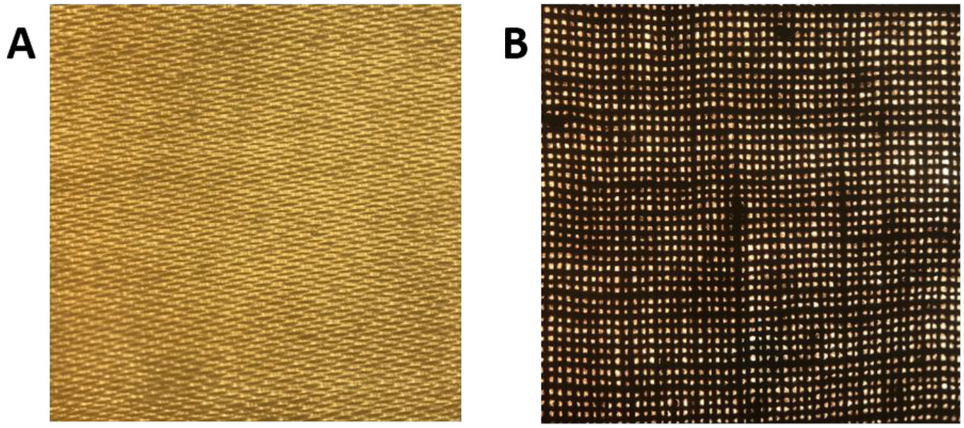


Figure 1:
Light visibility through a more dense fabric (A; 200 threads per inch (tpi) cotton pillow case) and less-dense fabric (B; 60 tpi open-weave cotton)

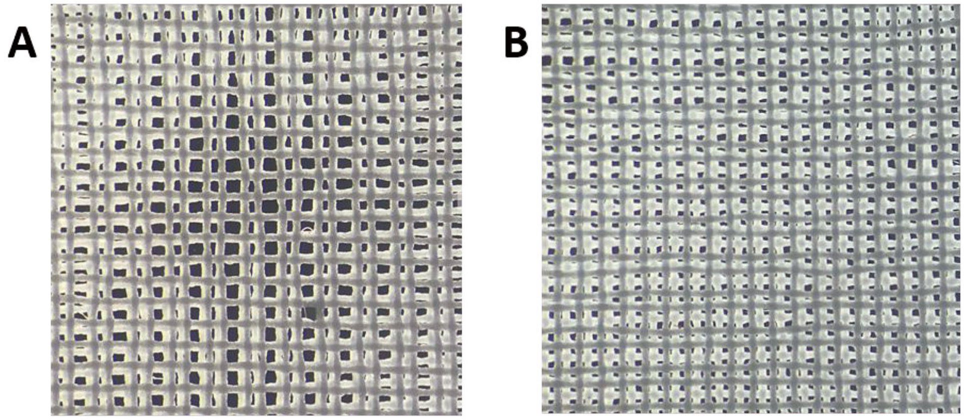


Figure 2:

Pores in 2 layers of 75 tpi polyester chiffon that are (A) aligned and (B) misaligned. These two microscopy photos were backlit using crossed-polarized illumination; this results in the holes being black and the fibers being brightly lit and helps eliminate the ambiguity between a bright hole *versus* a bright fiber.

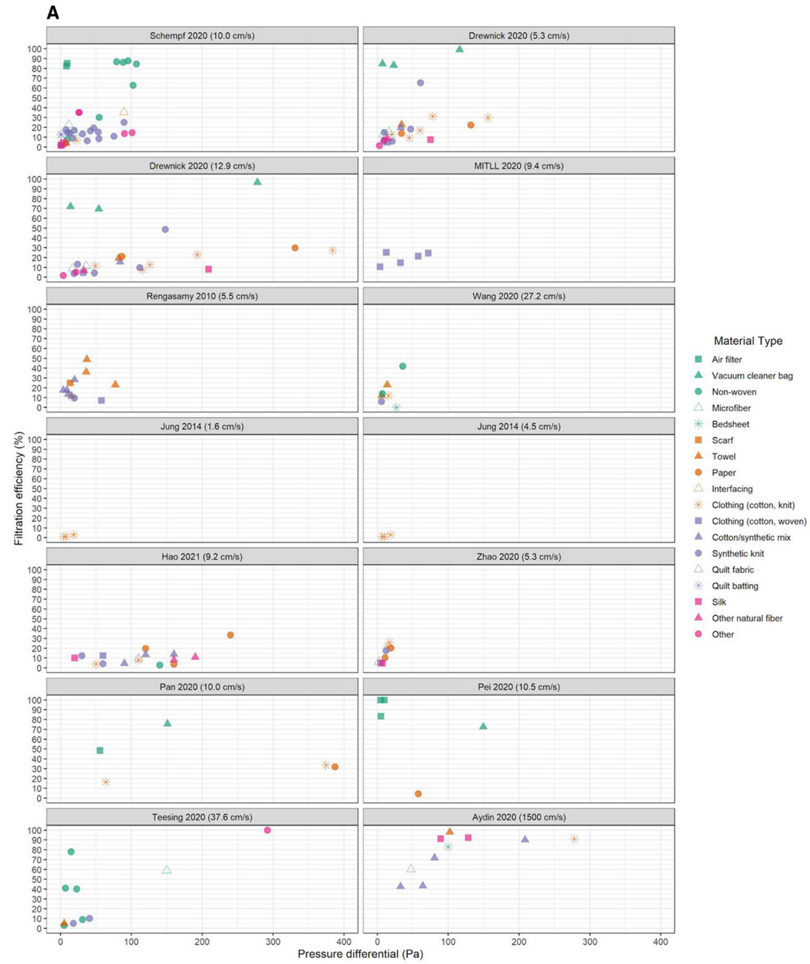

A
Schempf 2020 (10.0 cm/s)
Drewnick 2020 (5.3 cm/s)
Drewnick 2020 (12.9 cm/s)
MITLL 2020 (9.4 cm/s)
Rengasamy 2010 (5.5 cm/s)
Wang 2020 (27.2 cm/s)
Jung 2014 (1.6 cm/s)
Jung 2014 (4.5 cm/s)
Hao 2021 (9.2 cm/s)
Zhao 2020 (5.3 cm/s)
Pan 2020 (10.0 cm/s)
Pei 2020 (10.5 cm/s)
Teesing 2020 (37.6 cm/s)
Aydin 2020 (1500 cm/s)
Filtration efficiency (%)
Pressure differential (Pa)
Material Type
Air filter
Vacuum cleaner bag
Non-woven
Microfiber
Bedsheet
Scarf
Towel
Paper
Interfacing
Clothing (cotton, knit)
Clothing (cotton, woven)
Cotton/synthetic mix
Synthetic knit
Quilt fabric
Quilt batting
Silk
Other natural fiber
Other

Figure 3.
Filtration efficiency *versus* pressure differential for (A) single and (B) multiple layers of various materials for studies with most material pressure differentials <150 Pa. Single data points from Aydin 2020 and Rengasamy 2010 omitted from (B) for clarity.

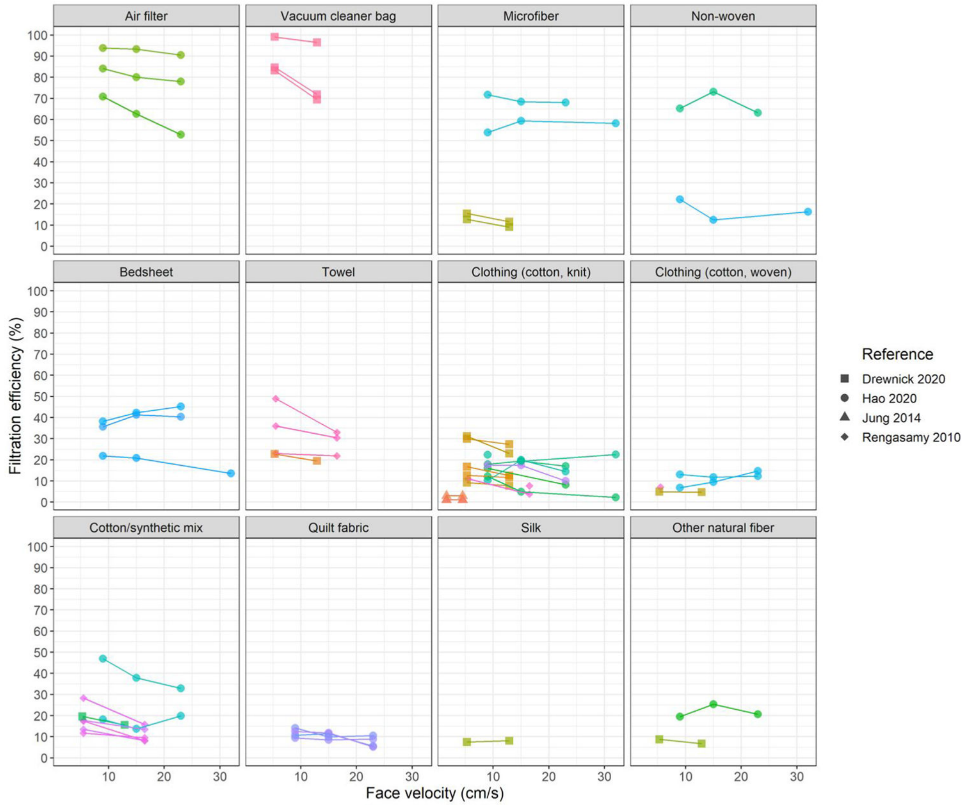
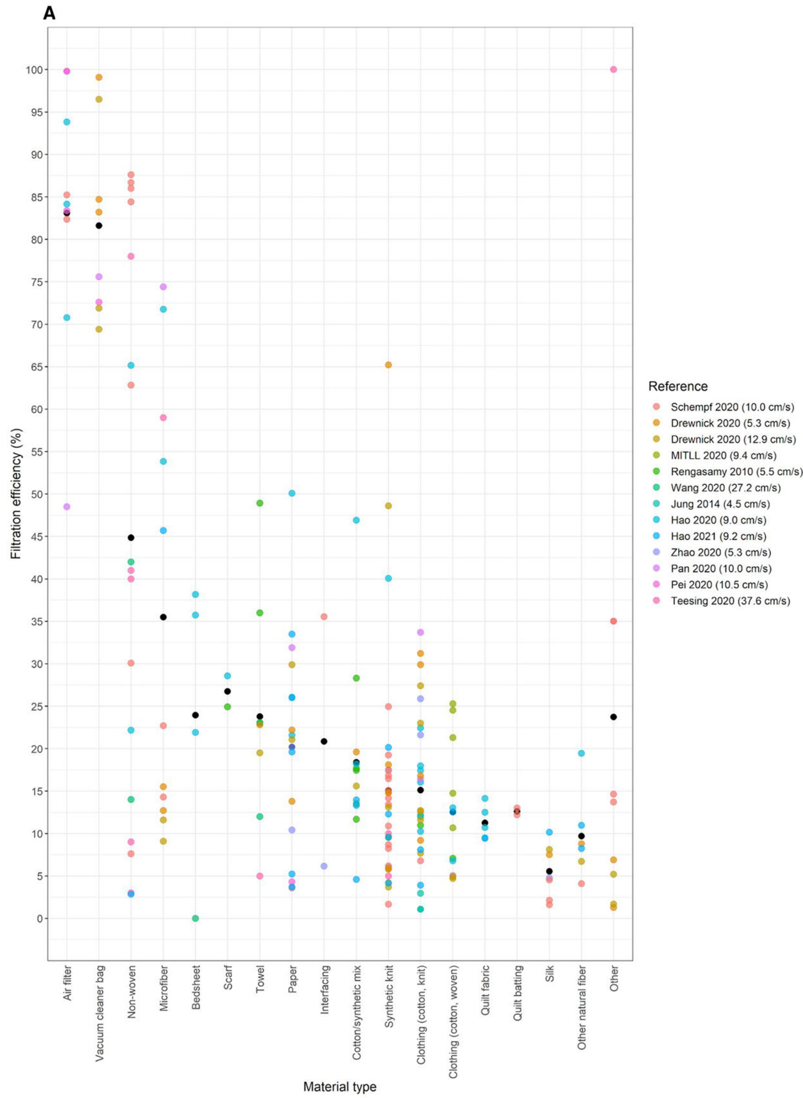


Figure 4.

Face velocity *versus* filtration efficiency for a single layer of various materials.


A
Filtration efficiency (%)
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
Air filter
Vacuum cleaner bag
Non-woven
Microfiber
Bedsheet
Scarf
Towel
Paper
Interfacing
Cotton/synthetic mix
Synthetic knit
Clothing (cotton, knit)
Clothing (cotton, woven)
Quilt fabric
Quilt batting
Silk
Other natural fiber
Other
Material type
Reference
Schempf 2020 (10.0 cm/s)
Drewnick 2020 (5.3 cm/s)
Drewnick 2020 (12.9 cm/s)
MITLL 2020 (9.4 cm/s)
Rengasamy 2010 (5.5 cm/s)
Wang 2020 (27.2 cm/s)
Jung 2014 (4.5 cm/s)
Hao 2020 (9.0 cm/s)
Hao 2021 (9.2 cm/s)
Zhao 2020 (5.3 cm/s)
Pan 2020 (10.0 cm/s)
Pei 2020 (10.5 cm/s)
Teesing 2020 (37.6 cm/s)

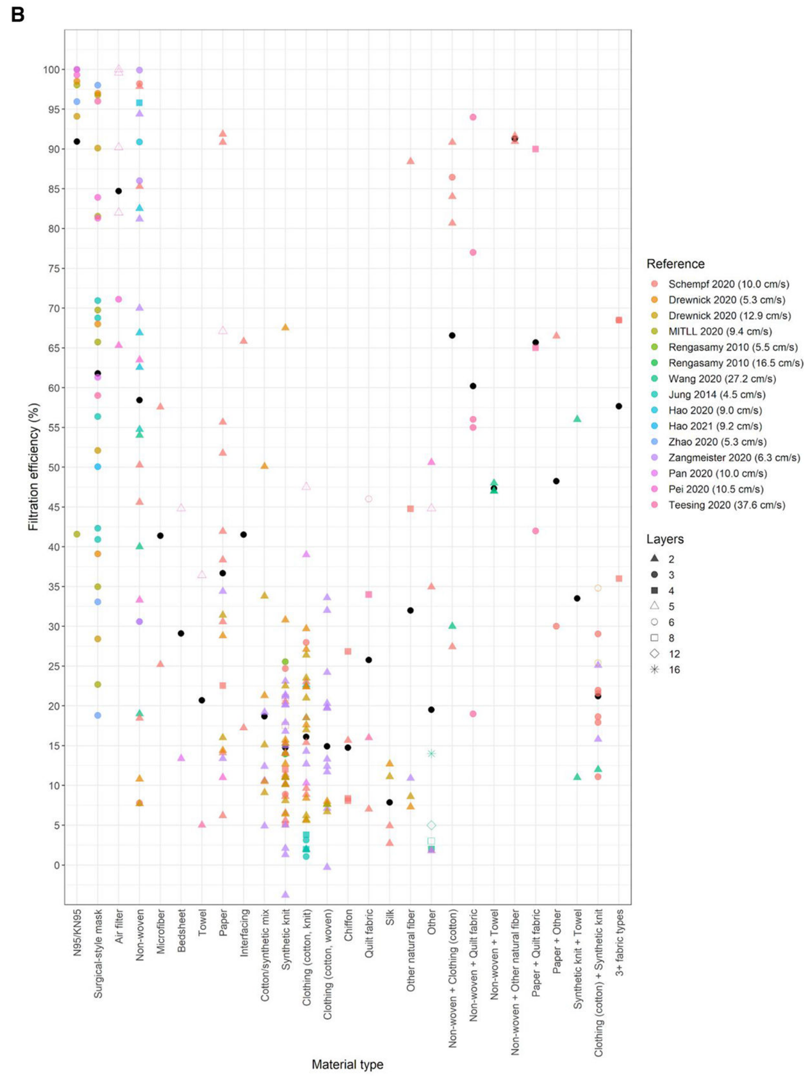


Figure 5.

Filtration efficiency for a (A) single and (B) multiple layer of various materials. Combinations of fabric with only one data point were omitted for clarity. The black dot indicates the mean filtration efficiency for each material type.

Table 1.

Maximum pressure differentials specified by various standards. Note that the measurement methods vary among the standards.

Standard	N95 / FFR1-3			Surgical masks		Fabrics for masks
	Face velocity	Inhalation	Exhalation	Flow rate	Inhalation and Exhalation	
EU[1] EN 149/13274	Inhalation: 95 L/min over 150 cm^2 = 10.6 cm/s	[4] 210/240/300 Pa	210 Pa	8 L/min over 4.9 cm^2 = 27.2 cm/s	[5,7] 40/40/60 Pa/cm^2 over 4.9 cm^2 (196/196/294 Pa)	[7] 70 Pa/cm^2
/14683, CWA 17553	Exhalation: 160 L/min over 150 cm^2 = 17.8 cm/s					
NIOSH[2] TEB-APR-STP-0059	85 L/min over 150 cm^2 = 9.4 cm/s	343 Pa	245 Pa	---	---	---
ASTM[3] F2299 or F2101	---	---	---	8 L/min over 4.9 cm^2 = 27.2 cm/s	[6,7] 50/60/60 Pa/cm^2 over 4.9 cm^2 (245/294/294 Pa)	---
China GB2626, YY0469	85 L/min over 25 mm-diameter sample (4.9 cm^2)	350 Pa	250 Pa	8 L/min over 25 mm-diameter sample (4.9 cm^2)	[7] 49 Pa/cm^2	

1. EU = European Union

2. NIOSH = U.S. National Institute for Occupational Safety and Health

3. ASTM International (formerly the American Society for Testing and Materials)

4. For Filtering Facepiece Respirators (FFRs) 1, 2, and 3, respectively

5. For surgical masks type I, II, and IIR, respectively.

6. For surgical mask barrier levels of 1, 2, and 3, respectively

7. Pressure per area does not have clear physical meaning and the theory behind these units is unclear.

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Table 2.

Quality assessment of studies that tested the filtration efficiency of particles

Reference	Peer-reviewed	Standard methods used?	Quantitative pressure differential available (Pa)	Quantitative filtration efficiency available	Fabrics described in enough detail so study could be replicated	Number of replicates
[26]	No	Non-standard	Yes	Yes	Yes	Not specified
[40]	Yes	Non-standard	Yes	Yes	Yes	9
[33]	No	Non-standard	Yes	Yes	Yes	2—8
[41]	Yes	Non-standard	Yes	Yes	Yes	3
[42]	Yes	NIOSH and KDFA	Yes	Yes	No	3
[32]	Yes, but followed by substantial corrections	Similar to ASTM F2299 PFE, but numerous deviations	No	Yes	No	7
[47]	Yes	Similar to ASTM F2299 PFE	No	Yes	Yes	1
[34]	No	Non-standard	No	Yes	Yes	9—27
MITLL (unpublished)	No	NIOSH (minor differences)	Yes	Yes	No	2
[35]	No	Non-standard	No	Yes	Yes	10
[48]	No	NIOSH (3 L/min instead of 85 L/min)	Yes	Yes	No	3
[49]	Yes	NIOSH	Yes	Yes	No	1
[50]	Yes	NIOSH (33 L/min instead of 85 L/min)	Yes	Yes	No	3
[51]	No	NIOSH (60 L/min instead of 85 L/min)	Yes	Yes	Yes	1
[52]	Yes	Non-standard	Yes	Yes	No	3
[53]	No	NIOSH (30 L/min instead of 85 L/min) & Chinese bacterial filtration efficiency (BFE) standard YY0469-2011	Yes	Yes	No	5
Wilson (unpublished)	No	Non-standard	No	No	Yes	1
[54]	Yes	EN 1822	Yes	Yes	Yes	5—11
[13]	Yes	NIOSH (32 L/min instead of 85 L/min)	Yes	Yes	No	3

Table 3.

Summary of experimental methods of studies that tested the filtration efficiency of particles

Reference	Area under test (cm^2)	Face velocity (cm/s)	Test particle	Particle size	Particle dispersion
26	0.785	From <10 to >300 for ΔP, 1500 for FE	Fluorescent beads	0.1 μm	Monodisperse
40	33.2 for filtration of particles <0.5 μm; 38.5 for filtration of particles 1—10 μm	5.3 and 12.9 ;2.8, 5.3, 9.1, 12.9, and 25.4 for evaluation of impact of face velocity on FE.	NaCl aerosol, charged and neutralized Ambient Aerosol	0.03 μm, 0.05 μm, 0.1 μm, 0.25 μm, 0.5 μm, 1 μm, 2.5 μm, 5 μm, 10 μm	Monodisperse & polydisperse
33	111, 67, 43	9.0, 15.0, 23.0	NaCl aerosols	0.3 μm MMAD	Monodisperse
41	43	9.2	NaCl aerosols	0.3 μm MMAD and 0.03-0.6 μm MMAD	Monodisperse & polydisperse
42	214	1.6 and 4.5	NaCl aerosols	0.075 ± 0.020 μm CMD	Polydisperse
32	59	Not determined	NaCl aerosols	<0.3 μm: 0.010—0.178 μm, >0.3 μm: 0.3—0.6 μm	Polydisperse
47	Not specified	Not specified	NaCl aerosols	0.006—0.22 μm	Polydisperse
34	0.785	297	Nanoparticles	0.01—10 μm (0.46 μm CAD)	Polydisperse
MITLL (unpublished)	3.8	9.4	NaCl aerosols	0.3—0.374 μm 0.3—10 μm (0.371 μm CMD); results presented are for particles 0.3-0.374 μm	Polydisperse
35	5.1	1650	Not specified	<0.1 μm	Polydisperse
48	4.9	10.0	NaCl aerosols	<5 μm	Monodisperse & polydisperse
49	12.6	10.5	NaCl aerosols	0.03, 0.05, 0.08, 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, and 1.0 μm	Monodisperse
50	100	5.5 for ΔP, 5.5 & 16.5 for FE	NaCl aerosols	Monodisperse: 0.02, 0.03, 0.04, 0.05, 0.06, 0.08, 0.1, 0.2, 0.3, 0.4 μm CMD & 0.075 ± 0.020 μmnm CMD	Monodisperse & polydisperse
51	100	10	NaCl aerosol	0.075 ± 0.020 μm CMD	Polydisperse
52	12.6	37.5	Ambient air	0.3, 0.5, 1.0 and 5.0 μm	Monodisperse
53	4.9 for ΔP; 100 for FE	27.2 for ΔP, 5 for FE	NaCl aerosols	0.075 ± 0.020 μm CMD	Polydisperse
54	4.0	6.3	NaCl aerosols	0.05—0.825 μm (not specified whether CMD or MMAD)	Polydisperse
13	100	5.3	NaCl aerosols	0.075 ± 0.020 μm CMD	Polydisperse