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Testing of commercial masks and respirators and cotton mask insert materials using SARS-CoV-2 virion-sized particulates: comparison of ideal aerosol filtration efficiency versus fitted filtration efficiency

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Abstract

Shortages in the availability of personal protective face masks during the COVID-19 pandemic required many to fabricate masks and filter inserts from available materials. While the base filtration efficiency of a material is of primary importance when a perfect seal is possible, ideal fit is not likely to be achieved by the average person preparing to enter a public space or even a healthcare worker without fit-testing before each shift. Our findings suggest that parameters including permeability and pliability can play a strong role in the filtration efficiency of a mask fabricated with various filter media, and that the filtration efficiency of loosely-fitting masks/respirators against ultrafine particulates can drop by more than 60% when worn compared to the ideal filtration efficiency of the base material. Further, a test method using SARS-CoV-2 virionsized silica nanoaerosols is demonstrated to assess filtration efficiency against nanoparticulates that follow air currents associated with mask leakage.

Graphical Abstract

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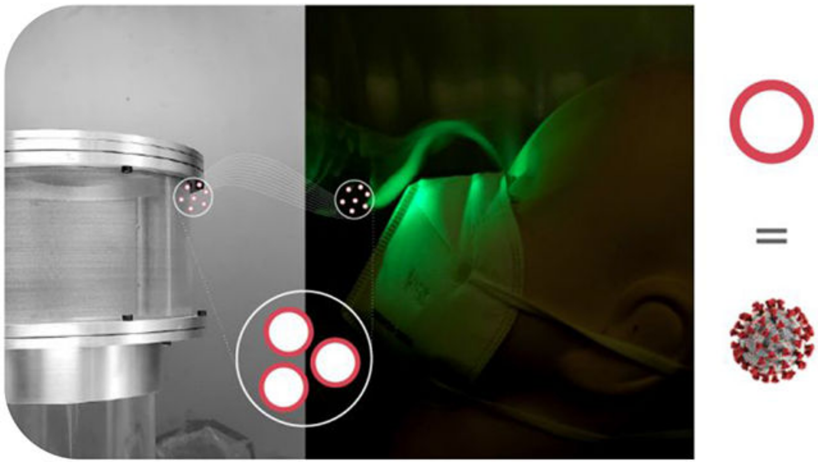
Author Contributions

The manuscript was written through contributions of all authors. / All authors have given approval to the final version of the manuscript.



Keywords

COVID-19; face mask; filtration; mask fit; aerosol; exposure testing

The use of masks and respirators as personal protective equipment (PPE) has garnered significant attention during the COVID-19 pandemic[1–4]. Shortages of certified PPE[5] (e.g., N95 and P100 respirators) required the general public and healthcare workers to fabricate practical immediate solutions from readily available materials[6]. While innovative, these improvised solutions often lack the testing required to verify their efficacy against penetration by external aerosols.

Multiple research groups have reported the performance of improvised filter materials[2,4,7,8]. Their findings have proven useful in discovering broadly available materials that can provide effective filtration against possible virus-carrying particulates. To date, these studies generally measure filtration efficiency of a base filter media in an ideal-fit scenario, where materials are challenged within a sealed container and leakage is not considered. Proper fit is important, and air permeability of the filter material plays a role in where particles may travel in a loosely fitting mask, especially where smaller particulates are concerned which may more easily follow air vectors[9,10] around an imperfect fit.

There is a critical knowledge gap between understanding the dependencies on the relationship between filter material properties and mask fit. Indeed, one of the benchmark testing standards, ASTM F2299:2017 “Standard Test Method for Determining the Initial Efficiency of Materials Used in Medical Face Masks to Penetration by Particulates Using Latex Spheres”, calls out many of these limitations, including that it “does not assess the overall effectiveness of medical face masks in preventing the inward leakage of harmful particles”[11]. This shortcoming has been demonstrated in the testing of medical masks before[12]; while the base material used to make common medical masks may demonstrate strong filtration efficiency according to established methods, the masks themselves often fail a basic quantitative fit test due to poor fit and resulting leakage[13].

A multitude of experts have proclaimed that airborne transmission of COVID-19 is a major and even primary source of the spread of the virus[14,15]. Use of face masks in public is especially critical to the reduction of virion exhalation by carriers of the virus; face masks significantly reduce the travel distance and concentration of viruscarrying particulates exhaled from the nose and mouth of COVID-19-positive individuals[1,3]. It is the opinion of the US Centers for Disease Control and Prevention (CDC) and multiple research teams that wearing of masks in public should be strongly encouraged due to the scientific evidence that mask usage reduces transmission from virus carrying-individuals, whether they are symptomatic, presymptomatic, or asymptomatic[1,3,8,16]. Recent evidence has shown, for instance, when two Missouri hair salon employees and their customers were wearing masks and other guidelines followed, symptomatic transmission of COVID-19 from the employees to the customers was avoided[17]. Therefore, wearing masks to protect others continues to be a main focus of CDC recommendations; "The cloth face cover is meant to protect other people"[18].

The present work seeks to address concerns that publication of only the ideal filtration efficiency of materials in perfectly sealed settings can give mask wearers a false sense of security when venturing into areas of high exposure risk; of specific concern are healthcare workers and persons known to be at-risk due to age or pre-existing conditions. While a material or combination of materials may reportedly offer high filtration efficiency in an ideal, well-sealed test scenario, masks made from or combined with these materials may not provide an equivalent level of protection when worn. Persons who must enter areas presenting high risk of infection should be careful to wear respirators that are properly fitted and rated for filtration efficiency according to fitted filtration efficiency data where possible, and fit testing should be performed in professional settings before shifts begin.

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) virions have been reported to range from 60-140 nm in size, with an average size of 125 nm typically referenced[19]. The current study was designed to evaluate the filtration efficiency of respirators, masks, and filter media against the smallest possible virus-carrying particulates, as recent data indicates that COVID-19 is transmitted by both large and small particles and small particles are especially at risk for remaining airborne for extended durations[20,21]. An investigation of the viability of minimally-sized particulates and individual virions as correlated to carrier particle size is presented elsewhere[22].

A polydisperse silicon dioxide nanoaerosol was generated according to published methods[23] and used as the challenge aerosol. Nanoaerosols regularly produced the average particle concentrations and size distribution shown in Figure 1. Summarily, a nanoaerosol with median diameter of around 40 nm was generated by tightly controlling the pressure and flow rate of nitrogen gas over tetraethyl orthosilicate before passing through a tube furnace at 850°C and out through a diffuser for ejection of the aerosol inside a 1.36 m^3 electropolished stainless steel enclosure built to an ANSI standard[24] with total particle concentrations measuring around 1,000,000 particles/cm^3. This method was chosen over the more common salt generation techniques due to the tunability of particle characteristics presented by the method and to offer an alternative procedure to supplement existing published data.

The ideal base filtration efficiency of selected materials was measured by cutting samples into discs and clamping without tension in cartridges measuring 37 mm in diameter. Sampling volume for filtration efficiency and pressure drop measurements was tuned to 0.5 LPM, inducing an airflow rate of 0.0465 LPM/cm^2 over the filter media. This rate represents a similar standardized flow rate as may be expected from a user under light activity (10-12 LPM), accounting for the ~20x larger surface area of a typical face mask or respirator, which will vary slightly depending upon design. All testing was performed within a Class 1000 cleanroom to provide minimal background particulate counts (<10 particles/cm^3).

Several commercially available masks and respirators were also tested as received without further modification. One variety of N95 respirator was evaluated (3M 8511) as well as a generic dust mask (Rite Aid MaxiMask), a medical mask (Medline), and a KN95 respirator (SupplyAid). A handmade dual-layer 600 thread count cotton mask was produced according to a popular design[25], in which various filter materials were inserted for filtration efficiency measurements, including: #4 coffee filter (Melitta), paper "shop" towel (Scott), Filtrete 1500 (3M), surgical wrap (Halyard), vacuum filter bag (Shop-Vac®), N95 nonwoven material (Hollingsworth and Vose) and FTR467 ULPA material (APC Filtration, Inc.). This cotton mask design includes a metal wire stitched into the bridge of the nose area and drawstrings on each side to enable a closer fit.

Masks/respirators were attached to a soft headform with the nasal cavity modified to accommodate intake ports for aerosol measurement equipment, connected using static-dissipative tubing. These masks/respirators were fitted to the headform consistently using physical markers to ensure equivalent fit across tested materials, with qualitative visual and tactile inspection ensuring no obvious gaps or crevices were present. This method was followed in lieu of quantitative fit testing in keeping with resources available to a typical user of a homemade face mask (namely, providing best fit possible by touch and sight) in order to capture filtration efficiency of masks in a real-use scenario.

Further, quantitative fit testing (i.e. using TSI Portacount) cannot differentiate between particles that penetrate the filter media versus particles that leak through areas of poor fit; fit factor is quantified as the ratio of measured particulate concentration outside versus inside the mask or respirator, where any particulates measured inside the mask are assumed to have arrived due to leakage. As many of the tested mask materials do not provide highly efficient particulate filtration, quantitative fit testing by existing methods is not appropriate. Instead, removal and reattachment of the masks between samplings was conducted to capture the statistical variance associated with this necessarily qualitative method, providing a quantitative measure of repeatability.

Nanoaerosol measurements were made using a Nanoscan 3910 scanning mobility particle sizer (SMPS; TSI, Inc.), sampling 0.5 LPM. Detailed measurements were taken at particle sizes of 60 nm and 125 nm at a rate of 1 per second for a total of 180 seconds per sample, with samples taken in triplicate for a total of at least 540 measurements per filter media tested. These two particle sizes were chosen to represent the minimum and average reported SARS-CoV-2 virion size, respectively[19].

The experimental configuration for ideal base filtration testing is illustrated in Figure 2 (left). The SiO_2 challenge aerosol described previously was generated in an electropolished steel environmental chamber designed according to the specifications of ANSI/CAN/UL 2904, measuring 4’x3’x3’ with cleanroom air (background total particulate concentration <10 particles/cm^3) injected at a rate sufficient to induce one full chamber air exchange per hour. Ports at the top of the chamber allowed for intake of the challenge aerosol, which passed through the sealed 37 mm cartridge on its way to the characterization equipment. A blank 37 mm cartridge was inserted for measurement of unfiltered aerosol concentration immediately before the measurement of every filter media sample, which formed the basis for filtration efficiency calculations. By this method, ideal filtration efficiency of various media using methods similar to those reported previously[2,7,26] was determined.

Filtration efficiency of masks and respirators (whether as-received in the case of commercial items, or as inserted in a 2-layer cotton mask in the case of filter media) was measured using the setup illustrated in Figure 2 (right). Alterations between the mask and ideal filtration testing setups were limited to the insertion of the headform into the chamber and the corresponding sampling location (located an equivalent distance from the diffuser as in the previous arrangement, albeit laterally rather than vertically). Samples were collected from a background line measuring the aerosol concentration just outside the mask/respirator immediately before the measurement of aerosol concentration through the nose of the masked headform in order to provide evaluation of filtration efficiency. Sampling occurred at a rate of 0.5 LPM; increasing the rate of airflow to 12 LPM by the addition of a second sampling pump through the second nostril of the headform did not significantly alter filtration efficiency measurements (measured particulate concentration changed by no more than 10% with the introduction of additional airflow).

The pressure drop across filter materials was measured using a dual input differential manometer (HHP886, Omega). Filter materials were mounted within the same 37 mm cartridge used for base filtration efficiency tests during pressure drop measurements at a rate of 0.5 LPM.

The base filtration efficiency of each tested mask material, as tested under ideal filtration circumstances within a sealed 37 mm cartridge, is reported in Figure 3. A single layer of 600 thread count cotton provided the lowest measured filtration efficiency (26.2% and 17.4% efficiency at filtering 60 nm and 125 nm particles, respectively), whereas a double layer of nonwoven N95 material and single layers of KN95, 3M 8511, and FTR467 ULPA materials demonstrated better than 98% filtration efficiency of both particulate sizes.

The measured pressure drop across each filter material as a means for quantifying relative air permeability is reported in Figure 4.

The filtration efficiency of all materials dropped significantly in mask form compared with the base ideal filtration efficiency of the material itself (Figure 5). Few materials provided a significant increase in filtration efficiency over the cotton mask. Notably, the dust mask provided negligible protection against 60 nm and 125 nm particles.

The 3M 8511 and KN95 respirators excelled in the base media filtration efficiency measurements, achieving greater than 98% filtration efficiency of the SiO_2 nanoaerosol. However, when fit to the headform as reported in Figure 5, filtration efficiency dropped to less than 40%, slightly better than the fitted cotton mask. To verify that this drop in efficiency was due to fit quality as opposed to other considerations (such as leakage at seams on the manufactured product), KN95 respirators were also sealed to the headform using a thermoplastic adhesive to provide a leak-free fit and tested. When sealed, the KN95 respirators provided filtration efficiency (Figure 5) very near to the base KN95 material filtration efficiency reported previously in Figure 3 (96.7 +/−0.2% when sealed to the headform compared to 98.1 +/− 1.6% base filtration efficiency of the KN95 material against 60 nm SiO_2 particles).

Most tested materials did not significantly improve cotton mask performance as an insert even if excellent base filtration efficiency was exhibited; in most cases, the cotton mask offered practically equivalent levels of protection without the insertion of the extra layer.

Among insert filter materials that did significantly increase filtration efficiency, air permeability and pliability appear to be important factors. If a material is relatively impermeable, airflows (and the aerosols they carry) may be more likely to follow contours around the mask into leaks and other areas of low resistance rather than seek to penetrate the filter material; cascade impactors take advantage of similar principles of differential inertia in order to segregate particulates by size[27]. More pliable materials were observed to qualitatively fit and fill the cotton mask more effectively, allowing for a closer fit to the face, reducing opportunities for leaks. Illustratively, while the FTR467 ULPA material exhibited the best base filtration efficiency of all measured materials (better than 99.8%), it provided the worst protection as an insert, offering no additional protection over the unfilled cotton mask; it was also the least permeable and least pliable material tested. Similarly, while a double layer of N95 material provided excellent filtration efficiency in base measurements while maintaining adequate permeability, its relative stiffness appears to have limited its efficacy as a cotton mask insert, though other unidentified factors may have also contributed. The highest performing mask insert materials (the surgical wrap and ShopVac® materials) exhibited a combination of strong base filtration efficiency and air permeability and were also among the most qualitatively pliable of the tested materials. There are likely other factors such as electrostatic interactions at play that were not quantified during these experiments. These results suggest that a combination of pliability and permeability should be considered alongside suspected or measured filtration efficiency when choosing a material for homemade mask or mask insert.

Fit clearly plays a critical role in the ability of a mask or respirator to protect its user from particulate inhalation. The as-received items did not show nearly the filtration efficiency when worn by the headform as was measured in base form despite apparent visual and tactile fit across the face of the headform, unless great effort was taken to seal the respirator-skin interface using adhesive. The bridge of the nose provides the most exaggerated contour difference and therefore presents the most likely region where leaks will be present, followed by the chin and jawline. These features may vary greatly across individuals, exacerbating fit issues; further research is needed to perform equivalent measurements using headforms of a range of representative dimensions to quantify how fit variance affects filtration efficiency.

In conclusion, our results demonstrate the importance of fit on filtration efficiency. Two outcomes are desired; firstly, while wearing a homemade mask can and does significantly reduce virion-sized particulate exposure (as-worn filtration efficiencies of 15-40% are reported here) masks of this style cannot provide the level of protection measured and more commonly reported in ideal-fit scenarios. Users should, therefore, exercise caution when entering areas of high exposure risk and consider using PPE known to create a better sealed fit, such as a half-or full-face respirator, when contact with infected persons is inevitable, and perform quantitative fit testing before shifts where possible. These implications also hold true for mask and respirator usage in other activities (such as construction), as fit affects the ability of the mask or respirator to protect the wearer against ultrafine particulates represented by the SiO_2 nanoaerosol used in this study.

Secondly, those seeking to create new PPE designs should prioritize the integration of fit testing along with penetration testing; we suspect the greatest source of leakage remains around the bridge of the nose. Innovation ensuring a better seal could provide a greater return in overall reduced viral exposure compared to the expenditure of effort toward improving base material filtration efficiency or the addition of sterilization agents.

It should also be noted that researchers have recently hypothesized that usage of masks that block large droplets but remain vulnerable to smaller aerosols may actually contribute to the development of immunity and occurrence of infection with reduced COVID-19 related symptoms[28]. In essence, allowing leakage of small particles that carry a lower viral load is suggested to provide opportunity for inoculation without overwhelming bodily defenses. If this nascent theory holds true, then the leakage of small aerosols in mild exposure situations may actually benefit the wearer (though vulnerable populations and those entering areas with known high exposure potential may still wish to take fullest precautions).

Mask usage remains a critical part of reducing exposure, lowering the rate of infection, and allowing economies to remain open in some capacity during a pandemic; these findings do not diminish the well-demonstrated fact that masks significantly reduce the travel distance and concentration of droplets and aerosols released by the mask wearer. Greater understanding of the relationship between filter media properties, mask fit, and filtration efficiency will lead to PPE configurations that afford better levels of protection to users while the activities required to sustain life are conducted.

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ABBREVIATIONS

PPE	personal protective equipment
CDC	US Centers for Disease Control and Prevention
SARS-CoV-2	severe acute respiratory syndrome coronavirus 2

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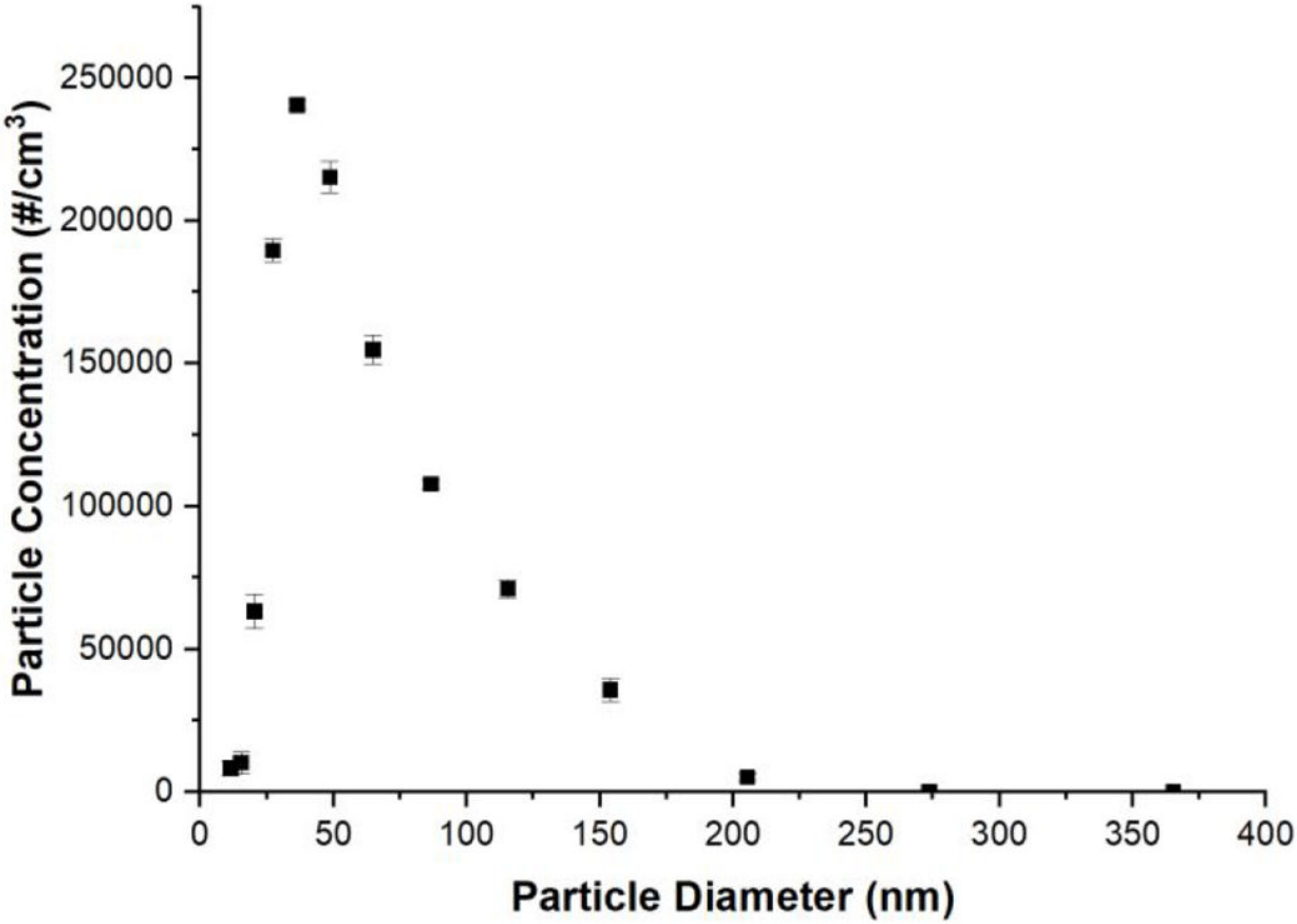

Figure 1.

A SiO_2 nanoaerosol was generated for filtration efficiency studies, with the peak concentration centered around 40 nm in diameter.

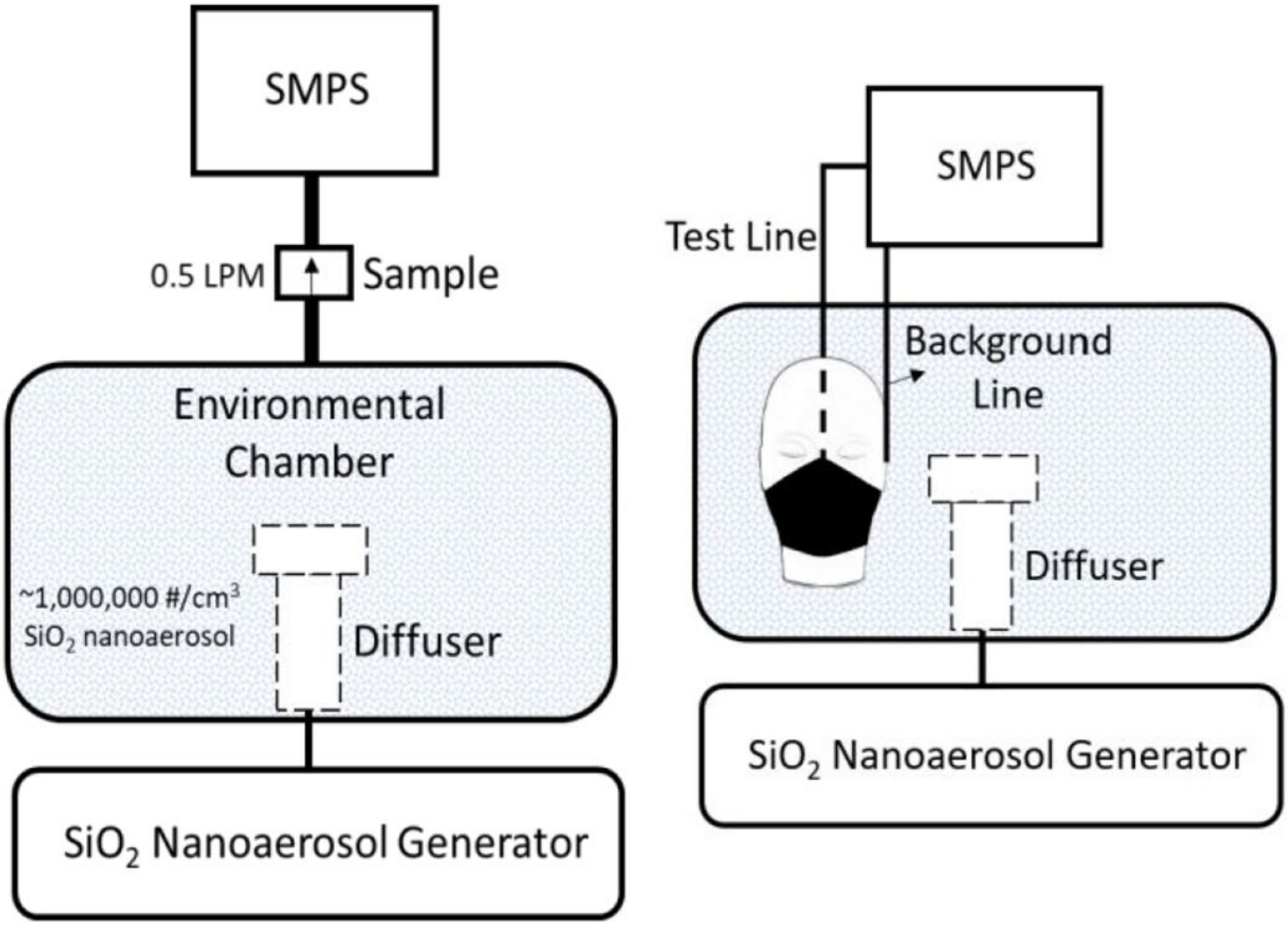

Figure 2.

Left: Base filtration efficiency of materials was tested in-line between a SiO_2 nanoaerosol-filled chamber and scanning mobility particle sizer (SMPS). Right: Filtration efficiency in mask form was tested using a soft headform modified with sampling ports in the nasal cavity. Components are not to scale.

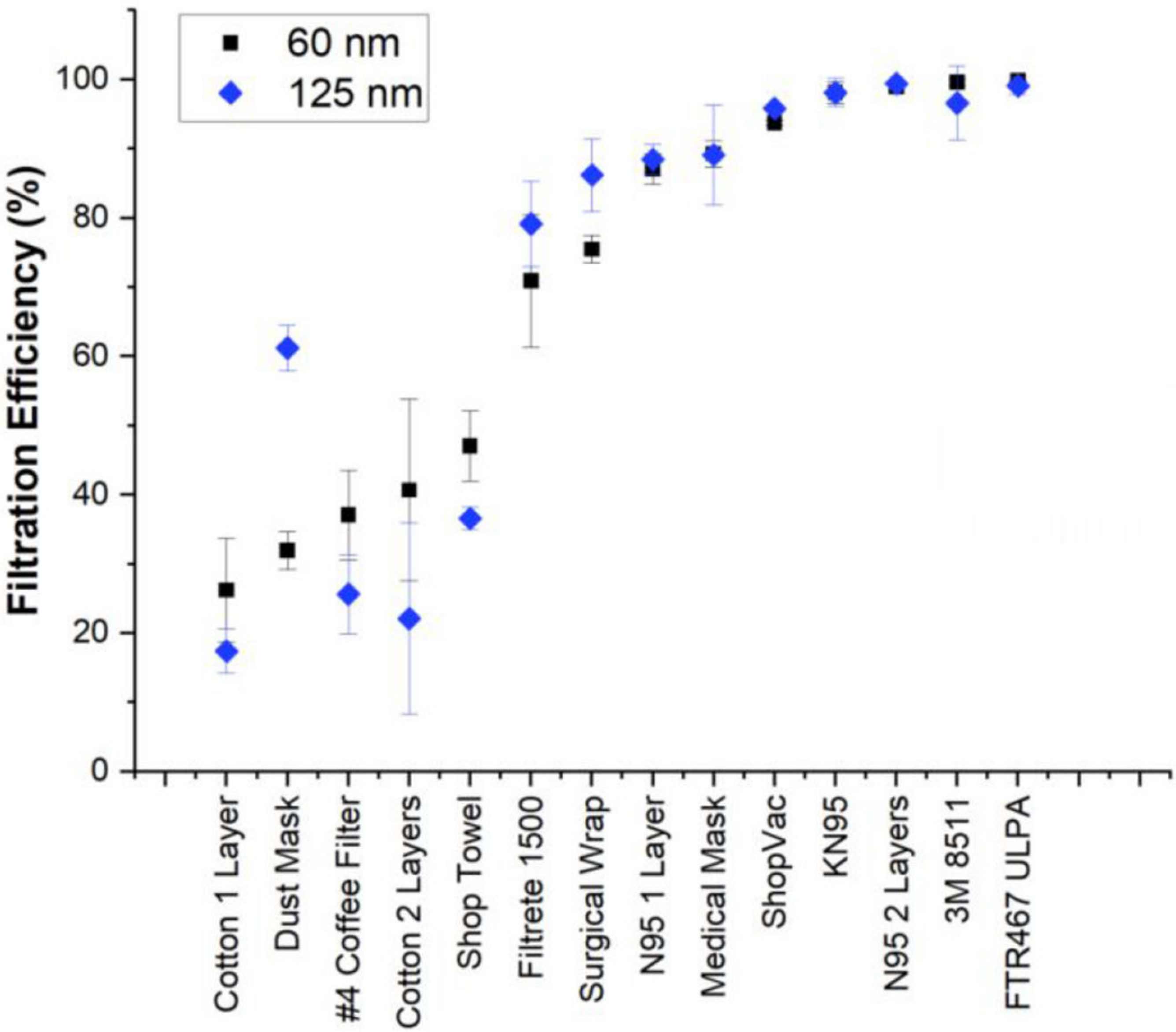

Figure 3.
The base filtration efficiency of each tested fabric ranged from as low as 17.4% to greater than 99.98%.

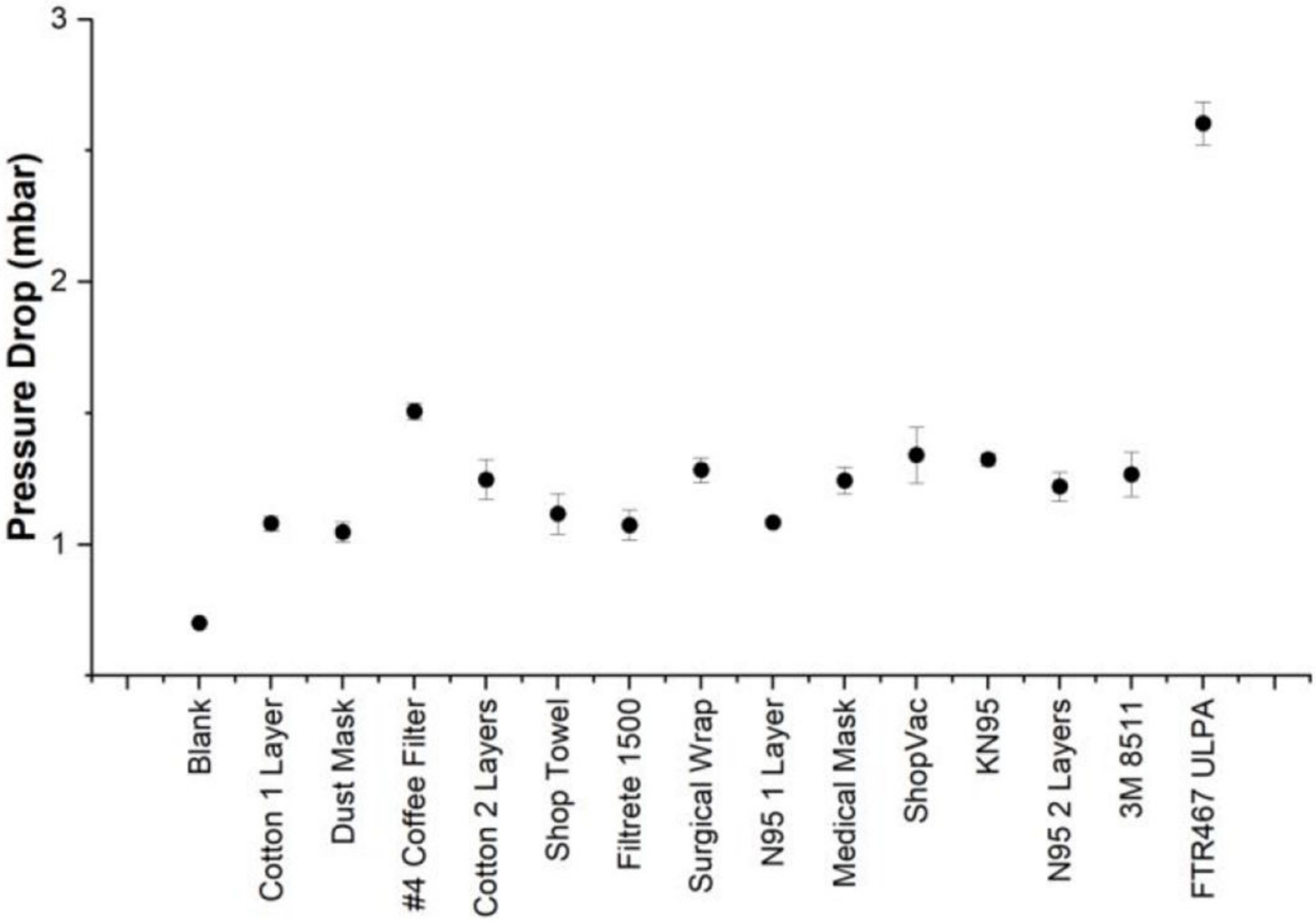

Figure 4.

The measured pressure drop across filter media were largely similar; the FTR467 ULPA material exhibited a pressure drop that would likely preclude use in a passive filtration mask, as it is designed for use in pleated, high surface area filter cartridges for powered applications.

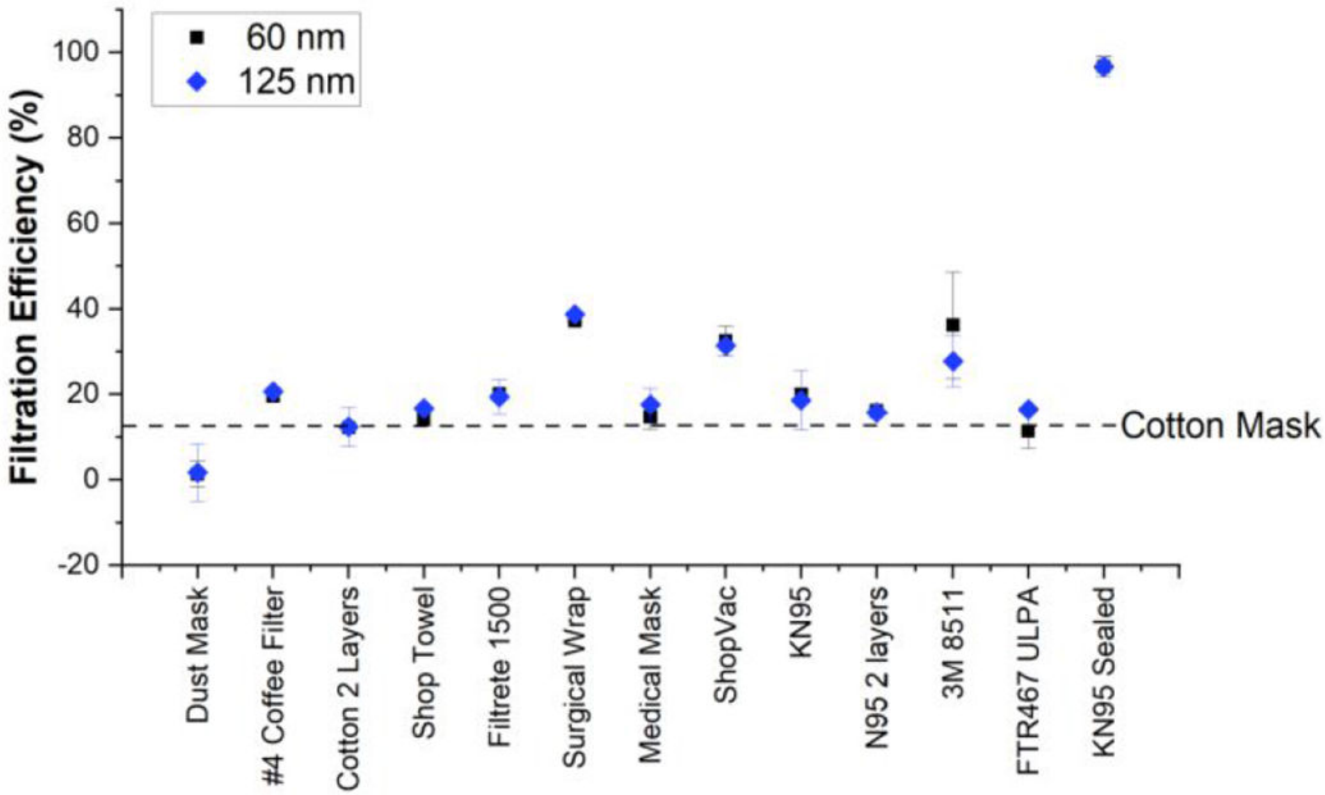

Figure 5.

When inserted into a 2-layer cotton mask, all filter materials exhibited a significant drop in filtration efficiency compared to measured base filtration efficiency. The 3M 8511 and KN95 respirators as well as the medical and dust masks were all tested as-received in mask form, whereas the remainder were tested through insertion between the two layers of the cotton mask. A KN95 respirator that was sealed to the headform before testing with thermoplastic adhesive (i.e. to demonstrate a leak-free fit) provided filtration efficiency very near its base filtration efficiency, proving that the cause of efficiency reductions was related primarily to fit quality.