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LETTER TO THE EDITOR

# Comment on "Aerosol Filtration Efficiency of Common Fabrics Used in Respiratory Cloth Masks"

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Recently, an article titled "Aerosol Filtration Efficiency of Common Fabrics Used in Respiratory Cloth Masks" was published in *ACS Nano*,[1] followed by a two-page correction.[2] This article and correction presents high filtration efficiencies and low pressure drops for some common fabrics such as woven cotton, silk, chiffon, and polyester. On the basis of the data presented, the original article concludes that certain combinations of textiles can be used to construct a filter with efficiencies >80% for particles with diameters of less than 300 nm and >90% for particles greater than 300 nm, approaching one of the criteria of the NIOSH 42 CFR 84 and ASTM F2100 certification standards, respectively, for respirators and surgical masks as recommended by the Center for Disease Control for infection prevention in healthcare settings.[3−8] The implications of these published claims[1,2] that "combinations of various commonly available fabrics used in cloth masks can potentially provide significant protection against the transmission of aerosol particles", along with the stated filtration efficiencies, have received broad popular attention, providing guidance and assurances on the construction of personal protection equipment for the general population.[9−14] The subsequent article correction is substantial and indicates that the stated filtration efficiencies were determined at very low flow rates; however, the actual flow rates are not provided. Our comment expresses concerns regarding the underlying data and conclusions, backed by quantitative measurements using similar materials. Here, we quantify the impact of the article's experimental design on conclusions relating to the materials' measured breathability and flow impedance of combined layers, as well as implications for filtration measurements and comparisons.

In the original article (submitted 4/18/20, accepted 4/21/20), Table 1 compared measured filtration efficiencies of materials for two particle size channels, <300 nm and >300 nm, as well as the measured pressure drop across the material.[1] The table specified that all entries were measured at a fixed volumetric flow rate of 1.2 CFM (34 L/min) and a similar Table S1 in the Supporting Information reports results on a different set of materials at a specified volumetric flow rate of 3.2 CFM (or 90.6 L/min). The correction[2] (submitted 6/4/20, posted 6/18/20) clarified to the reader that the volumetric flow rates were determined before any material was placed in the system. The correction did not specify how the flow rate responded to insertion of each material, seemingly because the flow rate was not measured with the material in place, but simply noted that the flow rates were "significantly lower (order of magnitude or more) than typical resting respiratory rates". Without information on both pressure and flow rate, the breathability is undetermined for all materials and hybrid combinations in the paper and claims that the materials are breathable should be reconsidered. By measuring pressure drop *versus* flow, we determine breathability for a number of textile samples similar to those used in the article and compare our results to the claims made in the paper. The breathability, characterized by a flow resistance, also allows us to estimate the flow rates corresponding to the pressures specified in the paper, and we discuss the implication of these resulting low and variable flow rates on filtration results and comparisons.

To set the stage for our later discussion, we note that the flow rate has direct and significant implications for the particle filtration conclusions. The face velocity $v$, or average speed of impingement of aerosol particles on the filter media, is a vital parameter separating filtration regimes which determine the capture of fine particulate matter.[15,16] $v$ can be determined from the volumetric flow rate $F$ divided by the effective filter area $A$. For a typical commercial respirator area of $A = 150$ cm$^2$ and a $F = 85$ L/min flow rate as used in NIOSH 42 CFR 84 Subpart K test,[3] one determines a face velocity $v = F/A$ of 9.4 cm/s.

In an effort to reproduce the measurements of ref 1, we measured pressure drop *versus* face velocity in our three independent laboratories at separate institutions using samples taken from a shared set of materials. We compared results and saw agreement within 5−20% for each of the samples tested. Figure 1a shows an example data set of pressure drop across 1, 2, and 4 layers of a 500 thread per inch (tpi) cotton/polyester

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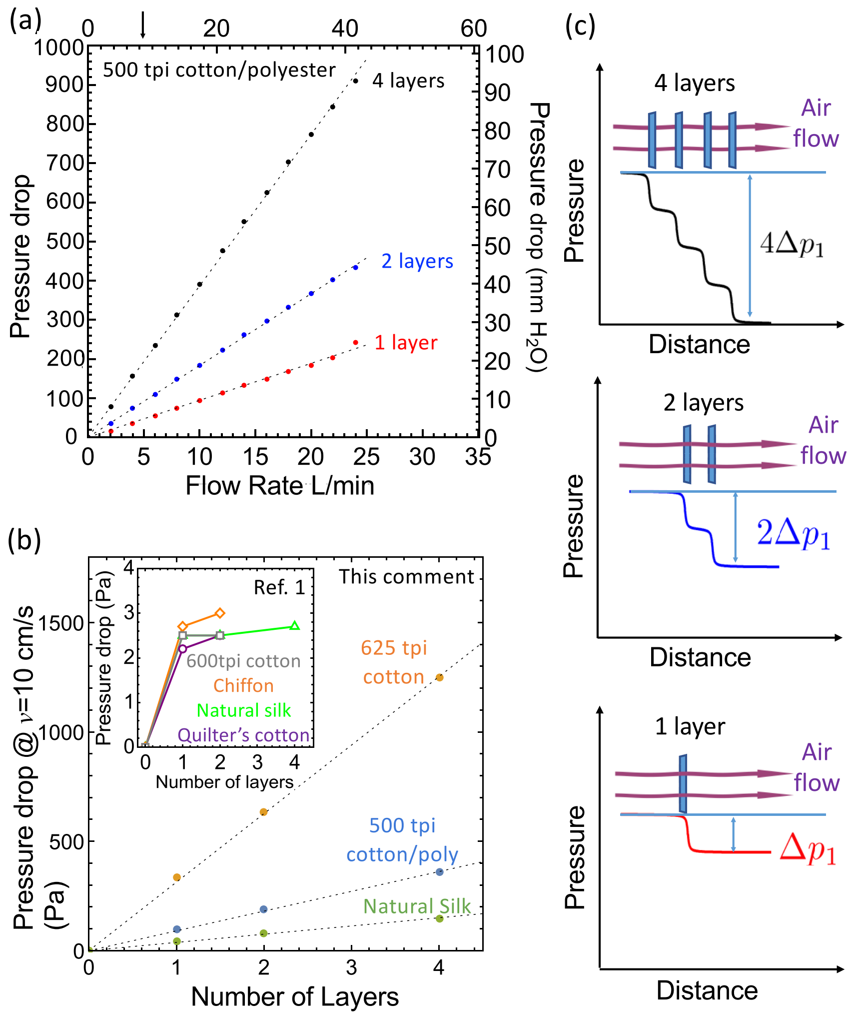


**Figure 1.** (a) Pressure drop *versus* face velocity for 1, 2, and 4 layers of 500 thread per inch cotton/polyester blend. The slope of each fitted line provides the impedance, which increases with the number of layers. The vertical arrow shows the face velocity relevant to NIOSH 42 CFR 84 tests of typical half-face respirators. (b) Pressure drop at 10 cm/s face velocity for three materials, showing the linear trend with layer number. The inset shows the layer dependence reported in ref 1. (c) Illustration of pressure dropping over 4, 2, and 1 layer at a fixed flow, demonstrating how additive contributions may be expected from independent layers under linear pressure−flow conditions.

blend, demonstrating a linear dependence of pressure drop on face velocity. We find similar linear behavior for every fabric or mask we have examined, including N95 respirators. The observed linear dependence of pressure drop $\Delta p$ on face velocity permits introduction[15,17,18] of the impedance $Z$, defined here as $\Delta p = Zv$, which quantifies breathability of a material. Table 1 summarizes the impedance results for samples of cotton at 300, 400, 625 tpi, a cotton/polyester blend with 500 tpi, and a natural silk averaged across our three independent laboratories. Note that the impedance varies significantly, depending on textile, number of layers, and thread count, with higher thread count of a given material generally having higher impedance. Impedance is important in considering mask performance because it relates directly to the comfort and breathability of the material when used as a face mask. The filter material impedance also influences the degree of protection of the mask because, as the impedance of the filter increases, the unfiltered tributary air flow through leaks in the mask also increases, reducing the overall degree of protection. For these reasons, low material impedance is as vital as high filtration efficiency in evaluating the protection of a mask design. Adherence to certification standards[3,4] ensures

**Table 1. Impedance Values for a Sample Set Averaged Across the Three Labs (Variation of Each Impedance Measurement Was at Most 20% across the Three Labs)**

| sample | number of layers | impedance (Pa s/cm) |
|---|---|---|
| 300 tpi cotton | 1 | 5.7 |
| | 2 | 11.3 |
| | 4 | 22.4 |
| 400 tpi cotton | 1 | 7.6 |
| | 2 | 16.1 |
| | 4 | 30.9 |
| 500 tpi cotton/polyester | 1 | 9.5 |
| | 2 | 18.6 |
| | 4 | 35.8 |
| 625 tpi cotton/polyester | 1 | 33.5 |
| | 2 | 63.1 |
| | 4 | 124.6 |
| natural silk | 1 | 4 |
| | 2 | 7.9 |
| | 4 | 14.8 |



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all physical property considerations relevant to safety are appropriate to their intended use.

At face velocities of 10 cm/s, we observe pressure drops ranging from 40 to 1250 Pa (4−127 mm $H_2O$). In addition to the variance, these are orders of magnitude higher than those reported in ref 1, shown in Figure 1b inset, which span 2.2−3.0 Pa, suggesting face velocities tested by the authors are orders of magnitude lower than typical regulatory test velocities. For reference, NIOSH 42 CFR 84 pass/fail criteria for a N95 respirator is 245 Pa (25 mm $H_2O$) for exhalation and 343 Pa (35 mm $H_2O$) for inhalation at the certification 85 L/min flow rate.[3] For a typical mask area of 150 cm$^2$, implying a face velocity $v$ = 10 cm/s, the resulting maximum impedances are 24.5 Pa s/cm for exhalation and 34.3 Pa s/cm for inhalation. Therefore, a single layer of 625 tpi cotton, in this case having a pressure drop of 335 Pa (34.1 mm $H_2O$) based on the impedance measurements given in Table 1, would not meet the minimum breathability criteria of N95 respirators. Four layers of 625 tpi cotton has a pressure drop of 1246 Pa (127.0 mm $H_2O$) at $v$ = 10 cm/s, greatly exceeding this breathability limit.

Figure 1b shows that the pressure drop at $v$ = 10 cm/s (or equivalently, the impedance of a sample) is proportional to the number of layers to a high degree of precision, and we note that this linear dependence is found for every material we have tested. One naturally expects this additive effect when the layers act independently and for small gas density variation across one layer (Figure 1c). In essence, this relation captures a familiar effect: two layers are half as breathable as one layer. In summary, we find the pressure drop to be linear in both layer number and flow for all samples as is commonly observed in a properly controlled flow system.

In contrast, ref 1 shows nonlinear behavior in both flow and layer number. The inset of Figure 1b shows the layer dependence of the pressure drop for some textiles reported in ref 1. All of the measured pressure values in ref 1 appear to be nearly the same value and do not show the observed ubiquitous linear dependence on the number of layers as expected. Flow dependence can also be deduced from the data for a N95 mask in ref 1. Standard N95 masks were measured by all three of our laboratories and found to have linear flow behavior over a wide range of face velocities and an impedance far higher than that implied by ref 1. In contrast, ref 1 finds, for a fully sealed N95 mask, that the pressure drop increases by a factor of 6 when the face velocity is increased from 10 to 26 cm/s, a factor of 2.6. Hence, data from textiles and N95 respirators suggest the presence of strong nonlinear behavior in both flow and layer number, which is not addressed in the article.

Observing Table 1 in ref 1, and using our impedance results, we can estimate the likely face velocity for the results provided in the article. Assuming the 600 tpi cotton sample of ref 1 has a similar impedance to our sample of 625 tpi cotton, as given in Table 1, then for one layer, where ref 1 reports a pressure drop of $\Delta p$ = 2.5 Pa, the resulting face velocity estimate gives $v = \Delta p/Z$ = 0.075 cm/s. For two layers of 625 tpi cotton, as the pressure drop is also reported as 2.5 Pa and the effective area was unchanged, the face velocity is estimated at 0.040 cm/s. Repeating this exercise for the coarser 500 tpi cotton/polyester blend sample gives $v$ = 0.263 cm/s for 1 layer and $v$ = 0.134 cm/s for 2 layers. As noted in the correction, these are orders of magnitude below typical velocities in regulatory tests,[3,4] which are typically 10−26 cm/s. Exceedingly low volume flow rates present experimental challenges and typically require long air exchange times; unless this were carefully controlled, anomalously high filtration efficiencies and large systematic uncertainties may result. In particular, systematic error associated with evaporation and aerosol interception in the tubing[19,20] could lead to an underestimate of the particulate count downstream and an overestimate of the filtration efficiency of the materials reported. Further, the schematic diagram of ref 1 appears to show a passive inlet on either side of the mask material, suggesting the mass flow in the apparatus is insufficiently controlled. For the apparatus to accurately measure pressure drops and filtration at controlled flows, at most, one open inlet or exhaust is permitted to ensure that flow continuity remains a determined system.[21,22]

Both theoretically[15−17] and experimentally,[15,22−24] filtration depends strongly on face velocity, as the article correction also noted. In particular, at very low face velocity, diffusive Brownian motion increases the path length of aerosol droplets in fibrous media; the resultant increased likelihood of fiber interception can lead to very high filtration efficiencies, as compared to the higher flow rates in the regime of human respiration.[15,16] Hence, in addition to the statement in the correction "conclusions and comparisons (with cloth fabrics) from our data regarding the N95 and surgical mask performance should not be drawn", it should also be added that no conclusion can drawn about comparative performance between different fabrics, multilayers of a given fabric, hybrid combinations, and certified filter media because they were measured under undetermined and highly variable flow conditions.

The correction acknowledges that the high filtration values measured are for very low pressure drop values associated with very low flow rates. The authors propose that reasonable volume flow rates, as would be required for breathing, the "strategy for cloth mask design would therefore be to increase the effective mask area significantly without increasing the seal perimeter in order to increase airflow, while retaining a low differential pressure, and a high filtration efficiency." While correct that a lower pressure drop can be expected at fixed flow for a larger area of material, the increase in area (and weight) would need to be larger by factors of 20 to 500 given typical textile impedances we have measured. It seems unlikely simple pleating could achieve an area increase of this magnitude, so innovative mask geometries would likely be required to enable this proposal. Further, care would need to be taken to ensure solutions did not create large internal volumes that could lead to dangerous configurations that hold oxygen-depleted exhaled air and reduce the oxygen accessible to the mask wearer.

As the authors of the correction[2] note "It is known that lower differential pressure across the filter can result in higher filtration efficiency." However, in the public interest, it is important to emphasize strongly that in the absence of a strategy for reducing the pressure by such a large factor, which we have argued above is unlikely, the efficiency rates given are in fact much higher than those reported for similar materials under realistic human respiratory conditions. For instance, the authors claim "the 600 TPI cotton is clearly superior with >65% efficiency at <300 nm and >90% efficiency at >300 nm". However, previous studies of common materials report filtration efficiency much lower than the claims of ref 1.[25−27] Recent results in the public domain report[28] that dual layers of some cottons only provide 7−23% filtration efficiency at a face velocity of 10 cm/s using standard NIOSH-certified test


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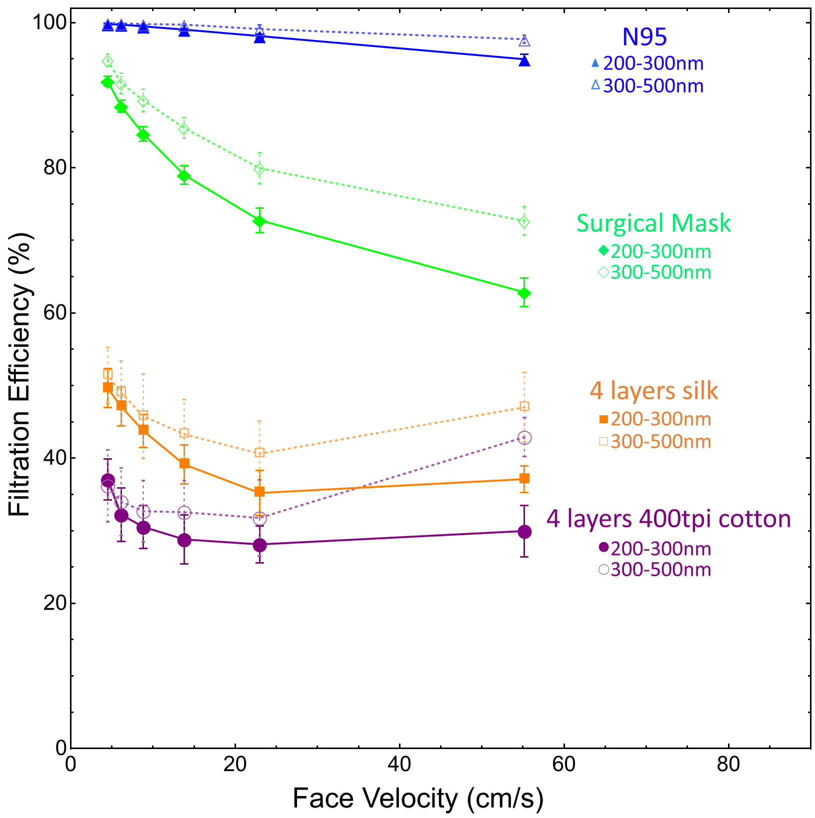


**Figure 2. Filtration efficiencies *versus* face velocity for four layers of 400 tpi cotton, four layers of silk, a surgical mask, and a N95 respirator. Efficiencies rise at low face velocities but are also all well below 60% at the lowest values measured for the cloth and silk samples. Note that four layers of 400 tpi cotton would not pass the NIOSH 42 CFR 84 criterion for breathability.**

equipment.[22] Other work[25] found that, at face velocities of 5.5 cm/s, efficiencies varied from only 3 to 33% for most cloth materials. More recently, examination of textiles has produced results which vary remarkably from those of ref 1[29−31] and find consistently that woven cotton textiles do not have high filtration efficiency.

Our own studies find filtration efficiencies for even four layer samples of cotton to be relatively low for face velocities ranging from 4 to 55 cm/s, tested against various challenge aerosols,[32,33] as shown in Figure 2. The filtration apparatus consisted of a filter holder connected to the inlet of an Airnet 201 particle detector using vacuum fittings, with the detector outlet connected to a small vacuum pump. The measured 2.6 L/min volume flow through the system is set by a critical orifice in the Airnet detector. The face velocity was adjusted by sandwiching the samples between laser cut annular rings with different size circular openings. Current outputs from the detector at two size bins (0.2−0.3 and 0.3−0.5 $\mu$m) were monitored using a microprocessor. Measurements were made with and without samples in place for 60 s and were used to determine the penetration ratio $P$ and filtration efficiency $f = 100 \times (1 - P)$. Importantly, the volume flow in the system did not change when samples were inserted into the filter holder. Ambient room particles served as the source for this measurement, but results were consistent with another system where we produced aerosol particles using a controlled combustion source from burned incense.

Figure 2 presents filtration efficiencies for four layers of 400 tpi cotton and four layers of silk for 200−500 nm particles as a function of face velocity, with a similar measurement of a certified N95 respirator and a surgical mask for comparison. All samples clearly show the expected enhancement of filtration efficiency at low face velocity. In our work on the materials presented in this comment, the filtration value we found for 4 layers of 625 thread per inch cotton at face velocities of 10 cm/s was 56% in the bin size 200−300 nm, but increases to 61% at 5 cm/s. Note that four layers of 400, 500, or 625 tpi samples had extremely high impedances to flow and would not be breathable if fashioned into a mask with a typical area of 150 $cm^2$.

In summary, our results on fabrics similar to those in ref 1 find pressure drops proportional to flow and layer number, and impedance values that indicate a number of combinations would not be breathable. The pressure drops found in ref 1 imply flow rates that are exceedingly small and would be difficult to achieve in practice. Furthermore, because the rates are necessarily different for every sample tested, filtration comparisons are suspect. Finally, we also point out that, when flow rates are so low, filtration efficiency numbers are likely strongly susceptible to measurement errors.

Importantly, while we have taken steps to clarify the quantitative conclusions of ref 1, we concur and emphasize that common materials are useful and are highly recommended to the public as reusable filtration media for masks during a pandemic. Mask construction should consider filtration efficiency and material flow impedance using a breathable number of layers and be constructed to fit well on the face. Common materials are not to be conflated with N95 masks in any way, as initially suggested by ref 1, but as stated in recent WHO guidance,[31] “The use of masks is part of a


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comprehensive package of the prevention and control measures that can limit the spread of certain respiratory viral diseases, including COVID-19."

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