Evaluating the efficacy of cloth facemasks in reducing particulate matter exposure

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<td>Shakya, Kabindra; University of Massachusetts, Amherst, Environmental Health Science Noyes, Alyssa; University of Massachusetts, Amherst, Environmental Health Science Kallin, Randa; University of Massachusetts, Amherst, Environmental Health Science Peltier, Richard</td>
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<tr>
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May 3, 2016

Morton Lippmann, PhD
Editor
Journal of Exposure Science and Environmental Epidemiology

Dear Dr. Lippmann,

Enclosed please find a revised manuscript entitled ‘Evaluating the efficacy of cloth facemasks in reducing particulate matter exposure’ by Kabindra M. Shakya, Alyssa Noyes, Randa Kallin and Richard E. Peltier.

We thank the editor for very helpful comments and suggestions that have helped to improve the manuscript. We have carefully edited the manuscript and addressed all comments by the editor. The responses to each comment are given in different color in the attached document. Any changes in the original manuscript are made with track changes. A separate copy of the manuscript without the track changes is also submitted.

Sincerely,

Richard E Peltier, MPH, PhD
Evaluating the efficacy of cloth facemasks in reducing particulate matter exposure

Kabindra M. Shakya, Alyssa Noyes, Randa Kallin, Richard E. Peltier

Department of Environmental Health Science, University of Massachusetts, Amherst

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Inexpensive cloth masks are widely used in developing countries to protect from particulate pollution albeit limited data on their efficacy exists. This study examined the efficiency of 4 types of masks (3 types of cloth masks and 1 type of surgical mask) commonly worn in the developing world. Five monodispersed aerosol sphere size (30-, 100-, and 500-nm, and 1- and 2.5 µm) and diluted whole diesel exhaust was used to assess facemask performance. Among the three cloth mask types, a cloth mask with an exhaust valve performed best with filtration efficiency of 80-90% for the measured PSL particle sizes. Two styles of commercially available fabric masks were the least effective with filtration efficiency of 39-65% for PSL particles, and they performed better as the particle size increased. When the cloth masks were tested against lab generated whole diesel particles, the filtration efficiency for three particle sizes (30, 100, and 500 nm) ranged from 15 to 57%. Standard N95 mask performance was used as a control to compare the results with cloth masks, and our results suggest cloth masks are only marginally beneficial in protecting individuals from particles smaller than 2.5 µm. Compared to cloth masks, disposable surgical masks are more effective in reducing particulate exposure.
Keywords: cloth facemasks, particulate exposure, surgical masks, developing nations

INTRODUCTION

Exposure to particulate matter is associated with respiratory and cardiovascular health effects and premature mortality\(^1\), and it reflects a global public health concern. Particles less than 2.5 µm (PM\(_{2.5}\)) are often considered more harmful than larger sized particles because of their ability to penetrate to human bronchi and lungs.\(^2\) The 68\(^{th}\) World Health Assembly passed a resolution in 2015 that underlined the importance of air pollution, attributing it to a cause of global health inequities.\(^3\)

Wearing personal facemasks has been thought to provide an immediate and short-term practical solution to individuals living in developing nations, who seek to reduce their exposure to high levels of air pollution without having to avoid highly polluted environments. Cloth masks are a popular choice, particularly in the developing world because they are inexpensive, locally-available, and washable. They usually consist of a synthetic or natural cloth material worn across the mouth and nose; they come with elastic straps, which can be worn behind the head or over the ears to maintain a fit to the face. There is anecdotal evidence that supports the widespread personal use of cloth masks, with local newspaper stories suggesting increases in retail sales of protective masks as air pollution rises.\(^4\) A few commercial vendors have launched products that claim to be highly effective in particle exposure reduction, however, these products are rarely the mask of choice by residents of developing nations due to their comparatively high cost and limited availability in the local marketplace. The most commonly encountered
inexpensive masks are marketed to users through popular media, including through fashion
shows in Beijing, suggesting these are products embraced by the public.\textsuperscript{5}

Anecdotal news reports, and our own personal observations, show cloth facemasks are
commonly used in many nations in South, Southeast, and Southwest Asia and beyond, including
Nepal, India, Bangladesh, China, United Arab Emirates, and Indonesia. It is thus plausible that
the combined population using such cloth facemasks could be easily estimated to reach many
millions of individuals. Such cloth facemasks are also used occupationally in agriculture\textsuperscript{6} and in
healthcare\textsuperscript{7-8}. However, peer-reviewed studies that evaluate the efficacy of such cloth masks are
limited\textsuperscript{9} despite its importance to millions of people. Most of these studies focus on industrial
exposure or respiratory infection prevention than on ambient airborne particles.

The work here reports on the effectiveness of cloth masks commonly worn by millions of
individuals, by comparing the cloth masks against commercially-available N95 masks. The main
research objective is to evaluate the filtration efficiency of various cloth facemasks against
standard particle of different sizes and the particles emitted from diesel combustion.

MATERIALS AND METHODS

Tested Masks

In this study, four different facemasks were assessed against laboratory-generated particles of
five different sizes under well-constrained laboratory conditions and using the state-of-the-art
particle instrumentation. Three cloth masks, and one pleated surgical mask, were purchased
from street vendors in Kathmandu, Nepal in 2014. Two commercially-available N95 masks
from two different manufacturers in the United States were also tested, including a rigid Moldex model [2701] and a 3M model [8200]. The Moldex mask (N95 mask2) and one of the cloth masks (cloth mask1) had a plastic and latex exhalation valve. N95 filtering facepiece respirators (N95 masks) are a class of certified respirators that have undergone a certified and laborious process to test their efficacy. Photographs of the tested cloth mask of three different types, along with two N95 masks are given in Figure S1 (Supplementary Section).

Polystyrene Latex Spherical Particles

Polystyrene latex (PSL) microspheres sizes were generated using a constant output atomizer (model 3076, TSI, Shoreview, MN). PSL are a colloidal solution of single-size latex spheres which, when aerosolized, produce a stream of monodisperse particles of a known size. PSL used in this study include Thermo Scientific Nanosphere Size Standards 30 nm (30 ± 1), 100 nm (102 ± 3), 500 nm (498 ± 9) and Duke Standards 1 µm (1.019 ± 0.015), and 2.5 µm (2.504 ± 0.027). PSL drops were added to deionized (DI) water (~300 ml) and pure nitrogen was used as the motive gas. The aerosol was passed through a silica-based water vapor denuder to dry the particles, and then into a controlled exposure chamber which contains an inanimate model (polystyrene mannequin head). Conductive tubing inserted inside the mannequin head extended from the mouth region and acted as an inlet behind any experimental masks, and carried samples to two particle sizing classifiers that detect the size and number of particles that penetrate the masks. These include an aerodynamic particle sizer (APS; Model: TSI 3321) and a scanning mobility particle sizer (SMPS; Model: TSI 3080 Electrostatic Classifier and TSI 3775 Condensation Particle Counter). These instruments are able to count and size particles with excellent precision and accuracy. A layer of parafilm was used around the edge of mask to
minimize leaks and to provide a better seal on the face of mannequin. Use of parafilm showed the increased efficiency of masks compared to those without parafilm, and thus all the experiments discussed here, were performed by using parafilm seal.

Diluted Whole Diesel Particles

Each mask was also tested against primary diesel particles generated in the laboratory to simulate real-world urban conditions. Whole exhaust from a single-cylinder diesel generator (Yanmar L100) operating under light load was injected into a 13 m$^3$ laboratory smog chamber made of fluorinated ethylene propylene (FEP), which then was diluted with zero air to bring the concentrations down to atmospherically relevant values that simulate a polluted environment in developing countries. Experiments were conducted with particle mass concentrations ranging from 45 µg/m$^3$ to 1060 µg/m$^3$. Commercially-available, ultralow sulfur diesel was used for combustion. Once diluted sufficiently, the aerosol from this chamber was passed onto the small sealed chamber constructed of stainless steel and aluminum, which contained the mannequin head (Figure 1) and mask. An experiment lasts for several hours, and wall loss corrections were observed by averaging concentrations before and after a mask trial.

Experimental setup

Experiments were performed separately for smaller sized particles (30-500 nm) using a SMPS (which is capable of sizing particles less than ~700 nm) and larger sized particles (1-2.5 µm) with the APS. During experiments, particles were continuously generated. Particles were first measured from the mannequin head without a mask to quantify a free exposure. The mannequins then were fitted with each mask type and the experiments were repeated. Eight
consecutive runs were made for each of the mask types; the first run was discarded, and only the
remaining seven runs from each experiment were used for the analysis. The first run was also
discarded for the free exposure condition. Particles were measured between mask changes (i.e.
no mask in place) in order to assess aerosol generation stability. The performance of each mask
type was compared against the average of the particles measured before and after testing the
specific mask type. A similar procedure for calculation was used for diesel generated particles.
Experiments were repeated three times for each mask type against PSL particles, and two times
against diesel generated particles at a total flow rate of 19 liters per minute. Each of these
experiments included eight sets of consecutive measurements. An experiment was also
conducted at the lower flow rate of 8 liters per minute to assess the effects of face velocity on
filtration efficiency.

A bypass flow design was used to introduce the aerosols in the chamber at 8 or 19 liters per
minute in order to assess for effects attributed to changes in face velocity across the mask
surface. The APS and SMPS sampled from this stream of aerosol. Unsampled air was passed
through a pump and was exhausted from the room. For each of the tested particles, a range of
particle size bins were used for data analysis. For 30 nm particles, we computed the total particle
counts to include three sizes (28.9, 30, & 31.1 nm), and for 100- and 500-nm particles, we
compared the particles of two sizes, 98.2 & 101.8 and 495.8 & 514 nm, respectively. Similarly,
for comparing 1 µm and 2.5 µm sized particles, we compared the particles of three sizes, 1.037,
1.114, & 1.197 µm and of two sizes, 2.458 & 2.642 µm, respectively. All other data from
outside these specific ranges was discarded. This was to ensure SMPS or APS instrument
imprecision bias had no effect on the results. Particle removal efficiency of each mask was
calculated by dividing the non-penetrated particles (difference between the particle counts from
mannequin with and without mask) by the total number of particles (no mask):

\[
\text{Efficiency (\%)} = \frac{\text{No Mask} - \text{Mask}}{\text{No Mask}} \times 100
\]

RESULTS

Performance of cloth facemasks against PSL standard particles (at 19 liters per minute)

PSL experiments allow an evaluation of specific size penetration across the different mask types
(Figure 2). Overall, cloth facemasks lead to a measurable reduction of total particle counts.
However, there was variability among the performance of cloth masks and also among different
particle sizes. Among the tested cloth mask types, a cloth mask with an exhalation valve (cloth
mask 1) performed better compared to the cloth masks without the exhalation valve (cloth masks
2 & 3). The filtration efficiencies of cloth masks 2 & 3 varied among the different PSL sizes.
The greatest penetration through the cloth masks 2 & 3 occurred for smaller particle sizes. It is
interesting to note that the two worst performing masks (cloth masks 2 & 3) performed better for
larger particle sizes; that is, they perform poorly on removal of the smallest particles.

Reproducibility of the two experiments was worse for two cloth masks (cloth masks 2 & 3). At a
flow rate of 19 liters per minute, average particle number concentrations of laboratory generated
PSL particles were \(2.77 \times 10^5\), \(1.05 \times 10^5\), and \(2.84 \times 10^3\) (\#/cm\(^3\)) for 30-, 100-, and 500-nm size
ranges, respectively. Because of the lower particle number concentrations, total raw counts were
used for comparing the particle sizes 1- and 2.5-\(\mu\)m. Raw counts are raw detected particle counts
but without any corrections for splitting across the channels.
Performance of cloth facemasks against PSL standard particles at lower flow rate (at 8 liters per minute)

When the experiments were repeated at the flow rate of 8 liters per minute, the efficiency of all types of masks improved (Figure 3). The largest increase was observed with two cloth masks (cloth mask 2 & 3) that performed worse at 19 liters per minute.

Performance of cloth facemasks against diesel-combustion particles

We also compared the performance of masks for particles generated from diesel engine exhaust. Not surprisingly, most of the diesel-combustion particles were of a size smaller than 500 nm (Figure 4). Unlike the PSL trials, where particles are present in discrete size ranges, diesel exhaust is generated in a polydispersed manner with particles present across the entire size range. This allows for an analysis across discrete sizes consistent with the PSL experiments, but also as a bulk efficiency calculation by integrating particles across the entirety of the size distribution from diesel.

The efficiency of cloth masks against particle of three specific sizes, 30 nm, 100 nm, and 500 nm are shown in Figure 5, which match the size bins chosen for study in the PSL experiments. Again, the cloth mask with an exhaust valve (cloth mask1) had the highest efficiency for 30 and 100 nm particle sizes among the three cloth mask types. But cloth mask2 outperformed cloth mask1 for 500 nm particles.

By assuming an average particle density, particle mass distribution was computed for the experimental size range (14.6-710.5 nm). This allows us to integrate the total mass of particles
across the entire size distribution, and better reflects real world exposures. Average particle
concentration for whole diesel was $4.13 \times 10^2$, $2.66 \times 10^4$, and $4.46 \times 10^3$ ($#/cm^3$) for 30-, 100-, and 500-nm size ranges, respectively. Average total mass concentrations from all the
experiments were $529 \pm 306 \mu g/m^3$. Cloth mask types 1 & 2 had filtration efficiency of 34% and
40% of particulate mass, respectively. Cloth mask3 performed the worst with the efficiency of
only 14% of particulate mass.

Comparison of three cloth face mask types with a surgical mask and N95 mask

Not surprisingly, N95 masks performed better compared to any cloth face masks for all particle
sizes (Figure 2). At a lower flow rate (Figure 3), the efficiency of cloth mask1 and surgical mask
was comparable to N95 masks suggesting that these masks are sensitive to flow rate. Cloth
mask1 had less penetration of smaller particles compared to the surgical mask. Observed
filtration efficiency of the surgical mask appears to be similar to cloth mask1, with overall
efficiency being slightly better for the surgical mask (Figure 3).

A single factor ANOVA test showed that efficiency of all masks against PSL particles were
significantly different to each other ($p<0.01$) except for 2.5 μm ($p=0.05$). An independent t-test
(Table S1) confirmed the performance differences between all cloth masks and N95 mask1
($p<0.01$) (Table S1) indicating that all cloth mask types were significantly different for all sizes
compared to the N95 mask1. There was no significant difference between the performances of
N95 mask1, the surgical mask, and the N95 mask2 for particle sizes of 30 and 500 nm.

Efficiency of cloth masks were better (69-94%) for large sized particles (>1 μm) compared (44-
93%) to small sized particles (<1 μm). However, N95 mask, a cloth mask with the exhalation
valve (cloth mask 1), and a surgical mask performed the best for this size range.

N95 mask1 performed better compared to N95 mask2 for PSL particles at a flow of 19 liters per
minute. The three replications of experiments using PSL particles were consistent for two N95
masks and the surgical mask (Figure 2). An exception to this was the 30 nm PSL for both N95
masks, and 500 nm PSL for N95 mask2 and surgical mask, where the results vary among the
replication of experiments (Figure 2). Variability among the repeated experiments was poorest
for cloth mask2 and cloth mask3 trials. The performance of the surgical mask was comparable
to those of the N95 mask for large sized particles (>1 μm). The results suggest greater protection
from particles by wearing a surgical mask (78%) and a cloth mask with the exhaust valve (cloth
mask1) (81%) compared to simple cloth masks (39-46%) (Figure 2).

Similar to PSL particles trials, the surgical mask also performed better compared to cloth masks
for diesel-generated particles (Figure 5). Filtration efficiency of cloth mask1 and cloth mask2
was better compared to cloth mask3. Cloth mask1 performed the best among the three cloth
masks except for 500 nm PSL. Interestingly, efficiency of cloth mask2 was also comparable to
cloth mask1. Consistent with results from the PSL particle experiments, N95 mask2 performed
worse than N95 mask1 in the whole diesel experiments.

DISCUSSION

Among the four mask types tested, cloth mask1 and the surgical mask were the most efficient in
preventing the penetration of PSL particles at both flow rates (8 & 19 liters per minute). When
these masks were tested against diesel-generated particles, the surgical mask was still reasonably effective, and the other mask types were less effective.

Unfortunately, the least effective two mask types (cloth masks 2 & 3) are also inexpensive, reusable, and are widely used in developing countries, implying they are a popular consumer choice where pollution mitigation is warranted. These two masks were purchased by our team for 10 Nepali rupees (1 US dollar = 95 Nepali rupees on the purchase date). Surgical masks also remain a popular choice to reduce personal exposure to particulates. Penetration through these two cloth masks (2 & 3) decreased when the particle size increases (Figure 2). Previous studies have reported an increase in efficiency with increasing in particle size for other types of respirators. Overall, simpler cloth masks (cloth mask 2 & 3) provide the least amount of apparent protection from particulate exposure, where penetration of particles through cloth masks was more than 50% for the smallest particles (<=500 nm) tested at a flow of 19 liters per minute.

Cloth mask1, the best performer of the cloth masks, also has a conical or tetrahedral shape, allowing the edge to conform closely to the mannequin’s contours. The worst performing cloth masks were simple rectangles with loops to connect behind the ear. It is possible that this design does not allow a sufficient fit on the mannequin, allowing the leakage of significant fraction of particles to penetrate through the mask. While this was apparently true on a test mannequin, the leaks from such shape of masks is also likely true for real-world uses.
In general, all tested masks were deficient in capturing diesel-generator exhaust particles. For these experiments, the particle mass averaged between 45 and 1060 µg/m$^3$ and was meant to reflect a highly polluted urban location. Only N95 mask1 and the surgical mask demonstrated particle removal efficiency above 65%, with the remaining masks removing fewer particles. This is an important concern because diesel exhaust comprises a significant fraction of urban emissions, particularly in developing nations where low-cost diesel vehicles are frequently used. These particles tend to be small, with typical mean particle sizes in the range of 100-150 nm, which suggests that they are especially difficult to capture on filtration material, even though they are known to induce a number of significant health impacts. Physical properties such as sizes, shapes, and aspect ratios affect the penetration of particles through the masks. Diesel particles have different and variable physical properties than uniform PSL particles, and maintaining identical diesel aerosol concentrations between different experiments was particularly challenging. Compared to the experiments with PSL particles, diesel particle concentrations delivered to the chamber were more variable for the control conditions (i.e. without mask), which might have resulted in additional uncertainty in filtration efficiency calculations between PSL particles and diesel particle experiments. Further studies with better-controlled and more consistent diesel particle concentrations are needed to better quantify the efficiency of cloth masks against diesel particles. Relevant, real-world aerosol exposure models – that is diesel and ambient particles – need additional focus and research because most facemask studies to date focus either on PSL, sodium chloride (NaCl), DOP (dioctyl phthalate) particles or biological media. Filtration efficiency of masks may depend on particle types, particle loading, or other features. For example, with the increased particle mass loading, penetration increases for DOP particles while it decreases for NaCl particles, though this is
based on results from aerosol exposures unlikely in the real world and we know even less about
facemask performance under ambient uses.

This study shows that wearing cloth masks reduced the exposure to some extent (~39-65% for
cloth mask 2 & 3, and 80-90% for cloth mask 1 against PSL particles for the flow rates of 8 and
19 liters per minute). The results also showed such masks could reduce personal exposure to
large (>1 micrometer in diameter) particles (Figures 2 and 3). This has clear public health
relevance as many millions of individuals are estimated to be living in regions with high levels of
particulate matter\textsuperscript{19-20}, many of who may choose to select an intervention to reduce their health
risk. However, a more informed choice in mask type is warranted because many of the least
expensive, and commonly used, cloth mask products perform poorly when compared to
alternative options available on the market.

The comparatively high degree of protection of the surgical masks was a surprising finding in
this study. These masks are typically made of woven polyester and cellulose with small elastic
ear loops. These types of masks are typically the least expensive, but are usually considered
disposable. Previous studies have shown that the penetration of particles through the surgical
mask was greater compared to N95 masks.\textsuperscript{11-13, 21} He et al.\textsuperscript{12} also observed particle penetration
across a surgical mask to be within 20% and concluded that surgical masks may be beneficial
only for the particles larger than 500 nm. Sande et al.\textsuperscript{22} observed the highest particle removal
efficiency from the simultaneous use of a respiratory mask (European equivalent of a N95
mask), followed by surgical mask, compared to using only homemade cloth mask. Our findings
show that compared to some cloth masks, surgical masks alone can provide better protection
from particulate exposure. While Sande et al. work suggest the simultaneous use of an N95 mask to reduce exposure, this is not likely an option for the developing world where these masks are not physically or economically available to the general population.

Mask fit on the selected model is one of the main uncertainties of this study and likely explains most of the experimental variability in this study. The experiments were performed on the mannequin head placed inside a controlled exposure chamber with a known concentration of specific size ranges. Real-world environmental conditions will be different and factors such as perspiration, relative humidity, wind, tidal volume, can all affect facial geometry and fit and may play a role on the filtration efficacy of such masks. The tested particles were latex spheres of same composition and the particles generated from the same source such as diesel combustion. The real environment samples will have highly variable particle components. While the testing used an inanimate model, real-world conditions were satisfactorily simulated across both monodispersed PSL testing, and a more diverse mixture of diesel pollutants, the latter of which more closely reflects common real-world exposure mixtures. Though we compared the penetration of particles through masks with the concentrations measured before and after testing of masks, there may be uncertainties that arise from not having the consistent aerosol concentrations throughout the experiments.

Typical respiratory rate for adults is 12-18 breaths per minute with an average of 8 liters of air inspired per minute. We performed the experiments at a constant flow rate (19 and 8 liters per minute) while human breathing flow is most likely to be of a sinusoidal pattern. The use of
variable flow rates would introduce significant uncertainty because it would vary the face
velocity across the mask itself, and this would affect particle residence time in the mask and alter
rates of particle loss from diffusion. Thus, flow rates of our experiments may not be
representative of variable human breath rates (normal breathing, deep breathing, light exercise,
etc.). Efficiency of all the masks was noted to improve at lower flow rates, thus, the flow rate and
the pattern of flow might also affect the efficiency of such masks. A decrease in collection
efficiency from N95 respirators compared to expected level against virions (20-300 nm) were
also reported by Balazy et al. Such decrease in efficiency was observed mainly at high
respiratory flow rates. Though the facemasks were tightly fit around the mannequin head, the
experimental setup might still be more prone to error than the real environment because of the
use of a continuous sampling flow. Uncertainties also exist in extrapolating observed results here
to real world conditions due to variability and differences in facial structures in these nations.
For example, mannequin heads used in this study are likely to be smaller than Asian faces (Table
S2). Filter penetration and faceseal leakage are the two principal factors that contribute to the
effectiveness of a mask. Particle collection processes are affected by diffusion,
electrostatic attraction, impaction, and interception depending on the particle sizes. Pressure
drop across the filter media can also lead to poor performance of the masks.
There were some important differences between our experimental setup and traditional N95
testing protocols, which are conducted with monodispersed particles that consist of dried NaCl
crystals. The samples collected here were collected at approximate 8 or 19 liters per minute. This difference is important because of the objective of the N95 test itself is to demonstrate the
effectiveness of a commercial product under worst case scenarios, whereas the methods
described here reflect more typical uses by the public. Further, a robust ‘fit test’ is indicated in
N95 testing, where masks are custom fit to conform to the geometry of a face; here, where an
expanded polystyrene mannequin head was used, may permit particles to penetrate into the
sampling area by small leaks around the mask. Even with parafilm, the leaks were not
completely avoided because expanded polystyrene does not mock skin and the leakage is not
completely sealed at the edges of the mask. As a result, 95% efficiency was elusive, even for
certified N95 masks where our results were closer to 76-92% efficiency. However, the results
observed were reasonable approximations of mask performance, and are likely to be reflective of
real-world applications of face masks by the general public where formal fit testing is rarely, if
ever, performed.

CONCLUSIONS

In selecting a choice to reduce personal exposure, a cloth mask with an exhaust valve performed
best compared to other styles, where efficiency of cloth masks against standard particle sizes of
five sizes, 30-, 100-, and 500-nm, and 1- and 2.5-μm, ranged from 39 to 65%. All masks
performed worse for diesel combustion particles compared to monodispersed particles. The
filtration efficiency of cloth masks for particles emitted from diesel combustion ranged 15 to
57% for total particle concentrations (for 30-, 100-, and 500-nm) and 13 to 40% for total
particulate mass. As expected, N95 masks were effective in removing most tested particles.
Disposable surgical masks were found to be surprisingly effective (efficiency of 78-94% for PSL
particles; 79% for whole diesel). Given the observed variability in mask efficacy across different
particle types and components, one cannot assume that the use of an inexpensive facemask leads
to significant decreases in exposure, especially if an individual makes personal choices to not
avoid high concentration environment because they assume they are protected from these contaminants. As a widely used public health intervention strategy, especially across the developing world, great care must be given in selection of inexpensive cloth masks for exposure reduction efforts.

CONFLICT OF INTEREST
The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS
REP, AN, KMS contributed to the design, method, and data analysis. AN, RK, and KMS performed the experiments. All authors contributed to the article.

Supplementary Information accompanies the paper on the Journal of Exposure Science and Environmental Epidemiology website (http://www.nature.com/jes).

REFERENCES


Figure 1. Experimental setup of (a) diesel generated particles (b) atomizer to generate PSL particles.
Figure 2. Efficiency of masks in removal of five PSL particle sizes at a flow rate of 19 liters per minute. Error bars are the standard deviation from three experiments.

85x53mm (300 x 300 DPI)
Figure 3. Efficiency of masks in removal of five PSL particle sizes at a flow rate of 8 liters per minute.
Figure 4. Size distribution of diesel combustion particles sampled with no mask and with various types of masks.

98x66mm (300 x 300 DPI)
Figure 5. Efficiency of masks in removal of diesel combustion particles (at a flow of 19 liters per minute). Only 30, 100, and 500 nm size range of diesel combustion particles are plotted here. Solid circles are the efficiencies computed for total mass (14.6 – 710.5 nm) penetration through specific mask type.

80x49mm (300 x 300 DPI)
Supplementary Information

Evaluating the efficacy of cloth facemasks in reducing particulate matter exposure

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This supplement contains additional results from statistical tests and photographs of the masks, and measurements of mannequin.

Table S1. p-values from an independent t-test between each of the mask types and N95 Mask1 (n = 14).

<table>
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Table S1. p-values from an independent t-test between each of the mask types and N95 Mask1 (n = 21) for the experiment at the flow rate of 19 liters per minute.

<table>
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<th>Mask types</th>
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<td>0.017</td>
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Table S2. Facial characteristics of mannequin (Yu et al., 2012)

<table>
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<th>Description</th>
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<td>Minimal frontal breadth</td>
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<tr>
<td>Head breadth</td>
<td>24</td>
</tr>
<tr>
<td>Nasal root breadth</td>
<td>1.5</td>
</tr>
<tr>
<td>Interpupillary breadth</td>
<td>5.5</td>
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<td>Face width</td>
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<td>Nose breadth</td>
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<tr>
<td>Bigonial breadth</td>
<td>10</td>
</tr>
<tr>
<td>Face length</td>
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</tr>
<tr>
<td>Nose length</td>
<td>4.8</td>
</tr>
<tr>
<td>Nose protrusion</td>
<td>2</td>
</tr>
</tbody>
</table>
Figure S1. Photographs of three different types of cloth masks examined in this study.

Reference
Corresponding Author Name: [Name]
Manuscript Number: [MST-01-123]

Reporting Checklist

This checklist is used to ensure good reporting standards and to improve the reproducibility of published results. Please respond completely to all questions relevant to your manuscript. For more information, please visit the journal's Guide to Authors.

- Check here to confirm that the following information is available in the Material & Methods section:
  - the exact sample size (n) for each experimental group/condition, given as a number, not a range;
  - a description of the sample collection allowing the reader to understand whether the samples represent technical or biological replicates (include how many animals, strains, culture etc.);
  - a statement of how many times the experiment was replicated in the laboratory;
  - definitions of statistical methods and measures: (For small sample sizes (n<5) descriptive statistics are not appropriate, instead plot individual data points;
    - very common tests, such as t-test, simple x² tests, Wilcoxon and Mann-Whitney tests, can be unambiguously identified by name only, but more complex techniques should be described in the methods section;
    - are tests one-sided or two-sided?
    - are there adjustments for multiple comparisons?
    - statistical test results, e.g., P values,
    - definition of 'center values' as median or mean;
    - definition of error bars as s.d. or s.e.m. or c.l.

Please ensure that the answers to the following questions are reported in the manuscript itself. We encourage you to include a specific subsection in the methods section for statistics, reagents and animal models. Below, provide the page number, or section and paragraph number.

Statistics and general methods

1. How was the sample size chosen to ensure adequate power to detect a pre-specified effect size? (Give section/paragraph or page #)

For animal studies, include a statement about sample size estimate even if no statistical methods were used.

2. Describe inclusion/exclusion criteria if samples or animals were excluded from the analysis. Were the criteria pre-established? (Give section/paragraph or page #)

3. If a method of randomization was used to determine how samples/animals were allocated to experimental groups and processed, describe it. (Give section/paragraph or page #)

For animal studies, include a statement about randomization even if no randomization was used.

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4. If the investigator was blinded to the group allocation during the experiment and/or when assessing the outcome, state the extent of blinding. (Give section/paragraph or page #)

For animal studies, include a statement about blinding even if no blinding was done.

5. For every figure, are statistical tests justified as appropriate?

Do the data meet the assumptions of the tests (e.g., normal distribution)?

Is there an estimate of variations within each group of data?

Is the variance similar between the groups that are being statistically compared? (Give section/paragraph or page #)

Reagents
6. Report the source of antibodies (vendor and catalog number)

7. Identify the source of cell lines and report if they were recently authenticated (e.g., by STR profiling) and assessed for mycoplasma contamination

Animal Models
8. Report species, strain, sex and age of animals

9. For experiments involving live organisms, include a statement of compliance with ethical regulations and identify the committee(s) approving the experiments.

10. We recommend consulting the ARRIVE guidelines (Prall et al, 2015) to ensure that other relevant aspects of animal studies are adequately reported.

Academic Journal Rechecklist – revised May 2015 2

216x295mm (300 x 300 DPI)
Human subjects
11. Identify the committee(s) approving the study protocol.

12. Include a statement confirming that informed consent was obtained from all subjects.

13. For publication of patient photos, include a statement confirming that consent to publish was obtained.

14. Report the clinical trial registration number (at ClinicalTrials.gov or equivalent).

15. For phase II and III randomized controlled trials, please refer to the CONSORT statement and submit the CONSORT checklist with your submission.

16. for tumor marker prognostic studies, we recommend that you follow the REMARK reporting guidelines.

Data deposition
17. Provide accession codes for deposited data. Data deposition in a public repository is mandatory for:
   a. Protein, DNA and RNA sequences
   b. Macromolecular structures
   c. Crystallographic data for small molecules
   d. Microarray data

Deposition is strongly recommended for many other datasets for which structured public repositories exist; more details on our data policy are available in the Guide to Authors. We encourage the provision of other source data in supplementary information or in unstructured repositories such as Dryad and DDBJ. We encourage publication of Data Descriptors (see Scientific Data) to maximize data reuse.

18. If computer code was used to generate results that are central to the paper’s conclusions, include a statement in the Methods section under “Code availability” to indicate whether and how the code can be accessed. Include version information as necessary and any restrictions on availability.

Associate Editor's Comments to Author:

The authors have addressed the majority of the reviewer comments and improved the manuscript, but there are several areas that require further revision, including:

1) Rather than editing and condensing the two introductory sentences in the abstract in response to one of the peer reviewer's comments, these sentences have simply been moved to the end of the abstract where they do not fit very well. It is recommended that the authors edit these sentences and come up with a more succinct background sentence for the front of the abstract.

Original two sentences are removed and it is edited as (lines 9-10):

Inexpensive cloth masks are widely used in developing countries to protect from particulate pollution albeit limited data on their efficiency exists.

We feel this this clarifies the abstract significantly.

2) In the materials and methods section, more is needed on why parafilm seals were used and how this was done (e.g., how much parafilm was applied). In addition, while discussed in the author responses, there is no discussion in the paper that experiments were conducted with and without parafilm seals and how these results compare. One of the peer reviewers identified this is as a significant issue in the paper, and more is thus needed to directly address this issue.

Following is added in lines 91-94.

A layer of parafilm was used around the edge of mask to minimize the leak and provide better seal on the face of mannequin. Use of parafilm showed the increased efficiency of masks compared to those without parafilm, and thus all the experiments, discussed here, were performed by using parafilm seal.

3) Materials and Methods, Diluted Whole Diesel Particles: What were the target concentrations- i.e., more specificity is needed than just "atmospherically relevant values."

Experiments were performed to simulate the atmospheric relevant values in developing countries with high particulate pollution. This is based on our own, and many published findings of aerosol conditions near roadways in the developed world, where concentrations were routinely found in these ranges. Followed lines have been edited (lines 102-103):

... to atmospherically relevant values in polluted environment in developing countries. Experiments were conducted with mass concentration ranging from 45 ug/m3 to 1060 ug/m3.

4) Materials and Methods, Experimental Setup: What are the three sets of experiments? 8 LPM, 19 LPM, ?

Manuscript has been edited for clarity. These were replications of experiments for the specific conditions and the experiments were to assess face velocity effects across filtration material. It now appears as: (lines 120-124):

Experiments were repeated three times for each mask type against PSL particles, and two times against diesel generated particles at a total flow rate of 19 liters per minute. Each of these experiments included eight sets of consecutive measurements. An experiment was also
conducted at the lower flow rate of 8 liters per minute to assess the effects of face velocity on filtration efficiency.

5) The first paragraph of the Results section is a mishmash of many results and requires re-organization and careful editing. There is too much here in one paragraph.

We agree with this concern and have shortened this paragraph. Two sentences on efficiency were removed because it was already described with the equation in the preceding section. Several other edits were employed as well for clarity.

6) The first paragraph of the Results section ends with the new statement that "Raw counts are the particle counts without any corrections." However, there is no discussion anywhere in the paper regarding what sorts of "corrections" were made.

Particle number concentrations, presented in the paper, are from SMPS instrument, and there are no additional corrections on this data. Raw counts are used for the measurement from Aerodynamic Particle Sizer (APS) instrument. "Raw counts are the lowest level of data representation, raw detected particle counts put into channels by size, but without any corrections. Mapping of particle size within the program can cause single counts to be split across two channels." We have added the sentence for clarification. It now appears as (lines 156-157):

Raw counts are raw detected particle counts but without any corrections for splitting across the channels.

7) There is now a new subheading "Performance of cloth facemasks against PSL standard particles at lower flow rate." Does this mean that the prior subheading "Performance of cloth facemasks against PSL standard particles" is describing higher flow rate results?

That’s correct. For clarity, 19 liters per minute/8 liters per minute has been added inside the brackets in the headings.

8) Information has now been added on average particle number concentrations for the diesel particle tests, but information should also be provided for particle mass concentrations since this paragraph is focused on particle mass concentrations.

Following sentence has been added (line 184):

Average total mass concentrations from all the experiments were 529 ± 306 µg/m3.

9) The Results section contains a number of new statements that are vague and unclear. For example, what is meant by the statement that "Interestingly, efficiency of cloth mask2 was also comparable." Comparable to what? The sentence "Compared to cloth mask1, the cellulose surgical mask worked better only for particles of large sizes..." does not appear to be entirely consistently with the data in Figure 3 because it looks like there is a marginally larger capture efficiency for 30 nm particles for the surgical mask. What is meant by the statement that "Though the three separate experimental trials performed for each of the mask types from PSL experiments were relatively robust"? In the subsection Comparison of three cloth face mask types with a surgical mask and N95 mask, a variety of findings are discussed that would appear to be specific to either the 18 LPM or 9 LPM tests, but the authors often do not specify the flow rate. Given that the authors are switching
between discussion of 18 LPM vs. 9 LPM results, there needs to be more consistent noting of which results are being discussed. Overall, the Results section should be carefully reviewed and tightened up.

The manuscript has been edited.

Line 220:

Interestingly, efficiency of cloth mask2 was also comparable to cloth mask1.

The previous sentence has been removed and the following is added (lines 193-195):

Observed filtration efficiency of the surgical mask appears to be similar to cloth mask1, with overall efficiency being slightly better for the surgical mask (Figure 3).

"Though the three separate experimental trials performed for each of the mask types from PSL experiments were relatively robust". This sentence is removed and following is added to the manuscript (lines 208-212):

The three replications of experiments using PSL particles were consistent for two N95 masks and the surgical mask (Figure 2). An exception to this was the 30 nm PSL for both N95 masks, and 500 nm PSL for N95 mask2 and surgical mask, where the results vary among the replication of experiments (Figure 2). Variability among the repeated experiments was poorest for cloth mask2 and cloth mask3 trials.

10) In response to a reviewer comment, there is now new text in the Discussion section stating that maintaining identical aerosol concentrations throughout the experiments was particularly a challenge for the experiments performed with diesel exhaust. However, there is no mention of this in the Methods or Results section- this should be noted with specific findings earlier. More is needed here, especially as to if/how this relates between the discordant findings for PSL versus diesel particles.

Following is added in the Method section (lines 106-107):

An experiment lasts for several hours, and wall loss corrections were observed by averaging concentrations before and after a mask trial.

The following sentence is now moved to lines 257-259:

Diesel particles have different and variable physical properties than uniform PSL particles, and maintaining identical diesel aerosol concentrations between different experiments was particularly challenging.

The following sentences were added to discussion section (lines 256-263):

Physical properties such as sizes, shapes, and aspect ratios affect the penetration of particles through the masks. Diesel particles have different and variable physical properties than uniform PSL particles, and maintaining identical diesel aerosol concentrations between different experiments was particularly challenging. Compared to the experiments with PSL particles, diesel particle concentrations delivered to the chamber were more variable for the control conditions (i.e. without mask), which might have resulted in additional uncertainty in filtration efficiency calculations between PSL particles and diesel particle experiments.
11) In the second paragraph of the revised Discussion section, there is a sentence that reads "Such an increase in efficiency with the particle size was not observed for all mask types, however." What is the basis for this sentence? Most show increased capture efficiency with size, and for those that do not, efficiencies are similarly high regardless of size. Please discuss in greater detail the basis for this sentence and potential explanations, or remove.

This sentence has been removed; this was an unintentional error.

12) Although one sentence has been added regarding the heterogeneous nature of diesel particles in terms of aerodynamic sizes, shapes, and aspect ratios, more is needed as to why lower capture efficiencies were observed for the diesel particle experiments for similarly sized particles as the PSL particles. This is barely touched upon in the manuscript and it requires more explanation. Also, does reference 17 address diesel particles?

The manuscript did appear that the reference no. 17 relates to diesel particles. This section has been edited (lines 256-271).

Physical properties such as sizes, shapes, and aspect ratios affect the penetration of particles through the masks.17 Diesel particles have different and variable physical properties than uniform PSL particles, and maintaining identical diesel aerosol concentrations between different experiments was particularly challenging. Compared to the experiments with PSL particles, diesel particle concentrations delivered to the chamber were more variable for the control conditions (i.e. without mask), which might have resulted in additional uncertainty in filtration efficiency calculations between PSL particles and diesel particle experiments. Further studies with better-controlled and more consistent diesel particle concentrations are needed to better quantify the efficiency of cloth masks against diesel particles. Relevant, real-world aerosol exposure models – that is diesel and ambient particles – need additional focus and research because most facemask studies to date focus either on PSL, sodium chloride (NaCl), DOP (dioctyl phthalate) particles or biological media. Filtration efficiency of masks may depend on particle types, particle loading, or other features. For example, with the increased particle mass loading, penetration increases for DOP particles while it decreases for NaCl particles18, though this is based on results from aerosol exposures unlikely in the real world and we know even less about facemask performance under ambient uses.

13) There is a new sentence referring to the fact that particle sources are less likely to be at such close proximity in the ambient environment as for these experiments. The authors should note how this may have affected their findings.

Related paragraph has been removed.

14) The Discussion remains very long and in places unfocused, and would benefit from additional revisions and more concise sentences. For example, the first paragraph (formerly the second paragraph) is just a repeated listing of results that were already described in the prior section without any "discussion."

Finally, the manuscript continues to need careful editing to improve upon the grammar and readability of the paper.

Manuscript has been thoroughly edited for grammar and readability.
Evaluating the efficacy of cloth facemasks in reducing particulate matter exposure

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Inexpensive cloth masks are widely used in developing countries to protect from particulate pollution albeit limited data on their efficacy exists. This study examined the efficiency of 4 types of masks (3 brands types of cloth masks and 1 type of surgical mask) commonly worn in the developing world. Five monodispersed aerosol sphere size (30, 100, and 500 nm, and 1- and 2.5 µm) and diluted whole diesel exhaust was used to assess facemask performance. Among the three cloth mask types, a cloth mask with an exhaust valve performed best with filtration efficiency of 80-90% for the measured PSL particle sizes. Two styles of commercially available fabric masks were the least effective with filtration efficiency of 39-65% for PSL particles, and they performed better as the particle size increased. When the cloth masks were tested against lab generated whole diesel particles, the filtration efficiency for three particle sizes (30, 100, and 500 nm) ranged from 15 to 57%. Standard N95 mask performance was used as a control to compare the results with the cloth masks. Inexpensive cloth masks are commonly used by individuals to protect against particulate matter exposure, particularly in the developing world where pollution levels are often the highest. However, there is very limited data on the efficiency of such cloth masks, despite their widespread use worldwide. Our results suggest cloth masks...
are only marginally beneficial in protecting individuals from particles smaller than 2.5 µm. Compared to cloth masks, disposable surgical masks are more effective in reducing particulate exposure.

Keywords: cloth facemasks, particulate exposure, surgical masks, developing nations

INTRODUCTION

Exposure to particulate matter is associated with respiratory and cardiovascular health effects and premature mortality, and it reflects a global public health concern. Particles less than 2.5 µm (PM$_{2.5}$) are often considered more harmful than larger sized particles because of their ability to penetrate to human bronchi and lungs. The 68th World Health Assembly passed a resolution in 2015 that underlined the importance of air pollution, attributing it to a cause of global health inequities.

Wearing personal facemasks has been thought to provide an immediate and short-term practical solution to people living in developing nations, who seek to reduce their exposure to high levels of air pollution without having to avoid highly polluted environments. Cloth masks are a popular choice, particularly in the developing world, because they are inexpensive, locally available, and inexpensive, washable, and relatively inexpensive to protect a user from exposure to ambient airborne particles. They usually consist of a synthetic or natural cloth material worn across the mouth and nose, with elastic straps, which can be worn behind the head or over the ears to maintain a fit to the face. There is anecdotal evidence that supports the widespread personal use of cloth masks, with local newspaper stories suggesting increases in
retail sales of protective masks as air pollution rises. A few commercial vendors have launched products that claim to be highly effective in particle exposure reduction, however, these products are rarely the mask of choice by residents of developing nations due to their comparatively high cost and limited availability in the local marketplace. The most commonly encountered inexpensive masks are marketed to users through popular media, such as including through fashion shows in Beijing, suggesting these are products embraced by the public.

Anecdotal news reports, and our own personal observations, show cloth facemasks are commonly used in many nations in South, Southeast, and Southwest Asia and beyond, including Nepal, India, Bangladesh, China, Abu Dhabi, Dubai United Arab Emirates, and Indonesia. It is thus plausible that the combined population using such cloth facemasks could be easily estimated to reach many millions of individuals. Such cloth facemasks are also used occupationally in agriculture and in healthcare workers. However, peer-reviewed studies that evaluate the efficacy of such cloth masks are limited despite its importance to millions of people and most of these studies focus on industrial exposure or respiratory infection prevention than on ambient airborne particles.

The work here reports on the effectiveness of cloth masks, a preferred approach to air pollution exposure mitigation commonly worn by millions of individuals, by comparing compared with the cloth masks against free exposure (no mask) as well as commercially-available N95 masks. The main research objective is to evaluate the filtration efficiency of various cloth facemasks against standard particle of different sizes and the particles emitted from diesel combustion.
MATERIALS AND METHODS

Tested Masks

In this study, four different facemasks were assessed against laboratory-generated particles of five different sizes under well-constrained laboratory conditions and using the state-of-the-art particle instrumentation. Three cloth masks and one pleated surgical mask were purchased from street vendors in Kathmandu, Nepal in 2014. Two commercially-available N95 masks from two different manufacturers in the United States were also tested, including a rigid Moldex model [2701] and a 3M model [8200]. The Moldex mask (N95 mask2) and one of the cloth masks (cloth mask1) had a plastic and latex exhalation valve. N95 filtering facepiece respirators (N95 masks) are a class of certified respirators that have undergone a certified and laborious process to test their efficacy. Photographs of the tested cloth mask of three different types, along with two N95 masks are given in Figure S1 (Supplementary Section).

Polystyrene Latex Spherical Particles

Polystyrene latex (PSL) microspheres sizes were generated using a constant output atomizer (model 3076, TSI, Shoreview, MN). PSL are a colloidal solution of single-size latex spheres which, when aerosolized, produce a stream of monodisperse particles of a known size. PSL used in this study include Thermo Scientific Nanosphere Size Standards 30 nm (30 ± 1), 100 nm (102 ± 3), 500 nm (498 ± 9) and Duke Standards 1 µm (1.019 ± 0.015), and 2.5 µm (2.504 ± 0.027).

PSL drops were diluted added with to deionized (DI) water (~300 ml) and pure nitrogen was used as the motive gas. The aerosol was passed through a silica-based water vapor denuder to dry the particles, and then into a controlled exposure chamber which contains an inanimate model (polystyrene mannequin head). Conductive tubing inserted inside the mannequin head...
extended from the mouth region and acted as an inlet behind any experimental masks, and carried the aerosol samples to two particle sizing classifiers that detect the size and number of particles that penetrate the masks. These include an aerodynamic particle sizer (APS; Model: TSI 3321) and a scanning mobility particle sizer (SMPS; Model: TSI 3080 Electrostatic Classifier and TSI 3775 Condensation Particle Counter). These instruments are able to count and size particles with excellent precision and accuracy. A layer of parafilm was used around the edge of mask to minimize the leaks and to provide a better seal on the face of mannequin, where the inlet of conductive tubing protrudes. Use of parafilm showed the increased efficiency of masks compared to those without parafilm, and thus all the experiments discussed here, were performed by using parafilm seal.

Diluted Whole Diesel Particles
Each mask was also tested against primary diesel particles generated in the laboratory to simulate real-world urban conditions. Whole exhaust from a single-cylinder diesel generator (Yanmar L100) operating under light load was injected into a 13 m³ laboratory smog chamber made of fluorinated ethylene propylene (FEP), which then was diluted with zero air to bring the concentrations down to atmospherically relevant values that simulate a polluted environment in developing countries. Experiments were conducted with particle mass concentrations ranging from 45 μg/m³ to 10060 μg/m³. Commercially-available ultralow sulfur diesel was used for combustion. Once diluted sufficiently, the aerosol from this chamber was passed onto the small sealed chamber constructed of stainless steel and aluminum, which contained the mannequin head (Figure 1) and mask. An experiment lasts for several hours, and wall loss corrections were observed by averaging concentrations before and after a mask trial and the
particle concentrations from diesel exhausts was not the same throughout the experiment. We
used the blank measurement in between the testing of each mask type, and used them as the
reference for the comparison.

Experimental setup

Experiments were performed separately for smaller sized particles (30-500 nm) using a SMPS
(which is capable of sizing particles less than ~700 nm) and larger sized particles (1-2.5 µm)
with the APS. During experiments, particles were continuously generated. Particles were first
measured from the mannequin head without a mask to quantify a free exposure. The
mannequins then were fitted with each mask type and the experiments were repeated. Eight
consecutive measurements runs were made for each of the mask types; the first run was
discarded, and only the remaining seven runs from each experiment were used for the analysis.
The first run was also discarded for the free exposure condition. Particles were measured
between the changes of mask types mask changes (i.e. no mask in place) in order to assess
aerosol generation stability. The performance of each mask type was compared against the
average of the particles measured before and after testing the specific mask type. A similar
procedure for calculation was used for diesel generated particles. Three sets of experiments
were conducted. Experiments were repeated three times for each mask type against PSL particles,
and two sets of experiments times against diesel generated particles at the total flow rate of 19
liters per minute. Each of these experiments had included eight sets of consecutive measurements.
An experiment was also conducted at the lower flow rate of 8 liters per minute to assess the
effects of face velocity on filtration efficiency.
A bypass flow design was used to introduce the aerosols in the chamber at 8 or 19 liters per minute in order to assess for effects attributed to changes in face velocity across the mask surface. The APS and SMPS sampled from this stream of aerosol. Unsampled air was passed through a pump and was exhausted from the room. For each of the tested particles, a range of particle size bins were used for data analysis. For 30 nm particles, we computed the total particle counts to include three sizes (28.9, 30, & 31.1 nm), and for 100- and 500-nm particles, we compared the particles of two sizes, 98.2 & 101.8 and 495.8 & 514 nm, respectively. Similarly, for comparing 1 µm and 2.5 µm sized particles, we compared the particles of three sizes, 1.037, 1.114, & 1.197 µm and of two sizes, 2.458 & 2.642 µm, respectively. All other data from outside these specific ranges was discarded. This was to ensure SMPS or APS instrument imprecision bias had no effect on the results. Particle removal efficiency of each mask was calculated by dividing the non-penetrated particles (difference between the particle counts from mannequin with and without mask) by the total number of particles (no mask):

\[
\text{Efficiency} (\%) = \frac{\text{No Mask} - \text{Mask}}{\text{No Mask}} \times 100
\]

**RESULTS**

Performance of cloth facemasks against PSL standard particles (at 19 liters per minute)

PSL experiments allow an evaluation of specific size penetration across the different mask types (Figure 2). Overall, cloth facemasks lead to a measurable reduction of total particle counts. However, there was variability among the performance of cloth masks and also among different particle sizes, though certain masks performed better than others. The filtration efficiencies of cloth masks 2 & 3 varied among the different PSL sizes. Among the tested cloth mask types, a
cloth mask with an exhalation valve (cloth mask 1) performed better compared to the cloth masks without the exhalation valve (cloth masks 2 & 3). The filtration efficiencies of cloth masks 2 & 3 varied among the different PSL sizes. The greatest penetration through the cloth masks 2 & 3 occurred for smaller particle sizes. It is interesting to note that the two worst performing masks (cloth masks 2 & 3) performed better for larger particle sizes; that is, they perform poorly on removal of the smallest particles. Reproducibility of the two experiments was worse for two cloth masks (cloth masks 2 & 3). This comparison is made from the average number of particles from each of the seven measurements from three experiments at the flow of 19 liters per minute. Measurements under a “no mask” condition were used as a control and all the masks were compared with this control. At a flow rate of 19 liters per minute, average average particle number concentrations of laboratory generated PSL particles were $2.77 \times 10^5$, $1.05 \times 10^5$, and $2.84 \times 10^3$ $\text{#/cm}^3$ for 30-, 100-, and 500-nm size ranges, respectively (at a flow of 19 liters per minute for the measurement by SMPS instrument). Because of the lower particle number concentrations, total raw counts were used for comparing the particle sizes 1- and 2.5-µm (for the measurement by APS instrument). Raw counts are the raw detected particle counts without any corrections for splitting across the channels.

Performance of cloth facemasks against PSL standard particles at lower flow rate (at 8 liters per minute)

When the experiments were repeated at the flow rate of 8 liters per minute, the efficiency of all types of masks improved (Figure 3). The largest increase was observed with two cloth masks (cloth mask 2 & 3) that performed worse at 19 liters per minute.
Performance of cloth facemasks against diesel-combustion particles

We also compared the performance of masks for particles generated from diesel engine exhaust. Not surprisingly, most of the diesel-combustion particles were of a size smaller than 500 nm (Figure 4). Unlike the PSL datatrials, where particles are present in discrete size ranges, diesel exhaust is generated in a polydispersed manner, with particles present across the entire size range. This allows for an analysis across discrete sizes consistent with the PSL experiments, but also as a bulk efficiency calculation by integrating particles across the entirety of the size distribution from diesel.

The efficiency of cloth masks against particle of three specific sizes, 30 nm, 100 nm, and 500 nm are shown in Figure 5, which match the size bins chosen for study in the PSL experiments. Again, the cloth mask with an exhaust valve (cloth mask1) had the highest efficiency for 30 and 100 nm particle sizes among the three cloth mask types. But cloth mask2 outperformed cloth mask1 for 500 nm particles.

By assuming an average particle density, particle mass distribution was computed for the experimental size range (14.6-710.5 nm). This allows us to integrate the total mass of particles across the entire size distribution, and better reflects real world exposures. Average particle concentration for whole diesel was $4.13 \times 10^2$, $2.66 \times 10^4$, and $4.46 \times 10^3$ (#/cm$^3$) for 30-, 100-, and 500-nm size ranges, respectively. Average total mass concentrations from all the experiments were $529 \pm 306$ µg/m$^3$. Cloth mask types 1 & 2 had filtration efficiency of 34% and 40% of particulate mass, respectively. Cloth mask3 performed the worst with the efficiency of only 14% of particulate mass.
Comparison of three cloth face mask types with a surgical mask and N95 mask

Not surprisingly, N95 masks performed better compared to any cloth face masks for all particle sizes (Figure 2). At a lower flow rate (Figure 3), the efficiency of cloth mask1 and surgical mask was comparable to N95 masks suggesting that these masks are sensitive to flow rate. Cloth mask1 had less penetration of smaller particles compared to the surgical mask. Compared to cloth mask1, the cellulose surgical mask worked better only for particles of large sizes (1 and 2.5 µm). Observed filtration efficiency of the surgical mask appears to be similar to cloth mask1, with overall efficiency being slightly better for the surgical mask (Figure 3).

A single factor ANOVA test showed that efficiency of all masks against PSL particles were significantly different to each other (p<0.01) except for 2.5 µm (p=0.05). An independent t-test (Table S1) confirmed the performance differences between all cloth masks and N95 mask1 (p<0.01) (Table S1) indicating that all cloth mask types were significantly different for all sizes compared to the N95 mask1. There was no significant difference between the performances of N95 mask1, the surgical mask, and the N95 mask2 for particle sizes of 30 and 500 nm. Efficiency of cloth masks were better (69-94%) for large sized particles (>1 µm) compared (44-93%) to small sized particles (<1 µm). However, N95 masks, a cloth mask with the exhalation valve (cloth mask 1), and a surgical mask performed the best for this size range.

N95 mask1 performed better compared to N95 mask2 for PSL particles with an average efficiency of 88 and 76%, respectively at a flow of 19 liters per minute. The three replications of experiments against using PSL particles were relatively robust consistent for two N95 masks.
and the surgical mask (Figure 2). An exception to this was the 30 nm PSL for both N95 masks, and 500 nm PSL for N95 mask2 and surgical mask, where the results vary among the replication of experiments (Figure 2). Variability among the repeated experiments was the worst for cloth mask2 and cloth mask3 trials. Though the three separate experimental trials performed for each of the mask types from PSL experiments were relatively robust, the N95 mask2 generally performed worse for particles larger than 1 µm compared to the smaller particles studies (Figure 2). The performance of the surgical mask was comparable to those of the N95 mask for large sized particles (>1 µm). The results showed clear evidence of suggest greater protection from particles by wearing a surgical mask (78%) and a cloth mask with the exhaust valve (cloth mask1) (81%) compared to simple cloth masks (39-46%) (Figure 2).

Similar to PSL particles trials, the surgical mask also performed better compared to cloth masks for diesel-generated particles (Figure 5). Filtration efficiency of cloth mask1 and cloth mask2 was better compared to cloth mask3. Cloth mask1 performed the best among the three cloth masks except for 500 nm particle size PSLs. Interestingly, efficiency of cloth mask2 was also comparable to cloth mask1. Consistent with results from the PSL particle experiments, N95 mask2 performed worse than N95 mask1 in the whole diesel experiments.

**DISCUSSION**

Among the four mask types tested, cloth mask1 and the surgical mask were the most efficient in preventing the penetration of PSL particles at both flow rates (8 & 19 liters per minute). When these masks were tested against diesel-generated particles, the surgical mask was still reasonably
effective, and the other mask types were less effective. The surgical mask and cloth mask\textsuperscript{1} captured 79% and 57%, respectively, of five particle sizes.

Unfortunately, the least effective two mask types (cloth masks 2 & 3) are also inexpensive, reusable, and are widely used in developing countries, implying they are a popular consumer choice where pollution mitigation is warranted. These two masks were purchased by our team for 10 Nepali rupees (1 US dollar = 95 Nepali rupees as on the purchase date). Surgical masks also remain a popular choice to reduce personal exposure to particulates. Penetration through these two cloth masks (2 & 3) decreased when the particle size increases (Figure 2). Such an increase in efficiency with the particle size was not observed for all mask types, however. Previous studies have reported the an increase in efficiency with the increasing particle size for other types of respirators.\textsuperscript{14,15} Overall, simpler cloth masks (cloth mask 2 & 3) provide the least amount of apparent protection from particulate exposure. The penetration of particles through cloth masks was more than 50% for the smallest particles (\textless{}500 nm) tested at a flow of 19 liters per minute.

Cloth mask\textsuperscript{1}, the best performer of the cloth masks, also has a conical or tetrahedral shape, allowing the edge to conform closely to the mannequin’s contours. The worst performing cloth masks were simple rectangles with loops to connect behind the ear. It is possible that this design does not allow a sufficient fit on the mannequin, allowing the leakage of significant fraction of particles to penetrate through the mask. While this was apparently true on a test mannequin, the leaks from such shape of masks is also likely true for real-world uses.
In general, all tested masks were deficient in capturing diesel-generator exhaust particles. For these experiments, the particle mass averaged between 200-45 and 1000-1060 µg/m³ and was meant to reflect a highly polluted urban location. Only the N95 mask and the surgical mask demonstrated particle removal efficiency above 65%, with the remaining masks removing fewer particles. This is an important concern because diesel exhaust comprises a significant fraction of urban emissions, particularly in developing nations where low-cost diesel vehicles are frequently used. These particles tend to be small, with typical mean particle sizes in the range of 100-150 nm which suggests that they are especially difficult to capture on a filtration material, even though they are known to induce a number of significant health impacts.  

Physical properties such as sizes, shapes, and aspect ratios affect the penetration of particles through the masks. Diesel particles have different and variable physical properties than the standard uniform PSL particles, and unlike PSL, diesel particles have physical properties with distinct aerodynamic sizes and shapes, and they likely reflect a different aspect ratio which affect penetration of particles through the masks. Maintaining identical diesel aerosol concentrations throughout the experiments was particularly challenging for the experiments performed with diesel exhaust. We compared the performance of each of the masks with pre-and post-measurement without the masks. Compared to the experiments with PSL particles, measurements diesel particle concentrations delivered to the chamber made with diesel particles had much more variable concentrations for the control conditions (i.e., without mask), which might have resulted in additional uncertainty in filtration efficiency calculations. Inconsistencies in efficiencies of masks between PSL particles and diesel particles experiments. There is also a possibility of quick degradation of masks due to high diesel particle concentrations. Further studies with better-controlled and more consistent diesel particle
concentrations are needed to better quantify the efficiency of cloth masks against diesel particles.

Relevant, real-world aerosol exposure models – that is, diesel and ambient particles – need additional focus and research, as the area where more research is needed because most facemask studies to date focus either on PSL, sodium chloride (NaCl), DOP (dioctyl phthalate) particles or biological media. Filtration efficiency of filters/masks may depend on particle types, particle loading, or other features. For example, with the increased particle mass loading, penetration increases for DOP particles while it decreases for NaCl particles, though this is based on results from aerosol exposures unlikely in the real world and we know even less about facemask performance under ambient uses.

This study shows that wearing cloth masks reduced the exposure to some extent (~39-65% for cloth mask 2 & 3, and 80-90% for cloth mask 1 against PSL particles for the flow rates of 8 and 19 liters per minute). The results also showed such masks could especially be beneficial to reduce personal exposure of large (>1 micrometer in diameter) particles (Figures 2 and 3). This has clear public health relevance as many millions of individuals are estimated to be living in regions with high levels of particulate matter, many of who may choose to select an intervention to reduce their health risk. However, a more informed choice in mask type is warranted because many of the least expensive, and commonly used, cloth mask products perform poorly when compared to alternative options available on the market.

The comparatively high degree of protection of the surgical masks was a surprising finding in this study. These masks are typically made of woven polyester and cellulose with small elastic
ear loops. These types of masks are typically the least expensive, but are usually considered disposable. Previous studies have shown that the penetration of particles through the surgical mask was greater compared to N95 masks.\(^{11-13, 20, 21}\) He et al.\(^{12}\) also observed particle penetration across a surgical mask to be within 20% and concluded that surgical masks may be beneficial only for the particles larger than 500 nm. Sande et al.\(^{21, 22}\) observed the highest particle removal efficiency from the simultaneous use of a respirator mask (European equivalent of a N95 mask), followed by surgical mask, compared to using only homemade cloth mask. Our findings show that compared to some cloth masks, surgical masks alone can provide better protection from particulate exposure. While Sande et al.\(^{21, 22}\) work suggest the simultaneous use of an N95 mask to reduce exposure, this is not likely an option for the developing world where these masks are not physically or economically available to the general population.

Mask fit on the selected model is one of the main uncertainties of this study and likely explains most of the experimental variability in this study. The experiments were performed on the mannequin head placed inside a controlled exposure chamber with a known concentration of specific size ranges. Real-world environmental conditions will be different and the factors such as perspiration, relative humidity, wind, tidal volume, can all affect facial geometry and fit and may play a role on the filtration efficacy of such masks. The tested particles were latex spheres of same composition and the particles generated from the same source such as diesel combustion. The real environment samples will have highly variable particle components. While the testing used an inanimate model, real-world conditions were satisfactorily simulated across both -monodispersed PSL testing, and a more diverse mixture of diesel pollutants, the latter of which more closely reflects common real-world exposure mixtures. Though we compared the
penetration of particles through masks with the concentrations measured before and after testing of masks, there may be uncertainties that may arise from not having the consistent aerosol concentrations throughout the experiments.

Maintaining identical aerosol concentrations throughout the experiments was particularly a challenge for the experiments performed with diesel exhaust. The breathing zone of the mannequin head was in close proximity to the injection port to the chamber, attached to the atomizer, which is generating the particles. In the ambient environment, the particle source will less likely to be at such close proximity.

Typical respiratory rate for adults is 12-18 breaths per minute with an average of 8 liters of air inspired per minute. We performed the experiments at a constant flow rate (19 and 8 liters per minute) while human breathing flow is most likely to be of a sinusoidal pattern. The use of variable flow rates would introduce significant uncertainty because it would vary the face velocity across the mask itself, and this would affect particle residence time in the mask itself. and could alter rates of particle loss from diffusion. Thus, flow rates of our experiments may not be representative of variable human breath rates (normal breathing, deep breathing, jogging/light exercise, etc.). Efficiency of all the masks was noted to improve at a lower flow rate. Thus, the flow rate and the pattern of flow might also affect the efficiency of such masks.

A decrease in collection efficiency from N95 respirators compared to expected level against virions (20-300 nm) were also reported by Balazy et al.22-23. Such decrease in efficiency was observed mainly at high respiratory flow rates.24-25 Though the facemasks were tightly fit around the mannequin head, the experimental setup might still be more prone to error than the
real environment because of the use of a continuous sampling flow. We used parafilm around the edges of mask to seal the mask to some extent in the experiments. Uncertainties also exist in extrapolating observed results here to real world conditions due to variability and differences in facial structures in these nations. For example, mannequin heads used in this study are likely to be smaller than Asian faces (Table S2). Filter penetration and faceseal leakage are the two principal factors that contribute to the effectiveness of a mask. Particle collection processes are affected by diffusion, electrostatic attraction, impaction, and interception depending on the particle sizes. Pressure drop across the filter media can also lead to poor performance of the masks. There were some important differences between our experimental setup and traditional N95 testing protocols, which are conducted with monodispersed particles that consist of dried sodium chloride NaCl crystals. The samples collected here were collected at approximate 8 or 19 liters per minute. This difference is important because of the objective of the N95 test itself is to demonstrate the effectiveness of a commercial product under worst case scenarios, whereas the methods described here reflect more typical uses by the public. Further, a robust ‘fit test’ is indicated in N95 testing, where masks are custom fit to conform to the geometry of a face; here, where an expanded polystyrene mannequin head was used, which may permit particles to penetrate into the sampling area by small leaks around the mask. Even with parafilm, the leaks were not completely avoided because expanded polystyrene does not mock skin and the leakage is not completely sealed at the edges of the mask. As a result, 95% efficiency was elusive, even for certified N95 masks where our results were closer to 76-92% efficiency. However, the results observed were reasonable approximations of mask performance, and are likely to be
reflective of real-world applications of face masks by the general public where formal fit testing is rarely, if ever, performed.

CONCLUSIONS

In selecting a choice to reduce personal exposure, a cloth mask with an exhaust valve performed best compared to other styles, where efficiency of cloth masks against standard particle sizes of five sizes, 30-, 100-, and 500-nm, and 1- and 2.5-μm, ranged from 39 to 65%. All masks performed worse for diesel combustion particles compared to monodispersed particles. The filtration efficiency of cloth masks for particles emitted from diesel combustion ranged 15 to 57% for total particle concentrations (for 30-, 100-, and 500-nm) and 13 to 40% for total particulate mass. As expected, N95 masks were effective in removing most tested particles. Disposable surgical masks were found to be surprisingly effective (efficiency of 78-94% for PSL particles; 79% for whole diesel). Given the observed variability in mask efficacy across different particle types and components, one cannot assume that the use of an inexpensive facemask leads to significant decreases in exposure, especially if an individual makes personal choices to not avoid high concentration environment because they assume they are protected from these contaminants. As a widely used public health intervention strategy, especially across the developing world, great care must be given in selection of inexpensive cloth masks for exposure reduction efforts.

CONFLICT OF INTEREST

The authors declare no conflict of interest.
AUTHOR CONTRIBUTIONS

REP, AN, KMS contributed to the design, method, and data analysis. AN, RK, and KMS performed the experiments. All authors contributed to the article.

Supplementary Information accompanies the paper on the Journal of Exposure Science and Environmental Epidemiology website (http://www.nature.com/jes).

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N95 respirators provide 95% protection level against airborne viruses, and how adequate are

based performance evaluation of N95 filtering-facepiece respirators challenged with


Supplementary Information

Evaluating the efficacy of cloth facemasks in reducing particulate matter exposure

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This supplement contains additional results from statistical tests, photographs of masks, and measurements of mannequin.

Table S1. p-values from an independent t-test between each of the mask types and N95 Mask1 (n = 21) for the experiment at the flow rate of 19 liters per minute.

<table>
<thead>
<tr>
<th>Mask types\Particle Sizes:</th>
<th>30 nm</th>
<th>100 nm</th>
<th>500 nm</th>
<th>1 µm</th>
<th>2.5 µm</th>
</tr>
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<tbody>
<tr>
<td>N95 Mask2</td>
<td>0.020</td>
<td>0.004</td>
<td>0.100</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Cloth Mask1</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Cloth Mask2</td>
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<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>
Table S2. Facial characteristics of mannequin (Yu et al., 2012)

<table>
<thead>
<tr>
<th>Description</th>
<th>Measurement (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimal frontal breadth</td>
<td>11</td>
</tr>
<tr>
<td>Head breadth</td>
<td>24</td>
</tr>
<tr>
<td>Nasal root breadth</td>
<td>1.5</td>
</tr>
<tr>
<td>Interpupillary breadth</td>
<td>5.5</td>
</tr>
<tr>
<td>Face width</td>
<td>16</td>
</tr>
<tr>
<td>Nose breadth</td>
<td>3.5</td>
</tr>
<tr>
<td>Bigonial breadth</td>
<td>10</td>
</tr>
<tr>
<td>Face length</td>
<td>10.5</td>
</tr>
<tr>
<td>Nose length</td>
<td>4.8</td>
</tr>
<tr>
<td>Nose protrusion</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure S1. Photographs of three different types of cloth masks examined in this study.
Reference