Effectiveness of Common Fabrics to Block Aqueous Aerosols of Virus-like Nanoparticles

Steven R. Lustig,* John J. H. Biswakarma, Devyesh Rana, Susan H. Tilford, Weike Hu, Ming Su, and Michael S. Rosenblatt

ABSTRACT: Layered systems of commonly available fabric materials can be used by the public and healthcare providers in face masks to reduce the risk of inhaling viruses with protection that is about equivalent to or better than the filtration and adsorption offered by 5-layer N95 respirators. Over 70 different common fabric combinations and masks were evaluated under steady-state, forced convection air flux with pulsed aerosols that simulate forceful respiration. The aerosols contain fluorescent virus-like nanoparticles to track transmission through materials that greatly assist the accuracy of detection, thus avoiding artifacts including pore flooding and the loss of aerosol due to evaporation and droplet breakup. Effective materials comprise both absorbent, hydrophilic layers and barrier, hydrophobic layers. Although the hydrophobic layers can adhere virus-like nanoparticles, they may also repel droplets from adjacent absorbent layers and prevent wicking transport across the fabric system. Effective designs are noted with absorbent layers comprising terry cloth towel, quilting cotton, and flannel. Effective designs are noted with barrier layers comprising nonwoven polypropylene, polyester, and polyaramid.

KEYWORDS: COVID-19, personal protective equipment, face mask, filtration efficiency, nanoparticles

The personal protective equipment (PPE) shortage in the United States during the SARS-CoV-2 pandemic has put the issue of PPE availability directly into the public domain. Healthcare PPE shortages in the U.S. were triggered by massive shipments to China in early 2020 and subsequent production and transportation stoppages from outbreaks in China and Southeast Asia, the source of 80–90% of the U.S. PPE supply.† Masks reduce inhalation of aqueous viral aerosols emitted from infected individuals when talking, coughing, or sneezing.‡ Masks may also be beneficial by serving as a reminder for wearers to avoid touching their face and, thus, prevent transmission from the hands to the user’s nose, mouth, and eyes. Moreover, the Centers for Disease Control and Prevention (CDC) and state governments now either require or recommend the public wear face masks in public.§ It is increasingly more urgent to identify effective fabrics and mask designs for the public so there is no competition for healthcare provider PPE.¶ Understanding effective mask construction may enable safe homemade masks and reduce PPE supply issues during the pandemic. Moreover, the critical shortage of certified respirators and masks faced by Massachusetts hospitals forced hospital personnel to consider time-sensitive solutions for alternative PPE. Ideally, alternative PPE would be facile to assemble from largely available fabric stocks of local vendors and provide approximately equivalent or superior virus particle filtration compared with the certified PPE.

Commercially manufactured, certified respirators and surgical masks are generally considered more effective than homemade masks. N95 respirators that tightly seal around the mouth and nose are typically worn by healthcare providers caring for patients with infectious conditions that transmit via aerosolized pathogens. Surgical masks are designed to block direct fluid entry into the wearer’s nose and mouth from a splash, cough, or sneeze and are not designed to block aerosolized pathogens. Materials used for health care service face masks are subject to extensive performance criteria, including bacterial filtration efficiency, particle filtration
efficiency, fluid flow resistance, air flow resistance, flame
propagation rate, and skin reactivity as mandated by the
National Institute for Occupational Safety and Health
(NIOSH). The first two are directly related to the
effectiveness of the material to serve as a barrier to aqueous
viral aerosols. ASTM F2100-19E1 specifies assessing filtration
using 100-nm-sized particles of salt aerosol. The N95
certification indicates that 95% of the total particles in a salt
aerosol with an average particle size of 300 nm are blocked by
a material under standard conditions. N95 respirators are
typically used by physicians and surgeons. ASTM F2299/
F2299M-03(17) uses light-scattering particle counting of latex
spheres between 100 nm and 5 μm in diameter. Bacterial
filtration efficiency standards are described in ASTM F2101,
which requires aqueous bacterial aerosols having 3 μm
diameter droplets. Meanwhile, aqueous aerosols from speech,
 sneezing, and coughing have size distributions spanning several
orders of magnitude up to thousands of microns. The
SARS-CoV-2 virus itself is found in various shapes with
polydisperse diameters ranging between 60 and 140 nm. Salt
particles, latex spheres, bacteria, and viruses are widely
diverse in size, shape, surface chemistry, and interfacial
properties. These properties can affect the transport and
adhesion within the complex surfaces of materials used in PPE
face masks.

Comparative studies of common, household fabrics
generally indicate these materials are more permeable than
medical grade PPE and widely variable in their filtration
efficiencies. For example, Rengasamy et al. provide caution
that fabrics can exhibit a range of filtration efficiencies.
Examples of sweatshirts, t-shirts, towels, and scarfs from
different manufacturers were tested with polydisperse (75 ± 20
nm) salt aerosols and 13 sizes of monodisperse salt aerosols
(20 nm−1 μm) at face velocities of 5.5 and 16 cm/s. Particulate
transmission through the materials was determined by
measuring the particle count upstream and downstream of
the filter media using a scanning mobility particle sizer.
Fractional transmissions ranged from 40% to 90% for the
polydisperse aerosol and 40% to 97% for the monodisperse
aerosols at 5.5 cm/s. Davies et al. investigated the filtration
performance of common household fabrics to remove airborne
viruses and bacteria. Fabrics were exposed to aerosols
containing either Bacillus atrophaeus (0.95–1.25 μm) or
Bacteriophage MS2 (23 nm). Aerosols were delivered in a
closed chamber at 30 L/min, and particle counts were
measured upstream and downstream of the filter media.
Based on a combination of filtration efficiency and pressure
drop, the highest performing fabrics were a 100% cotton t-shirt
and a pillowcase. The surgical mask had a 96% mean filtration
efficiency for the 1 μm particles and 90% for the 23 nm
particles. In comparison, the 100% cotton t-shirt had a 69%
mean filtration efficiency for the 1 μm particles and 51% for
the 23 nm particles. The pillowcase had a 61% mean filtration
efficiency for the 1 μm particles and 57% for the 23 nm
particles. Hence these fabrics are far more permeable than N95
respirators. These investigations did not attempt to combine
multiple types of fabric layers to achieve comparable
performance to the NIOSH-certified medical respirators and
masks, such as the N95 respirators. Recently, Konda et al.
studied several common fabrics such as cotton, silk, chiffon,
flannel, and polyester blends with up to two layers. Cotton
guq and cotton/chiffon performed about as well as an N95
respirator at filtering saline aerosols. Although the method-
ology is in compliance with NIOSH 42 CFR Part 84 test
protocol, the instruments are noted to have poorer counting
efficiencies for particles smaller than about 300 nm.
Furthermore, unknown fractions of the aqueous aerosol
particles are lost by evaporation as well as breakup into
undetectable, smaller droplets. These aerosols did not contain
virus nanoparticles that could be independently identified
when transported through the materials. Blocking the transport
of virus particles is a prime function of mask fabric.

In response to the time-sensitive need for alternative PPE,
we identify commonly available fabric materials that the public
and healthcare providers can use in face masks to reduce the
risk of viral aerosol inhalation. Over 70 different common
fabric multilayer designs are compared to NIOSH-certified
medical respirators and ASTM-certified masks for filtration
efficiency using protocol conditions similar to those of ASTM
standards. A common design theme emerges for many layered
fabric designs that may reduce the risk of viral inhalation from
aerosolized contamination directly striking the mask in both
healthcare–patient interactions and public interactions with
limited physical distancing.

RESULTS AND DISCUSSION

Fluorescent, virus-like nanoparticles emulate the size and
surface character of SARS-CoV-2 virus particles and are readily
detected and counted. Rhodamine 6G is incorporated into
nanoparticles as it is highly photostable and fluoresces with
high quantum yield efficiency. It remains well partitioned
within the nanoparticle matrix of poly(lactic-co-glycolic acid). Figure 1 is a scanning electron microscope image of a small
cluster of primary nanoparticles. The core–shell structure is not thermally stable under the exposure to high energy
density, such as a focused electron beam in higher magnification,
and the nanoparticle will partially melt to present an irregular shape.

Figure 1. Scanning electron micrograph (SEM, Ultra 55, 10 keV)
of a small cluster of primary nanoparticles. The core–shell structure is not thermally stable under the exposure to high energy density, such as a focused electron beam in higher magnification, and the nanoparticle will partially melt to present an irregular shape.
Transport of nanoparticles in aqueous aerosol is predicated on forced convection air flux. For example, placing the aerosolizer jet in direct contact with the surface of an N95 respirator at 20 kPa gauge pressure results in instantaneous surface accumulation of water. No nanoparticles were detected on the opposite side of the respirator. This condition occurred for all materials and masks, except for the most open, highly porous weaves. Direct aerosol jetting onto the densely woven fabrics exhibits the same surface flooding result. Pore flooding traps nanoparticles, preventing transmission through the material. This result is independent of the aerosol pressure that could be applied. Similar pore flooding can occur in salt solution aerosol testing. Nanoparticle transmission through porous materials begins to occur without pore flooding as the steady-state volumetric flow rate of air exceeds the incident volumetric flow rate of aqueous aerosol. Partial flooding decreases the effective material porosity and leads to exaggerated filtration efficiency. In practical terms, dense fabric masks do not transmit nanoparticles into a mask, such as virus particles, without active respiration or permeating air convection.

The transmission measurement of nanoparticles through mask materials is based on test conditions that emulate ASTM methods, enable high precision and repeatability, and reproduce sensibly physiological conditions. The rate of human ventilation at rest is nominally 6 L/min^2^1^ and can increase several-fold upon active exertion. Our testing establishes a baseline steady-state air flow of 14 L/min^2^2 through each test material. Each test is subjected to a total threat of 2 mL aqueous solution containing the fluorescent virus-like nanoparticles at 0.5 mg/mL. This total threat volume is delivered by 26 pulses of aerosol, each lasting 1 s. The duration and overpressure of the pulses emulates forceful expiration, i.e., a spray resulting from a sneeze, cough, or speech from an infected individual. The steady-state air flow being in excess of restful ventilation replicates a slightly elevated ventilation rate as a safety margin, prevents pore flooding, and enables improved statistical repeatability in the nanoparticle count measurements. The pulsed aerosol droplets are polydisperse in size and closely match the size range from forceful expiration. Nanoparticles transmitted through the test material are collected at a distance of 1 mm on a glass slide. The gas flow and slide placement configure the system to be well within the estimated collection regime, i.e., particle capture limit. After a nanoparticle collides with the glass, the rebounded kinetic energy is insufficient to escape the attractive potential energy. Specific details about the aerosol transmission testing are described in the Methods Section; also see Figure 2.

Over 70 different common material arrays were evaluated under steady-state air permeation against pulsed aerosols that simulate forceful expiration. A list of materials is provided in the Supporting Information; see Table S1. Table 1 summarizes our most notable transmission results and comparative statistics. Data for the 5-layer N95 respirator by 3M are provided in the first row. This is the standard PPE recommended by the CDC when caring for SARS-CoV-2 patients undergoing an aerosolizing procedure. Several 30 mm diameter samples were cut from around the respirator. The fractional transmission is the nanoparticle count transmitted through the material, normalized by the incident nanoparticle count. The fractional transmission standard deviation across all sampled locations exceeds the typical standard deviation for the nanoparticle counting measurement. This suggests that the filtration efficiency is dependent on the location of the mask. This is reasonable for a stack of nonwoven layers that are pressed heterogeneously into a shape comprising highly varying curvature and thickness. Nonetheless the overall average and standard deviation of nanoparticle counts over 69 independent measurements are provided across the entire respirator. Specifically, the 5-layer N95 respirator by 3M displayed a fractional transmission of 0.56 ± 0.30 ppt. Remaining materials shown in Table 1 exhibited uniform fractional transmission among multiple replicate samples. Standard surgical masks, also evaluated in this study, are

![Figure 2. Schematic drawing of pulsed aqueous aerosol containing fluorescent, virus-like nanoparticles being drawn through layered materials by steady-state, forced convection air flux until transmitted nanoparticles are collected on a glass slide (left). Representative fluorescent micrograph of fluorescent, virus-like nanoparticles trapped on nonwoven polypropylene material (right). This illustration was created by Shoshanna Lustig for this article.](image)
Table 1. Permeability of Barriers Tested Featuring Commonly Available Fabrics and Materials

<table>
<thead>
<tr>
<th>Material Description</th>
<th>Fractional Transmission, parts per 1000 (N)</th>
<th>N95 Normalized Permeability Index (P-value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N95 mask (3M: #1860S Lot #15886, 5 layer)</td>
<td>0.56 ± 0.30 (69)</td>
<td>1.0 (−)</td>
</tr>
<tr>
<td>Transmission Statistically Lower Than N95 Mask (p &lt; 0.05)</td>
<td>0.16 ± 0.06 (27)</td>
<td>0.3 (0.001)</td>
</tr>
<tr>
<td>Sheldon G mask with cellulose filter</td>
<td>0.31 ± 0.07 (9)</td>
<td>0.5 (0.001)</td>
</tr>
<tr>
<td>white denim/OLY-FUN (x2)/white denim</td>
<td>0.40 ± 0.18 (18)</td>
<td>0.7 (0.004)</td>
</tr>
<tr>
<td>Kona cotton/OLY-FUN (x4)/Kona cotton</td>
<td>0.62 ± 0.06 (18)</td>
<td>1.1 (0.116)</td>
</tr>
<tr>
<td>Transmission Equivalent to N95 Mask (p &gt; 0.05)</td>
<td>0.47 ± 0.11 (36)</td>
<td>0.8 (0.148)</td>
</tr>
<tr>
<td>N95 mask (3M: #8200 Lot #B18198, 3 layer)</td>
<td>0.50 ± 0.18 (18)</td>
<td>0.9 (0.232)</td>
</tr>
<tr>
<td>Kona cotton (x2)/terry cloth (x2)</td>
<td>0.50 ± 0.12 (18)</td>
<td>0.9 (0.145)</td>
</tr>
<tr>
<td>Kona cotton (x4)</td>
<td>0.51 ± 0.24 (9)</td>
<td>0.9 (0.514)</td>
</tr>
<tr>
<td>lab coat/flannel/OLY-FUN (x2)/Kona cotton</td>
<td>0.57 ± 0.26 (9)</td>
<td>1.0 (0.942)</td>
</tr>
<tr>
<td>Kona cotton/terry cloth (x2)</td>
<td>0.62 ± 0.17 (18)</td>
<td>1.1 (0.318)</td>
</tr>
<tr>
<td>heavy tee shirt 100% cotton</td>
<td>0.64 ± 0.06 (18)</td>
<td>1.1 (0.060)</td>
</tr>
<tr>
<td>lab coat (x2)/flannel/OLY-FUN (x2)</td>
<td>0.69 ± 0.20 (9)</td>
<td>1.2 (0.093)</td>
</tr>
<tr>
<td>white 12 oz denim/Kona cotton (x2)/white 12 oz denim</td>
<td>0.70 ± 0.23 (9)</td>
<td>1.2 (0.122)</td>
</tr>
<tr>
<td>Kona cotton/white 12 oz denim (x2)/Kona cotton</td>
<td>0.79 ± 0.62 (9)</td>
<td>1.4 (0.293)</td>
</tr>
<tr>
<td>Kona cotton/OLY-FUN (x2)/Kona cotton</td>
<td>1.10 ± 0.89 (9)</td>
<td>2.0 (0.072)</td>
</tr>
<tr>
<td>Transmission Statistically Higher Than N95 Mask (p &lt; 0.05)</td>
<td>0.68 ± 0.08 (18)</td>
<td>1.2 (0.003)</td>
</tr>
<tr>
<td>procedure cone mask (Cardinal Health, #AT7509)</td>
<td>0.73 ± 0.14 (9)</td>
<td>1.3 (0.005)</td>
</tr>
<tr>
<td>Kona cotton/white flannel/Kona cotton</td>
<td>0.85 ± 0.15 (9)</td>
<td>1.5 (0.001)</td>
</tr>
<tr>
<td>Kona cotton/Pellon (x2)</td>
<td>0.86 ± 0.23 (72)</td>
<td>1.5 (0.001)</td>
</tr>
<tr>
<td>KN95 mask (GB2626-2006KN95)</td>
<td>0.91 ± 0.24 (18)</td>
<td>1.6 (0.001)</td>
</tr>
<tr>
<td>Kona cotton (x2)</td>
<td>0.92 ± 0.05 (18)</td>
<td>1.6 (0.001)</td>
</tr>
<tr>
<td>Kona cotton/Pellon (x2)/Kona cotton</td>
<td>0.95 ± 0.33 (45)</td>
<td>1.7 (0.001)</td>
</tr>
</tbody>
</table>

Fractional transmission is the nanoparticle count transmitted normalized by the incident nanoparticle count, reported with number of independent particle count measurements, N. N95 normalized permeability index is the fractional transmission of the material divided by the fractional transmission of the N95 mask (first table entry), reported with the unequal variances t-test probability that the transmission is no different from the N95 mask. Notes: (a) Average of data collected from multiple positions around the mask. The data show indications that the transmission is dependent on location on the pressed mask. (b) Design of Sheldon Gentling: outermost layer comprises ProCool Stretch-FIT Dri-QWick sports jersey fabric by AKAS Textiles & Laminations, innermost layer comprises Zorb 3D Stay Dry Dimple heavy duty fabric by AKAS Textiles & Laminations. All materials supplied by Wazoodle Fabrics. (c) Kona quilting cotton fabric, supplied by JOANN Fabrics and Crafts, Hudson, OH. (d) 65 GSM (grams per square meter) polypropylene nonwoven fabric. (e) Lab coat is a blend of polyester and polyaramid. (f) Pellon midweight #931TDT fusible polyester. (g) Pellon #SF101 fusible polyester. (h) Kona quilting cotton fabric treated with 2.2 wt % Scotchgard. (i) Pellon #PF4F fusible polyester. (j) https://www.joann.com/how-to-make-a-denim-face-mask/042188731IP326.html (accessed Apr 21, 2020). (k) High thread count (HTC), 52S horizontal and vertical thread counts/inch.
hydrophilic layers and barrier, hydrophobic layers. Although
the hydrophobic layers can adhere virus-like nanoparticles,
they may also repel droplets from adjacent absorbent layers
and prevent wicking transport. High fiber density and
tortuosity increase the probability of collision with aerosol
droplets. Effective designs are noted with absorbent layers
comprising terry cloth towel, quilting cotton, and flannel. For
example, two layers of terry cloth, two layers of white flannel,
and four layers of Kona quilting cotton exhibit fractional
transmissions of 0.50 ± 0.12, 0.51 ± 0.24, and 0.62 ± 0.17,
respectively. These commonly available mask materials exhibit
fractional transmissions within 10% of the five-layer N95
respirator. Effective designs are noted with barrier layers
comprising OLY-FUN (nonwoven polypropylene), lab coat
(polyester/polyaramid), cotton coated with spray-on fabric
protector, and traditional synthetic aliphatic and aromatic
polymer fibers. Although some terry cloth and cotton
multilayers are effective alone, inclusion of an additional
hydrophobic repelling layer is recommended to prevent
wicking transport for higher volume threats. Sole use of
denim is not effective: in general, the yarn bundles are very
dense but spaced with wide interweave gaps to promote
breathability in jeans. This is demonstrated by high fractional
transmission by two layers each of 4 oz lightweight blue denim,
7 oz midweight blue denim, and 11 oz heavy weight stretch
black denim of 3.91 ± 1.82, 7.61 ± 0.63, and 9.43 ± 0.99 ppt,
respectively. The two-layer denims exhibit 698%, 1359%, and
1684% higher fractional transmission than the 5-layer N95
respirator, respectively. The fusible polyesters considered are
also highly porous. Several additional layered systems exhibit
fractional transmission statistically equivalent to the duckbill
surgical mask. These may be effective in conjunction with
additional safeguards, such as social distancing and smaller
threat volumes.

CONCLUSIONS

Commonly available fabric materials can be used by the public
and healthcare providers in face masks to reduce the risk of
inhaling viruses from aerosols generated by coughs, sneezes,
and speech from infected individuals. The protection by some
layered designs offers protection about equivalent to or better
than the filtration and adsorption offered by 5-layer N95
masks. Effective materials comprise both absorbent, hydro-
philic layers and barrier, hydrophobic layers. Although the
hydrophobic layers can adhere virus-like nanoparticles, they
may also repel droplets from adjacent absorbent layers and
prevent wicking transport. Effective designs are noted with
absorbent layers comprising terry cloth towel, quilting cotton,
and flannel. Effective designs are noted with barrier layers
comprising nonwoven polypropylene, polyester, and polyar-
amid.

This work considers the results of this work and prior work,
recommended mask designs include those multilayered
combinations in Table 1 that exhibit transmission either
equivalent to or lower than the transmission offered by 5-layer
N95 masks. It is critical that the materials’ edges conform
snugly to the face to prevent aerosol from entering gaps
between the face and mask. The mask must not enable viral
imbibition by the lips, tongue, and saliva. Ideally, the mask
does not contact the lips, or there is at least one hydrophobic
layer fabric in contact with the face, so aerosol trapped from
the exterior does not wick through the mask and become
transported by the mouth. Because aerosol transport through a
mask is predicated on forced convection air flux, it is
recommended that individuals wearing masks reduce inhala-
tion intensity when placed in contact with an unsafe aerosol.

METHODS

Virus-Simulant Nanoparticles. Materials. Ethyl acetate, poly-
(lactic-co-glycolic acid) (PLGA), eicosane, rhodamine 6G, and
poly(vinyl alcohol) (PVA) were purchased from Sigma-Aldrich
(Billerica, MA, USA) and were used as-is without any further
processing or purification.

PLGA Nanoparticle Preparation. Nanoparticles (NPs) were
prepared by mixing 100 mg of PLGA pellets with 1 mL of ethyl
acetate, 20 μg of rhodamine 6G, and 12 mg of eicosane. The
resulting mixture was vortexed for 5–10 min until homogenized.
Two mL of 5 wt % PVA was added and sonicated for 2 min using an ice water bath
to prevent evaporation of ethyl acetate. This solution was mixed with
50 mL of 3 wt % PVA solution immediately after sonication and
stirred at 800 rpm for 2 h until the ethyl acetate evaporated. The
resulting solution was split into two centrifuge tubes and centrifuged
at 6000 rpm for 5 min followed by the removal of the supernatant.
The remaining precipitate was diluted with deionized water and
vortexed for another 5 min. The centrifugation and rinse were
repeated three times. The final precipitate was diluted with 35 mL
of water to obtain a final experimental concentration of ca. 7 mg/mL. A
small aliquot of dispersion was weighed both wet and dry to
determine accurately the actual NP concentration. This stock solution
was further diluted to 0.5 mg/mL for experimentation. This
concentration was chosen after a series of experiments to determine
optimal NP concentration such that NPs do not aggregate, did not
clog the fabrics, and did not clog the aerosol generator.

PLGA NP Size Distribution and Zeta Potential Tests. NP size
distribution, shown in Figure S1, and zeta potential tests, shown in

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Aerosol Transmission Testing. Test Apparatus. A test apparatus was designed to analyze the degree of transmission of aerosols through various materials. Figure 3 illustrates a schematic of the test apparatus and identifies the components. A labeled photograph shows the actual components in Figure S3. Design parameters for this system were informed by ASTM procedures that included as the equivalent of 50 μm. The images were cropped from the bottom by 50 pixels to remove any erroneous particles being counted due to text. The image was then converted to an 8-bit image at 20x optical zoom per fabric to determine particle concentration per area, and multiple experiments were conducted per fabric using the accompanying Olympus cellSense Standard 1.16 software. A constant gain and exposure were chosen of 18 dB and 1.109 s, respectively, and a fixed scale contrast was applied between 0.5 and 5000. Individual images were postprocessed in Imagej, similar to the droplet size distribution protocol. The raw images were further processed using Imagej to subtract the background with a 500-pixel rolling ball radius and a dark background. A scale of 160 pixels was identified as the equivalent of 50 μm. The images were cropped from the bottom by 50 pixels to remove the magnification and scale bar texts to remove any erroneous particles being counted due to the text. The image was then converted to an 8-bit image format in which the minimum and maximum contrast threshold was set to 15 and 250, respectively. This resulted in black (droplets) and white (background) images. These black and white images were then counted and measured via the Imagej counting feature, within the Analyze feature, using an ellipse outline method. An example of the subsequent image alterations is located in Figure S4. The ellipses are counted, and the diameter is measured to obtain the total distribution of droplets by size and frequency. The aforementioned procedure was automated by creating a custom Plugin using Imagej’s batch scripting language, to remove human bias during image analysis and to speed up analysis. The veracity of the script was confirmed by manual analysis of each step, per the image output examples. The size distribution and frequency were then plotted using GraphPad Prism v8.0.0.

Nanoparticle Distribution after Transmission through Fabrics. Nanoparticle distribution was measured by placing 1 cm glass slides onto the glass holder within the test apparatus and sprayed with fluorescent rhodamine tagged PLGA NPs. The NP-containing glass slides were then observed under an Olympus BX43 fluorescence microscope, containing an Olympus U-TV1XC center and Olympus XM10 camera. An X-CITE 120LED Boost laser controller from Excelitas Technology was used for a fluorescent laser source run at 45% power for fluorophore excitation. At least nine images were taken at 20X optical zoom per fabric to determine particle concentration per area, and multiple experiments were conducted per fabric using the accompanying Olympus cellSense Standard 1.16 software. A constant gain and exposure were chosen of 18 dB and 451 pixels. A constant scale contrast was applied between 0.5 and 5000. Individual images were postprocessed in Imagej, similar to the droplet size distribution protocol. The raw images were further processed using Imagej to subtract the background with a 500-pixel rolling ball radius and a dark background. A scale of 160 pixels was identified as the equivalent of 50 μm. The images were cropped from the bottom by 50 pixels to remove the magnification and scale bar texts to remove any erroneous particles being counted due to text. The image was then converted to an 8-bit image format in which the minimum and maximum contrast threshold was set to 15 and 250, respectively. This resulted in black (droplets) and white (background) images. These black and white images were then counted and measured via the Imagej counting feature, within the Analyze feature, using an ellipse outline method. An example of the subsequent image alterations is located in Figure S4. The ellipses are counted, and the diameter is measured to obtain the total distribution of droplets by size and frequency. The aforementioned procedure was automated by creating a custom Plugin using Imagej’s batch scripting language, to remove human bias during image analysis and to exponentially speed up analysis. The veracity of the script was confirmed by manual analysis of each step. The nanoparticle count and size distribution are included in Table 1.

ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsnano.0c03972.

Description and micrograph images of materials tested and Figures S1–S5 described in the Methods section (PDF)

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Notes

The authors declare no competing financial interest.

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