Face mask and Respirator Effectiveness:
Limiting exposures to airborne pathogens during COVID-19 and beyond

ISAM Webinar June 1st, 2020

Co-presenters:

Conor A. Ruzycki, PhD Candidate
Department of Mechanical Engineering
University of Alberta

Phillip Clapp, PhD
Center for Environmental Medicine, Asthma, and Lung Biology
The University of North Carolina at Chapel Hill
Outline

Definitions and nomenclature

Aerosol Generation in the Respiratory Tract
  • Evidence for transmission of CoViD-19 via aerosols

Filtration Theory; governing mechanisms
  • Mechanical deposition and electrostatics
  • Balancing filtration with breathability

Quantifying Fit

Quantifying Filtration

Takeaways and considerations
  • Mask/respirator use by the general public
Definitions and Nomenclature

Respirators vs. Masks

- Respirators are designed specifically to seal to the face
- Masks cover the mouth and nose, but do not create air-tight seal
Definitions and Nomenclature

Aerosols from an aerosol science perspective

- Gas-borne suspension of solid particles or liquid droplets
- Range in size from nanometers to several hundred micrometers
- Size is extremely important in predicting how aerosols behave under the action of various forces
- *Droplets and droplet nuclei (from medical literature) are aerosols; confusing definitions frequently arise with “airborne transmission”*
  - “Droplets” are large droplets with diameters greater than ~ 20 µm that are vectors for “droplet transmission”
  - “Droplet nuclei” are smaller droplets with diameters less than ~ 10 µm that are vectors for “airborne” or “aerosol transmission”
- Here, airborne transmission = transmission facilitated directly by an aerosol

Ref: Drossinos & Stilianakis, Aerosol Sci. Technol., 2020:54(6);639-643
Aerosol Generation in the Respiratory Tract

Various actions can lead to the creation of aerosols in the human respiratory tract (Asadi et al. 2020)

- Forceful events: sneezing, coughing
- Less obvious: talking, breathing, singing
- Wide range of droplet sizes can be emitted
  - tens of nanometers to hundreds of micrometers.

Emitted droplets composed primarily of respiratory fluid and anything located within

- Air within the lungs is humidified and at body-temperature; upon exhalation water evaporates off droplets until a new equilibrium state is reached
  - droplets shrink, potentially becoming solid particles

Ref: Asadi, Bouvier, Wexler, & Ristenpart, Aerosol Sci. Technol., 2020:54(6);635-638
Bourouiba, Dehandschoewercker & Bush, J. Fluid Mech., 2014:745;537-563 (image source, adapted from fig. 3)
Aerosol Generation in the Respiratory Tract

Aerosol spreads from the source

- Influenced by droplet/particle size, velocity and direction of expulsion, ambient air currents
- Contrary to popular reporting, “large droplets” do not immediately fall to the ground (Hinds 1999)
  - Settling velocity for 100 µm diameter water droplet ~ 25 cm/s
  - Settling velocity for 10 µm diameter water droplet ~ 0.3 cm/s

Droplets/particles can remain suspended for hours

CoViD-19; Potential for Airborne Transmission

Exhaled droplets can contain pathogens (SARS-CoV-2)

- Novel coronavirus (physical diameter ~ 120 nm) contained or encapsulated in expired particles/droplets; large droplets/particles could theoretically harbor a larger viral load
- Virus may remain viable in aerosolized form for several hours (van Doremalen et al. 2020)
- Evidence for transmission via asymptomatic/presymptomatic individuals (see Asadi et al. 2020)

CDC guidelines reflect likely transmission routes (i.e. fomite vs aerosol)

The virus may be spread in other ways

It may be possible that a person can get COVID-19 by touching a surface or object that has the virus on it and then touching their own mouth, nose, or possibly their eyes. This is not thought to be the main way the virus spreads, but we are still learning more about how this virus spreads.

Person-to-person spread

The virus is thought to spread mainly from person-to-person.

- Between people who are in close contact with one another (within about 6 feet).
- Through respiratory droplets produced when an infected person coughs, sneezes, or talks.
- These droplets can land in the mouths or noses of people who are nearby or possibly be inhaled into the lungs.
- COVID-19 may be spread by people who are not showing symptoms.

Role of Masks and Respirators

Masks: reduce likelihood of transmission events occurring in local environments

- Exhaled aerosols face a barrier to easy dispersal
- Remove some droplets before they shrink in size via evaporation
- Theoretically more effective when worn by a larger proportion of the population (via epidemiological modeling, e.g. Kai et al. 2020)
- Reduced viral counts in exhaled aerosols for seasonal coronavirus and influenza virus demonstrated in literature (Leung et al. 2020)

Respirators: protect the wearer by removing virus-laden droplets/particles

- Especially important for individuals who face a high risk of continual exposure
- Not a guarantee of safety, but reduce initial viral load in event of infection
  - (e.g. N95 implies >95% of particles/droplets removed)


Image source: Ertmer & Line-Ficocello, "Respiratory protection: Keeping you safe in the fight against COVID-19," presentation for 3M published April 22nd 2020
Filtration Theory: Removing Particles/Droplets

Single fiber filtration theory

- Mechanical deposition
  - Inertial impaction
  - Interception
  - Diffusion

- Most-penetrating-particle
  - 200 nm – 800 nm
  - Typical U-shaped efficiency curve

- Filtration Efficiency \[ E = 1 - \frac{c_{\text{out}}}{c_{\text{in}}} \]

Image sources: (top) Adapted from Fig. 5.2 in Dunnett. Ch. 5 Filtration Mechanisms, pp 89-117 in Aerosol Science: Technology and Applications. 2014.
(bottom) Fig. 7-9 in Raynor et al. Ch. 7 Sampling and Analysis Using Filters, pp 107-128 in Aerosol Measurement: Principles, Techniques, and Applications, 3rd ed. 2011
Electrostatic effects can vastly improve filtration for 200 nm to 800 nm diameter particles/droplets

- Difficult to model analytically, though various electrostatic mechanisms contribute to filtration (Wang 2001, Emi et al. 1987)

Electrostatics are used to great effect in commercial respirators

- Electret filters (w/ quasi-permanent dipoles on filter fibers, e.g. N95, P100)
- MPP shifts to smaller sizes (<100 nm)
- Contribution of electrostatics demonstrated via isopropanol treatment (Rengasamy et al. 2009)

Note: Penetration = 1 – Filtration Efficiency
Increasing filter thickness increases filtration, but at the cost of higher resistance to airflow

- Filtration efficiency scales asymptotically
- Resistance (pressure drop) scales linearly
- Example; for a filter made of $n$ layers, each with:
  - 15% filtration efficiency at MPP
  - A pressure drop of 15 Pa at 85 L/min

\[
E_{\text{total}} \approx 1 - (1 - E)^n
\]

\[
\Delta p_{\text{total}} \approx n \times \Delta P
\]

~19 layers to achieve >95%, but this causes a high $\Delta P$
Balance between filtration and pressure drop

- Diminishing returns for filtration versus pressure drop with addition of more layers

A large pressure drop is undesirable

- Harder to breathe through the mask/respirator for the wearer
- Airflow in masks/respirators with a high $\Delta P$ favors the formation of leaks
  - Air travels along the path of least resistance

Electret filters provide high filtration efficiencies for low pressure drops compared to materials utilizing only mechanical deposition mechanisms

- $>95\%$ with only mechanical deposition and a reasonable pressure drop is extremely difficult
Last Note: Respirator Classifications

USA: filtration performance of respirators certified under NIOSH 42 CFR Part 84

- N (not resistant to oil), R (resistant to oil), P (oil-proof)
- Filtration efficiency (minimum) of 95%, 99%, 99.97%
- N-series tested with salt (NaCl) aerosol with CMD near the MPP of electret filters (~75 nm)
- R, P series tested with dioctyl phthalate (DOP) oil aerosol with CMD of ~185 nm
- *N95 is not the best, but is sufficient in many situations!*

Similar certification standards exist in other countries, but beware of differences in test methods and acceptance criterion

- European FFP2 (>94% filtration)
- Chinese KN95 (>95% filtration)
- Canada: N95 are Class I Medical Devices. Health Canada typically refers to NIOSH certification, but has expedited authorization of FFP2 and KN95 respirators pending internal confirmation of quality
Comparison of FFP2, KN95, and N95 and Other Filtering Facepiece Respirator Classes

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter performance - (must be ≥ X% efficient)</td>
<td>≥ 95%</td>
<td>≥ 94%</td>
<td>≥ 95%</td>
<td>≥ 94%</td>
<td>≥ 95%</td>
<td></td>
</tr>
<tr>
<td>Test agent</td>
<td>NaCl</td>
<td>NaCl and paraffin oil</td>
<td>NaCl</td>
<td>NaCl and paraffin oil</td>
<td>NaCl</td>
<td></td>
</tr>
<tr>
<td>Flow rate</td>
<td>85 L/min</td>
<td>95 L/min</td>
<td>85 L/min</td>
<td>95 L/min</td>
<td>95 L/min</td>
<td>85 L/min</td>
</tr>
<tr>
<td>Total inward leakage (TIL)* - tested on human subjects each performing exercises</td>
<td>N/A</td>
<td>≤ 8% leakage (arithmetic mean)</td>
<td>≤ 8% leakage (arithmetic mean)</td>
<td>≤ 8% leakage (individual and arithmetic mean)</td>
<td>Inward Leakage measured and included in User Instructions</td>
<td></td>
</tr>
<tr>
<td>Inhalation resistance - max pressure drop</td>
<td>≤ 343 Pa</td>
<td>≤ 70 Pa (at 30 L/min) ≤ 240 Pa (at 95 L/min) ≤ 500 Pa (doggling)</td>
<td>≤ 350 Pa</td>
<td>≤ 70 Pa (at 30 L/min) ≤ 240 Pa (at 95 L/min)</td>
<td>≤ 70 Pa (at 30 L/min) ≤ 240 Pa (at 95 L/min)</td>
<td>≤ 70 Pa (w/valve) ≤ 50 Pa (no valve)</td>
</tr>
<tr>
<td>Flow rate</td>
<td>85 L/min</td>
<td>Varied – see above</td>
<td>85 L/min</td>
<td>Varied – see above</td>
<td>Varied – see above</td>
<td>40 L/min</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhalation resistance - max pressure drop</td>
<td>≤ 245 Pa</td>
<td>≤ 300 Pa</td>
<td>≤ 250 Pa</td>
<td>≤ 120 Pa</td>
<td>≤ 300 Pa</td>
<td>≤ 70 Pa (w/valve) ≤ 50 Pa (no valve)</td>
</tr>
<tr>
<td>Flow rate</td>
<td>85 L/min</td>
<td>160 L/min</td>
<td>85 L/min</td>
<td>85 L/min</td>
<td>160 L/min</td>
<td>40 L/min</td>
</tr>
<tr>
<td>Exhalation valve leakage requirement</td>
<td>Leak rate ≤ 30 mL/min</td>
<td>N/A</td>
<td>Depressurization to 0 Pa ≤ 20 sec</td>
<td>Leak rate ≤ 30 mL/min</td>
<td>visual inspection after 300 L/min for 30 sec</td>
<td></td>
</tr>
<tr>
<td>Force applied</td>
<td>-245 Pa</td>
<td>N/A</td>
<td>-1180 Pa</td>
<td>-250 Pa</td>
<td>N/A</td>
<td>-1,470 Pa</td>
</tr>
<tr>
<td>CO2 clearance requirement</td>
<td>N/A</td>
<td>≤ 1%</td>
<td>≤ 1%</td>
<td>≤ 1%</td>
<td>≤ 1%</td>
<td>≤ 1%</td>
</tr>
</tbody>
</table>

*Japan JMHLW-Notification 214 requires an Inward Leakage test rather than a TIL test.

https://multimedia.3m.com/mws/media/1791500O/comparison-ffp2-kn95-n95-filtering-facepiece-respirator-classes-tb.pdf
Regulation and Approval of Facepieces and Respirators in the US

**US Department of Health and Human Services**

- Federal agency responsible for certifying and testing all respirators used in US occupational settings
- Test/certify according to 42 CFR Part 84
- Excludes fit testing

**US Department of Labor**

- OSHA Agencies require employers to fit test workers who must wear these respirators on the job
- Fit testing to ensure protection

### FDA-regulated face masks

<table>
<thead>
<tr>
<th>Classification Regulation</th>
<th>Device Type</th>
<th>Product Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 CFR 878.4040</td>
<td>Mask, Surgical</td>
<td>FXX</td>
</tr>
<tr>
<td></td>
<td>Pediatric/Child Facemask</td>
<td>OXZ</td>
</tr>
<tr>
<td></td>
<td>Accessory, Surgical Apparel (Face Shield)</td>
<td>LYU</td>
</tr>
<tr>
<td></td>
<td>Surgical mask with antimicrobial/antiviral agent</td>
<td>OUK</td>
</tr>
<tr>
<td></td>
<td>Respirator, Surgical</td>
<td>MSN</td>
</tr>
<tr>
<td></td>
<td>N95 Respirator with Antimicrobial/ Antiviral Agent</td>
<td>ONT</td>
</tr>
<tr>
<td>21 CFR 880.6260</td>
<td>N95 Respirator for Use by the General Public in Public Health Medical Emergencies</td>
<td>ORW</td>
</tr>
<tr>
<td>21 CFR 880.6260</td>
<td>Respirator, N95, for Use by the General Public in Public Health Medical Emergencies</td>
<td>NZJ</td>
</tr>
</tbody>
</table>

Prior to COVID, our N95 respirator use was very low – mainly for care of TB patients (~12 confirmed cases TB per year).

Since COVID, UNC is using ~4000 N95 respirators per week.

These respirators, which filter out ≥95% of airborne particles, must be used in patient rooms and during screening and intake.

UNC Hospitals had ~10,000 new but expired N95 respirators stored from the H1N1 pandemic.

Are these respirators safe to use now?

https://www.med.unc.edu/emergmed/clinical-care/
Expired N95 Respirators and Face Masks to Test
Study Design – The Testing Chamber

• Mask/respirator filtration efficiency tests were conducted in a 10ft x 10ft custom-built stainless steel exposure chamber in the US EPA Human Studies Facility on UNC Chapel Hill’s campus.
Study Design – Ambient Particle Generation

• A TSI 8026 Particle Generator designed for respirator fit testing was used to supplement ambient particle counts with NaCl particles with a count median diameter of 0.04 μm.

• Particle counts in the chamber were allowed to stabilize for 30 minutes prior to testing.
Study Design – Installing the Fit Test Probe

**Step 1:** Load a sample probe onto the piercing tool.

**Step 2:** Load a push nut onto the magnetic push nut tool.

**Step 3:** Use the piercing tool to puncture the respirator from the inside. Push the point through far enough to be seen from the other side.

**Step 4:** On the outside of the respirator, align the push nut tool over the end of the exposed point. Hold the tools in-line with each other and firmly push them together as far as possible.

The respirator is now ready for fit testing.

https://www.tsi.com/getmedia/d34fe715-d5e6-4514-8c03-8b110ef1a408/Fit_Test_Probe_Kit-2980059-USA?ext=.pdf
Study Design – Measuring Particle Penetration

- A pair of TSI 3775 Condensation Particle Counters were used to continuously monitor particles (0.02 – 3 um) in the chamber just outside the facemask and behind the mask.

- Sampling rate of one second.

- Chamber particle counts/cc as measured just outside the facemask were typically in the range of 2000-5000.

- The temperature during testing ranged from 23 to 29.5°C, and the relative humidity was between 10 and 50%.
Study Design – Measuring Particle Penetration

• A pair of TSI 3775 Condensation Particle Counters were used to continuously monitor particles (0.02 – 3 um) in the chamber just outside the facemask and behind the mask.

• Sampling rate of one second.

• Chamber particle counts/cc as measured just outside the facemask were typically in the range of 2000-5000.

• The temperature during testing ranged from 23 to 29.5C, and the relative humidity was between 10 and 50%.
Test Parameters

OSHA Modified Ambient Aerosol CNC Quantitative Fit Testing Protocol For Filtering Facepiece Table A–2—RESPIRATORS.

Bending at Waist (50 sec)
Reading Aloud (30 sec)
Looking Left and Right (30 sec)
Looking Up and Down (30 sec)

Test Parameters

Filtration Efficiency Results: Expired 3M 1860

<table>
<thead>
<tr>
<th>Test</th>
<th>% Particle Penetration</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending at Waist (50sec)</td>
<td>1.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Reading (30sec)</td>
<td>2.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Looking L/R (30sec)</td>
<td>1.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Looking U/D (30sec)</td>
<td>1.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

% Effectiveness (avg. over duration of test)  
97.0% ± 1.0%  
(n=3)  

Preliminary Data

Sickbert-Bennett, E., et.al., 2020, Manuscript Under Review
Filtration Efficiency Results: Expired 3M 8210

Average Particle Penetration for Each Test

<table>
<thead>
<tr>
<th>Test</th>
<th>% Particle Penetration</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending at Waist (50sec)</td>
<td>1.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Reading (30sec)</td>
<td>1.6</td>
<td>0.8</td>
</tr>
<tr>
<td>Looking L/R (30sec)</td>
<td>1.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Looking U/D (30sec)</td>
<td>1.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

% Effectiveness
(avg. over duration of test)

98.5% ± 0.4%
(n=3)

Preliminary Data

Sickbert-Bennett, E., et.al., 2020, Manuscript Under Review
### Average Particle Penetration for Each Test

<table>
<thead>
<tr>
<th>Test</th>
<th>% Particle Penetration</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending at Waist (50sec)</td>
<td>32.6</td>
<td>4.4</td>
</tr>
<tr>
<td>Reading (30sec)</td>
<td>26.6</td>
<td>4.9</td>
</tr>
<tr>
<td>Looking L/R (30sec)</td>
<td>30.4</td>
<td>2.5</td>
</tr>
<tr>
<td>Looking U/D (30sec)</td>
<td>33.3</td>
<td>3.6</td>
</tr>
</tbody>
</table>

% Effectiveness (avg. over duration of test)  

69.2% ± 3.7%  
(n=3)  

Preliminary Data
Filtration Efficiency Results: Procedure Mask with Ear Loops

Average Particle Penetration for Each Test

<table>
<thead>
<tr>
<th>Test</th>
<th>% Particle Penetration</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending at Waist (50sec)</td>
<td>57.1</td>
<td>11.5</td>
</tr>
<tr>
<td>Reading (30sec)</td>
<td>48.8</td>
<td>6.7</td>
</tr>
<tr>
<td>Looking L/R (30sec)</td>
<td>87.9</td>
<td>7.9</td>
</tr>
<tr>
<td>Looking U/D (30sec)</td>
<td>64.2</td>
<td>9.1</td>
</tr>
</tbody>
</table>

% Effectiveness (avg. over duration of test)

37.1% ± 7.2%  
(n=3)

Preliminary Data

Sickbert-Bennett, E., et.al., 2020, Manuscript Under Review
# Comparison of Respirator/Mask Filtration Efficiencies

**Table 1. Facemask percent effectiveness against submicron particle penetration (n=number of masks tested).**

<table>
<thead>
<tr>
<th>Facemask (Common)</th>
<th>Condition</th>
<th>Approved</th>
<th>% Effectiveness</th>
<th>SD</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M 8210 N95</td>
<td>New</td>
<td>Yes*</td>
<td>97.9</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>3M 8210 N95</td>
<td>Expired 2011</td>
<td></td>
<td>98.5</td>
<td>0.4</td>
<td>3</td>
</tr>
<tr>
<td>3M 1860 N95</td>
<td>New</td>
<td>Yes*</td>
<td>98.5</td>
<td>0.4</td>
<td>1</td>
</tr>
<tr>
<td>3M 1860 N95</td>
<td>Expired 2009</td>
<td></td>
<td>97.0</td>
<td>1.0</td>
<td>3</td>
</tr>
<tr>
<td>Surgical Mask with Ties</td>
<td>New</td>
<td>NA</td>
<td>69.2</td>
<td>3.7</td>
<td>3</td>
</tr>
<tr>
<td>Surgical Mask with ear loops</td>
<td>New</td>
<td>NA</td>
<td>37.1</td>
<td>7.2</td>
<td>3</td>
</tr>
</tbody>
</table>

Bold font denotes mask functioned at or above 95% filtration efficiency

*Denotes NIOSH-approved N95 particulate filtering facepiece respirators

[https://www.cdc.gov/niosh/npptl/topics/respirators/disp_part/N95list1sect3.html](https://www.cdc.gov/niosh/npptl/topics/respirators/disp_part/N95list1sect3.html)

Sickbert-Bennett, E., et.al., 2020, Manuscript Under Review
Does Sterilization of N95 Respirators Reduce Filtration Efficiency?

• The CDC and FDA have issued Emergency Use Authorizations (EUAs) for sterilization and reuse of N95 respirators.

• UNC Hospitals could use steam, hydrogen peroxide gas, or ethylene oxide gas to sterilize respirators, but will respirators be effective afterwards?
Sterilized N95 Respirators to Test
Filtration Efficiency Results: EO Sterilized 3M 1860

Average Particle Penetration for Each Test

<table>
<thead>
<tr>
<th>Test</th>
<th>% Particle Penetration</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending at Waist (50sec)</td>
<td>1.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Reading (30sec)</td>
<td>2.3</td>
<td>0.7</td>
</tr>
<tr>
<td>Looking L/R (30sec)</td>
<td>1.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Looking U/D (30sec)</td>
<td>1.0</td>
<td>0.3</td>
</tr>
</tbody>
</table>

% Effectiveness (avg. over duration of test)

98.3% ± 0.8% (n=3)

Preliminary Data

Sickbert-Bennett, E., et.al., 2020, Manuscript Under Review
Filtration Efficiency Results: Steam Sterilized 3M 1870+

Average Particle Penetration for Each Test

<table>
<thead>
<tr>
<th>Test</th>
<th>% Particle Penetration</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending at Waist (50sec)</td>
<td>0.7</td>
<td>0.2</td>
</tr>
<tr>
<td>Reading (30sec)</td>
<td>1.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Looking L/R (30sec)</td>
<td>0.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Looking U/D (30sec)</td>
<td>0.9</td>
<td>0.4</td>
</tr>
</tbody>
</table>

% Effectiveness (avg. over duration of test)  

98.4% ± 0.6%  
(n=3)
### Filtration Efficiency Results: H$_2$O$_2$ Gas Sterilized 3M 1860

#### Average Particle Penetration for Each Test

<table>
<thead>
<tr>
<th>Test</th>
<th>% Particle Penetration</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending at Waist (50sec)</td>
<td>1.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Reading (30sec)</td>
<td>2.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Looking L/R (30sec)</td>
<td>1.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Looking U/D (30sec)</td>
<td>1.1</td>
<td>0.3</td>
</tr>
</tbody>
</table>

- **% Effectiveness (avg. over duration of test)**: 98.4% ± 0.5% (n=3)

**Preliminary Data**

Sickert-Bennett, E., et.al., 2020, Manuscript Under Review
Comparison of Respirator/Mask Filtration Efficiencies

<table>
<thead>
<tr>
<th>Facemask (Common)</th>
<th>Condition</th>
<th>Approved</th>
<th>% Effectiveness</th>
<th>SD</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M 8210 N95</td>
<td>New</td>
<td>Yes</td>
<td>97.9</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>3M 8210 N95</td>
<td>Expired 2011</td>
<td></td>
<td>98.5</td>
<td>0.4</td>
<td>3</td>
</tr>
<tr>
<td>3M 1860 N95</td>
<td>New</td>
<td>Yes</td>
<td>98.5</td>
<td>0.4</td>
<td>1</td>
</tr>
<tr>
<td>3M 1860 N95</td>
<td>Expired 2009</td>
<td></td>
<td>97.0</td>
<td>1.0</td>
<td>3</td>
</tr>
<tr>
<td>3M 1860 N95</td>
<td>EtO Sterilized</td>
<td></td>
<td>98.1</td>
<td>0.5</td>
<td>3</td>
</tr>
<tr>
<td>3M 1860 N95</td>
<td>H2O2 Sterilized</td>
<td></td>
<td>98.4</td>
<td>0.5</td>
<td>3</td>
</tr>
<tr>
<td>3M 1870+ Aura N95</td>
<td>New</td>
<td>Yes</td>
<td>99.2</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>3M 1870+ Aura N95</td>
<td>Autoclaved</td>
<td></td>
<td>98.0</td>
<td>0.4</td>
<td>3</td>
</tr>
<tr>
<td>Surgical Mask with Ties</td>
<td>New</td>
<td>NA</td>
<td>69.2</td>
<td>3.7</td>
<td>3</td>
</tr>
<tr>
<td>Surgical Mask with ear loops</td>
<td>New</td>
<td>NA</td>
<td>37.1</td>
<td>7.2</td>
<td>3</td>
</tr>
</tbody>
</table>

Bold font denotes mask functioned at or above 95% filtration efficiency

*Denotes NIOSH-approved N95 particulate filtering facepiece respirators (https://www.cdc.gov/niosh/nptl/topics/respirators/disp_part/N95list1sect3.html)

Preliminary Data

Sickbert-Bennett, E., et.al., 2020, Manuscript Under Review
Wait, how many different respirators does UNC Hospitals have?

- UNC has received nearly 20,000 donated respirators from our community during the COVID pandemic.

- Many of these respirators claim to be as effective as NIOSH-approved N95 respirators, but they aren’t certified by NIOSH.

- How should hospitals use/prioritize these types of respirators?
Data from a Sample of Donated Products We Have Tested

<table>
<thead>
<tr>
<th>Facemask (Less Common)</th>
<th>Condition</th>
<th>Approved</th>
<th>% Effectiveness</th>
<th>SD</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dasheng DTC-3Z with head straps</td>
<td>New</td>
<td>Yes*</td>
<td>99.2</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>Moldex 2200 N95</td>
<td>New</td>
<td>Yes*</td>
<td>97.8</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>One Sperian HC-NB295F Duckbill</td>
<td>New</td>
<td>Yes*</td>
<td>97.7</td>
<td>0.7</td>
<td>1</td>
</tr>
<tr>
<td>Dasheng DTC-3W with head straps</td>
<td>New</td>
<td>Yes*</td>
<td>95.5</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Willson Saf-T Fit N1105 M/L (Honeywell)</td>
<td>New</td>
<td>Yes*</td>
<td>93.0</td>
<td>1.8</td>
<td>1</td>
</tr>
<tr>
<td>Safe-Life N95 B150</td>
<td>New</td>
<td>No</td>
<td>85.9</td>
<td>2.0</td>
<td>1</td>
</tr>
<tr>
<td>Jia Hu Kang KN-95 Mask with ear loops</td>
<td>New</td>
<td>No</td>
<td>85.1</td>
<td>2.2</td>
<td>1</td>
</tr>
<tr>
<td>Dasheng DTC-3X with ear loops</td>
<td>New</td>
<td>Yes*</td>
<td>79.7</td>
<td>4.4</td>
<td>1</td>
</tr>
<tr>
<td>Dasheng DTC-3X-2 with ear loops</td>
<td>New</td>
<td>Yes*</td>
<td>76.8</td>
<td>5.5</td>
<td>1</td>
</tr>
<tr>
<td>Counterfeit DTC3X &quot;NIOSH N95&quot; with ear loops</td>
<td>New</td>
<td>No</td>
<td>76.2</td>
<td>6.7</td>
<td>1</td>
</tr>
<tr>
<td>Guangdong Fei Fan KN95</td>
<td>New</td>
<td>Yes*</td>
<td>53.2</td>
<td>6.8</td>
<td>1</td>
</tr>
</tbody>
</table>

**Table 1. Facemask percent effectiveness against submicron particle penetration (n=number of masks tested).**

**Preliminary Data**

Bold font denotes mask functioned at or above 95% filtration efficiency

*Denotes NIOSH-approved N95 particulate filtering facepiece respirators ([https://www.cdc.gov/niosh/npptl/topics/respirators/disp_part/N95list1sect3.html](https://www.cdc.gov/niosh/npptl/topics/respirators/disp_part/N95list1sect3.html))

†Denotes authorized imported, non-NIOSH-approved respirators manufactured in China ([https://www.fda.gov/media/136663/download](https://www.fda.gov/media/136663/download))

Sickbert-Bennett, E., et.al., 2020, Manuscript Under Review
But what about homemade masks? Have you tested those?
But what about homemade masks? Have you tested those?

Table 4. Measured Percent effectiveness for homemade and modified surgical/procedural masks.

<table>
<thead>
<tr>
<th>Mask</th>
<th>Condition</th>
<th>% Effectiveness</th>
<th>SD</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shop Towel Mask, 1 layer, rubber band behind neck</td>
<td>DIY</td>
<td>53.9</td>
<td>7.7</td>
<td>1</td>
</tr>
<tr>
<td>Shop Towel Mask, 1 layer, yarn ties</td>
<td>DIY</td>
<td>41.9</td>
<td>8.5</td>
<td>1</td>
</tr>
<tr>
<td>Shop Towel Mask, 1 layer, rubber band ear loops</td>
<td>DIY</td>
<td>54.3</td>
<td>6.0</td>
<td>1</td>
</tr>
<tr>
<td>Shop Towel Mask, 2 layers, rubber band behind neck</td>
<td>DIY</td>
<td>74.0</td>
<td>6.6</td>
<td>1</td>
</tr>
<tr>
<td>Homemade Cotton Mask, 3 layers, ear loops</td>
<td>DIY</td>
<td>53.2</td>
<td>7.1</td>
<td>1</td>
</tr>
<tr>
<td>3D-printed mask, Benhams nonwoven material, 1 layer</td>
<td>DIY</td>
<td>70.1</td>
<td>4.6</td>
<td>1</td>
</tr>
<tr>
<td>3D-printed mask, Benhams nonwoven material, 2 layers</td>
<td>DIY</td>
<td>88.2</td>
<td>1.9</td>
<td>1</td>
</tr>
<tr>
<td>3D-printed mask, surgical mask material</td>
<td>DIY</td>
<td>80.1</td>
<td>3.3</td>
<td>1</td>
</tr>
<tr>
<td>3D-printed mask, Shop Towel material, 2 layers</td>
<td>DIY</td>
<td>58.8</td>
<td>4.8</td>
<td>1</td>
</tr>
<tr>
<td>Surgical Mask with ear loops</td>
<td>New</td>
<td>37.1</td>
<td>7.2</td>
<td>3</td>
</tr>
<tr>
<td>Surgical Mask with ear loops, MIT Fix-The-Mask</td>
<td>Modified</td>
<td>78.2</td>
<td>3.3</td>
<td>1</td>
</tr>
<tr>
<td>Surgical Mask with ear loops, hair clip joining loops</td>
<td>Modified</td>
<td>64.8</td>
<td>5.1</td>
<td>1</td>
</tr>
<tr>
<td>Surgical Mask with ear loops, MIT Fix high on head</td>
<td>Modified</td>
<td>76.6</td>
<td>3.3</td>
<td>1</td>
</tr>
<tr>
<td>Surgical Mask with ear loops, 3D-printed “ear guards”</td>
<td>Modified</td>
<td>61.7</td>
<td>6.5</td>
<td>1</td>
</tr>
</tbody>
</table>

Bold font denotes mask functioned at or above 95% filtration efficiency

Preliminary Data
Data from UNC shows range of performance for N95 (or equivalent) respirators

- Potential causes of failure: poor fit versus poor filtration
- Measurements of material filtration efficiency useful in isolating causes

Mfiltration efficiency also of interest with homemade materials

- Limited quality data available that describes filtration efficiencies of homemade masks
- Remember; masks primarily meant to capture some droplets upon exhalation and reduce spread of virus-laden aerosol into environment (i.e. protect others)
  - Can a certain material or mixture of materials provide better filtration for the user?
Tests conditions under NIOSH certification for N-type respirator

- High flowrate (85 L/min)
- Small particle size (75 nm) near the MPP of electret filters
- Electrically-neutralized particles
- Filter preconditioned at high humidity (~80%) for 25 hours
- Measurement of instantaneous concentration
- Test aerosol concentration < 200 mg/m^3
- Test proceeds until minimum efficiency observed or aerosol mass on filter reaches 200 mg

Thought to provide a conservative estimate of filtration compared to typical use (Rengasamy et al. 2016)
Quantifying Filtration: Extending Testing to Range of Sizes

Most penetrating particle

- NIOSH procedure uses an aerosol with a CMD of ~75 nm, near the MPP of electret filters.
- Absent electrostatic effects, MPP shifts to 200 – 800 nm
  - Isopropanol treatment (Rengasamy et al. 2009)
- Testing with only small particles may overestimate filtration for filters lacking strong electrostatic deposition mechanisms
  - Diffusion is an efficient filtration mechanism for small particles, and may compensate for lack of electrostatics

Testing with a range of particle sizes is preferable when measuring filtration performance of novel (i.e. homemade, externally-sourced, under-characterized, etc.) material

Ref: Rengasamy, Eimer & Shaffer, Ann. Occup. Hyg., 2009:53(2);117-128 (image source, fig. 8)
Neutralized, dried polydisperse salt aerosol

Particles introduced into plenum and allowed to settle into test chamber

3-way valve allows for comparison of aerosol concentration in blank and filter lines via alternating measurements

Concentrations measured using ELPI

Pressure drop measured across filter

Test Conditions

30 L/min flowrate (set by calibration of ELPI)

Face velocity of 10.3 cm/s (NIOSH ~ 9.3 cm/s, Rengasamy et al. 2016)

Good number concentrations achieved in ELPI stages 1 to 10 (from 29 nm to 4.02 µm)
Results: N95 Respirators (and Equivalents)

Many N95s (or equivalents) perform well
- Medical-grade respirators from reputable manufacturers provide good performance
- Legitimate NIOSH certification* coincides with >95% filtration as measured here
- Some respirators without explicit NIOSH certification provide >95% efficiency

Note: not all N95 (or equivalent) respirators labelled as such provide >95% filtration for all particles between 30 nm and 4 µm!
- Careful attention must be placed on the source and testing standards

List of NIOSH-Approved Respirators: https://www.cdc.gov/niosh/npptl/topics/respirators/disp_part/default.html
Filtration and pressure drop vary widely with “homemade” materials

- Data here is ideal case, corresponding to zero leaks when worn (unlikely!)
- Variation in material properties make a priori prediction of homemade mask filtration extremely difficult
- Some materials offer better filtration than others for reasonable $\Delta P$
  - Mixtures of some natural and synthetic fabrics may provide better filtration by facilitating electrostatic effects (see Konda et al. 2020)

Ref: Konda et al., ACS Nano 2020:14(5);6339-6347
Masks: Filtration vs Pressure Drop

Reminder; balance between filtration and pressure drop

- NIOSH upper limit of ~245 Pa $\Delta P$ during exhalation for respirators
- *Masks generally do not seal to the face*
- A higher resistance to airflow will encourage more air to bypass filtration entirely
- More data needed to determine optimal balance between pressure drop, filtration and leakage
- A “good” material for homemade masks:
  - Can be layered a few times without causing a large (>100 Pa) pressure drop
  - Facilitates electrostatic effects (Konda et al. 2020)
  - Can be cleaned regularly

A “poorly-performing” mask is better than nothing

- In conjunction with social distancing and proper hand/mask hygiene, widespread mask use by the general population can help control otherwise exponential growth of the pandemic, and reduces the risks of resurgence upon economic reopening and relaxation of social distancing (Esposito et al. 2020)

Refs: Konda et al., ACS Nano 2020:14(5);6339-6347
Takeaways and Considerations

Respirators

- Protect the wearer and reduce viral load in the event of infection
- Essential for those under risk of continual exposure (healthcare, essential, etc.)
- Expired N95s (up to 11 years beyond date) maintained >95% filtration efficiency
- Some sterilization methods (EO and H202) may allow for reuse, but other methods (steam) can impair function due to deformation
- Non-approved N95s (and equivalents) may fail to provide >95% filtration efficiency
- *Fit is extremely important for proper function*

Masks

- Masks provide a barrier to easy dispersal and remove some large droplets upon exhalation
- A “poorly-performing” mask is better than nothing, but some materials may provide somewhat better protection for the user
- Claims of filtration efficiency for homemade masks must be verified; differences in e.g. thread count, wash cycles, weave vs knit mean vague descriptions (“cotton mask”) aren’t truly indicative of performance
- Avoid creating too high a pressure drop
  - Air will tend to bypass filtration
  - Impedes breathing (also occurs with respirators)
References

- Drossinos & Stilianakis, Aerosol Sci. Technol., 2020:54(6);639-643
- Asadi, Bouvier, Wexler, & Ristenpart, Aerosol Sci. Technol., 2020:54(6);635-638
- Bourouiba, Dehandschoewercker & Bush, J. Fluid Mech., 2014:745;537-563 (image source, adapted from fig. 3)
- van Doremalen et al., N. Engl. J. Med., 2020:382(16);1564-1567
- Leung et al., Nat. Med. 2020:26;676-680
- Wang, Powder Technol., 2001:118;116-170
- Rengasamy, Eimer & Shaffer, Ann. Occup. Hyg., 2009:53(2);117-128 (image source, fig. 8)
- Sickbert-Bennett, E., et.al., 2020, Manuscript Under Review
- Rengasamy et al., J. Occup. Environ. Hyg. 2016:14(2);92-103
- Konda et al., ACS Nano 2020:14(5);6339-6347
Acknowledgements

UofA Department of Mechanical Engineering
Aerosol Research Group
Warren Finlay, PhD
Andrew Martin, PhD
Reinhard Vehring, PhD
Hui Wang, PhD
Scott Tavernini, MSc
Patrick Deng

Special thanks to the machine shop staff and
H.O. for technical and laboratory support

Research efforts were partially funded through
Natural Sciences Engineering Research Council
of Canada and Mitacs.

UNC Mucociliary Clearance and
Aerosol Research Laboratory
William Bennett, PhD
Kirby Zeman, PhD
Jihong Wu, MD

US EPA Human Studies Facility
David Diaz-Sanchez, PhD
James Samet, PhD
Jon Berntsen, PhD
Hao Chen, PhD
Haiyan Tong, PhD

UNC Health Care
Emily Sickbert-Bennett, PhD
David Weber, MD
Carol Lewis, MBA
Daniel Lehman, MHA

UNC CEMALB
David Peden, MD
Ilona Jaspers, PhD
Phillip Bromberg, MD
Contact Information and Questions

For more information, contact:

Conor A. Ruzycki: cruzycki@ualberta.ca

Phillip Clapp: phillip_clapp@med.unc.edu

Questions?