Facial Masks during COVID-19: Homemaking, Disinfection and Imaging

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Collaborators
SLAC National Accelerator Laboratory
Stanford: Prof. Steven Chu, Prof Larry Chu, Prof. Wah Chiu, Dr. Amy Price
4C Air Team: Dr. Lei Liao, Mervin Zhao and others
The DeMaND Team:
Prof. May Chu (Colorado), Selcen Kilinc-Balci (CDC/NIOSH), Brian H. Harcourt (CDC) Ying Ling Lin (WHO) and many others
Virus sizes: 20 nm to 400 nm

SARS-COV-2
(∼150nm)

- related to SARS
  and MERS
- spread via close contact
- infect lung cells
- cause pneumonia

Influenza virus

Virus Structure
After seconds (depending on humidity), droplets evaporate in air to become aerosols (<1 μm), which stay in air for days.

Indoor: wearing masks
Outdoor: If crowded, wearing masks

https://www.medrxiv.org/content/10.1101/2020.04.01.20050443v1
Filtration materials in mask

1) Micronsize fibers (1-10 µm) forming 3D structures with porosity~90%
2) Need electric static charge to increase particle capture efficiency

$$E = \frac{\lambda}{2\pi \varepsilon_0 r}$$

For $r \geq R$

Spunbond fibers: 10-40 µm diameter
Meltblown fibers: 1-10 µm diameter

http://hyperphysics.phy-astr.gsu.edu/hbase/electric/elecyl.html
Homemade masks
Community-made masks
From Prof. May Chu

Sample Description:
The hand-made masks appear to be a four-layer structure comprised of woven – spunbond – spunbond -woven. The spunbonded material is the standard Oly-Fun Fabric which can be bought online (https://www.hobbylobby.com/Fabric-Sewing/Utility-Fabrics/Multi-Purpose-Fabric/Oly-Fun-Fabric/p/MP29918).

The single layer of Oly-Fun fabric has a typical efficiency of 15% while two layers of Oly-fun fabric has a typical efficiency of 30%.

Testing Procedure:
4C Air conducted a standard filtration efficiency test used in NIOSH N95, 42 CFR Part 84 (Respiratory Protective Devices). Tests were conducted on an “Automated Filter Tester” 8130A (TSI, Inc.) using 0.26 μm (mass mean diameter) NaCl as the aerosol source under a flow rate of 85 L/min.

6 FFRs were tested before any treatments were performed. 3 FFRs were tested after the triboelectric charging and 3 FFRs were treated after the hot gas charging.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Efficiency (%)</th>
<th>Pressure drop (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>49.72</td>
<td>88.00</td>
</tr>
<tr>
<td>2</td>
<td>43.66</td>
<td>73.00</td>
</tr>
<tr>
<td>3</td>
<td>44.02</td>
<td>89.00</td>
</tr>
<tr>
<td>4</td>
<td>46.54</td>
<td>85.00</td>
</tr>
<tr>
<td>5</td>
<td>47.29</td>
<td>88.00</td>
</tr>
<tr>
<td>6</td>
<td>43.66</td>
<td>95.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>After triboelectric charging</th>
<th>Efficiency (%)</th>
<th>Pressure drop (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52.18</td>
<td>87.00</td>
</tr>
<tr>
<td>2</td>
<td>51.65</td>
<td>85.00</td>
</tr>
<tr>
<td>3</td>
<td>49.24</td>
<td>95.00</td>
</tr>
</tbody>
</table>

20 minutes resting after triboelectric charging

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Efficiency (%)</th>
<th>Pressure drop (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>47.22</td>
<td>86.00</td>
</tr>
<tr>
<td>2</td>
<td>45.46</td>
<td>82.00</td>
</tr>
<tr>
<td>3</td>
<td>45.36</td>
<td>92.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>After hot gas charging</th>
<th>Efficiency (%)</th>
<th>Pressure drop (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>48.30</td>
<td>93.00</td>
</tr>
<tr>
<td>5</td>
<td>45.37</td>
<td>98.00</td>
</tr>
<tr>
<td>6</td>
<td>42.16</td>
<td>97.00</td>
</tr>
</tbody>
</table>
Fabric selection

Commonly found cloths

- Commonly used fabric types were selected
- Among them: cotton, rayon, and silk are organic, the rest are synthetic fabrics

- Tested with Automated Filter Tester 8130A, TSI, Inc.
- Flow rate of 32 L/min
- 0.26 μm (mass median diameter) NaCl aerosol

(Yi Cui et. al. unpublished results)
Cellulose products
Commonly found paper or sanitary products

- Kitchen paper towel
- Facial tissue
- Xerox A4 paper

- Tested with Automated Filter Tester 8130A, TSI, Inc.
- Flow rate of 32 L/min
- 0.26 μm (mass median diameter) NaCl aerosol

(Yi Cui et al. unpublished results)
Material selection

Summary of initial and charged filtration efficiencies

\[ Q = - \frac{\log \left( 1 - \frac{E}{100} \right)}{\Delta P} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>Source</th>
<th>Structure</th>
<th>Basis weight (g/m²)</th>
<th>Initial Efficiency (%)</th>
<th>Initial Pressure drop (Pa)</th>
<th>Filter quality factor, Q (kPa⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Personal Protection Materials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polypropylene 1</td>
<td>Particulate FFR</td>
<td>Melblown (nonwoven)</td>
<td>25</td>
<td>95.94 ± 2</td>
<td>9.0 ± 2.0</td>
<td>162.7 ± 21.3</td>
</tr>
<tr>
<td>Polypropylene 2</td>
<td>Surgical mask</td>
<td>Melblown (nonwoven)</td>
<td>26</td>
<td>33.06 ± 0.95</td>
<td>34.3 ± 0.5</td>
<td>5 ± 0.1</td>
</tr>
<tr>
<td>Polypropylene 3</td>
<td>Surgical mask</td>
<td>Melblown (nonwoven)</td>
<td>20</td>
<td>18.81 ± 0.5</td>
<td>16.3 ± 0.5</td>
<td>5.5 ± 0.1</td>
</tr>
<tr>
<td><strong>Household Materials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polypropylene 4 (PP-4)</td>
<td>Spunbond</td>
<td>Nonwoven</td>
<td>30</td>
<td>6.15 ± 2.18</td>
<td>1.6 ± 0.5</td>
<td>16.9 ± 3.4</td>
</tr>
<tr>
<td>Cotton 1'</td>
<td>Clothing</td>
<td>Woven</td>
<td>116</td>
<td>5.04 ± 0.64</td>
<td>4.5 ± 2.1</td>
<td>5.4 ± 1.9</td>
</tr>
<tr>
<td>Cotton 2'</td>
<td>Clothing</td>
<td>Knit</td>
<td>157</td>
<td>21.62 ± 1.84</td>
<td>14.5 ± 2.1</td>
<td>7.4 ± 1.7</td>
</tr>
<tr>
<td>Cotton 3'</td>
<td>Clothing</td>
<td>Knit</td>
<td>360</td>
<td>25.88 ± 1.41</td>
<td>17 ± 0.0</td>
<td>7.6 ± 0.4</td>
</tr>
<tr>
<td>Polyester</td>
<td>Clothing</td>
<td>Knit</td>
<td>200</td>
<td>17.5 ± 5.1</td>
<td>12.3 ± 0.5</td>
<td>6.8 ± 2.4</td>
</tr>
<tr>
<td>Silk</td>
<td>Napkin</td>
<td>Knit</td>
<td>84</td>
<td>4.77 ± 1.47</td>
<td>7.3 ± 1.5</td>
<td>2.8 ± 0.4</td>
</tr>
<tr>
<td>Nylon</td>
<td>Clothing</td>
<td>Woven</td>
<td>164</td>
<td>23.33 ± 1.18</td>
<td>244 ± 5.5</td>
<td>0.4 ± 0</td>
</tr>
<tr>
<td>Cellulose</td>
<td>Kitchen towel</td>
<td>Bonded</td>
<td>42.9</td>
<td>10.41 ± 0.28</td>
<td>11 ± 0.0</td>
<td>4.3 ± 2.8</td>
</tr>
<tr>
<td>Cellulose</td>
<td>Facial tissue</td>
<td>Bonded</td>
<td>32.8</td>
<td>20.2 ± 0.32</td>
<td>19 ± 1</td>
<td>5.1 ± 3.2</td>
</tr>
<tr>
<td>Cellulose</td>
<td>Copy paper</td>
<td>Bonded</td>
<td>72.8</td>
<td>99.85 ± 0.02</td>
<td>1883.6 ± 39.3</td>
<td>1.5 ± 0.2</td>
</tr>
</tbody>
</table>

(Yi Cui et. al. unpublished results)
(Yi Cui et. al. unpublished results)
Triboelectric charging
Method and observations

- Samples under friction produce static (triboelectricity)
- Clear observation of attractive force
- Samples are tested immediately after 10 seconds of “charging”
- Samples are further tested after resting to test decay

(Yi Cui et. al. unpublished results)
(Yi Cui et. al. unpublished results)
Humidity Dependence of Static Charge

(Yi Cui et. al. unpublished results)
Summary and ranking of materials tested here based on $Q$, with relevant comments for each material.

<table>
<thead>
<tr>
<th>$Q$ (kPa$^2$)</th>
<th>Efficiency (%)</th>
<th>Material</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;100</td>
<td>&gt;95</td>
<td>Polypropylene meltblown (charged)</td>
<td>Material found in FFRs (used for reference)</td>
</tr>
<tr>
<td>30</td>
<td>10-20</td>
<td>Charged polypropylene (PP-4)</td>
<td>Charged value after overnight, polypropylene spunbonds can vary (different basis weight has different efficiency) but some charging all increases the spunbonds tested here and has low pressure</td>
</tr>
<tr>
<td>15</td>
<td>5-10</td>
<td>Uncharged polypropylene (PP-4)</td>
<td>Initial polypropylene spunbonds can vary in efficiency, but most tested had low pressure drops</td>
</tr>
<tr>
<td>5-10</td>
<td>20</td>
<td>Cotton</td>
<td>Knit and woven can vary in initial pressure drop, select cotton without any visible pores under light illumination or use multilayers</td>
</tr>
<tr>
<td>5-10</td>
<td>20</td>
<td>Polyester</td>
<td>Similar to cotton</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>Polypropylene meltblown (uncharged)</td>
<td>Material found in surgical masks (used for reference)</td>
</tr>
<tr>
<td>5</td>
<td>10-20</td>
<td>Facial tissue, paper or kitchen towel</td>
<td>Low mechanical strength, but may be possible to integrate into some masks with other cloths as a composite material</td>
</tr>
<tr>
<td>&lt;5</td>
<td>5</td>
<td>Silk</td>
<td>If cotton and/or polyester are unavailable, otherwise the same comments as cotton</td>
</tr>
<tr>
<td>&lt;1</td>
<td>20</td>
<td>Nylon (woven)</td>
<td>The nylon tested were had very high pressure drop, if using nylon for facial masks the nylon needs to have a lower pressure drop to be effective</td>
</tr>
</tbody>
</table>
Fabrics from Africa (from Prof. May Chu)

Left: T-Shirt bought in Kenya 2008; Middle: Sierra Leone West Africa Women’s Cooperative; Right: Traditional Kenya Wedding

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Efficiency (%)</th>
<th>Pressure drop (Pa)</th>
<th>~Q (kPa⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-Shirt Kenya</td>
<td>15.06</td>
<td>24</td>
<td>2.9</td>
</tr>
<tr>
<td>West Africa</td>
<td>8.84</td>
<td>17</td>
<td>2.4</td>
</tr>
<tr>
<td>Kenya Wedding</td>
<td>7.21</td>
<td>7</td>
<td>4.5</td>
</tr>
</tbody>
</table>
Disinfection of N-95 level masks
## Mask Standards

<table>
<thead>
<tr>
<th>Mask Type</th>
<th>Single-use medical face mask</th>
<th>Surgical Mask</th>
<th>Protective face mask for medical use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standards</td>
<td>YY/T 0969-2013</td>
<td>YY 0469-2011</td>
<td>GB19083-2010</td>
</tr>
<tr>
<td>Particle size</td>
<td>3µm bacteria aerosol</td>
<td>3µm bacteria aerosol 0.3µm NaCl aerosol</td>
<td>0.3µm NaCl aerosol</td>
</tr>
<tr>
<td>Filtration efficiency particle filtration efficiency (PFE)</td>
<td>BFE ≥ 95%</td>
<td>BFE ≥ 95%</td>
<td>PFE ≥ 95% (I)</td>
</tr>
<tr>
<td>Bacteria filtration efficiency (BFE)</td>
<td></td>
<td>PFE ≥ 30%</td>
<td>PFE ≥ 99% (II)</td>
</tr>
<tr>
<td>Liquid blocking capability, mmHg</td>
<td>/</td>
<td>≥ 120</td>
<td>PFE ≥ 99.97% (III)</td>
</tr>
</tbody>
</table>

*Single-use medical face mask*  
*Surgical mask*  
*Protective face mask for medical use*
## Mask Standards

<table>
<thead>
<tr>
<th>Mask types</th>
<th>Protective face mask for medical use</th>
<th>Industrial Protective Mask</th>
<th>Daily Protective masks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standards</td>
<td>GB 19083-2010</td>
<td>GB 2626-2019</td>
<td>GB/T 32610-2016</td>
</tr>
<tr>
<td>Particle size</td>
<td>0.3µm NaCl aerosol (mass median size)</td>
<td>0.3µm NaCl aerosol</td>
<td>0.3µm NaCl aerosol</td>
</tr>
<tr>
<td>Filtration efficiency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particle filtration efficiency</td>
<td>PFE≤95% (I)</td>
<td>PFE≥90%</td>
<td>PFE≥90% (III)</td>
</tr>
<tr>
<td>(PFE)</td>
<td>PFE≥99% (II)</td>
<td>PFE≥95%</td>
<td>PFE≥95% (II)</td>
</tr>
<tr>
<td>Bacteria filtration efficiency</td>
<td>PFE≥99.97% (III)</td>
<td>PFE≥99.97%</td>
<td>PFE≥99% (I)</td>
</tr>
<tr>
<td>(BFE)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid blocking capability, mmHg</td>
<td>80</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>
Filtration materials in

Can N95 Respirators Be Reused after Disinfection? How Many Times?
Lei Liao, Wang Xiao, Mervin Zhao, Xuanze Yu, Haotian Wang, Qi Qi Wang, Steven Chu, and Yi Cui*
Similar as the NIOSH-testing condition
TSI 8130A, 0.26um NaCl particles (mean mass diameter),
Fabric level: 32 L/min flow
Mask level: 85 L/min flow
## N95 Meltblown Fabric Disinfection

TSI 8130A, 0.26um NaCl particles, 32 L/min flow

<table>
<thead>
<tr>
<th>Samples</th>
<th>Meltblown fiber media</th>
<th>Static-charged cotton</th>
<th>E. Coli. Disinfection Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Filtration efficiency (%)</td>
<td>Pressure drop (Pa)</td>
<td>Filtration efficiency (%)</td>
</tr>
<tr>
<td>70°C hot air in oven, 30min</td>
<td>96.60</td>
<td>8.00</td>
<td>70.16</td>
</tr>
<tr>
<td>UV light, 30min</td>
<td>95.50</td>
<td>7.00</td>
<td>77.72</td>
</tr>
<tr>
<td>75% alcohol, soaking and drying</td>
<td>56.33</td>
<td>7.67</td>
<td>29.24</td>
</tr>
<tr>
<td>Chlorine-based disinfection, 5min</td>
<td>73.11</td>
<td>9.00</td>
<td>57.33</td>
</tr>
<tr>
<td>Hot water vapor from boiling water, 10min</td>
<td>94.74</td>
<td>8.00</td>
<td>77.65</td>
</tr>
</tbody>
</table>

### Conclusion

Do not use alcohol-based or Chlorine-related chemicals for mask disinfection since they will reduce the static charge in meltblown micron fibers and cottons, and thus reduce the filtration efficiency.
N95 Meltblown Fabric Disinfecting

Dry heat: <30% Humidity

75°C, 30min
85°C, 20min
100°C, 10min
125°C, 10min
N95 Meltblown Fabric Disinfecting Cycle

Each Cycle: 20 min 85°C/per cycle, different humidities

A

B

C

D

30% humidity
N95 Mask Disinfecting Cycling

20 min 85°C/per cycle

E

F
Heat (dry, humid) on COVID-19 Disinfection

https://www.medrxiv.org/content/10.1101/2020.03.15.20036673v2.full.pdf+html

Table. Stability of SARS-CoV-2 at different environmental conditions.

<table>
<thead>
<tr>
<th>Time</th>
<th>4°C Mean ±SD</th>
<th>22°C Mean ±SD</th>
<th>37°C Mean ±SD</th>
<th>56°C Mean ±SD</th>
<th>70°C Mean ±SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 min</td>
<td>N.D.</td>
<td>6.21 ±0.27</td>
<td>N.D.</td>
<td>6.65 ±0.14</td>
<td>6.34 ±0.17</td>
</tr>
<tr>
<td>5 mins</td>
<td>N.D.</td>
<td>6.7 ±0.15</td>
<td>N.D.</td>
<td>4.62 ±0.44</td>
<td>U</td>
</tr>
<tr>
<td>10 mins</td>
<td>N.D.</td>
<td>6.63 ±0.07</td>
<td>N.D.</td>
<td>3.84 ±0.32</td>
<td>U</td>
</tr>
<tr>
<td>30 mins</td>
<td>6.51 ±0.27</td>
<td>6.52 ±0.28</td>
<td>6.57 ±0.17</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>1 hr</td>
<td>6.57 ±0.32</td>
<td>6.33 ±0.21</td>
<td>6.76 ±0.05</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>3 hrs</td>
<td>6.66 ±0.16</td>
<td>6.68 ±0.46</td>
<td>6.36 ±0.19</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>6 hrs</td>
<td>6.67 ±0.04</td>
<td>6.54 ±0.32</td>
<td>5.99 ±0.26</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>12 hrs</td>
<td>6.58 ±0.21</td>
<td>6.23 ±0.05</td>
<td>5.28 ±0.23</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>1 day</td>
<td>6.72 ±0.13</td>
<td>6.26 ±0.05</td>
<td>3.23 ±0.05</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>2 days</td>
<td>6.42 ±0.37</td>
<td>5.83 ±0.28</td>
<td>U</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>4 days</td>
<td>6.32 ±0.27</td>
<td>4.99 ±0.18</td>
<td>U</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>7 days</td>
<td>6.66 ±0.05</td>
<td>3.48 ±0.24</td>
<td>U</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>14 days</td>
<td>6.04 ±0.18</td>
<td>U</td>
<td>U</td>
<td>U</td>
<td>U</td>
</tr>
</tbody>
</table>

70°C in solution, 5min, Complete Disinfection

70°C Dry Heat, 60min, Complete Disinfection

https://www.medrxiv.org/content/10.1101/2020.04.11.20062018v1
Heat Under Different Humidity on N95 Meltblown Fabric

![Graph showing the efficiency and resistance of N95 meltblown fabric under different humidity conditions.](image-url)
Summary of Heating Methods

Dry heat below 100C is safe for N95 Meltblown Fabric

Humid heat below 95C (<100C) is safe for N95 Meltblown Fabric
UV Testing, 254nm, 8W light bulb

Notes on the UV-C methods:
1) Penetration; The shadow effects of 3D porous structures
2) UV illumination uniformity issue
3) UV Dose measurement
4) UV degradation of PP fibers and elastic straps.

Implementing the UV-C method requires good engineering control, probably more suitable for industry scale disinfection.
Notes on other disinfection methods

1) Ethylene oxide: toxic, needs to release the residue (need to good engineering control, Industry scale)

2) Vaporized hydrogen peroxide: cautious about the toxic byproduct, needs to release the residue (need to good engineering control, Industry scale)

3) ClO₂: cautious about toxic byproduct, etching straps, needs to release the residue (need to good engineering control, Industry scale)

4) Ozone: cautious about toxic by product, needs to release the residue (need to good engineering control, Industry scale)
NaCl particle distribution inside N95 Meltblown fabric

Hye Ryoung Lee, Yi Cui et. al. unpublished results
Polymer Nanofibers for Future Tech

Polymer Nanofibers for Future Technology

In-situ PM2.5 Capture

Summary

Homemade Masks
1. Polypropylene (charged and uncharged)
2. Cotton
3. Polyester
4. Facial tissue
5. Silk

Disinfection of N-95 level Masks
1. Dry heat below 100C is safe for N95 Meltblown Fabric
2. Humid heat below 95C (<100C) is safe for N95 Meltblown Fabric

Future Directions
Develop easy criteria for layman to pick the fabric
- Eye inspection (no visible holes)
- Thread counts
- Breathing try
Thank you!

Collaborators:
Stanford: Prof. Steven Chu, Prof Larry Chu, Prof. Wah Chiu, Dr. Amy Price

4C Air Team: Dr. Lei Liao, Mervin Zhao and others

The DeMaND Team:
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