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

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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:
Prof. May Chu (Colorado), Selcen Kilinc-Balci (CDC/NIOSH), Brian H. Harcourt (CDC) Ying Ling Lin (WHO) and many others

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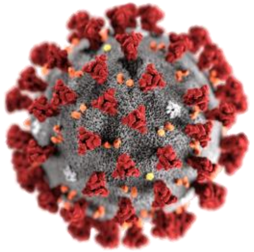
Virus sizes : 20 nm to 400 nm

SARS-COV-2
(~150nm)



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

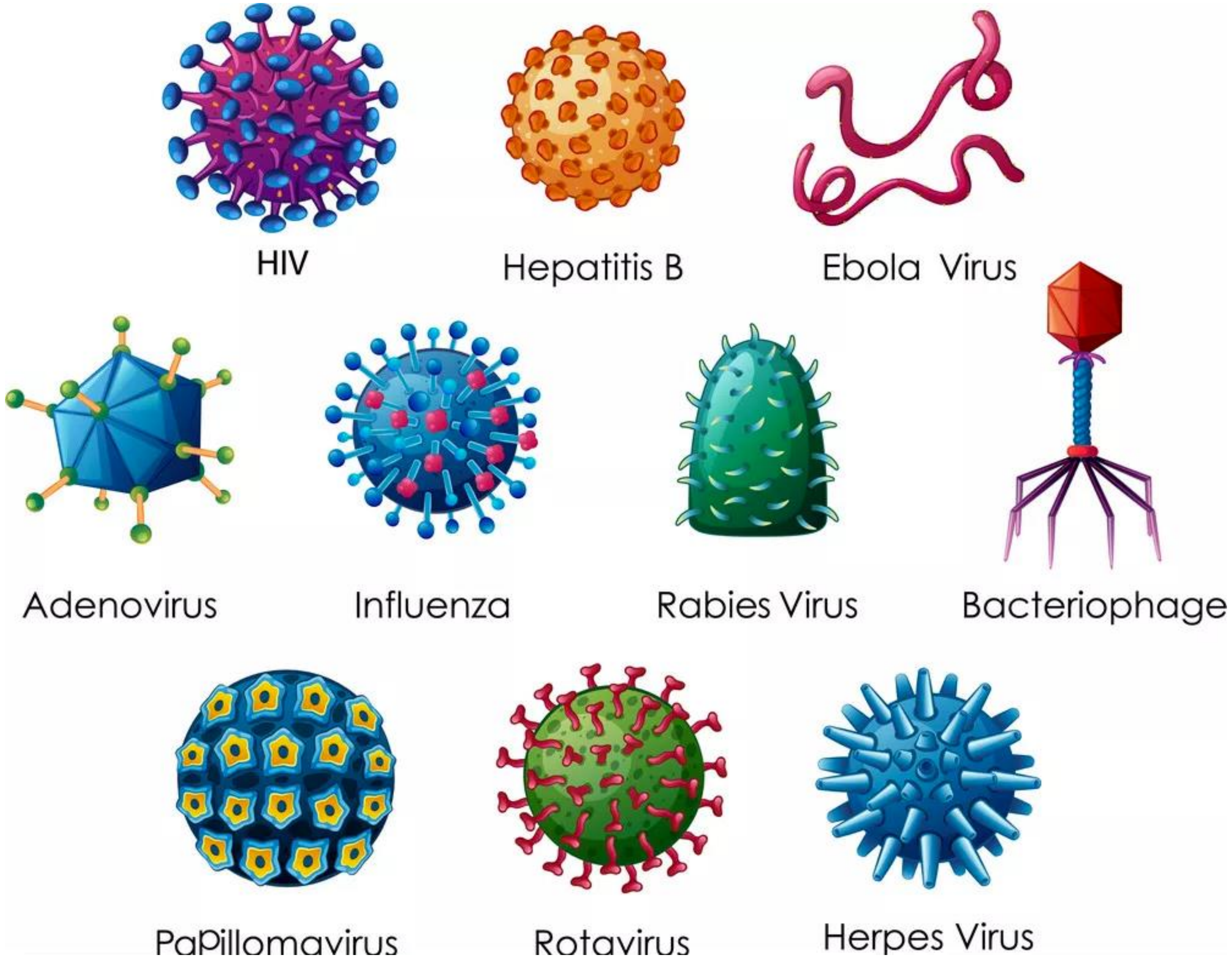
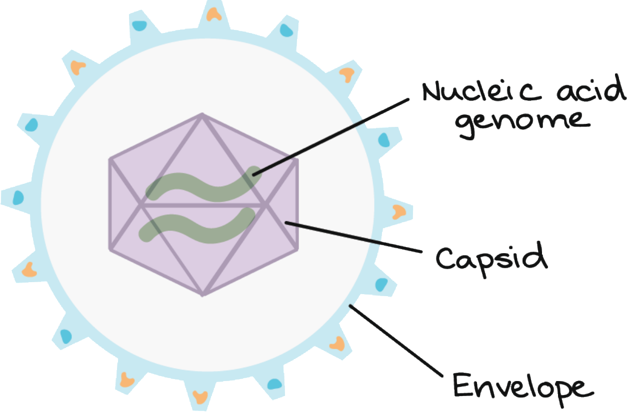
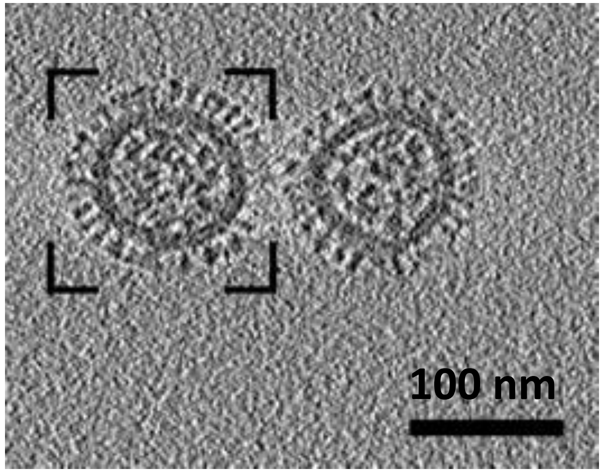


Image adapted from Google

Virus Structure

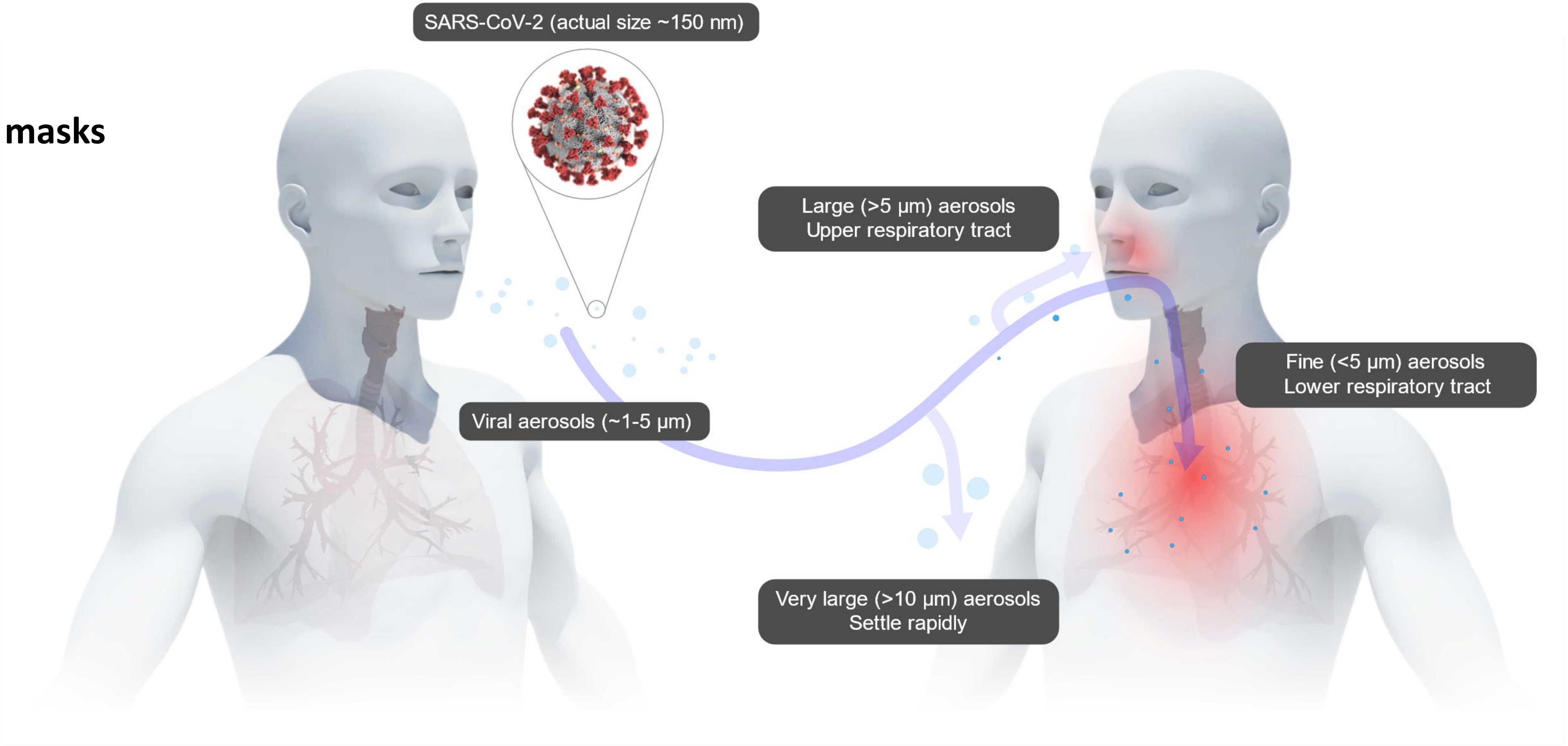




Influenza virus

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

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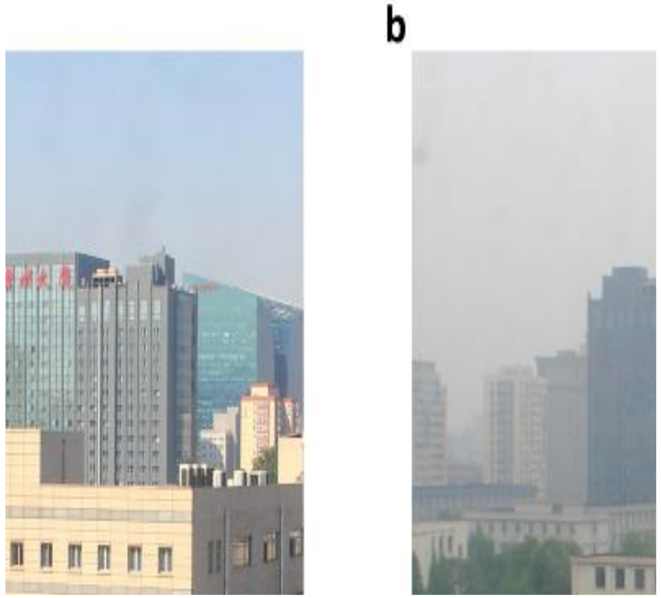
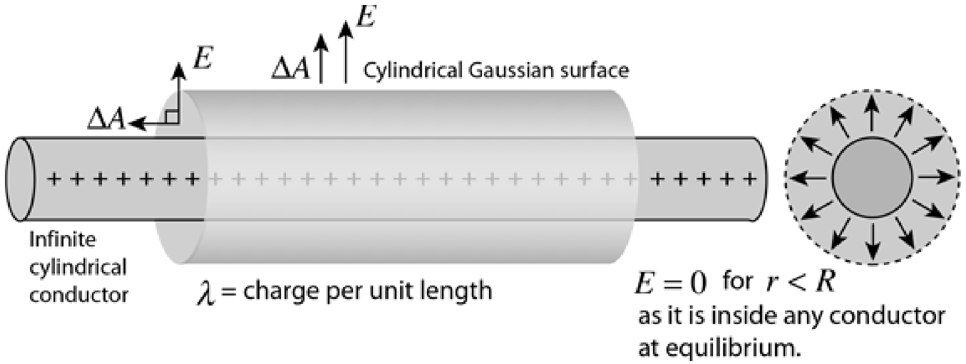


1) Micronsize fibers (1-10 μm) forming 3D structures with porosity~90%
2) Need electric static charge to increase particle capture efficiency

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



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

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Product images:

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.

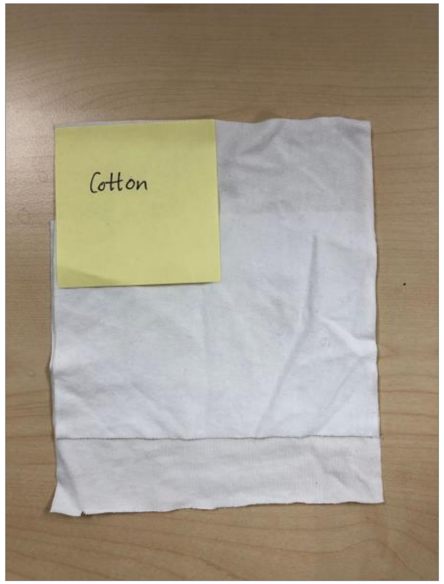
Testing Data:

Initial		
Sample #	Efficiency (%)	Pressure drop (Pa)
1	49.72	88.00
2	43.66	73.00
3	44.02	89.00
4	46.54	85.00
5	47.29	88.00
6	43.66	95.00
After triboelectric charging		
	Efficiency (%)	Pressure drop (Pa)
1	52.18	87.00
2	51.65	85.00
3	49.24	95.00
20 minutes resting after triboelectric charging		
1	47.22	86.00
2	45.46	82.00
3	45.36	92.00
After hot gas charging		
4	48.30	93.00
5	45.37	98.00
6	42.16	97.00

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

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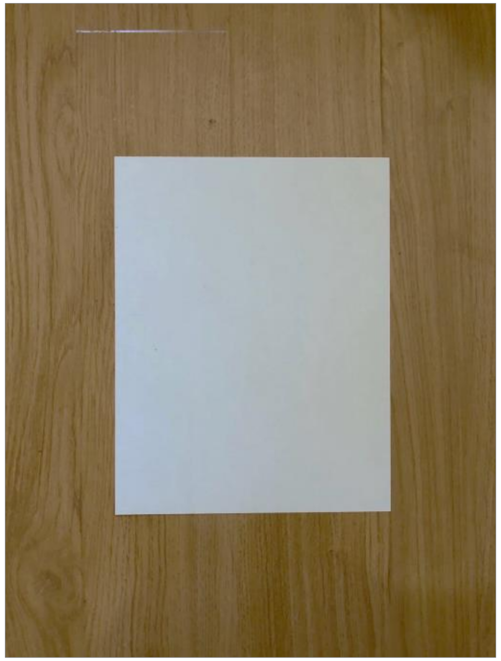
Kitchen paper towel

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

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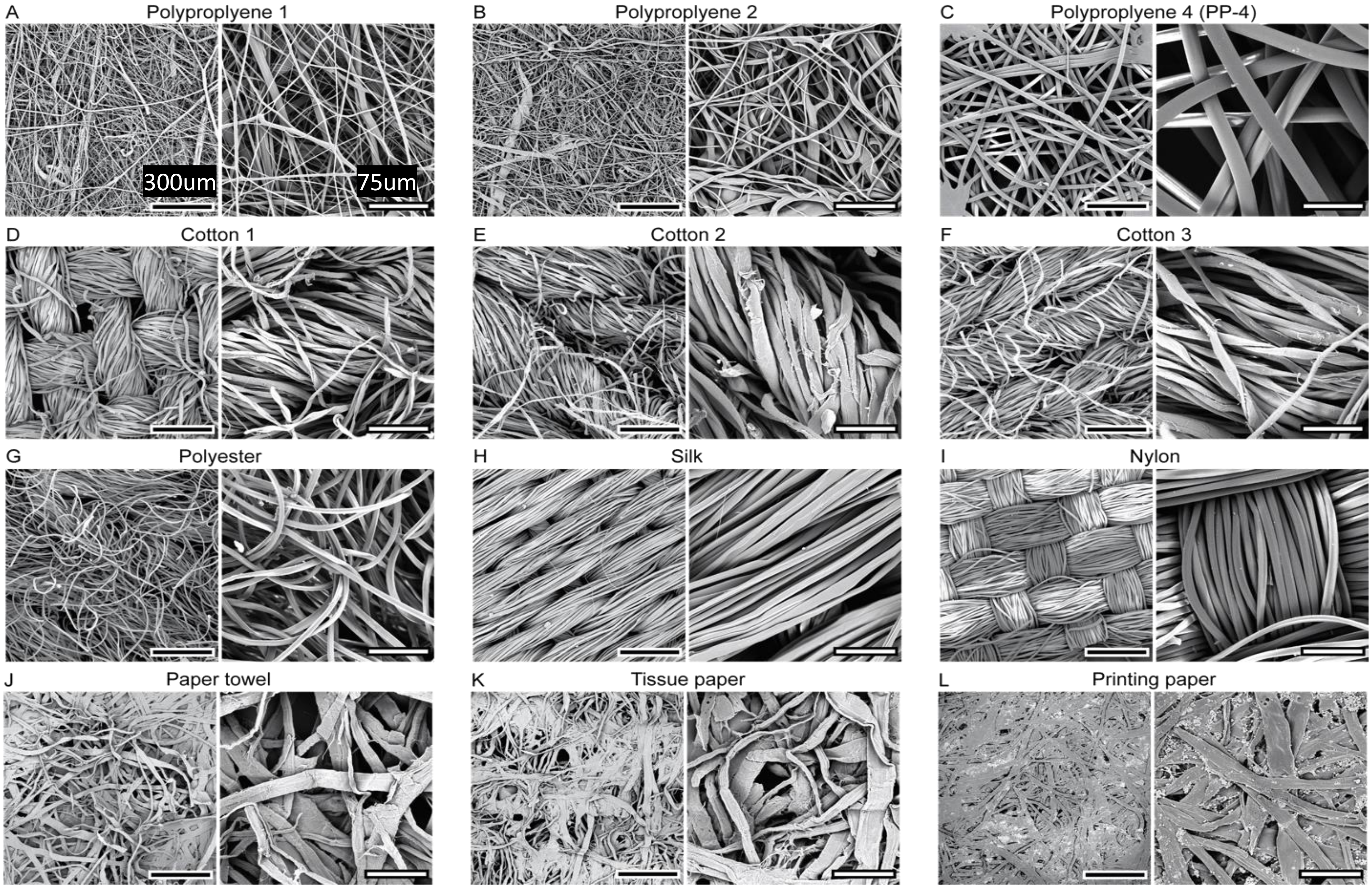
Summary of initial and charged filtration efficiencies

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

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

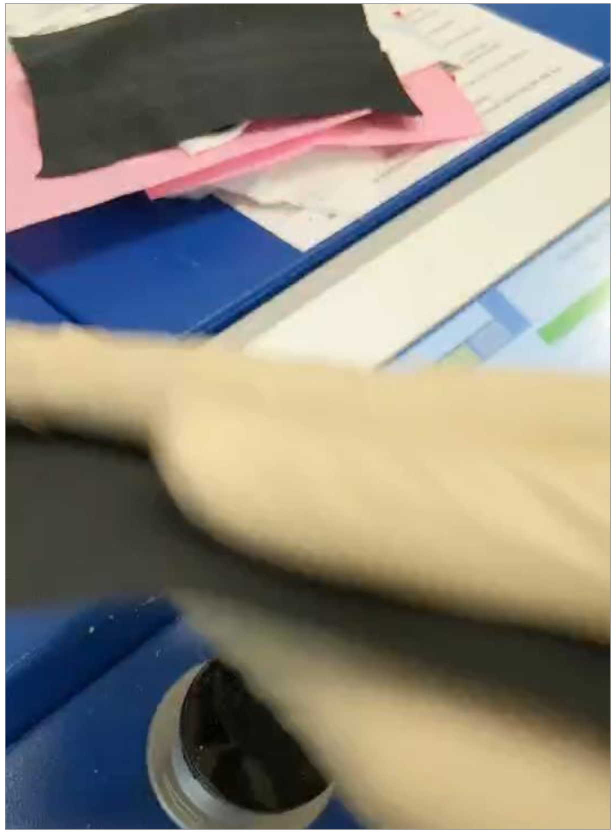
(Yi Cui et. al. unpublished results)



(Yi Cui et. al. unpublished results)

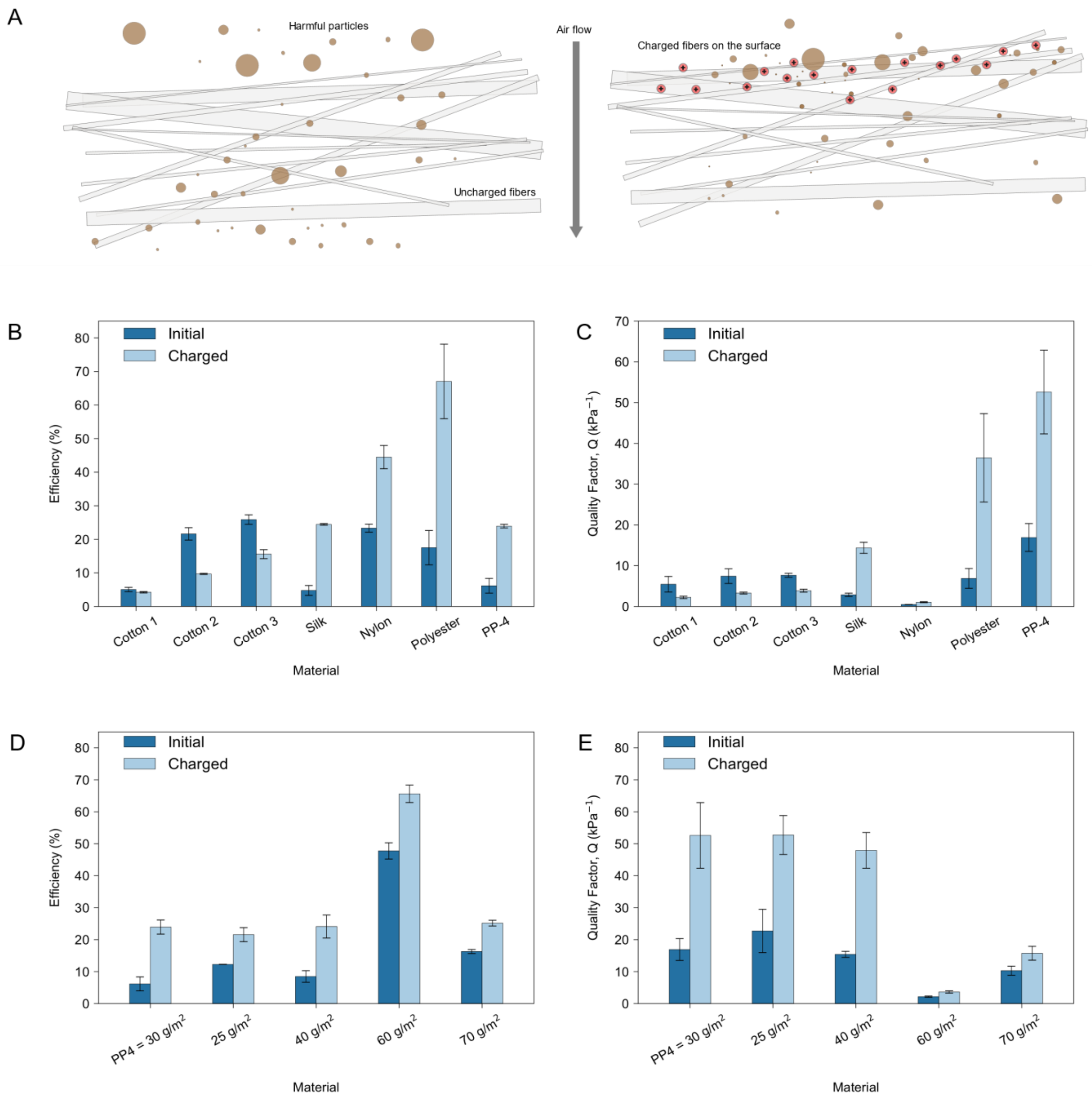
Triboelectric charging

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)



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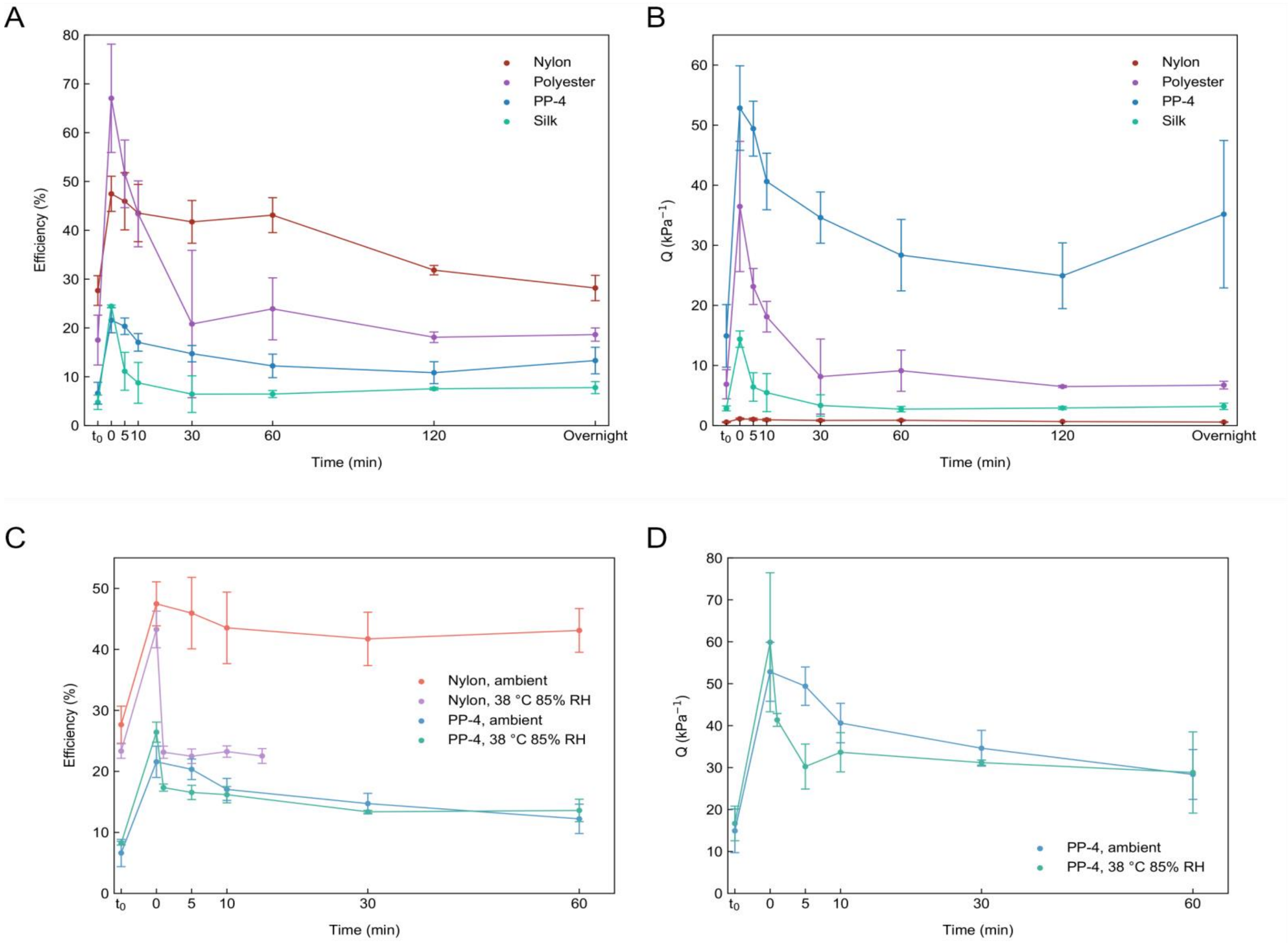
(Yi Cui et. al. unpublished results)

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.

~Q (kPa^{-1})	~Efficiency (%)	Material	Comments
>100	>95	Polypropylene meltblown (charged)	Material found in FFRs (used for reference)
30	10-20	Charged polypropylene (PP-4)	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
15	5-10	Uncharged polypropylene (PP-4)	Initial polypropylene spunbonds can vary in efficiency, but most tested had low pressure drops
5-10	20	Cotton	Knit and woven can vary in initial pressure drop, select cotton without any visible pores under light illumination or use multilayers
5-10	20	Polyester	Similar to cotton
5	30	Polypropylene meltblown (uncharged)	Material found in surgical masks (used for reference)
5	10-20	Facial tissue, paper or kitchen towel	Low mechanical strength, but may be possible to integrate into some masks with other cloths as a composite material
<5	5	Silk	If cotton and/or polyester are unavailable, otherwise the same comments as cotton
<1	20	Nylon (woven)	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

Fabrics from Africa (from Prof. May Chu)

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

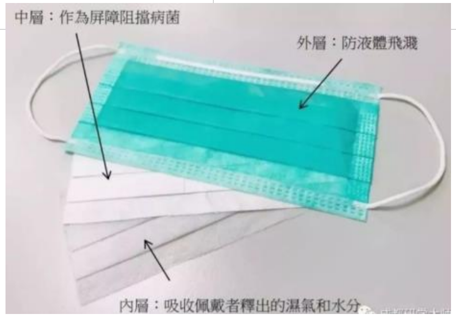
Sample #	Efficiency (%)	Pressure drop (Pa)	~Q (kPa^{-1})
T-Shirt Kenya	15.06	24	2.9
West Africa	8.84	17	2.4
Kenya Wedding	7.21	7	4.5

Disinfection of N-95 level masks

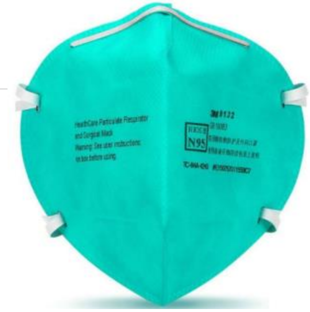
Mask Standards

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

Single-use medical face mask



Surgical mask



Protective face mask for medical use

Mask Standards

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

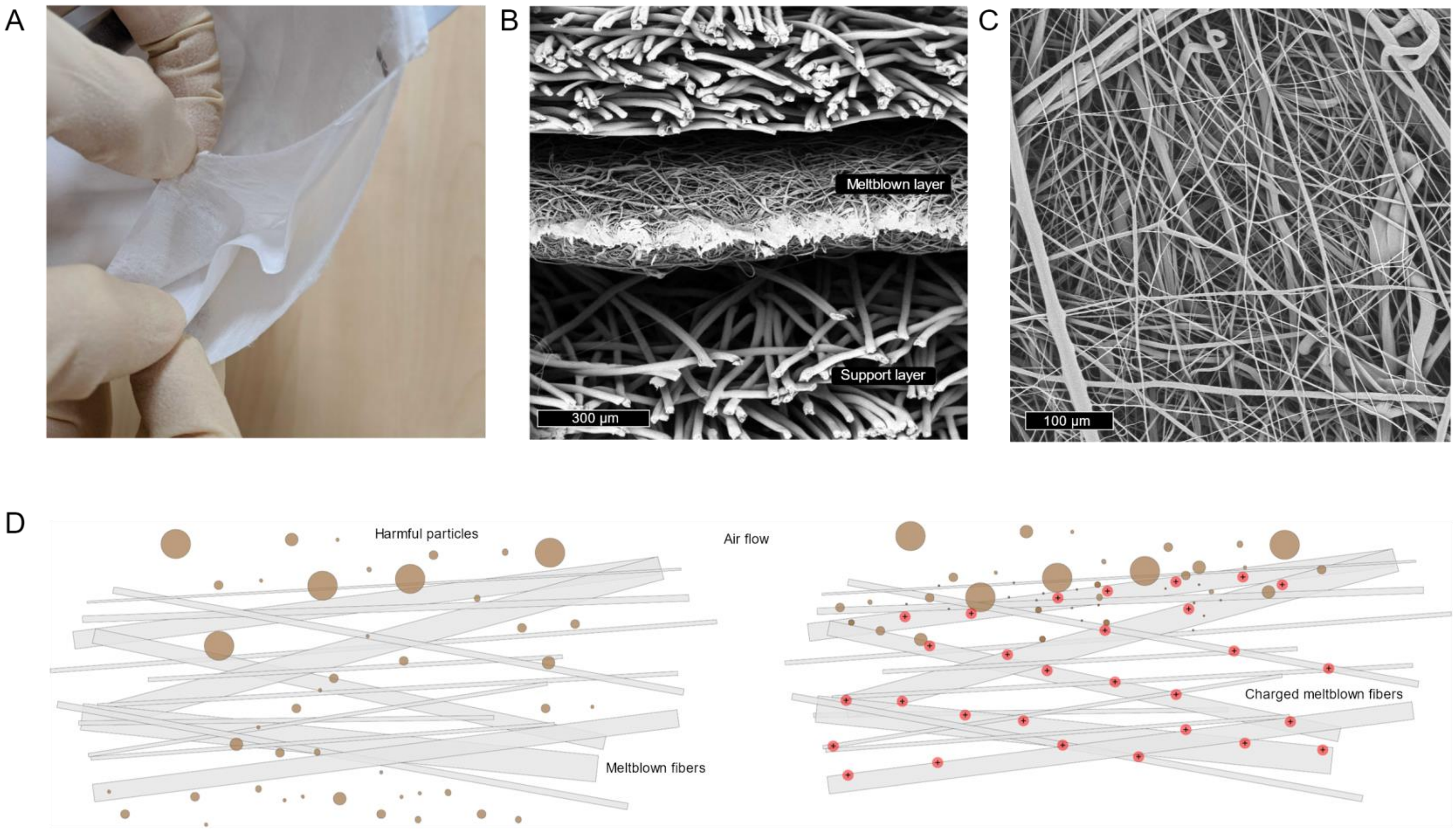
Filtration materials in ACS NANO

www.acsnano.org

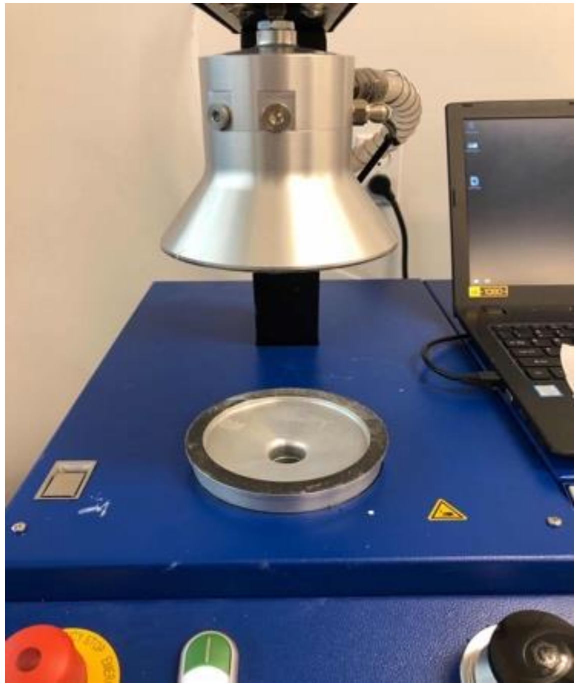
Can N95 Respirators Be Reused after Disinfection? How Many Times?

Lei Liao, Wang Xiao, Mervin Zhao, Xuanze Yu, Haotian Wang, Qiqi Wang, Steven Chu, and Yi Cui*

Cite This: https://dx.doi.org/10.1021/acsnano.0c03597 Read Online



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

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

Samples	Meltblown fiber filtration media		Static-charged cotton		E. Coli. Disinfection Efficiency
	Filtration efficiency (%)	Pressure drop (Pa)	Filtration efficiency (%)	Pressure drop (Pa)	
70℃ hot air in oven, 30min	96.60	8.00	70.16	4.67	>99%
UV light, 30min	95.50	7.00	77.72	6.00	>99%
75% alcohol, soaking and drying	56.33	7.67	29.24	5.33	>99%
Chlorine-based disinfection, 5min	73.11	9.00	57.33	7.00	>99%
Hot water vapor from boiling water, 10min	94.74	8.00	77.65	7.00	>99%
Initial samples before treatment	96.76	8.33	78.01	5.33	

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.

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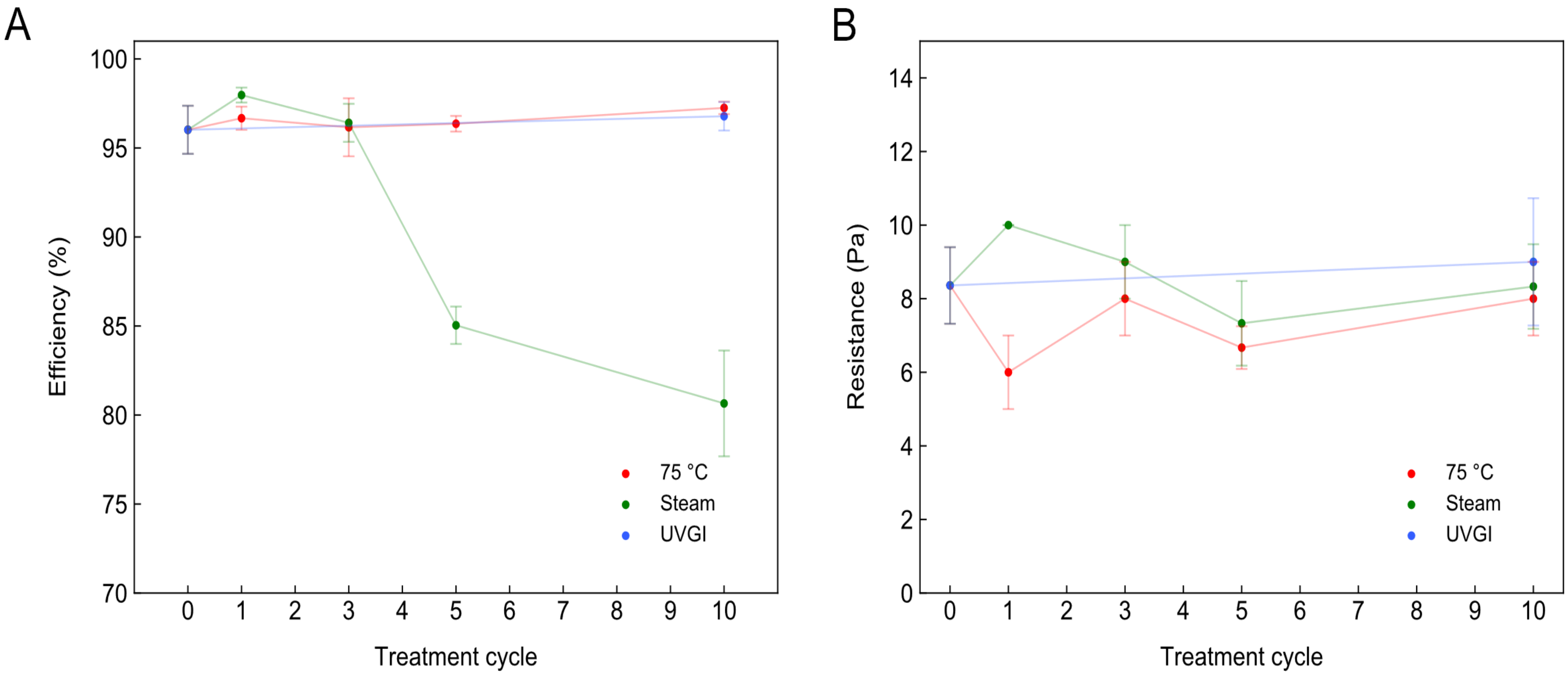
4C Air



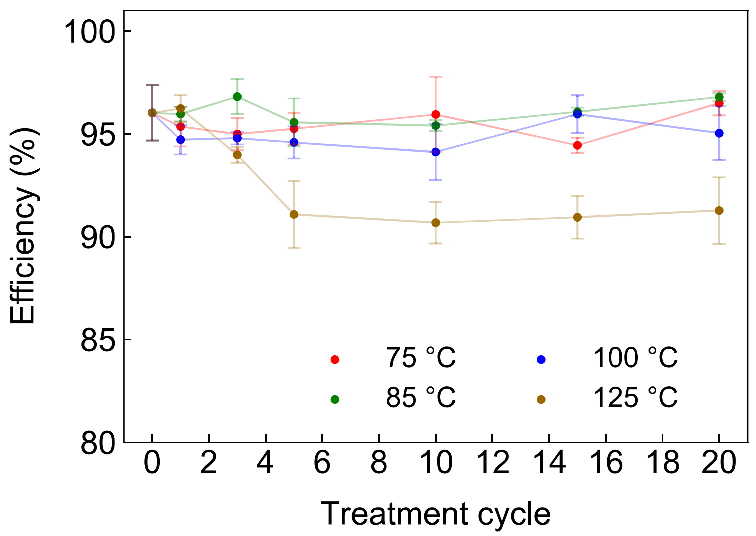
https://dx.doi.org/10.1021/acsnano.0c03597

N95 Meltblown Fabric Disinfecting (

Dry heat: <30% Humidity

75°C, 30min
85°C, 20min
100°C, 10min
125°C, 10min

G



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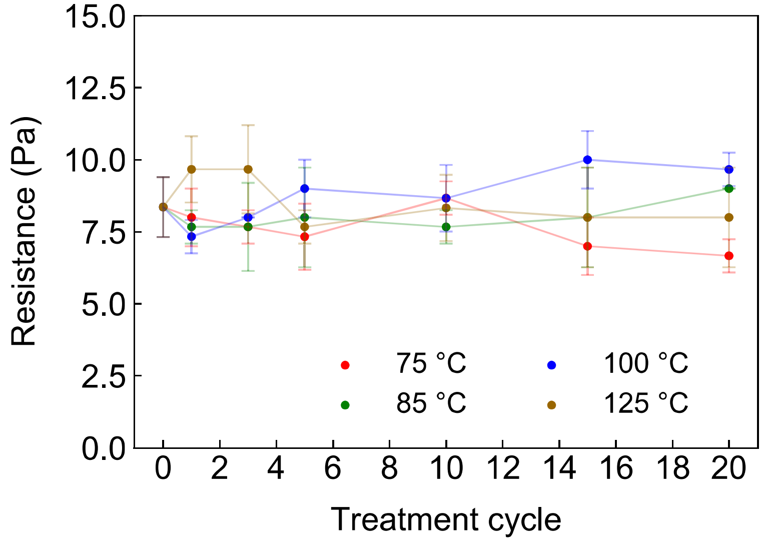

N95 Meltblown Fabric Disinfecting Cy

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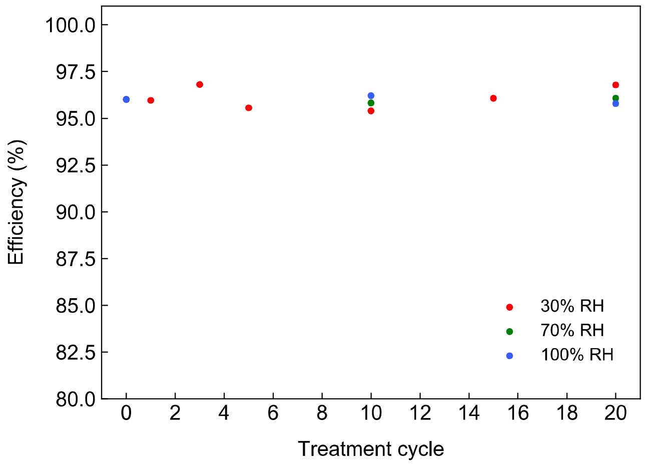
Each Cycle: 20 min 85°C/per cycle, different humidities

A



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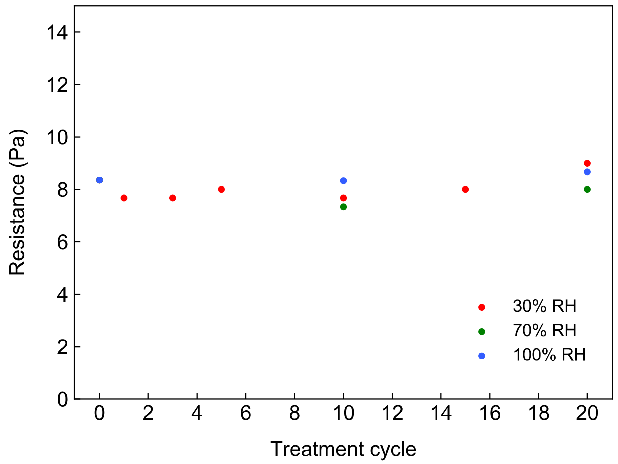

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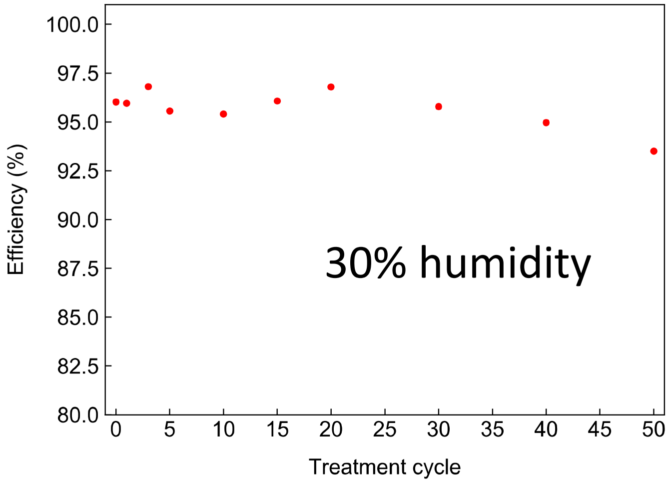

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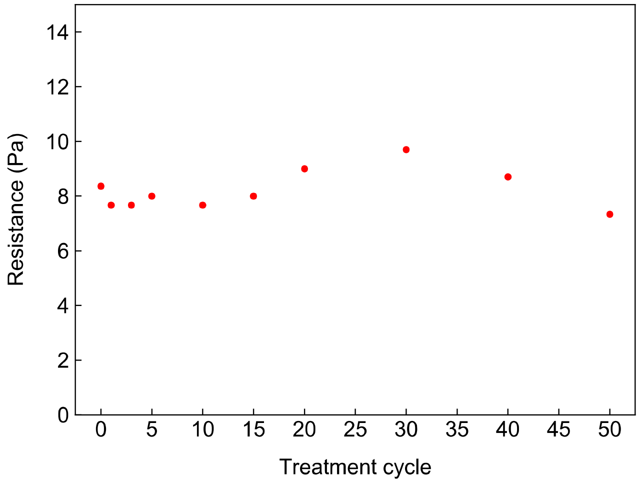

N95 Mask Disinfecting Cycling

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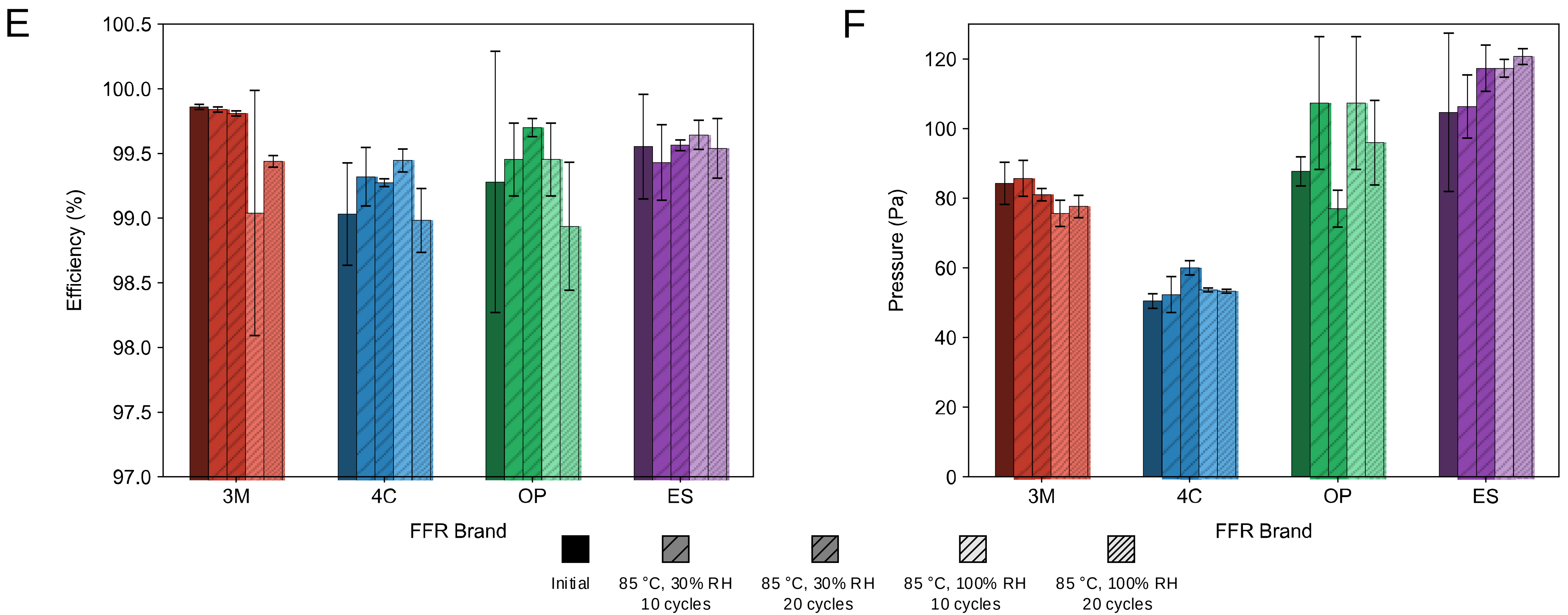
20 min 85°C/per cycle



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.

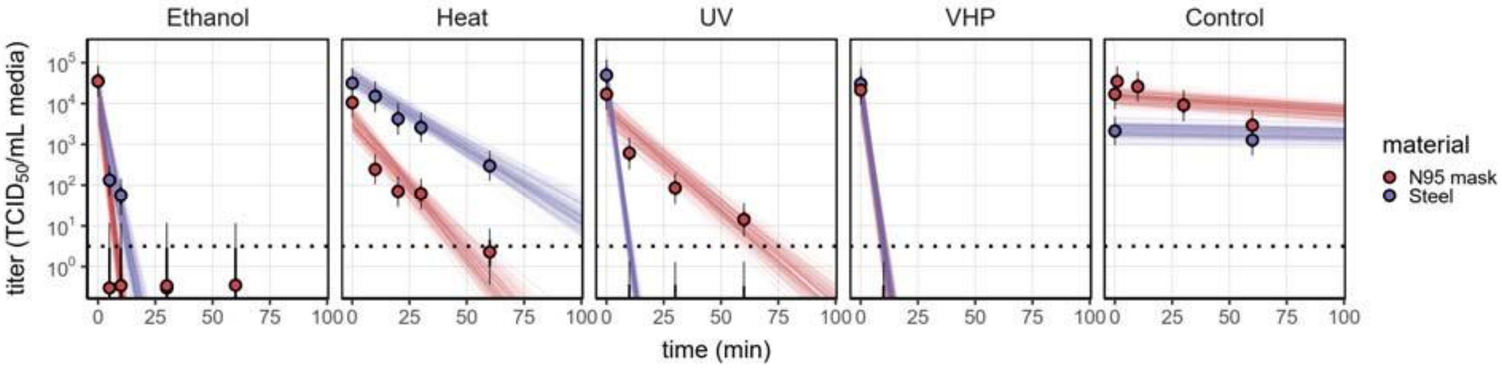
70°C in solution, 5min, Complete Disinfection

Time	Virus titre (Log $TCID_{50}$/mL)									
	4°C		22°C		37°C		56°C		70°C	
	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD
1 min	N.D.	N.D.	6.51	0.27	N.D.	N.D.	6.65	0.1	5.34	0.17
5 mins	N.D.	N.D.	6.7	0.15	N.D.	N.D.	4.62	0.44	U	-
10 mins	N.D.	N.D.	6.63	0.07	N.D.	N.D.	3.84	0.32	U	-
30 mins	6.51	0.27	6.52	0.28	6.57	0.17	U	-	U	-
1 hr	6.57	0.32	6.33	0.21	6.76	0.05	U	-	U	-
3 hrs	6.66	0.16	6.68	0.46	6.36	0.19	U	-	U	-
6 hrs	6.67	0.04	6.54	0.32	5.99	0.26	U	-	U	-
12 hrs	6.58	0.21	6.23	0.05	5.28	0.23	U	-	U	-
1 day	6.72	0.13	6.26	0.05	3.23	0.05	U	-	U	-
2 days	6.42	0.37	5.83	0.28	U	-	U	-	U	-
4 days	6.32	0.27	4.99	0.18	U	-	U	-	U	-
7 days	6.65	0.05	3.48	0.24	U	-	U	-	U	-
14 days	6.04	0.18	U	-	U	-	U	-	U	-

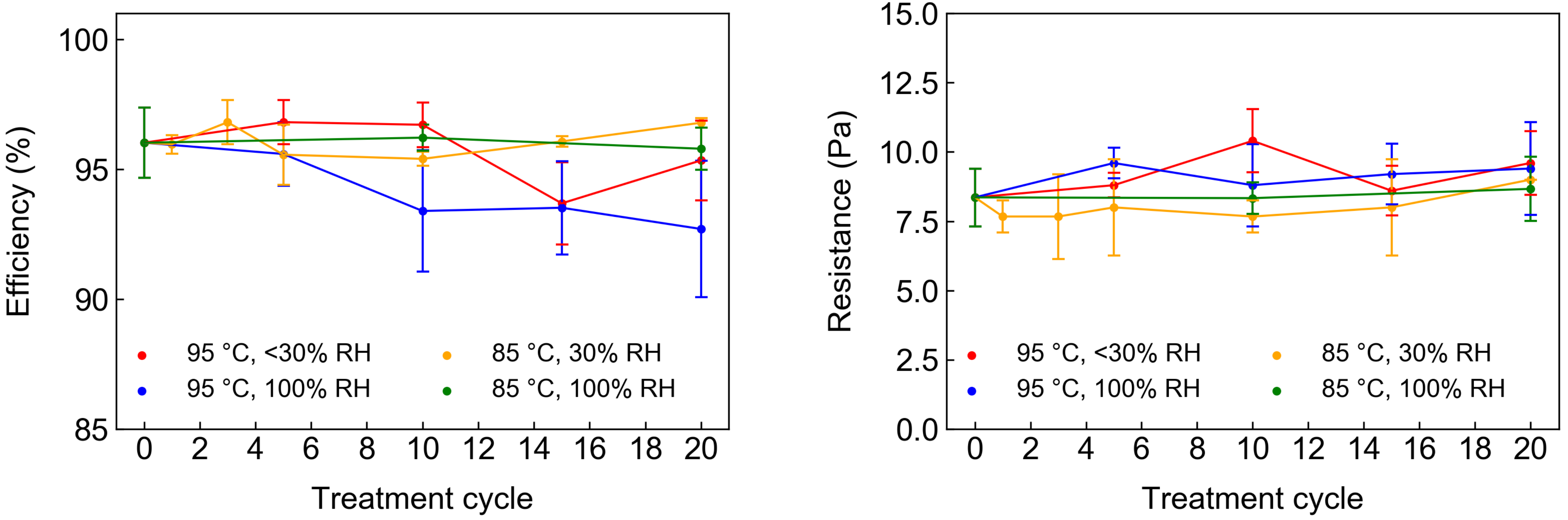
A) Temperature*

https://www.medrxiv.org/content/10.1101/2020.04.11.20062018v1

70°C Dry Heat, 60min, Complete Disinfection



Heat Under Different Humidity on N95 Meltblown Fabric

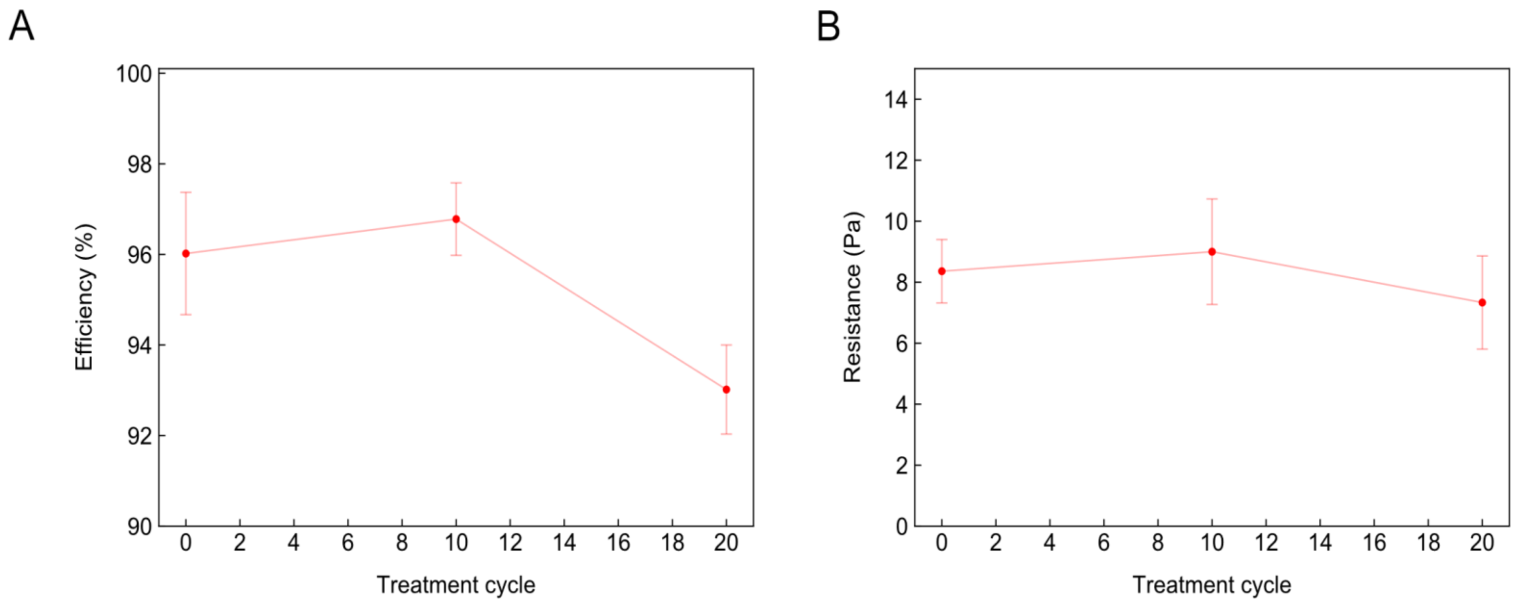


Summary of Heating Methods

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)

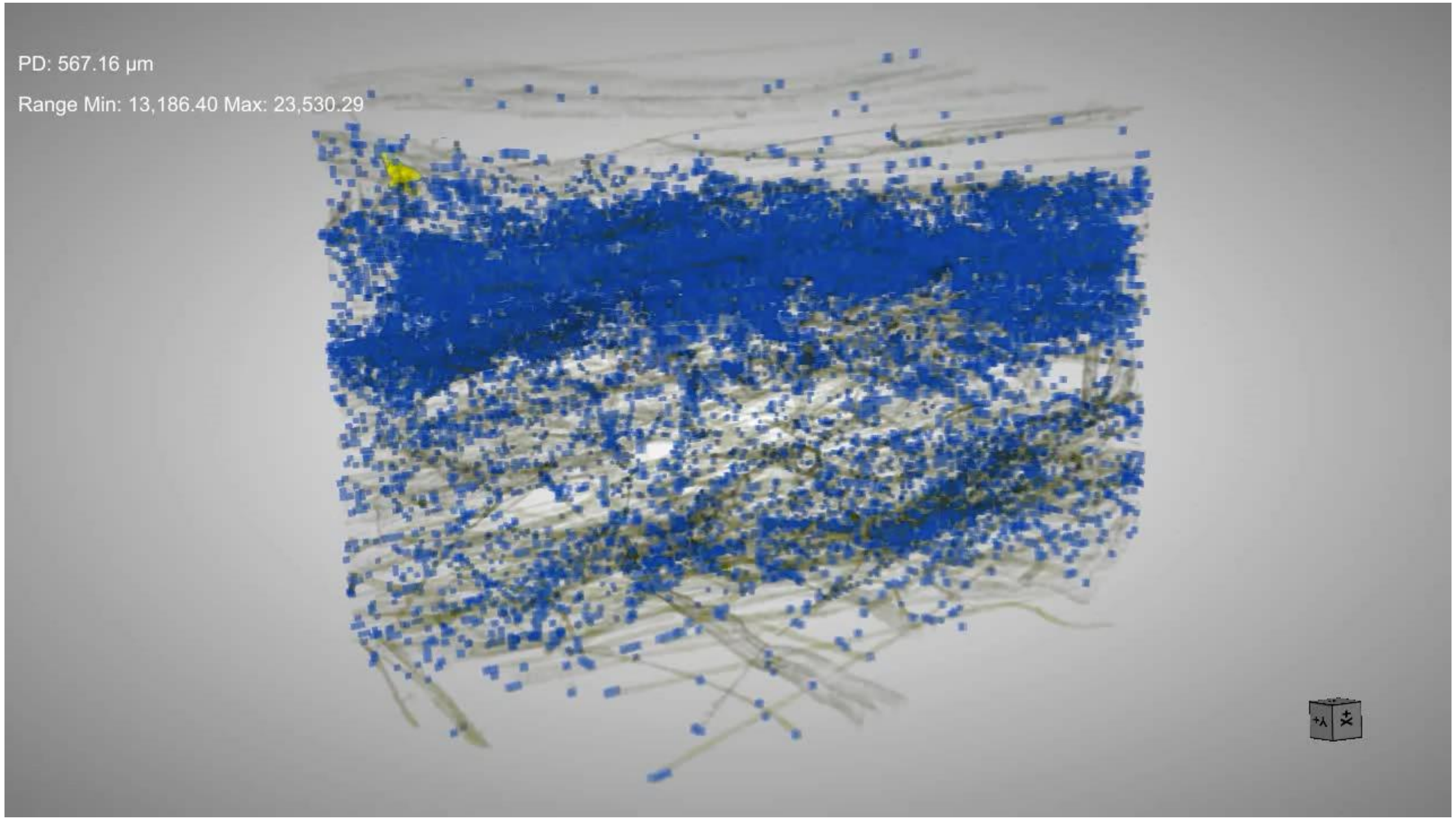
2) Vaporized hydrogen peroxide: cautious about the toxic byproduct, needs to release the residue (need to good engineering control, Industry scale)

3) ClO_2: cautious about toxic by product, 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

X-Ray CT



Hye Ryoung Lee, Yi Cui et. al. unpublished results

Polymer Nanofibers for Future Tech

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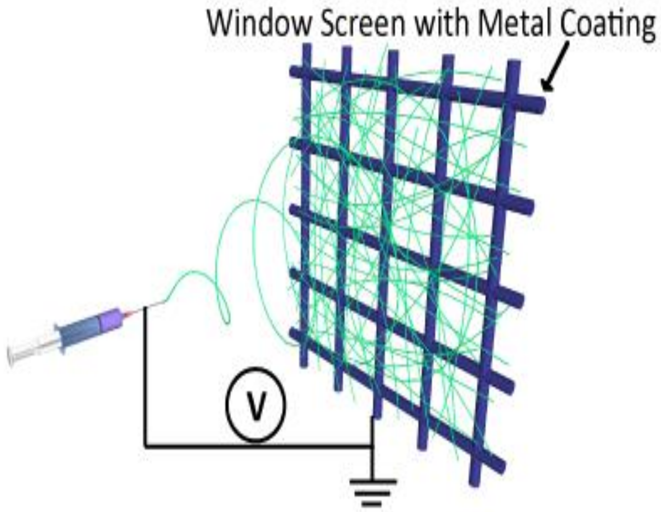
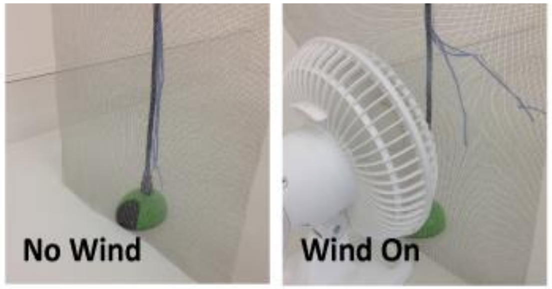
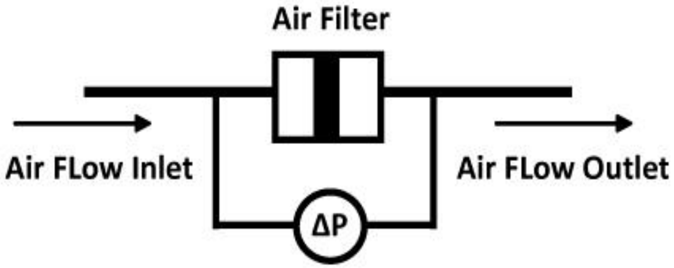




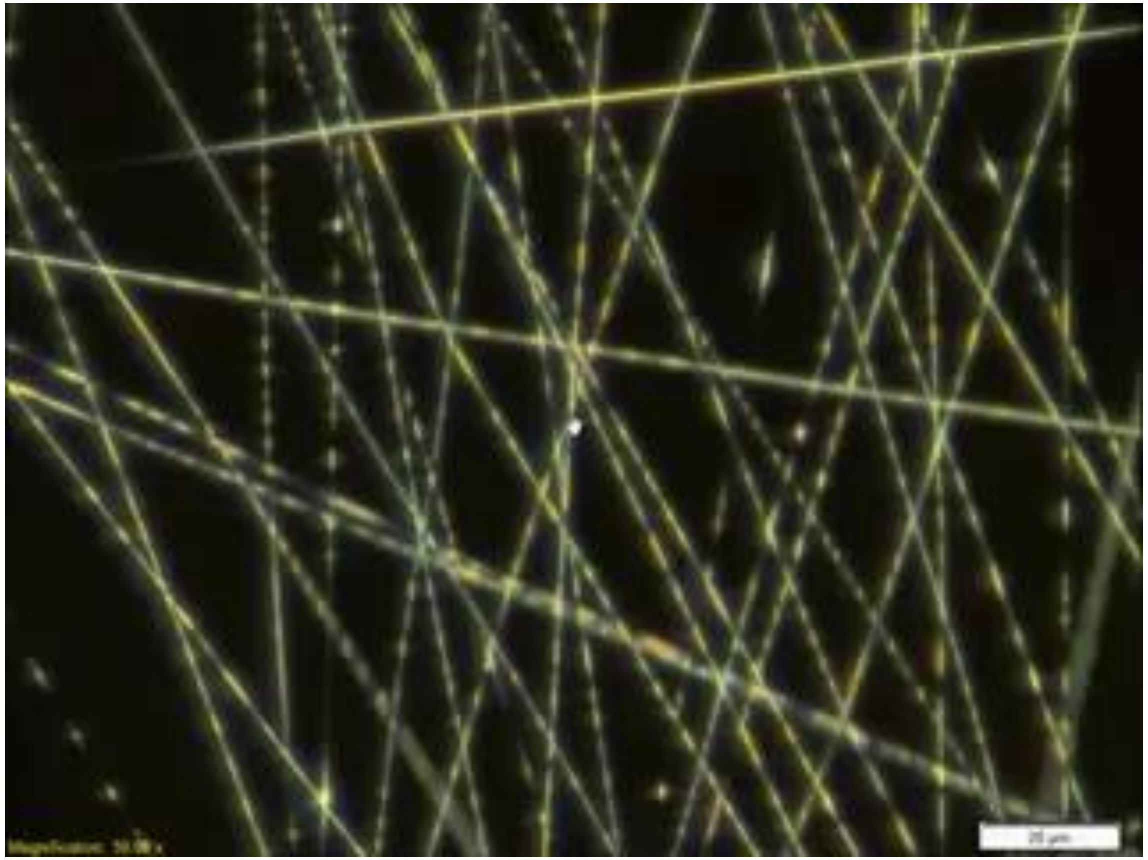


T%	90%	60%	30%
$PM_{2.5}$	95%	>99%	>99.9%
PM_{10}	>97%	>99%	>99.9%

Yi Cui lab, *Nature Communications* **volume 6**, Article number: 6205 (2015).

Polymer Nanofibers for Future Technology

In-situ PM2.5 Capture



[Yi Cui lab, *Nature Communications*] **volume 6**, Article number: 6205 (2015).

Summary

Homemade Masks

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

Future Directions

Develop easy criteria for layman to pick the fabric

- Eye inspection (no visible holes)
- Thread counts
- Breathing try

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

Thank you!

Collaborators:
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