Developing home-disinfection and filtration efficiency improvement methods for N95 respirators and surgical facial masks: stretching supplies and better protection during the ongoing COVID-19 Pandemic

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ABSTRACT

The U.S. CDC announced on 04/03/2020 that all citizens should wear face coverings when in public, potentially increasing demand for medical face masks from the public and exacerbating mask shortages for Covid-19 response staff. One solution is reuse after disinfection for the general public. Prior studies have shown that heating for 30 mins at 70°C or above effectively kills SARS, including SARS-CoV-2, and Influenza viruses on masks. Black carbon (BC) particles generated from a kerosene-lamp were used as a proxy for Coronavirus aerosols to test mask performance after disinfection given overlapping size distributions. We determined filtration efficiency (FE) measurements by comparing BC values on both sides of the respirators or masks (Moldex N95 and 3M N95 respirators, HSI surgical masks) placed under vacuum on mannequins. To obtain the maximum FE, each mask type was first measured while taped or modified to tightly fit a mannequin's face when new and after each heating cycle. No reduction in average FE was observed even after 10 disinfection cycles, with FE statistically greater than 95% for N95 respirators and 70% for surgical masks. In sharp contrast, the FE of all medical masks with no additional sealing decreased to ~ 40%, confirming the effectiveness of facial masks relies upon a tight fit. For solving this issue, we designed a method for making individualized custom nose clips to hold a mask tightly to face; FE of 3M N95 respirators and surgical masks remained above 95% and 80%, respectively. Surprisingly, the FE of three homemade thick cloth coverings (in normal use) were 55%. Though more work is still needed, this result supports the public announcements that the public could wear cloth coverings instead of N95 respirators or surgical masks in low-risk environments. When worn with a customized nose clip, N95 respirators and surgical masks have higher FE than the CDC design for cloth coverings.

Keywords: COVID-19, disinfection, reusability, N95 respirator, surgical mask, homemade cloth covering, kitchen oven

INTRODUCTION

Within the past few weeks, the world has encountered a global viral pandemic that has infected about 2.4 million people worldwide, with the US reaching 737,000 as of April 19, 2020, based on data presented in the John Hopkins University Coronavirus Dashboard (JHU, 2020). With the infections and deaths spiralling exponentially across the globe, healthcare services are experiencing a crisis in providing adequate care for the growing number of patients. Wearing proper personal protective equipment (PPE) including masks is critical for health care professionals who are exposed more often and at higher doses. The world does not have enough PPE available to meet this pandemic and especially masks have recently become limited in supply.

Initially wearing masks for healthy persons was not recommended by the CDC. However, this recommendation has been challenged. A New York Times article on 03/27/2020 pointed out that "more Americans should probably wear masks for protection" (Sheikh, 2020). Science magazine also supported this recommendation (Servick, 2020). Finally, on April 3, the CDC and the White House announced that all citizens should wear facial cloth coverings when in public (CDC, 2020b). On 04/15, New York State Governor Andrew M. Cuomo ordered residents to wear masks in public. These announcements could increase the public demand on the critical resource during the ongoing wave of patients going to the hospital when first responders and hospital staff need them more than ever.

Air-purifying respirators or APRs function by removing airborne droplets or aerosols through filtration and impaction, whether that be chemical or physical. The one most strongly recommended by the government for hospital workers is the N95 class. The N refers to “not resistant to oil”, while the 95 represents the “rating” or filter class, that it removes at least 95% of airborne particles when there is a perfect seal. An N95 respirator works through the use of interwoven microfibers made through a melt blowing process typically of polypropylene and electrostatically charged fibers to increase retention efficiency of smaller particles and reduce backpressure. The goal of surgical masks is primarily to protect others from large-particle droplets, splashes, sprays, or splatter containing germs (viruses and bacteria) generated by the wearer. Surgical masks are not primarily designed to remove small particles to protect the wearer given the looser fit and lower back pressure filter material.

Given the lack of supplies, community groups and now the CDC are promoting the use of homemade cloth coverings sometimes referred to as “last-resort masks” sewn or made from home supplies. Although the last-resort coverings won’t have the same theoretical maximum filtration efficiency (FE) as N95 respirators for filtration of airborne droplets and aerosols (Rengasamy *et al.*, 2010), these homemade coverings when worn by infected people still serve some of the same functions by reducing the number of infected droplets and aerosols from spreading away from an infected carrier who may be asymptomatic (Davies *et al.*, 2013); Large variations in FE have been reported, but because material types and thickness of these cloth coverings vary between studies, it is difficult to compare results directly (Davies *et al.*, 2013; Rengasamy *et al.*, 2010). Finally, all masks and coverings may also be protective by reducing the touching of the nose and mouth areas. All of these protections are increased by having a good fitting seal all around the perimeter of the mask and assuming that they don’t touch the inner or outer surfaces of their masks except by the elastic bands during use, including when putting the mask on and off.

Popular methods being promoted for overcoming the shortage are to increase the supply through industrial manufacturing, to regulate the number of masks being used by civilians, or to reuse masks after disinfection protocols. Industrial manufacturing will require more time to catch up to the global pandemic, and regulated curtailment of mask distribution to civilians could compromise civilian health for healthcare professionals. Despite the fact that CDC has asked civilians not to buy N95 respirators or surgical masks, a substantial fraction of people already had these masks and are still actively searching for them, since many of them believe masks provide better protection than cloth coverings. Being able to reuse these masks would also help to reduce the demand for purchasing more.

Treatment to allow reuse of masks is not a new idea with a handful of published studies starting as early as 2003 (CDC, 2020a; Duan *et al.*, 2003; Heimbuch *et al.*, 2011; Kenney *et al.*, 2020; Martella *et al.*, 2019; Price & Chu, 2020; Song *et al.*, 2020). Several methods of sanitation were proposed, including heat treatment (Oven, dry air), alcohol soaking, chlorine soaking, steam or hydrogen peroxide (H_2O_2) treatment, and UV sterilization (Viscusi *et al.*, 2009). A large portion of testing for disinfection methods was tested previously on the SARS virus, which is thought to be a good proxy for the survival of SARS-CoV-2 that has caused COVID-19 (Song *et al.*, 2020). According to a research paper on CoV-P sensitivity to heating and UV irradiation, the virus became non-infectious after 30-min exposure at 75 degrees C (Duan *et al.*, 2003). Similarly, a paper from Fudan University conducted similar experiments using an influenza virus as a proxy for the Coronavirus. They concluded that using a hairdryer for 30 minutes, which also allowed the mask to reach 70 degrees C, effectively inactivated the Influenza pathogen (Song *et al.*, 2020). Recently, Fischer from National Institute of Allergy and Infectious Diseases and (NIAID) and his colleagues directly used the SARS-CoV-2 to test four disinfection methods (UV, 70ºC heat, ethanol, and H_2O_2) and found all methods can inactivate SARS-CoV-2, though the speed was different (Fischer *et al.*, 2020). Stanford researchers found that chlorine-based solutions and alcohol solutions were detrimental to the static charge in the melt-blown fabric used in most N95 respirators, resulting in reduced efficiency (Price & Chu, 2020). Furthermore, these reagents are also hard to come by during the pandemic. One potential concern of UV disinfection is that it may have a “limited penetration depth” and may risk an inefficient disinfection of deeper layers of the fabric. Hydrogen peroxide can be another option as well. But all UV and H_2O_2 disinfection need special equipment that can be costly and more appropriate for large scale disinfection needs of hospitals (CDC, 2020a).

The studies from NIAID and Stanford provided a strong foundation for the dry heat treatment of facial masks that include electrostatically charged fibers, providing no observable negatives in their experiments (Fischer *et al.*, 2020; Price & Chu, 2020). However, they only presumed continued filtration efficiency as a result of penetration and pressure drop experiments of two separated fabric layers or a fraction of masks by punching, rather than directly testing the efficiency on whole masks (Fischer *et al.*, 2020; Price & Chu, 2020). We believe it is important to test the whole masks rather than individual layers since the whole masks may get damaged (e.g., the string, the hinge between the two layers, the nose pad) by disinfection which may impact the performance. Punching potentially damages the integrity of mask materials and may not be appropriate for evaluating reusability of the whole mask.

Coronaviruses have a diameter of approximately 60–140 nm, being a spherical and relatively large virus (Cascella *et al.*, 2020). Freshly generated black carbon particles overlap that size-range, having particles from 15 to 500 nm (Arnold *et al.*, 2014; Baitimirova *et al.*, 2012; Long *et al.*, 2013), and are thus an appropriate proxy for testing FE of masks for viruses. The coronavirus also spreads through respiratory droplets released from saliva, mucus, and other respiratory fluids in a larger size range from 10^4-10^5 nm (Cascella *et al.*, 2020) that is more easily removed by filtration. Furthermore, we present a method for the public to reuse their masks using their home appliance for disinfection. Larger medical facilities may have access to vendors with industrial processes that can disinfect large numbers of masks at once. If surgical masks and N95 respirators that are already being used by the public are effectively reusable through dry heat disinfection, mask waste will be reduced, thus helping to reduce the shortage. We also demonstrate the filter efficiency of the CDC design of homemade cloth coverings, supporting evidence for the public using these homemade coverings, further reducing the shortage of medical masks. This study has two purposes: 1) to determine the reusability of facial masks after disinfection in ovens, including kitchen ovens in US homes and 2) to develop a practical solution for improving mask performance.

MATERIALS AND METHODS

Materials List

- **Plastic Mannequins:** Two 15" tall male mannequin heads were purchased from the Only Mannequins® Outlet (East Orange, NJ).
- **Silicone Mannequins:** custom-made by Joshua Turi (Designs to Deceive, LLC). The full-size head is fabricated out of a Platinum-cure silicone with a shore hardness of 10. An additive was used to soften the silicone even further to give the feel and movement of human skin. A rigid urethane core was used to hold the shape of the head form.
- **Masks and cloth face coverings:** Moldex 2600 N95 respirators purchased from McMaster-Carr, 3M Aura N95 9210+ respirator and HSI surgical masks (Earloop face mask ASTM level 1, Henry Schein Inc.) were provided by Dr. Bauer from Good Samaritan Hospital in Suffern NY; Cloth face coverings were made at the first author's home by following the video instructions by Dr. Jerome Adams on the CDC website (CDC, 2020b). The three face coverings (100% cotton sweater, 100% cotton dress (half), and 100% polyester scarf) were tested to examine whether there was a difference in FE as a function of fiber materials.
- **Brown paper lunch bags for storage of masks between use:** to mimic how home users could store the masks between use with the individual's name written on the bag. Both paper bag and mask can be disinfected together each time.
- **Oven:** Fisher Scientific oven with accurate heating temperature ranging between 50ºC to 150 ºC (±3 ºC). This oven was used for a heating temperature at 77 ºC. We also tested the kitchen gas oven (Amana) in the researcher's home; digital heating settings of this oven start at 170F, which is ~ 77 ºC. All oven temperatures were confirmed by a mercury thermometer.
- **Oven bag:** Reynolds Kitchens™ oven bags (turkey size)
- **The combustion chamber and exposure chamber**: Two plastic boxes were purchased from Home Depot. The combustion chamber is a 26-gallon storage bin with external dimensions of 60 cm (L) x 47.3 cm (W) x 51.1 cm (H). The combustion chamber is used to hold the lamp generating black carbon (i.e., soot). The exposure chamber is a 22.5-gallon storage box with external dimensions of 75.6 cm x 46.6 cm x 34.3 cm. The exposure chamber holds the mannequin with a facial mask covering the mouth and nose. The two chambers are connected by a laminated cardboard tube found at home with an external diameter of 4.0 cm and a length of 20.0 cm.
- **Lamp oil burner and lamp oil:** The burner was a Parasene 499 Paraffin Warm Light Cold-Frame Heater. This burner without the glass cup has been used to generate almost pure black carbon in prior studies (Cai *et al.*, 2014; Yan *et al.*, 2011). Ultra-pure paraffin lamp oil (Lamplight Farm Inc, Menomonee, WI) was used as the fuel.
- **Air pump:** Medo USA Inc VP0625-V1014-P2-0511 Linear Pump is used for generating two vacuum lines each at 10 liters per minute (LPM) airflow for a total through flow of 20 LPM. Spot checks including at the beginning and end indicated that the flow of each inlet was at 10 (±0.5) LPM throughout the experiments. The first inlet drew air from the exposure chamber and the second inlet drew air through the mannequins' orifice at roughly the breathing rate of adult humans at rest.
- **Black carbon (soot) monitors**: Two MA 200 microAeth real-time monitors made by Aethlabs (San Francisco, CA) were used to measure BC level. The microAeth® MA200 is a compact 5 wavelength monitor with an automatic filter tape advance system. The settings of both units were 30 seconds per reading, single spot sampling with an ATN threshold of 30 before an automatic tape advance; a flow rate of 50 ml/min was used for the unit measuring the high concentrations in the exposure chamber (BC Sensor 2), and a flow rate of 150 ml/min for the unit measuring the concentrations behind each mask or covering (BC sensor 1).
- **Materials for making plastic nose clips**: A heat-moldable plastic sheet (8" x 12" x 1/16" thick) from Polly Plastics; an 1 mm thick felt made of Kunin® PET fiber (9" x 12") from Jo- Ann store; 2

mm diameter elastic cord, two bag clips, and a thermometer which reaches 150°F (65°C), all of which can be purchased via online stores.

Experimental Procedures

Figure 1 shows the schematic setup of the test system, which includes a combustion chamber, an exposure chamber, a mannequin with a yellow surgical mask, a pump sucking air into the exposure chamber and through the mask, and two BC monitors. Holes were drilled in the combustion and exposure chambers for introducing air into the combustion chamber and connecting it to the exposure chamber. The burner was placed inside of the combustion chamber and a small fraction of soot produced in the combustion chamber was sent to the exposure chamber by the fan and the 20 LPM of air being drawn though the exposure chamber by the vacuum pumps (Figure 1). In the exposure chamber, the BC level was measured both in the chamber and in the air behind the masks to calculate filtration efficiency (FE). Both the pump and two BC monitors were flow-calibrated before usage.

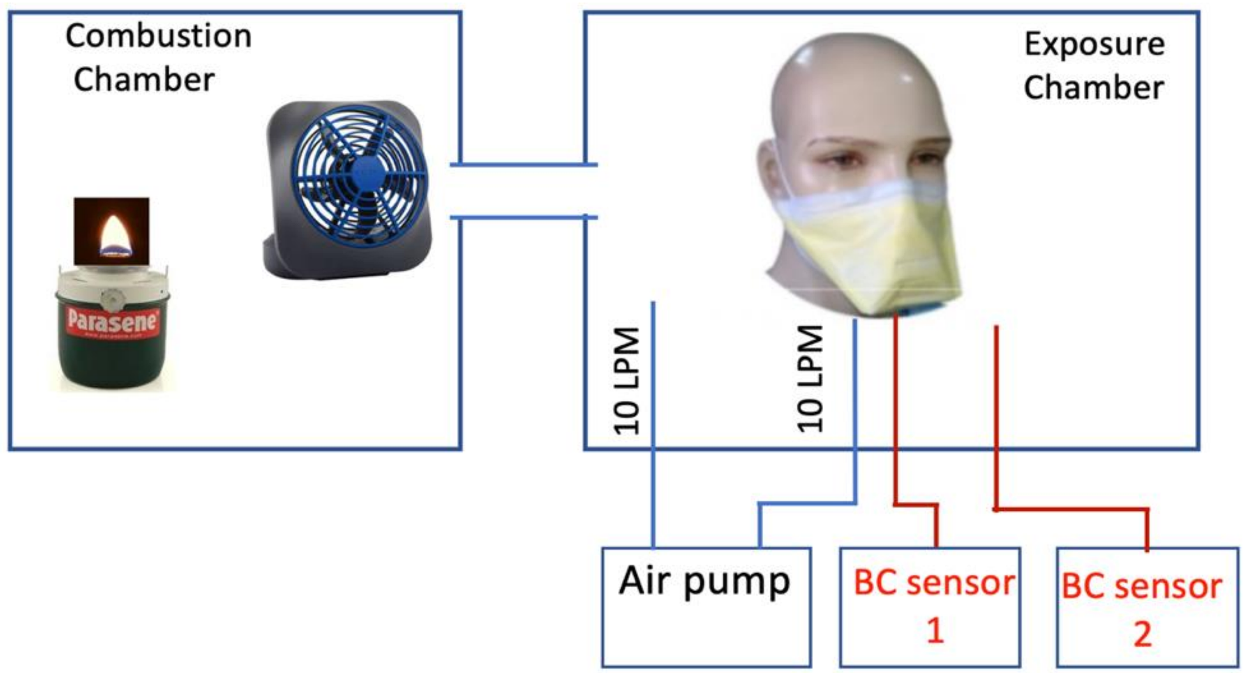

Figure 1. A schematic plot showing the laboratory setup.

We followed the CDC instruction video to make three cloth coverings (CDC, 2020b). Briefly we folded the cloth material mentioned above to about 4 inches wide, then placed two rubber bands about 3.5 inches from the two ends, folded the ends along with the rubber bands, and then placed it onto the silicone head form (Figure 2). We used the same disinfection heating approach as for the other masks although the CDC recommends that you wash and dry the masks in home appliances.

Experimental design testing performance before and after disinfection was shown in Table I. Three replicate masks were tested to ensure the reproducibility of the results. A mask was placed on the mannequin, then put inside of the exposure chamber as shown in Figure 1. For each experiment before lighting the kerosene lamp and measuring filter efficiencies, we measured background BC levels in the exposure chamber (BC Sensor 2) and behind the mask (BC Sensor 1).

Three types of experiments were carried out.

- First, N95 respirators and surgical masks were tested while being sealed to the mannequin, either by taping or modifications to create a good seal (Figure 3): specifically, the Moldex N95 respirators were mounted to the plastic mannequin by duct tape around the perimeter, while the tight fit of the 3M N95 respirators to the silicone head was achieved by careful tightening of elastic bands and adding an additional string around the head that held two spongy rolls against the nose pad to eliminate any possible gap (Figure 3).
- Second, experiments that mimicked "static normal use" were done just using the masks' elastic bands on the ears or silicone head as appropriate.
- Third, FE was measured in masks that were tightly sealed by the customized external nose clip (details provided below).

Figure 2. Photos showing the wearing of home-made cloth coverings. A) white 100% sweater, B) 100% cotton dress, and 3) 100% polyester scarf.

Table I. The Experimental Procedure for Each Type of Three Masks over the Course of 10 Disinfection Cycles (tightly-sealed masks); 30 measurements (meas) = 10 meas/mask x 3 replicates for each mask type. We stopped testing the Moldex N95 respirators after the 3rd cycle because of the nose pad issues.

	Baseline	1st heating	Cycle1	2nd heating	Cycle 2	3rd heating	Cycle 3	4th-10th heating	Cycle 10
Moldex N95	30 meas		30 meas		30 meas		30 meas	No experiments	No meas
3M N95	30 meas	at 77 °C 30 mins	30 meas	at 77 °C 30 mins	30 meas	at 77 °C 30 mins	30 meas	at 77 °C 30 mins	30 meas
HSI Surgical	30 meas		30 meas		30 meas		30 meas		30 meas

After all tubing was connected to the vacuum pump and running the MA200 monitors for a minimum of 20 minutes for the first experiment of each day, we covered the lid of the exposure chamber. In the combustion chamber, we then lit the burner, turned on the fan, and covered the lid of the combustion chamber. After 2 mins, we started to use the BC levels from the two BC monitors. Data used were 5-minute averages (10 subsequent readings at 30 sec each). We kept the BC monitors on throughout the day as we repeated the above steps, 3 times in total for each type of mask.

Figure 3. Sealing a Moldex N95 respirator to plastic mannequin with duct tape (A) and a 3M mask modified by using an additional elastic band and rolls made from a kitchen scouring pad to press the mask on either side of the nose of the silicone head (B); this was the inspiration for the customized nose clip.

Ten disinfection cycles: The masks were wrapped in aluminium foil and placed inside the oven at 77°C for 30 mins. We measured the performance of new N95 respirators and surgical masks on mannequins before heating, then their performance (on a mannequin inside the exposure chamber) after each heating cycle for the first three disinfection cycles. The FE was not measured after the 4^{th} disinfection cycle until the 10^{th} cycle, but all cycles still included the mounting and dismounting step, allowing the masks to cool and be mounted onto the mannequins with adjustments for tightening, and then removed for another disinfection cycle. By this mounting and dismounting step, we included in each cycle additional stretching and stress on the mask materials. The FE of cloth coverings was first measured before any heat disinfection, then measured again after the 10^{th} disinfection cycle.

Home Appliance Protocol for disinfection: This experiment was designed to explore whether disinfection heating can be conducted in US homes and to provide a simple protocol.

1) After use, remove the mask by the elastic bands (without touching the outer or inner surfaces of the mask which could be contaminated with the virus) and place it in a paper brown lunch bag. Close the bag and write name on the bag. Keeping the mask with same user reduces wear and tear on the mask.
2) Place the paper bag and the mask in an oven-proof container with a tight-fitting lid. We used a Reynolds Kitchens^{TM} oven bag.
3) Set oven temperature to 170°F (77°C) and wait for the oven to come to temperature.
4) Place the oven bag with paper bag and masks in the centre of the preheated oven.
5) Set a timer for 45 minutes to allow additional time for the interior of the bag/container to get to temperature.

6) Take the bag out of the oven and leave to cool. Store the paper bag with the mask in a plastic Ziploc until needed again.

The customized nose clip cannot be disinfected in the oven since the plastic clip will melt. Use alcohol or bleach in a zioloc bag for disinfection instead.

Protocol for making a homemade, customized, external nose clip for obtaining tighter fit with commercial masks. A YouTube online instruction video is available (Yan et al., 2020). Briefly, two strips (0.5 inch x 8 inch) are cut from a 8” x 12” sized heat-moldable plastic sheet using scissors (Figure 4). One of the two strips is then cut into 3 equal pieces (2.67” long and 0.5” wide). A strip (7” x 0.5”) was cut from the felt sheet (Figure 4). Place the 8” long plastic strip on top of the felt strip, then place two 2.67” plastic strips on the top of the 8” long strip, leaving 1” in the middle empty. Clamp all these pieces together with two bag clips, and put in 60°C (140°F) hot water until the strips become translucent; take out from the water and unclamp. Now all pieces should be stuck together but moldable. Press the strip assembly, in the horizontal direction, with the felt pad side against the middle section of the nose and cheeks. Press and adjust the strip assembly as necessary to fit the curve of nose and cheek. After two minutes of cooling, the strip assembly should retain the shape of the curves of your face. Place one end in 60°C water until translucent and soft and immediately make a hole using a pointy rod, awl or pencil. Repeat this with the other end to have holes in both sides. Insert a pre-cut 18” elastic cord through the holes and tie knots in both ends (Figure 4). After placing around head, one can pull the knotted cord ends back around the neck and tie together for additional tightness as needed.

Figure 4. The major parts of the plastic nose clip and the photos showing how the nose clip is worn on top of a Aura N95 respirators and an HIS surgical mask for improving the fit of the mask to the face. The items listed in the left photo: A) the complete plastic nose clip, B) pieces cut from a heat-moldable plastic sheet, aligned for making the external nose clip, C) a felt strip cut from a felt sheet, D) elastic cord, and E) bag clips.

We tested the filtration efficiency of 3M N95 respirators, HIS surgical masks, and homemade cloth coverings by placing the customized nose clip on top of masks and tightening the strip by tying up two string ends around the back of the head (Figure 4). For testing wearing comfort, two co-authors wore masks with their customized nose clips for 5 hours each.

Statistical analysis: Paired Student T-Test was used to compare the mean FE of masks before and after disinfection and between tightly fit and normal usage scenarios. We also used student T-test to determine whether the mean FE of masks was significantly greater than certain guidelines, for example 95% for N95 respirators.

RESULTS

Consistency in Data from Two BC Monitors and Sampling Ports behind Masks

Before each experiment, two inlets of BC sensors were placed side-by-side in the exposure chamber (outside the masks) to test whether the two units provide consistent data. The average of measurement difference between two units is within 12%, indicating the consistent data being provided by the units. Pre-experiment background BC levels measured by BC Sensor 1 and 2 before the kerosene lamp was lit were always below 0.2 µg/m^3 for both BC monitors. In comparison, after the kerosene lamp was burning, BC levels measured across all experiments and mask types including measurements from both BC Sensors ranged from a minimum of 4 µg/m^3 to a maximum of 100 µg/m^3.

To test whether there was a sampling bias caused by the very different flow rates of the two holes in the mannequin mouth behind the mask (one at 10 LPM from the pump and the other at 0.15 LPM from the BC sensor), we compared data from the MA200 unit sampling from a mannequin hole behind the mask to the data of the other MA200 unit sampling off the 10 LPM air stream (with a tee) sucking from the other hole in the mannequin's mouth. The percentage difference between the two sensors are within 12% between two sensors for BC levels below 10 µg/m^3 and within 2% when BC level higher than 10 µg/m^3. The consistent data between the two units across all measured BC levels (0.8 – 80 µg/m^3) indicate a lack of sampling bias for these nanoparticles (Figure 5).

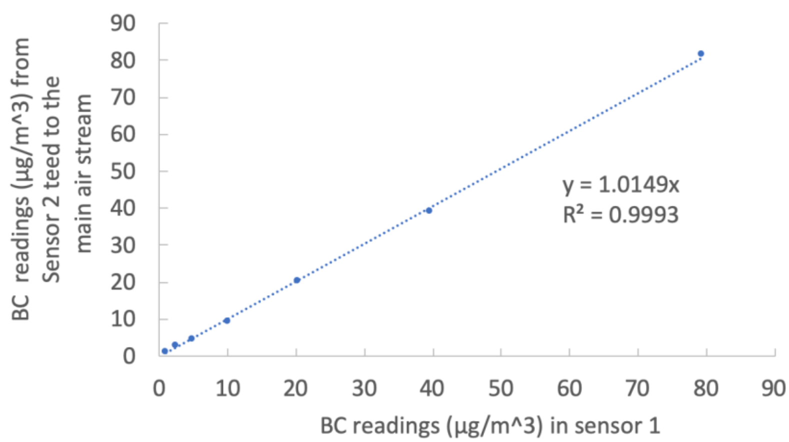

Figure 5. Comparison of data from BC Sensor 1 sampling from the mannequin's hole at 150 ml/min behind the mask and data of the other MA200 unit moved to be sampling off the 10 LPM air stream (via a tee-fitting) sucking from the other hole in the mannequin's mouth.

Comparison of Mask Performance between Tightly-sealed versus Static Normal Wear

Table II shows a comparison in filtration efficiency of masks between masks that are sealed by taping or additional tightening versus static normal use by untrained public. The FE of tightly-sealed N95 respirators and surgical masks are significantly greater that those measured under normal wearing conditions, demonstrating that the tight fit of the mask is a key factor controlling the mask performance for particle filtration. Even surgical masks (not N95) can filter out ca. 80% of black carbon when additional tightening is provided to improve the seal. All the disposable respirators or masks had much lower FE (around 40%) during the static normal use allowing 60% particles to get through, mainly from the gap around the nose. Depending on the shape of an individual's face, any of these masks including the rigid Moldex masks might work better or worse than observed here. Interestingly, the home-made "last resort masks" had a higher FE (i.e., 55%) than the disposable masks (40%) in these static normal use case scenarios.

Consistent Performance after Repeated Heat Disinfection for Disposable Masks

Figure 6 shows the filtration efficiency of N95 respirators and surgical masks (tightly fit to mannequins) before and after multiple rounds of disinfection. The average efficiency for two N95 respirators are significantly higher than 95% efficiency after the first 3 disinfection cycles, confirming that the heat treatments did not compromise the FE of the two N95 respirators. Interestingly, the FE of surgical masks increases from 78% to about 84% after one heating and stays significantly higher than the baseline in later cycles. However, the variation in the baseline measurements was high (Figure 6). The nose pads of the Moldex masks got peeled off and we did not include them after the 3rd disinfection cycle. We also tested separate Moldex N95 respirators from the same box without any heat disinfection and the nosepads also came off after limited handling. The integrity and FE of 3M N95 respirators and HSI surgical masks remained high even after 10 disinfection cycles. Cloth coverings show statistically similar results after 10 disinfections (Figure 7).

Table II. Comparison of Mean Filtration Efficiency (%) (and standard deviation in parentheses) for Three Different Mask Wearing Methods: Tight Fit by Taping or Tightening (Figure 2, after 3 heat disinfection cycles), the Static Normal Use after 3 Heat Disinfection Cycles, and Worn with Custom-made Nose Clips (after 10 heat disinfection cycles).

	Moldex N95 Respirators	**3M N95** Respirators	**Surgical Masks**	**Cloth Masks**
Sealed by taping or additional tightening of rolls made by a scoring pad	99.4 (0.4)***	95.2 (6.1) ***	78.8 (21.6) ***	No experiments[a]
Static normal use	43.0 (7.1)	39.6 (18.4)	41.69 (17.1)	54.4 (13.6)
Worn with custom-made external plastic nose clip	No experiments[b]	97.7 (3.7) ***	88.1 (13.6) ***	51.6 (8.8)[#]

Note: a) impossible to seal completely; b) all nose pads in three Moldex masks became unattached and were not included in the later experiments.
*** notes $p<0.0001$, null hypothesis (the same mean compared to the static normal use) can be rejected.
# $p = 0.19$, null hypothesis (the same mean compared to the static normal use) cannot be rejected.

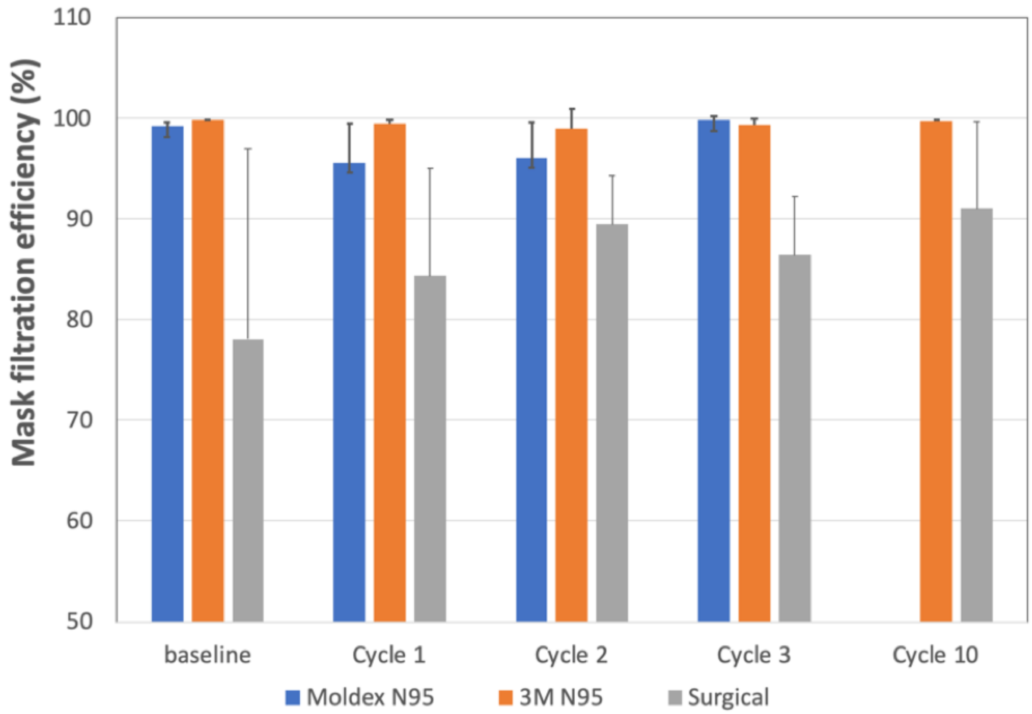

Figure 6. Average filtration efficiency of Moldex and 3M N95 respirators (with a tight fit) and HSI surgical masks when new (baseline) and along 10 disinfection cycles. The error bars are one standard deviation; The Moldex N95 respirators were not included after Cycle 3 because the nose pads peeled off. All N95 FE data are significantly greater than 95% (student t-test, p<0.05) and all data from HSI surgical masks are significant greater than 70% (p<0.05). For surgical masks (in gray), cycles 2, 3, and 10 data are significantly higher than the baseline FE.

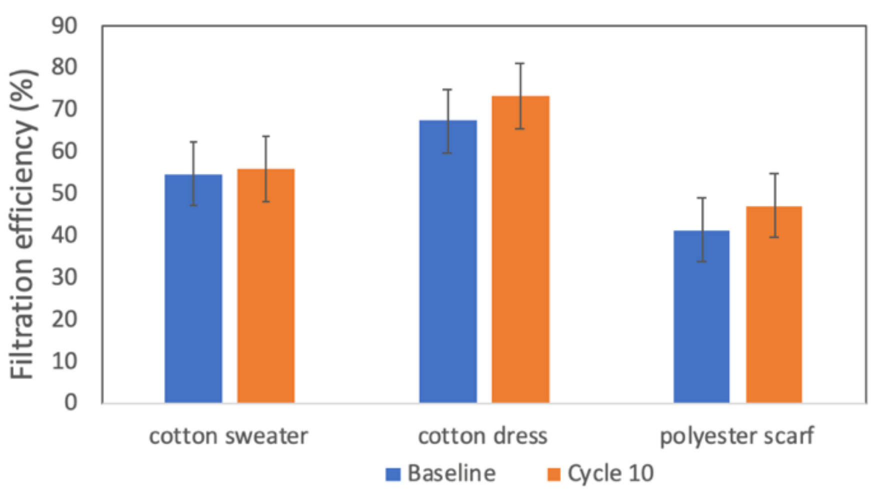

Figure 7. Average filtration efficiency of three homemade coverings (with a normal fit) when new and after 10 cycles of disinfection. The error bars are one standard deviation.

Wearing of Masks during Experiments

We did not notice any obvious changes in the color of the N95 respirators, the elasticity of string, nor the bendability of the nose clip. However, the nose pads in Moldex N95 respirators were peeled off after the 2nd run. The 3M N95 respirators and surgical masks showed no issue in all parts of masks, including the nose pads.

The Use of Home Appliances for Disinfection

The general public will not have access to special disinfection equipment available in some labs or hospitals, therefore it is important to be able to disinfect these masks in their homes after each trip outside the home (public transportation, grocery shopping, etc). Our result shows that filter performance remains high after the disinfection protocol. We placed the mask in the oven bags to avoid some slight possibility of releasing viruses from the masks during the heating and exhausting to the indoor home environment. The oven bags ensures the gas and any viruses are held inside the container.

The Performance Improvement with the External Nose Clip

Two co-authors molded the strip on their faces and wore their customized nose clip for 5 hours (with the masks) and did not feel any discomfort. Table II showed the results of the performance of three 3M and three HSI masks (after 10 cycles of heat disinfection) with the external nose clip invented by co-authors. The tight fit by the additional nose clip increased the average FE from ~40% (without the nose clip) to 98% for 3M N95 respirators and from 42% to 88% for the HSI surgical masks.

DISCUSSION

Protection from Covid-19

For the general public, the primary goal of the CDC and White House recommendation of wearing homemade face covers when in public is to lower the probability of transmission by protecting others from viable coronavirus transmission in droplets and aerosols produced by the mask wearer who may be infected but asymptomatic. There have been a small number of studies that directly looked at the impact of different facial masks worn by health care workers as protection for viral infections from either small droplets or fine aerosols with inconsistent results (MacIntyre *et al.*, 2017; Offeddu *et al.*, 2017; Radonovich *et al.*, 2019; Smith *et al.*, 2016). Two studies of household use of facial masks have also found little evidence of protection against virus infections but this may largely be due to poor compliance issues (Cowling *et al.*, 2008; MacIntyre *et al.*, 2009).

Medical staff who are treating Covid-19 patients are recommended to wear N95 respirators that have been properly fitted to protect themselves from both small droplets and fine aerosols, even though there is limited and conflicting evidence of viable coronavirus in small aerosols that could stay aloft longer. A recent study found viral RNA in air samples collected in isolation rooms treating patients with severe SARS-CoV-2 and those with mild infections (Santarpia *et al.*, 2020). Although one study found viable coronavirus in the medical staff areas in a Wuhan Hospital where PPE was taken on and off before tightening (Liu *et al.*, 2020) but not after, a different study in Singapore found no evidence for coronavirus in hospital settings (Ong *et al.*, 2020).

Thus, while experts still cannot agree on the airborne transmission of SARS-CoV-2, all the masks as well as the facial covering provided some significant level of protection to the wearer against breathing in ultrafine and fine aerosols in the size range of coronavirus. At the same time, the filter removal efficiency was not perfect even in these static tests suggesting that social distancing and hand washing are also important protective practices. We use filtration efficiency as a simple metric that should be related to how well the mask/covering would work for both keeping viruses from the wearer inside the mask as well as keeping viruses outside of the mask from coming in.

Mask Reuse to Ameliorate the Current Mask Shortage Issue

The current study demonstrates the continued good performance of the N95 respirators and surgical masks for particulate removal after disinfection. Though we did not use the coronavirus to test filter efficiency, the freshly generated BC particles that were used overlap the size range of this virus (60-140 nm). Several studies already demonstrated the dry heating at 70°C or above for 30 mins can adequately kill a coronavirus (Fischer *et al.*, 2020; Song *et al.*, 2020). Though this method can disinfect these viruses, it is not a standard operation protocol that has been widely tested and used for killing pathogens. For example an autoclave at 121 °C is normally used to kill pathogens such as cholera. Our study provides direct evidence of maintained FE for the whole mask. The prior Stanford study on filter reuse after disinfection only measured the particle removal efficiency of separate filter layers within the mask. Fischer et al. used the mask materials punched from N95 respirators, and stated that the mask performance decreased after the second disinfection. The punch can lead to the disintegration of the mask materials and would not be appropriate for testing reusability. Our study showed that the FE of surgical masks increases after the first disinfection and stays high in later cycles (Figure 6). This may be due to a lower moisture level in the masks after the disinfection. More studies are needed for figuring out the cause.

Caution Needed for Checking the Integrity of Masks Especially the Nose Pad

Our results suggest that most masks can be reused several times. We did not see obvious wear and tear in strings, nose clip and the edge of the 3M N95 respirators or HIS surgical masks. However, the nose pad of one type of occupational mask (Moldex N95) tested was easily removed or peeled off. In our experiment, the heat disinfection didn't appear to cause the damage to the nose pad since we observed the same problem on other examples of the same mask type that did not go through the heating protocol. For Moldex masks, we placed the nose pad in the same position in cycles 2 & 3, but we did find it more difficult to obtain a good seal after that point. This is not necessarily applicable to the situation of human usage, but it clearly demonstrated the handling of masks during reuse can lead to possible issues affecting the fit, which could impact the FE of the masks.

The Use of Home Appliances for Disinfection

As mentioned above, the regular public may not have access to special equipment (UV lamps or pressurized hydrogen peroxide chambers) nor even access to common chemicals such as 70% alcohol or bleach during the pandemic. Ideally, the masks can be safely disinfected for repeated use to reduce the pressure on the mask supply for health practitioners. The suggested protocol for the general public for using home ovens and enclosures with tight fitting bags can be used for this purpose. Different ovens may have different starting temperatures; therefore, it needs to be checked prior to disinfection (needs to be at least 160 F). To be cautious, we strongly recommend placing the masks in a sealed enclosure such as a pressure cooker or sealed oven bag before placing the masks in the oven.

Poor Mask Performance in Regular Usage

Our experiment shows minimizing leakage by inserting rolls (made from scoring pads) between an additional elastic cord and the cheek near the nose pad is critical for gaining the best mask performance (Table II). We only obtained filtration efficiency of ~40% for these disposable masks under regular wearing conditions, comparable with results in Jung *et al.* 2014. This is a serious issue and demands design changes to improve performance. Our work is consistent with prior studies indicating the importance of the mask fit (Coffey *et al.*, 2004; Crutchfield *et al.*, 1999; Jung *et al.*, 2014; Lee *et al.*, 2008) and that the nose area can be the main leakage point (He *et al.,* 2013). Though both 3M masks and the surgical masks have flexible metal clips to press the internal nose pad against the skin around the nose and under the eyes, the holding force of the internal metal clips is not strong enough. The extra pushing force by adding an additional elastic cord and customized nosepad provided much better performance. This research welcomes manufacturers or the general public to find better practical and aesthetic solutions for these fit issues.

Improved Performance with Wearing an Inexpensive Additional Nose Clip

Because of the poor performance, the chance of the wearer getting exposed to viruses is much higher, due to only about 40% of filtering efficiency. Based on our roll-pressing experiments, we found the small additional force around the nose (rather than the whole mask) can lead to improved mask performance. The heat moldable plastics allowed us to mold the plastics based on each individual's face shape. The excellent performance demonstrates the improvement by this additional nose clip. The clip is only about 4 mm thick and did not obstruct the wearer's line of sight when looking down. The two co-authors who wore it did not feel any discomfort (e.g., skin redness, headache, sweating, or tiredness) even after wearing for 5 hours. In addition, the cost is inexpensive. A sheet of the model plastic costing about $6 can make up to about 12 nose-clips. Adding the felt string and elastic cords, the total cost of materials is well below $2 per clip. However, due to the fact that it is made from heat moldable plastic, the customized nose clip cannot be disinfected in the oven or home drier; alcohol or bleach solution can be used if available.

The study provides not only a practical approach for reusing the masks through disinfection in kitchen ovens but also inexpensive and non-invasive solutions to improving the mask performance. The repeated usage of masks hopefully can lower current mask shortage tension and reduce the chance of getting exposed in the public transportation system for the general public.

Though our current focus is to fight with COVID-19 pandemics, the approaches developed in this study can be used to fight with other epidemics and pandemics, which are almost sure to happen in the future. Besides, they can also be used to substantially reduce exposure to air pollutants in hazy days and allergens in the pollen season.

Limitations

This emergent research has several limitations due to carrying out the research for the evolving pandemic while under the stay at home conditions. Our focus is to develop methods for the general public to disinfect their masks and improve the masks effectiveness. These methods need to be validated to be used for occupation and health care workers, given their much more complicated working environments. The tests were on a static mannequin overestimating filtration removal efficiency when compared to tests done with physical movements (Grinshpun *et al.*, 2009). The impact of disinfection on the fit factor was not adequately considered in this study and can be included in future studies. Furthermore, all tests were done at a low flow rate of 10 LPM estimating average adult minute ventilation rates at rest, while 85 LPM is used in NIOSH standard test procedures (NIOSH, 2009, 2019). Black carbon has not been established as a standard particle for testing mask performance. The constant flow rate is also a limitation since human breathing is better modeled by cyclic flows (in and out), which can impact mask usage (Bahloul *et al.*, 2014; Haruta *et al.*, 2008). We also did not investigate whether the simple modification by wearing an additional nose clip we developed increases filtration efficiency while talking and moving. Furthermore, time restrictions have limited the number of types of masks that could be completed.

CONCLUSIONS

The experiments unambiguously support the hypothesis that certain N95 respirators and surgical masks maintain their filtration efficiency after several dry-heating disinfection cycles. A simple home protocol was developed that can be used with home appliances. People would be able to disinfect N95 respirators and surgical masks with intact nose pads using a dry heat oven at 77 °C for 30 mins, up to 10 uses and potentially more, if the mask is still in good condition. The similar but reduced particle removal efficiency of all the masks under static normal use stresses the need to pay attention to how the masks are worn and suggests that home-made masks can be just as effective in infiltration as normally worn commercial N95 respirators and surgical masks. This similarity can be promoted for keeping commercial supplies for our first responders and medical staff. However other factors such as the fit factor and comfort of homemade masks still need to be examined. The reduced efficiency also confirms prior literature that there is a need for improving how these masks fit faces. We showed that the usage of a customized nose clip, which had been molded based on individual face shape, improved the fit substantially and thus the filtration efficiency of these masks under static conditions. These inexpensive modification (< $2 in material fees) appeared comfortable for hours of wearing.

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