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Quantitative Fit and Breathability Testing to Evaluate and Improve Homemade Mask Design Configurations

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Quantitative Fit and Breathability Testing to Evaluate and Improve Homemade Mask Design Configurations

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in

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by

Candice Lia Sirmollo

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ABSTRACT OF THE THESIS

Quantitative Fit and Breathability Testing to Evaluate and Improve Homemade Mask Design Configurations

by

Candice Lia Sirmollo

Master of Science, Graduate Program in Chemical and Environmental Engineering
University of California, Riverside, September 2021
Dr. Don Collins, Chairperson

Homemade masks are commonly used as an alternative to commercial masks to protect the general public from the spread of infectious respiratory diseases such as COVID-19. However, very little is understood concerning the influence of mask designs and the fit of masks on different face shapes and sizes. In this study, standardized quantitative fit testing was conducted with 5 participants to evaluate 48 mask design configurations. The fit of common homemade mask designs was investigated, as well as the influence of variations of nose bridges, elastic or tie options, and 23 material combinations. Relative to a surgical mask alone, double masking with a two-layer quilt cotton mask on top of a surgical mask resulted in only a 0.6% improvement in the average overall fit factor (OFF), while embedding surgical mask material layers in a homemade mask resulted in an OFF that was 57.9% higher than that of the original mask and was the third highest of all of the masks tested. An outer brace worn over a mask was shown to improve the average OFF of all participants by 24.3%. Fourteen homemade mask design configurations ranked higher than a surgical mask in regards to their average OFF, removing between 65.5 and 81.3% of particles from ambient air, 11 of which ranked higher than a KN95 mask. The pressure drop of different material combinations was also measured over a range of face velocities to evaluate their breathability. These results suggest that there are many homemade mask options that can provide just as much protection as commercially available options.

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Supplementary

1. Introduction

Certain infectious pathogens can spread via droplets and airborne aerosols. Droplet transmission consists of droplets larger than 5 μm whereas airborne transmission involves airborne virus-containing particles less than 5 μm (Jones and Brosseau, 2015; Kutter et al., 2018). Both of these modes of transmission are significant and follow different mechanisms in regard to transport in the air and deposition along the human respiratory tract. The dominant mode of transmission is often debated (Gralton et al., 2011; Liu et al., 2017), even for the flu (Offeddu et al., 2017), and can vary depending on the type of pathogen or virus as well as the environmental conditions. The amount of time that airborne virus-containing particles can stay in the air and how long they remain infectious, referred to as viral viability, requires further investigation and depends on many factors such as the size and type of virus, temperature, relative humidity, and airflow (Marr et al., 2019; Nicas et al., 2005; Tellier et al., 2019). Size distributions of human exhaled particles in aerosol plumes generated by coughing or sneezing have been measured in several studies (Fennelly, 2020; Jarvis, 2020; Johnson et al., 2011; Morawska and Cao, 2020). It has been demonstrated, for COVID-19 (Liu et al., 2020) and influenza (Lindsley et al., 2021) containing particles in particular, that smaller particles in the size range for airborne transmission generally are present at higher number concentrations than those in the droplet transmission size range (Chen et al., 2020; Jarvis, 2020). Airborne transmission of various respiratory viruses such as measles, SARS, chickenpox (Tellier et al., 2019), influenza (Yan et al., 2018), and tuberculous (Fennelly, 2020) have been observed.

At the beginning of 2020, the world was faced with a fast-spreading deadly pandemic of the SARS-CoV-2 virus, more commonly referred to as COVID-19. Daily routines, activities, and gatherings were cancelled indefinitely and everything shut down. Guidance from global and national health agencies included recommendations that the general public practice social distancing, wash their hands frequently, and wear face coverings to slow the spread of the virus. In response to studies providing evidence that airborne transmission is a dominant pathway of COVID-19 transmission (Chen et al., 2020; Morawska and Cao, 2020; Yao et al., 2020; Zhang et al., 2020) and that the COVID-19-containing aerosol can stay airborne and infectious for hours (Santarpia et al., 2020), the Centers for Disease Control and Prevention (CDC) officially recognized that COVID-19 can spread via airborne transmission and that masks can protect against this pathway. With the distribution of vaccines to the public starting in late 2021 and accelerating in 2021, the United States saw a decrease in new cases and a re-opening of sectors that had been shut down. However, vaccine hesitancy and the potential for vaccinated individuals to still catch and transmit the virus led to a subsequent significant rise in new cases. This has resulted in a returned emphasis on the importance of masks for protection against the virus, and so the widespread use of face masks will likely continue in the future.

Masks can provide the wearer with considerable protection from both droplet and airborne transmission of respiratory viruses, especially when used in combination with other precautions. For healthcare workers, the World Health Organization (WHO) recommends the usage of respiratory protection devices capable of efficiently filtering 0.3 μm particles, such as N95 respirators, when working near patients that could have a virus such as SARS or COVID-19 that is transmittable via airborne particles (Medicine, 2006). To demonstrate the effectiveness of universal masking across a population, several mask-use model studies (Eikenberry et al., 2020; Fisman et al., 2020; Kai et al., 2020; Leffler et al., 2020; Mittal et al., 2020), case studies (Bundgaard et al., 2021; Hendrix et al., 2020), and theoretical rationale letters (Esposito et al., 2020; Sunjaya and Jenkins, 2020) have been published since the pandemic began that defend universal masking to prevent the spread of COVID-19. There are various theories surrounding the topic of masks and universal masking: one suggests that masks can protect the wearer by reducing the dose of the virus, which would consequently result in either no disease or a milder disease (Gandhi et al., 2020), while another is that universal masking could result in variolation, where a milder form of the disease results in lasting immunity, similar to when a majority of a population is vaccinated (Gandhi and Rutherford, 2020).

To protect against contagious viral diseases with high rates of infection, the general public may be encouraged to use homemade and cloth masks when N95 respirators or surgical masks are unavailable, being reserved for the medical community, and when there are widespread concerns about the reliability of counterfeit commercial masks. Some may also prefer to wear a homemade or cloth mask rather than a commercial mask simply because of comfort, personal expression, aesthetics, or long-term reusability. The efficacy of homemade masks to prevent droplet transmission via inhalation (Wilson et al., 2020), airborne transmission via inhalation (Prather et al., 2020; Ueki et al., 2020), and of surgical masks to prevent both (Leung et al., 2020) has been investigated. Homemade masks have also been shown to prevent outward particle emission from the wearer (Asadi et al., 2020; Fischer et al., 2020; Li et al., 2021; Lindsley et al., 2021). Several review papers have been published that provide further evidence that the usage of cloth masks in the general public can slow the spread of respiratory transmissible diseases (Chua et al., 2020; Clase et al., 2020; Howard et al., 2021; Liao et al., 2021; MacIntyre and Chughtai, 2020; Sharma et al., 2020). Airborne transmission via virus-containing particles can be an important form of transmission for many types of infectious diseases and its mechanisms should be considered when selecting a mask.

Given the plethora of mask materials available, it is helpful to compare the performance of those commonly used in homemade masks so that the public can make more informed decisions. Thus, comprehensive investigations of the filtration efficiency (Bagheri et al., 2021; Drewnick et al., 2021; Guha et al., 2021; Hao et al., 2020, 2021; Joo et al., 2021; Konda et al., 2020; Kwong et al., 2021; Leith et al., 2021; Pan et al., 2021; Pei et al., 2020; Rengasamy et al., 2010; Rogak et al., 2021; Wang et al., 2020; Zangmeister et al., 2020; Zhao et al., 2020) and pressure drop (Aydin et al., 2020; Bagheri et al., 2021; Drewnick et al., 2021; Guha et al., 2021; Kwong et al., 2021; Leith et al., 2021; Li et al., 2012; Rengasamy et al., 2010; Sheets et al., 2020; Wang et al., 2020) of homemade mask materials under controlled laboratory settings have been conducted. The efforts of those studies have resulted in design recommendations including use of materials with tight weaves and low porosity, multiple layers of different types of materials, and a filter layer with electrostatic charge such as flannel or silk. They have also emphasized the importance of a good fit that minimizes leaks.

To describe the efficacy of cloth masks when fitted to a human face or manikin headform, several studies have reported their measurements using a set of non-standardized fit testing parameters. These parameters include particle removal efficiency ($\% = 100 \times \frac{(C_{outside} - C_{inside})}{C_{outside}}$), inward and outward protection efficiency ($OPE\ \% = 100\ \times \left(1 - \frac{C_{mask}}{C_{no\ mask}}\right)$), fitted filtration efficiency ($\% = 100\ \times \left(1 - \frac{C_{inside}}{C_{outside}}\right)$), and total inward leakage ($\% = 100\ \times \frac{C_{inside}}{C_{outside}}$), where C_{inside} is the concentration measured from inside of the mask, $C_{outside}$ is the ambient concentration measured outside of the mask, C_{mask} is the concentration measured in an exposure chamber when a mask is worn, and $C_{no\ mask}$ is the concentration measured in an exposure chamber when no mask is worn. Among the studies that reported particle removal efficiency, Shakya et al. (2017) used a manikin to test three different commercially available cloth masks and Mueller et al. (2020) tested 15 homemade masks with or without nylon stockings to evaluate the fit based on the methods of Cooper et al. (1983). To obtain the inward and outward protection efficiency, Pan et al. (2021) tested 11 face coverings on a manikin including cloth masks, a surgical mask, and a face shield. To measure the fitted filtration efficiency compared to the ideal filtration efficiency, Clapp et al. (2021) tested consumer grade cloth masks and mask modifications on one human volunteer that performed various exercises while exposed to generated NaCl particles between 0.02 and 0.6 µm, while Hill et al. (2020) tested cotton insert materials on a headform. Cherrie et al. (2018) had 10 participants perform exercises to measure the total inward leakage of one cloth mask bought at a store and simultaneously measured black carbon particles generated by an engine from inside the exposure chamber and inside the mask.

Standardized fit testing of cloth masks on human participants has also been conducted and is described in five published studies, with each following the Occupational Safety and Health Administration (OSHA) Respiratory Protection Standard 29 CFR 1910.134. For each of the studies, fit factors for each mask and each participant were obtained. Of these studies, 3 of them only tested one mask: one had 3 participants test one cloth mask (Dato et al., 2006), another had 28 adult and 11 child participants test one tea cloth mask (van der Sande et al., 2008), and the last had 21 participants test one cotton t-shirt mask that the participants made themselves (Davies et al., 2013). O'Kelly et al. (2021) had 3 participants test 5 simple fabric masks made without a filter or nose wire, including a bandana, a cloth mask with stretchy material, a pleated mask, and 2 masks designed to contour to one's face (O'Kelly et al., 2021). Lindsley et al. (2021) investigated 15 cloth masks, including store-purchased cloth face masks, gaiters, and bandanas, each of which was tested by 3 of the 11 total participants and with a pliable skin headform with the goal of evaluating their efficacy for source control. Gaps associated with a loosely fitted mask have been estimated to result in over a 60% decrease in filtration efficiency relative to the filtration efficiency of the base materials (Hill et al., 2020; Konda et al., 2020). These fit testing measurements provide valuable information in regards to the level of protection that different cloth masks can provide when worn by a human under real-world conditions.

Existing research has been used to inform government responses to pandemics and protect the general public but there is still much that is not understood concerning the large variety of homemade mask designs and the fit of those masks on different face shapes and sizes. Several studies have cited the need for further research in this area (Chughtai et al., 2013; Konda et al., 2020; Medicine, 2006). To address this critical knowledge gap, the fit of homemade face mask on different face shapes and sizes has been evaluated with the goal of providing the public with the knowledge of which masks and material combinations provide optimal protection from the transmission of airborne respiratory diseases under real-world conditions. The breathability of different material combinations has also been tested by measuring the pressure drop over a range of face velocities.

2. Methods

2.1 Fit Testing Setup

Standardized quantitative fit testing was conducted with 5 human volunteers and 48 different mask design configurations, including some commercial masks. During fit testing, a water-based Condensation Particle Counter (CPC) (MAGIC-200, Aerosol Devices Inc.) alternated between measuring the particle number concentrations in the room air and in the air from behind the mask by using an automated 3-way valve. The CPC has a sample flow rate of 0.3 L min^{-1} and detects particles in the size range of ~5 nm to 2.5 μm, which spans the size range of typical airborne virus-containing particles (Gralton et al., 2011; Lindsley et al., 2021; Liu et al., 2020). A small sampling probe (TSI model 8025-N95 Fit Test Probe Kit) inserted through the material allowed air to be sampled from behind the mask while the mask was worn by the participant. Conductive silicone tubing was connected directly between the sampling probe on the mask and the 3-way valve leading to the particle counter (Figure 1a). Because the sample flow rate of the CPC is relatively low compared to typical human inspiratory flow rates (~5-7 L min^{-1} at rest and 100+ L min^{-1} during exercise), it is assumed that the air present behind the mask is being pulled in primarily by the wearer as opposed to the instrument. It is also assumed that any particles present behind the mask came either through leaks or through the mask materials.

A sequence of real-world exercises was performed by each participant while wearing each of the masks, according to the OSHA Respiratory Protection Standard 29 CFR 1910.134 for respirator fit testing. Each cycle consisted of normal breathing, deep breathing, head side to side, head up and down, talking out loud, grimacing, bending over and touching toes, and normal breathing (Table S2). For each exercise, air behind the mask was measured for 90 s, preceded and followed by a measurement of room air for at least 60 s. Participants recorded the times that they started and stopped each 90 s exercise. Each participant repeated the exercise sequence a total of three times for each mask that was tested to reduce uncertainty in the results. Minimal instruction was given concerning how to properly wear the masks in order to have real-world representations of the fit to a member of the general public. The participants were only instructed to adjust the nose wire and elastics so as to minimize leaks. Each participant tried on multiple mask sizes at the beginning of the project and was assigned a size (Table S1); further information regarding size selection can be found in the supplement.

The particle concentrations measured by the CPC were used to calculate the Fit Factor (FF) for each exercise, which is defined as the ratio of the particle concentration measured in ambient air before (1) and after (2) each exercise to that measured inside the mask, $Fit\ Factor = \frac{C_{Ambient\,1} + C_{Ambient2}}{2C_{Sample}}$. The OFF can be made more relatable by converting it to the % particles filtered (Eq. S1). A Fit Factor of 1 indicates 0% particles filtered, a FF of 2 indicates 50% filtered, and so on. A FF of 3 means that the air behind the mask is 3 times cleaner than the surrounding air.

A FF is influenced by the breathability of the material, the filtration efficiency of the material, the fit of the mask, and the size of the particles. Thus, FF's are more representative of the performance of masks worn by the public than material filtration efficiency measurements alone. The Overall Fit Factor (OFF) is calculated as the average of the individual FFs for all eight exercises (Eq. S2), differing from the OSHA Respiratory Protection Standard that excludes the grimace exercise from OFF calculations. Across all average OFF results, those calculated with the grimace exercise were 0.23% lower than those calculated excluding the grimace exercise.

Measurements were performed in a laboratory setting. No particles were generated for this testing; only particles in room air were used. An example of the variability in particle concentrations during a cycle of fit testing exercises can be found in Figure S1. Instrumentation was automated so that the researchers did not need to be present during testing. As this testing was conducted with human participants during the worldwide COVID-19 pandemic in 2020, approved safety protocol was followed during testing. To protect the participants and researchers from these risks, social distancing and hygiene recommendations from the CDC were followed and contact with participants minimized. This research was determined by the University of California Riverside Research and Economic Development (RED) office to be "not human subjects research" and did not fall under the regulations of the Institutional Review Board.

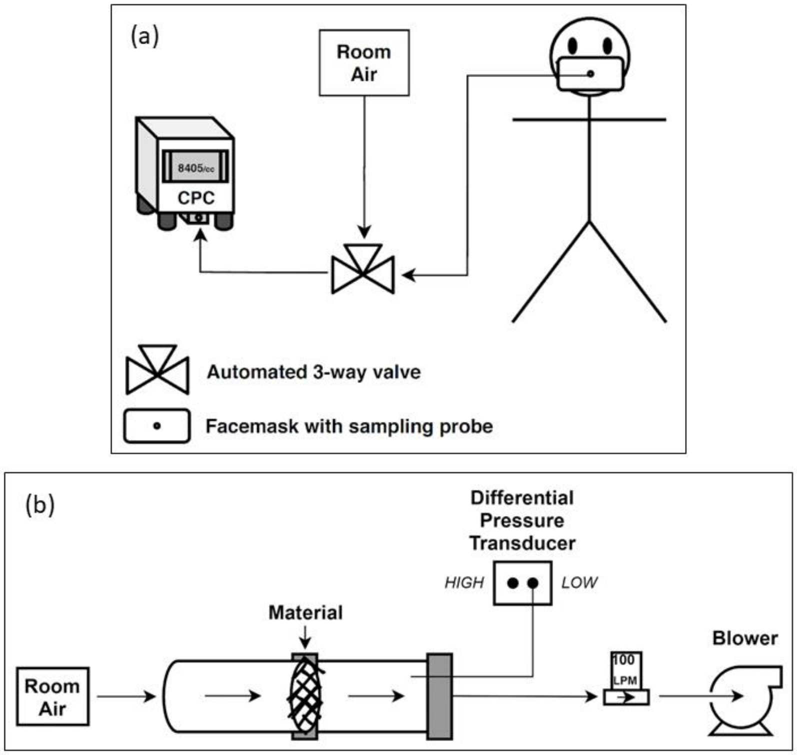

Figure 1. (a) Fit testing and (b) pressure drop testing setup for the experiments in this study.

2.2 Pressure Drop Setup

To evaluate the breathability of the masks tested in this study, the pressure drop across each material combination was measured. The materials were clamped onto one end of a cylindrical tri-clamp stainless steel spool connected to a blower that pulled room air through the material (Figure 1b). A calibrated flow meter connected downstream of the spool allowed for the measurement and control of the volumetric flow rate between 10 and 85 L min^{-1} as the blower speed was changed. To measure the differential pressure, the low pressure port of a pressure transducer (Cole Parmer 98073-28, 0 – 2.49 kPa) was connected to a tube inserted into the spool cavity downstream of and directly adjacent to the material and the high pressure port was open to room air. Aluminum metal tape was used to cover half of the area of the material clamped into the spool, so that the material area (40.5

cm^2) would result in realistic face velocities (Eq. S3) ranging from 5 to approximately 35 cm s^{-1} without the need to alter the spool diameter or volumetric flow rate range.

3. Mask Construction

Mask designs were chosen to represent the variety of basic designs that home sewists used during the pandemic. As there were diverse pleated mask designs, the design selected for this study to represent the Pleated mask type was based on the most popular YouTube video tutorial (as of April 2020) (Figure 2d). For the Fitted mask type, the “UVH” (Synonyms: “Florence”, “Fu”) mask was selected because it is an open source design that has been used and promoted by many sewist groups (Squad, n.d.) (Figure 2a). For the Boat mask type, also known as “Octagon”, “3d”, and “Aplat”, a design used and promoted by the same sewist groups was chosen (Squad, n.d.) (Figure 2b). A unique Vertical Pleat design “TREFA37” was chosen to explore a different design type, although its use in the general public did not appear to be widespread (Figure 2c). Finally, a second pleated mask design called “Taber” with additional deep pleats, an open interior for adding filters, and that was cut diagonally against the bias, was chosen to explore a more complex pleated design.

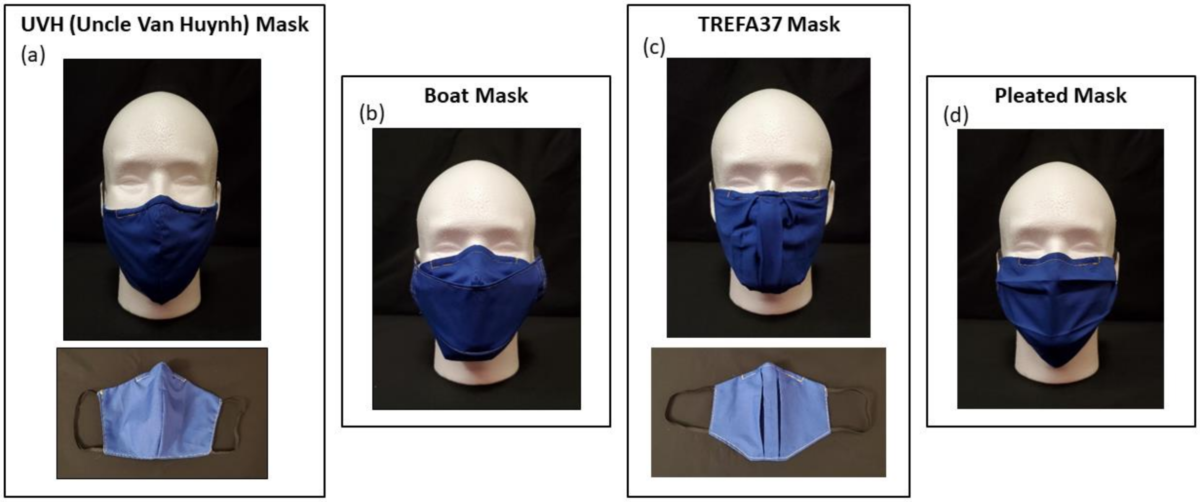

Figure 2. Photographs of the homemade mask designs investigated. The (a) UVH mask was designed by Joost De Cock, (b) Boat mask by Valerie Soe, (c) TREFA37 mask by DIY Trefa, and (d) Pleated mask by Erica Arndt.

Figure 2 shows images of some of the mask designs that were tested. The influence of features such as nose wires, elastics, and material combinations were evaluated for some of these masks. Unless otherwise stated, the mask design features consist of 12” upper and 10” lower (12/10”) head elastics and 4” aluminum (Al) nose wires.

A diverse array of materials was chosen for testing. When possible, materials were purchased from the most common and widely-available vendors for the US public. The following materials were used in this study and are referred to with these acronyms: bandana (B), cotton batting (CB), Filti insert (Fi), flannel (F), knit (K), light interfacing (LI), Lyocell (Lyo), medium interfacing (MI), microfiber (MF), muslin (M), 600 thread count percale (P), 500 thread count pima percale (PP), polyester shopping bag (PSB), polyester blue (PB), polyester gold (PG), quilt cotton blue (QCB), quilt cotton pink (QCP), quilt cotton white (QCW), surgical (Surg), and toolbox insert (TBI). In this paper, all three types of quilt cotton material are referred to as quilt cotton (QC) due to their similar pressure drop curves (Section 4.2). A majority of the masks have QC and M outer layers, where the M side is worn against one's face. For example, the QC_F_M material combination has three total layers where the first listed material, QC, is outward facing and visible to other people, the middle listed material, F, is situated in between the first and last listed materials, and the last listed material, M, is inward facing against one's face. Similarly, the QC_F_Fi_Fi_M material combination has five total layers where QC is outward facing, F, Fi, and Fi are the middle layers inside of the mask, and M is inward facing.

During the mask construction process, right, or printed, sides of outer fabric pieces were held together with sewing clips rather than pins to avoid introducing holes in the masks, and any additional material layers were added to the outside. Masks were sewn together on a consumer-grade sewing machine with default stitch spacing and a 6 mm (¼") seam allowance, and were left open on one side so they could be turned right-side-out. Corners were clipped and the masks were then carefully turned out, pulled into their intended shape, and pressed. For masks with nose wires, a 6 mm (¼") by 10 cm (4") channel was sewn in the center on the top, with a 1.25 cm (½") stitch gap to allow the insertion of the wire near the open end of the mask, inserted just below the outer-facing layer of the mask to maximize cushioning between the nose wires and the wearer's face. Masks were then closed on the end and top-stitched close to the edge on the sides and bottom. In the case of masks for which filter inserts would be applied, the fabric layer touching the face of the wearer was hemmed 1.9 cm (¾"), pressed, and topstitched before assembling to leave both sides open for inserting the filter.

Elastics, when applied to masks, were temporarily attached to the right sides of mask front pieces using washable quilter's tape at the indicated attachment points before sewing the mask. For masks with ties instead of elastic, the masks were left open on both sides before turning out, and the ties were clipped over the open sides and positioned so that approximately 46 cm (18") of the tie length was available for an upper tie and 36 cm (14”) of the length was available for a lower tie (referred to as 18/14” ties), and were top-stitched along the length of the tie. Elastic was added to the Boat mask by folding the two sides around the ends of the elastic and top-stitching in place. Pleats were applied to the Pleated mask design after turning out the layers, but before final top-stitching was applied. For the Vertical Pleat and Taber masks, pleats were applied to the fabric before stitching together, according to their individual directions. Taber masks were also hemmed 1.25 cm (½”) and zig-zag stitched at the raw edges at the mouth opening to prevent fraying.

All sewn masks were machine-washed on a delicate cycle with hot water using liquid detergent (Arm & Hammer) and machine dried on medium heat. The sampling probes were applied to the right sides of the masks, punctured approximately 5-6 cm from the top and 2 cm from the center to bring them close to the nose and mouth. There was some variation in the positions of the sampling probes owing to the varied mask designs, and probes on pleated masks were positioned to ensure that they were not covered by pleats inside the mask that might affect the airflow. Masks with filter inserts had them placed inside the mask after drying but before the insertion of the probe, so that the probe would pass through the insert. Masks were placed into plastic bags, sealed, and labeled with unique numbers prior to fit testing. For one mask design configuration that included a 10-wash test to compare the performance of the mask after 10 washes, the masks were machine-washed on a 35 min speed wash cycle with the same water, detergent, and drying parameters as used for initial preparation of all masks. In accordance with our standard operating procedure as reviewed by University of California Riverside Environmental Health and Safety, study coordinators wore sanitized gloves and masks while handling masks outside of plastic bags.

Facial measurements, listed in Table 1, of each of the five participants were taken to record information about face shape and size. Participants were provided with a soft tape measure and instructions on how to take these measurements, which were taken either by themselves, a family member, or a friend. Participants also took a profile (side view) photograph of themselves to determine nose and jaw angles. Examples of the locations of face measurements are shown in Figures S2 and S3.

Table 1. Face measurements of the participants involved in this study.

Facial Measurements	P1	P2	P3	P4	P5
Face height (cm)	14.0	14	11.5	13.0	14.3
Jaw width (cm)	13.5	17	11.5	11.5	14
Head circumference (cm)	61.2	58	55	56.5	55.3
Nose length (cm)	2.8	2	2	2.5	2.6
Nose width (cm)	3.8	4	2.8	3.6	3.1
Distance from nose to chin (cm)	7.5	7	6.2	7.5	8.0
Ear-chin length (cm)	36.0	32	26.5	29.4	31.2
Ear-nose length (cm)	34.3	33	27	28	31.3
Ear-bridge length (cm)	30.4	30	26	26.5	29.5
Jaw angle (°)	123.5	114.5	122	133	134
Nose angle A (°)	42.5	36	34	37	39
Nose angle B (°)	68	85	79.5	83	69.5

4. Results

Out of a total of 187 individual masks, participants 1 (P1), 2 (P2), 3 (P3), 4 (P4), and 5 (P5) tested a total of 48, 46, 26, 44, and 23 masks each, respectively. Six of the mask design configurations were tested by 2 participants, 10 by 3 participants, 20 by 4 participants, and 12 by 5 participants.

4.1 Fit Testing

4.1.1 General Designs

Among the homemade mask designs, the Pleated mask design had an average OFF of 1.74 averaged over N=5 participants, the Boat mask design had an average OFF of 1.91 (N=5), the TREFA37 mask design had an average OFF of 1.97 (N=4), and the UVH mask design had an average OFF of 2.03 (N=5). Each of the general homemade mask designs tested had a QC_QC material combination, 7" ear elastics, and a 4" Al nose wire. A Bandana, folded over once, was also tested and had an average OFF of 1.91 across 3 participants. Further homemade mask design features and improvements were tested on the UVH mask because it had the highest OFF value out of the general mask designs.

4.1.2 Design Components and Improvements

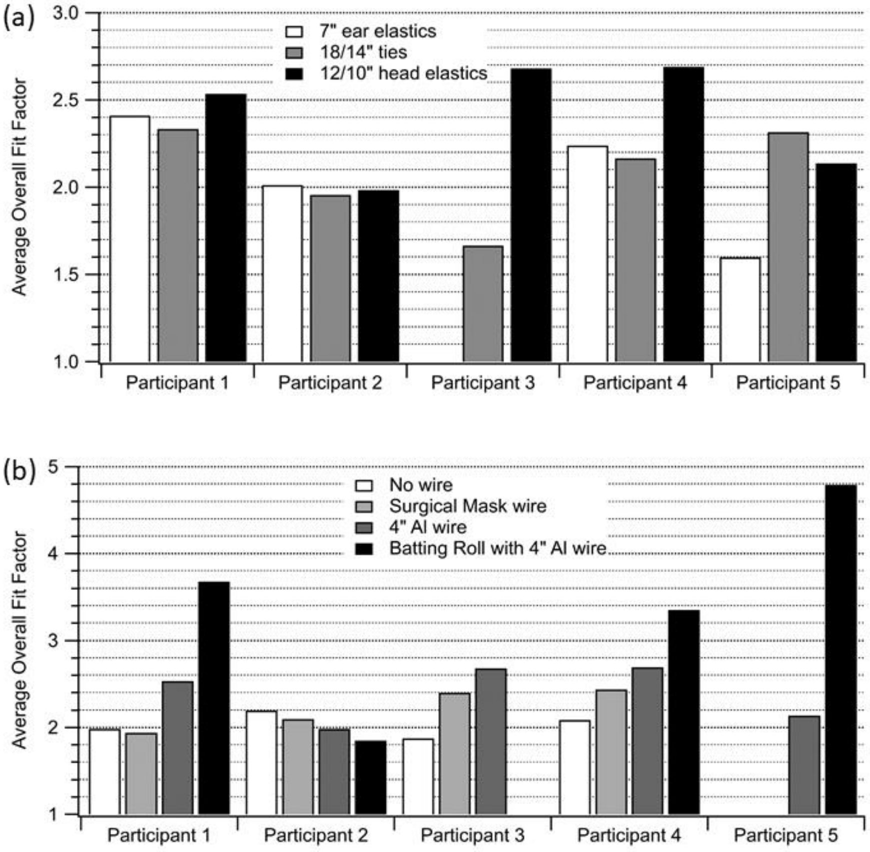

Figure 3. (a) Elastic tie and (b) nose wire options for homemade masks. The average OFF values, averaged across all participants, are as follows: (a) "7" ear elastics" (2.06), "18/14" ties" (2.09), and "12/10" head elastics" (2.34); (b) "No Nose Wire" (2.04), "Surgical Mask wire" (2.22), "4" Al wire" (2.34), and "Batting Roll with 4" Al wire" (3.42). The masks used in this comparison consisted of a UVH design with the QC_F_M material combination and were constructed with (a) the specified elastic or tie and 4" Al nose wire or (b) 12/10" head elastics and the specified nose wire.

Ear elastics, head elastics, and fabric ties that go around the head are all common ways of securing a homemade mask to the wearer's head. The fit factors of QC_F_M UVH masks with 7" ear elastics, 12/10" head elastics, and 18/14" ties were compared (Figure 3a). For three out of five participants, the mask with ear elastics performed slightly better than that with ties, although the average OFF of the mask with ties, averaged across all participants, was slightly higher than that of the mask with ear elastics. Out of the three options, the head elastics performed noticeably better than the rest, with an average OFF value 11.9% higher than with the ties. Therefore, these results suggest that use of head elastics, as opposed to ear elastics or head ties, improves the overall fit and efficiency of homemade masks.

The performance of nose wires and mask design improvements such as the usage of cotton batting for nose padding was also considered (Figure 3b). Relative to a mask with no nose wire, a mask with a soft surgical mask wire resulted in a 9.0% increase in the average OFF across all participants, a mask with a 4” Al nose wire resulted in a 14.7% increase, and adding a cotton batting roll along with a 4” Al nose wire resulted in a 68.0% increase. The surgical mask wire used consists of a flexible plastic-coated nose wire. Based on the marked improvement in the average OFF, the authors highly recommend the simple addition of an external cotton batting roll to homemade masks in combination with a rigid nose wire. For all participants other than P2, the batting roll added to a 4” Al nose wire resulted in a higher average OFF than either no wire, a surgical wire, or a 4” Al wire by itself. This may be associated with P2’s facial features or the way that they secured the masks and is further evidence of the need for additional research on the influence of face size and shape on the fit of homemade and other masks.

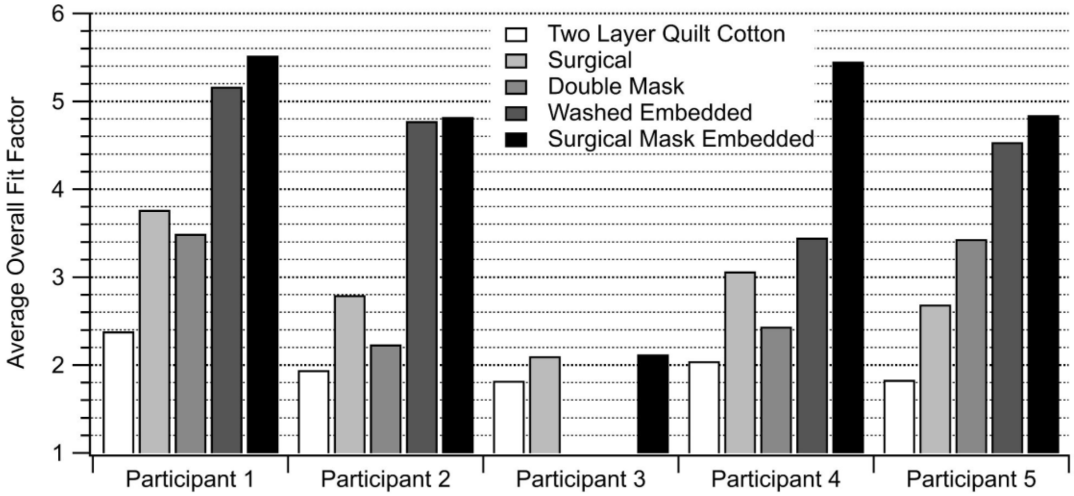

Figure 4. Comparison of the performance of different combinations of Surgical and UVH masks. The average OFF values, averaged across all participants, are as follows: "Two Layer Quilt Cotton" (2.03), "Surgical" (2.88), "Double Mask" (2.90), "Washed Embedded" (4.48), and "Surgical Mask Embedded" (4.55). All of the homemade masks had the UVH mask design and 4" Al wire. The two-layer QC mask had 7" ear elastics, while the rest of the homemade masks had 12/10" head elastics. The "Surgical Mask Embedded" mask is a UVH mask with materials from a commercial surgical mask (consisting of 3 layers) sewn between the QC and M outer layers. Each "Washed Embedded" mask was constructed identically to "Surgical Mask Embedded" but was washed and dried a total of 10 times.

Use of double masks has been a highly recommended practice, including by the CDC (Brooks et al., 2021). The performance of double masks relative to other combinations of QC and surgical masks is shown in Figure 4. Relative to a surgical mask by itself, sewing surgical mask materials into a UVH mask was found to increase the average OFF by 57.9%, whereas double masking with a two-layer quilt cotton mask on top of a surgical mask improved it by only 0.6%. Relative to a two-layer QC mask, embedding the surgical mask materials into a UVH mask resulted in a 124.7% (2.25 times) improvement in the average OFF. After 10 cycles in a residential washing machine and dryer, the UVH mask with embedded surgical mask materials only had a 1.5% decrease in its average OFF, showing that this specific mask design configuration and material combination can withstand long-term use.

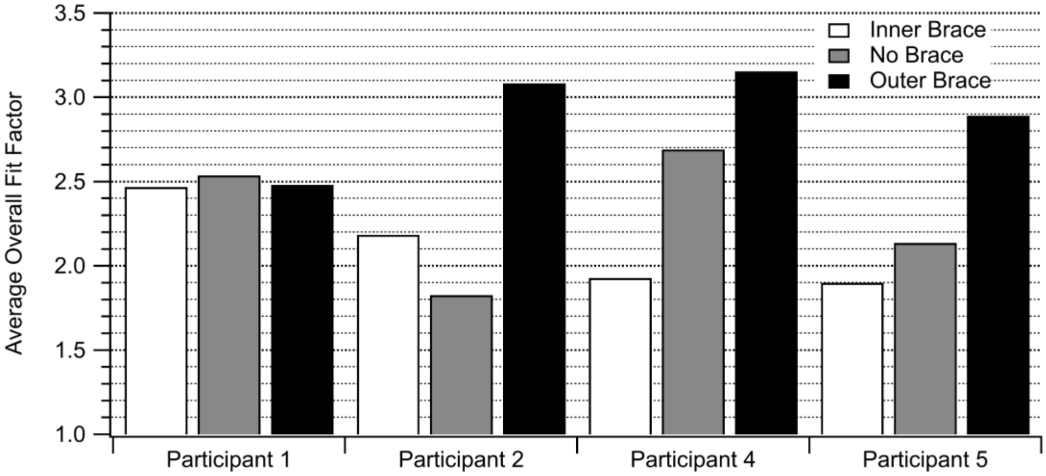

Figure 5. Comparison of the average OFF for "Inner Brace", "No Brace", and "Outer Brace" mask brace options for each participant. Averaged across all participants that tested the masks, the "Inner Brace" option had an average OFF of 2.12, the "No Brace" option had an average OFF of 2.34, and the "Outer Brace" option had an average OFF of 2.90. The masks used for these experiments were UVH masks constructed with the QC_F_M material combination, 12/10" head elastics, and a 4" Al nose wire.

For three out of four participants, the usage of a rigid inner brace decreased the average OFF. The inner brace is designed to push a mask away from one's face in order to make it easier to breathe, and in this study it also appears to have increased the size of the gaps along the wearer's face. Use of an outer elastic brace worn over a mask resulted in a 24.3% increase in the average OFF across all participants relative to a QC_F_M UVH mask with no brace at all (Figure 5). Based on the results presented in Figure 5, the authors recommend the usage of an outer brace as opposed to an inner brace. However, without further investigation it remains uncertain whether even an outer brace will improve the fit factor for every mask or for every face shape or size.

"Ear savers", which are strips of fabric or plastic with buttons or hooks meant to reduce strain on ears from elastic were also tested. A mask with an ear saver attached to the ear elastics of a QC_QC Pleated mask was tested by 4 participants and had an average OFF value of 1.73, which is almost the same as the average OFF of the same mask without the ear saver (1.74). Thus, despite the comfort that ear savers may provide the wearer, these results indicate that using them with a homemade mask will not improve the level of protection. To evaluate a type of mask that could be used by those with a sensory impairment, a QC_F_M UVH mask with a 10 cm by 5 cm clear vinyl window was tested and resulted in an average OFF of 3.44, ranking #7 in Table 2. Although it was not investigated, it is possible that the unexpectedly high OFF from the mask with a vinyl window was either because the positioning of the sampling probe was different than others or that the vinyl window provided some stiffness in the front, keeping the mask off of the mouth and opening up more side fabric for filtering.

4.1.3 Material Combinations

Many materials were used in the masks, including common sewing materials such as flannel, knit, interfacing, cotton batting, and polyester, filter insert materials such as Filti and toolbox shop towels, and miscellaneous materials found around one's house such as percale, which is used for bedsheets, reusable polyester shopping bags, Lyocell, which is used in clothing, and microfiber towels. Various combinations of these materials were tested with the goal of optimizing the filtration and breathability of the masks (Figure 6). Some materials were more conducive to fitting snugly around the face and preventing gaps, such as cotton batting, while others such as the polyester shopping bag material were stiff and left open a lot of gaps, as reflected in the resulting fit factors. The 23 material combinations in Figure 6 are from masks with identical design features, and any differences in the average OFF values reflect influences of multiple factors such as the number of layers, breathability, thread count, water resistance, electrostatic charge, and stretchiness or flexibility of the materials (Chughtai et al., 2013).

Following guidance from the CDC, the PB_F_M and PG_F_M material combinations were tested and had higher average OFF values than all other 2-, 3-, and 4-layer material combinations in Figure

6. Adding one layer of TBI or Fi insert material was observed to increase OFF by 55.1% and 32.4% relative to a QC_F_M UVH mask, respectively. The filtration efficiency of the materials alone in laboratory conditions was not measured in this study due to the large number of recent studies that have specifically investigated those properties.

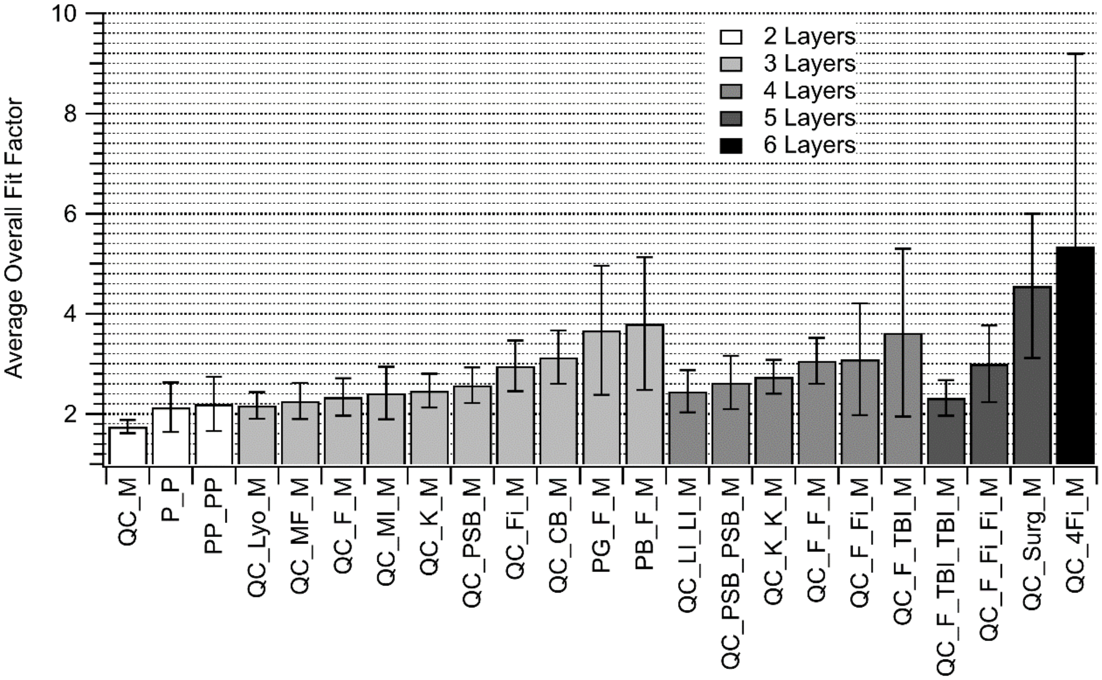

Figure 6. Average OFF values of 23 different homemade material combinations, with standard deviation shown with error bars. The average OFF values were averaged across all participants that tested each mask. All of the masks were constructed with the UVH mask design, 12/10" head elastics, and 4" Al nose wire. The average OFF values averaged over N participants are as follows: "QC_M" (1.75; N=2), "P_P" (2.13; N=3), "PP_PP" (2.20; N=3), "QC_Lyo_M" (2.17; N=2), "QC_MF_M" (2.26; N=3), "QC_F_M" (2.34; N=5), "QC_MI_M" (2.42; N=3), "QC_K_M" (2.46; N=5), "QC_PSB_M" (2.57; N=4), "QC_Fi_M" (2.96; N=5), "QC_CB_M" (3.13; N=5), "PG_F_M" (3.67; N=2), "PB_F_M" (3.80; N=4), "QC_LI_LI_M" (2.46; N=3), "QC_PSB_PSB_M" (2.63; N=4), "QC_K_K_M" (2.74; N=2), "QC_F_F_M" (3.06; N=3), "QC_F_Fi_M" (3.09; N=4), "QC_F_TBI_M" (3.62; N=4), "QC_F_TBI_TBI_M" (2.32; N=2), "QC_F_Fi_Fi_M" (3.00; N=2), "QC_Surg_M" (4.55; N=5), and "QC_4Fi_M" (5.34; N=4).

Table 2. List of the top performing masks, ranked according to the average OFF value averaged over N participants. All of the homemade masks in this table have 12/10” head elastics and 4” Al nose wires. The following masks were excluded from this table because they were tested on less than 3 participants: “UVH Polyester Gold” (PB_F_M) and “UVH Flannel 2X Filti Insert” (QC_F_Fi_Fi_M).

Top Performing Masks						
Ranking	Mask Name	Average OFF all	Standard Deviation of Average OFF all	% Particles Removed	Material Combination	N Participants
1	N95	30.8	27.5	96.7	N/A	5
2	UVH 4X Filti	5.34	3.84	81.3	QC_4Fi_M	4
3	UVH Surgical Embedded	4.55	1.44	78.0	QC_Surg_M	5
4	UVH Polyester Blue with Batting Roll	4.41	1.43	77.3	PB_F_M	4
5	UVH Polyester Blue	3.80	1.33	73.7	PB_F_M	4
6	UVH Flannel 1X Toolbox Insert	3.62	1.68	72.4	QC_F_TBI_M	4
7	UVH Flannel with Vinyl Window	3.44	1.25	70.9	QC_F_M	4
8	UVH Flannel with Batting Roll	3.42	1.23	70.7	QC_F_M	4
9	UVH Cotton Batting	3.13	0.53	68.1	QC_CB_M	5
10	Taber 2X Toolbox Insert	3.13	0.63	68.0	QC_TBI_TBI	3
11	UVH Flannel 1X Filti Insert	3.09	1.11	67.7	QC_F_Fi_M	4
12	UVH 2X Flannel	3.06	0.46	67.4	QC_F_F_M	3
13	KN95	3.00	1.61	66.7	N/A	5
14	UVH Filti	2.96	0.50	66.2	QC_Fi_M	5
15	UVH Flannel with Outer Brace	2.90	0.42	65.5	QC_F_M	4
16	UVH + Surgical Double Mask	2.90	1.01	65.5	QC_QC_Surg	4
17	Surgical	2.88	0.89	65.3	N/A	5

The top performing masks in this study are shown in Table 2. Many of the top ranking homemade masks were designed with commonly used materials (flannel, polyester-cotton blend, cotton batting), filter inserts (toolbox insert), and design modifications (batting roll). The N95 fit factors presented here are well below the minimum fit factor pass level of 100, as stated in 29 CFR 1910.134 Appendix A.C.3, which may be associated with the participants not having access to professional OSHA-certified respirator fit testing. However, members of the general public often do not have access to professional fit testing as well, so the N95 results listed in Table 2 may be reflective of the efficiency that an average person wearing an N95 mask during day to day activities may expect. Across all masks, P1, P2, P3, P4, and P5 had an average percent difference from the average OFF of all participants of +5.2, -7.8, -13.1, +12.2, and -3.8%, respectively.

4.2 Pressure Drop

Three different QC materials were used during mask construction due to the difficulty of obtaining identical materials during the beginning of the 2020 pandemic, but were chosen from the same brand. Comparisons of the pressure drop relative to face velocity of material combinations with different QC materials are shown in Figure S4. Relative to typical ranges in pressure drops for other material combinations, the pressure drop curves for material combinations with different QC materials are fairly similar. For this reason, the results of identical masks with different QC types are grouped together for analysis purposes.

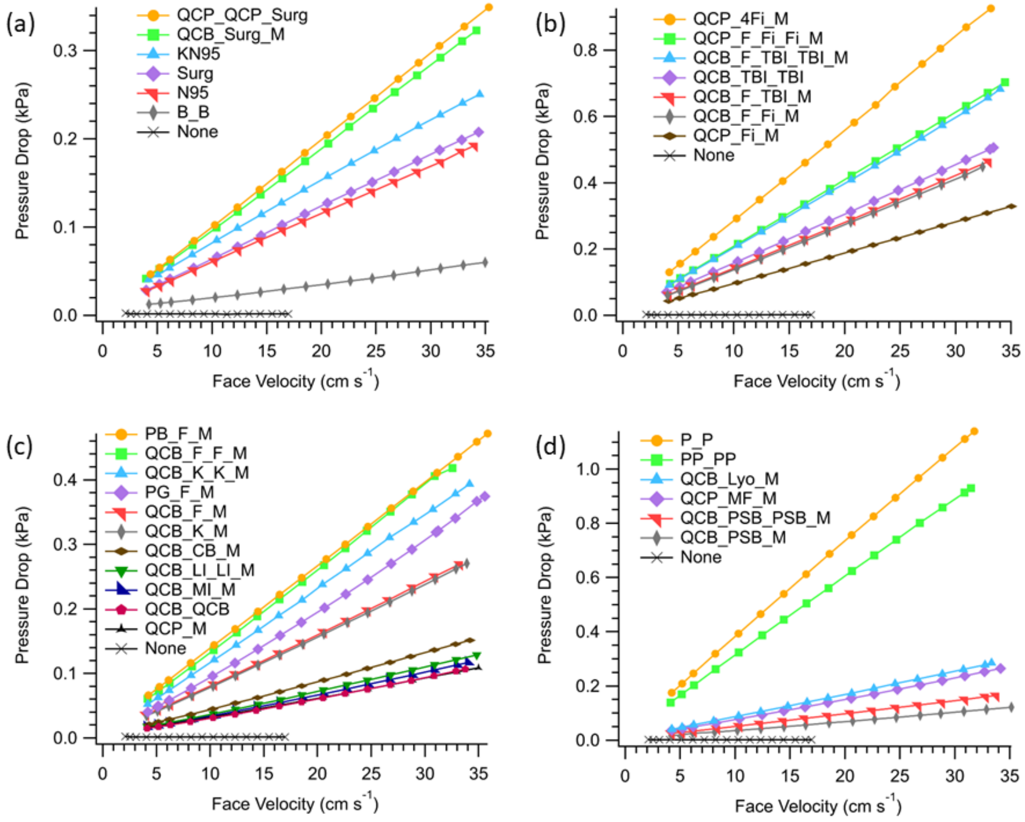

Figure 7. Pressure drops through all tested material combinations across a range of face velocities for (a) commercial materials, (b) insert materials, (c) common materials, and (d) miscellaneous materials. For instances where a given mask material combination was tested with both QCB and QCP quilt cotton materials, the pressure drop of the QCB material combination was plotted here. The "None" baseline is the measured pressure drop of the testing system when no material was inserted and has a slope of -4.34E-06 and an average value of 1.58E-03 +/- 0.23E-03 kPa.

As expected, with increasing face velocity, the measured pressure drops increased, meaning that the material becomes less breathable as the individual breathes at a higher flow rate (Figure 7). For each material combination, pressure differentials were measured at approximately the following flow rates: 10, 12.5, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, and 75 L min^{-1}, corresponding to face velocities ranging from 4 to approximately 35 cm s^{-1}. Pressure drops were measured at each flow rate for a minimum of 60 seconds before moving onto the next flow rate. R-squared values of the pressure drop curves in Figure 7 are above 0.997 for all material combinations. The slopes of linear fits of the data for each of the 30 tested material combinations are listed in Table 3.

Table 3. Slopes (kPa·s cm^{-1}) of the pressure drop versus face velocity curves for each of the following 30 material combinations. The materials are ordered from most breathable on top to least breathable on bottom.

Material Combination	Slope (kPa·s cm^{-1})
B_B	1.55E-03
QCP_M	3.02E-03
QCB_QCB	3.12E-03
QCB_PSB_M	3.36E-03
QCB_MI_M	3.37E-03
QCB_LI_LI_M	3.63E-03
QCB_CB_M	4.36E-03
QCB_PSB_PSB_M	4.73E-03
N95	5.47E-03
Surg	5.92E-03
KN95	6.99E-03
QCP_MF_M	7.61E-03
QCB_K_M	7.92E-03
QCB_F_M	8.00E-03
QCB_Lyo_M	8.35E-03
QCP_Fi_M	9.26E-03
QCB_Surg_M	9.36E-03
QCP_QCP_Surg	9.82E-03
PG_F_M	1.06E-02
QCB_K_K_M	1.15E-02
QCB_F_F_M	1.28E-02
PB_F_M	1.28E-02
QCB_F_Fi_M	1.36E-02
QCB_F_TBI_M	1.39E-02
QCB_TBI_TBI	1.48E-02
QCB_F_TBI_TBI_M	1.97E-02
QCP_F_Fi_Fi_M	2.02E-02
QCP_4Fi_M	2.76E-02
PP_PP	2.89E-02
P_P	3.51E-02

Pressure drop curves are shown for 6 commercial mask material combinations (Figure 7a), 7 insert mask material combinations (Figure 7b), 11 common mask material combinations (Figure 7c), and 6 miscellaneous mask material combinations (Figure 7d). The commercial mask materials in Figure

7a include combinations used for double masking (QCP_QCP_Surg), embedded masks (QCB_Surg_M), bandanas, surgical masks, and disposable respirators. The insert mask material combinations in Figure 7b consist of different numbers of layers of Filti and Toolbox wipe insert materials in a homemade mask, with or without a flannel layer. The common mask materials in Figure 7c are materials regularly used for crafting or sewing purposes, including polyester, flannel, knit, interfacing, and cotton batting materials. The miscellaneous materials in Figure 7d represent combinations with materials found around the home such as different thread count sheets, Lyocell used for clothing, microfiber towels, and polyester reusable shopping bags.

Due to the influence of breathability, adding more layers does not necessarily increase filtration efficiency. For example, if a mask is difficult to breathe through, particles will be more likely to enter through gaps along the edges. Thus, based on these results, the usage of P_P or PP_PP material combinations are not recommended because of their poor breathability. The materials used in the double mask are slightly less breathable than a surgical mask embedded in a homemade mask. Interestingly, the polyester shopping bag material is quite breathable.

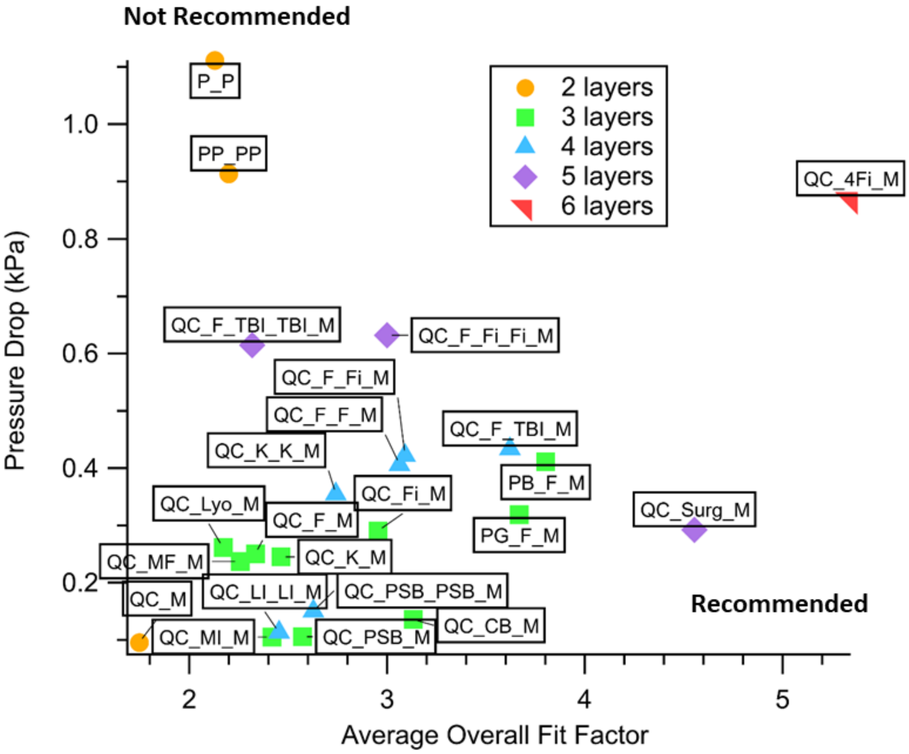

Figure 8. Scatterplot of the average OFF versus pressure drop for all material combinations. The pressure drops plotted here are for a face velocity of 30.9 ± 0.1cm s^{-1}, which is at the upper range of face velocities through masks worn by people. The material combination of each point is included and the number of layers is indicated by the marker type. The average OFF values for these material combinations are for the UVH mask design with 12/10" head elastics and a 4" Al nose wire.

Although the average OFF values generally increased with more layers, the 6-layered QC_4Fi_M mask had a pressure drop that was considerably higher than all but the percale masks, which would reduce the comfort and ease of breathing for the wearer. Adding one layer of cotton batting material inside of a UVH mask provided a good balance of the fit factor and breathability, ranking #9 of all of the masks tested in this study. We recommend using 3-4 material layers with the exception of the QC_Surg_M 5-layer material combination that has a much lower pressure drop than the same number of layers of typical homemade mask materials.

5. Conclusions

The performance of homemade masks can depend on many factors such as the fit, material filtration efficiency, and breathability. In this study, mask design features and material combinations were evaluated by conducting standardized quantitative fit testing for a total of 187 masks and 5 human participants. The fit factor results are representative of the particle filtration efficiency of in-use masks because the measurements reflect the combined influences of fit, filtration efficiency of the material, and pressure drop through the mask. The face velocity-dependent breathability of the tested material combinations was also evaluated. This research is primarily focused on the protection that masks can provide the wearer from inhalation of airborne infectious viral particles.

To protect the wearer from airborne transmission, it is imperative that individuals select a mask that fits them well and creates a good seal around their face to prevent particles from leaking in along the sides. In this study, certain mask design features were demonstrated to provide a better fit and consequently provide greater protection for the participants. Although the five participants in this study may not be representative of every possible face shape or size, it is an improvement relative to the sample sizes in the available published literature on fit testing of homemade masks. We have seen sufficient evidence of the range in performance of the tested masks on the participants to be confident that the conclusions from this study would apply to a larger population. Size-dependent particle transport and removal mechanisms such as diffusion, impaction, and interception define the likelihood that a particle of a given size will pass through or around a mask, or will be filtered. The fit factors presented here likely differ from those that would be obtained had the particle size distribution in the room air matched that expected for virus-containing particles. However, those differences would impact the efficiency of all of the masks in a similar way, such that the relative performance of the different mask configurations and materials would be similar to that reported here.

Several homemade masks were identified to have OFF values comparable to or higher than those of commercial masks. Of those, masks with the UVH design, batting roll with Al nose wire, and head elastics were shown to result in the highest average OFF values. Although not specifically tested, the 4” Al nose wire and the batting roll may also minimize fogging of one’s eyeglasses. Sewing surgical mask materials into a homemade 2-layer cotton mask was shown to noticeably improve the average OFF for all participants, whereas wearing a 2-layer cotton mask over a surgical mask did not markedly improve performance over a surgical mask alone. Material combinations that had both high breathability and high OFF include QC_CB_M, QC_Surg_M, PB_F_M, and PG_F_M. Simple and effective ways to improve one’s mask without making a new one include adding an outer brace, an insert material, or a cotton batting roll for nose padding. These findings can be used to improve already-existing face masks and to develop improved design configurations and material combinations to achieve greater effectiveness, comfort, and versatility. These results suggest that there are multiple homemade mask options that have the potential to provide just as much protection from the spread of infectious respiratory diseases as commercially available options. Further investigations should be conducted in order to continue to improve the performance of homemade masks against pathogen transmission, especially to consider the particle size dependence of FFs.

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Supplementary

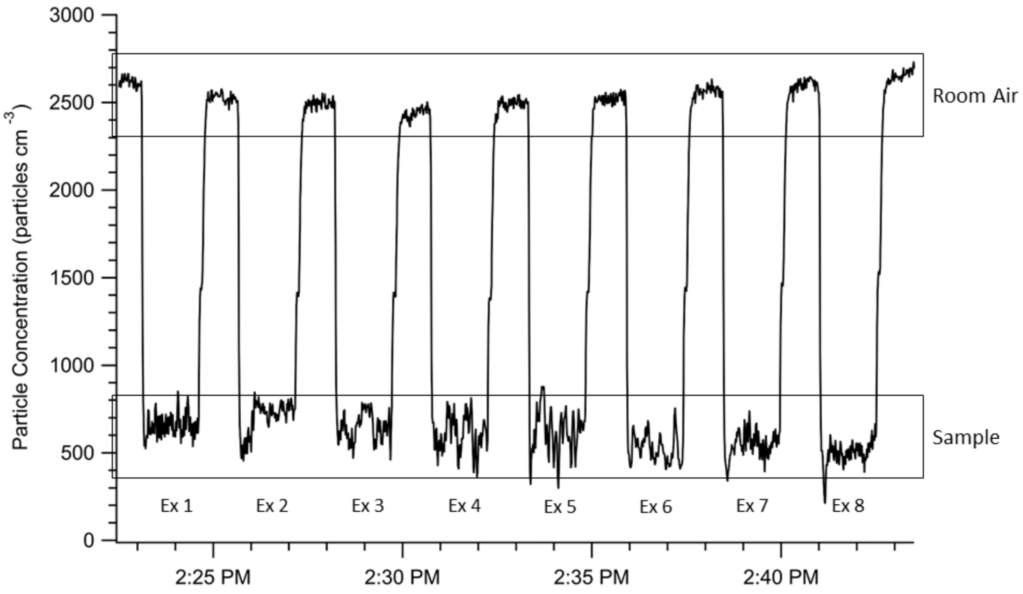

Figure S1. Particle concentration measured during an example fit testing exercise cycle. The CPC alternates between measuring room air and sample air from behind the mask for exercises 1 to 8. The variability in room air particle concentration during this test session is comparable to that observed during other tests.

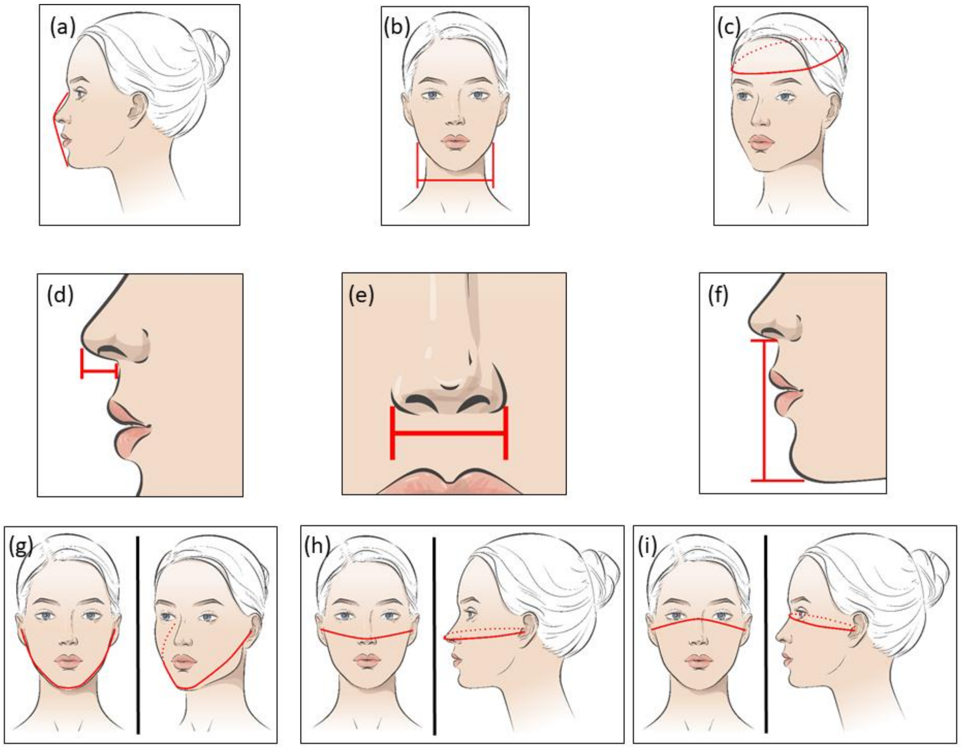

Figure S2. The locations of the following facial measurements are shown in this figure: (a) face height, (b) jaw width, (c) head circumference, (d) nose length, (e) nose width, (f) distance from nose to chin, (g) ear-chin length, (h) ear-bridge length, and (i) ear-nose length. Modified and used by licensed permission of Freepik Company, S.L, from Nicelook - Freepik.com (2021).

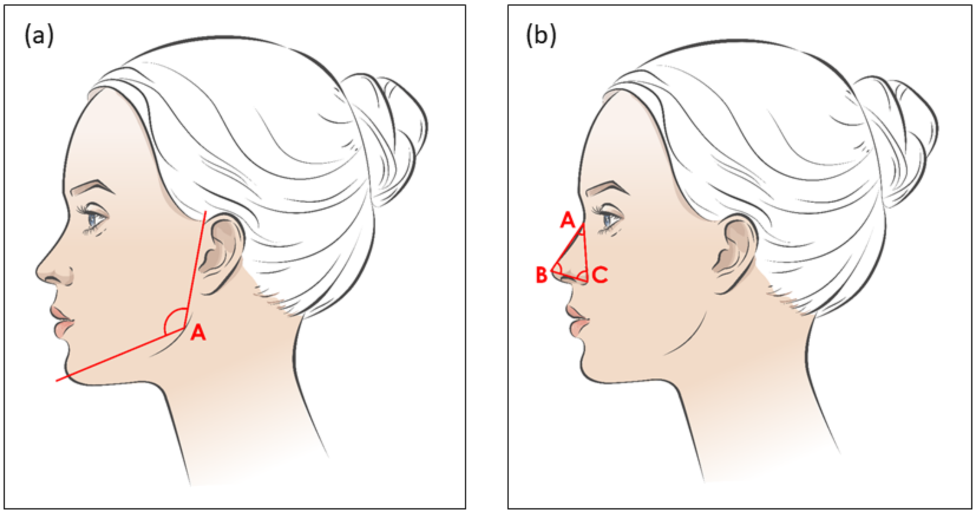

Figure S3. The location of (a) jaw and (b) nose angle facial measurements extracted from profile pictures of participants in this study. The nose angle A is commonly referred to as the nasofacial angle. Modified and used by licensed permission of Freepik Company, S.L, from Nicelook - Freepik.com (2021).

Table S1. Average overall fit factors for different UVH mask sizes. The masks were constructed with QCW_QCW materials, 7" ears, and 4" Al wire.

UVH Average OFF	P1	P2	P3	P4	P5
Small			1.83	1.99	1.83
Medium	2.59	1.85	1.82	2.10	
Large	2.18	2.04			

Participants 1-4 selected 2 sizes of UVH masks for basic mask tests, from Small, Medium, and Large (S, M, L) sizes, and for Participants 2-4 the best performing mask size was chosen for tests with variations on materials (L, M, M respectively). Participant 2 was later switched to the M size mask when stiffer mask combinations suggested that the M size was more appropriate to their face. Although Participant 1 tested better on the initial M size mask, L was used for all subsequent testing due to their larger face size, and Participant 5 tested only size S due to having a smaller face size.

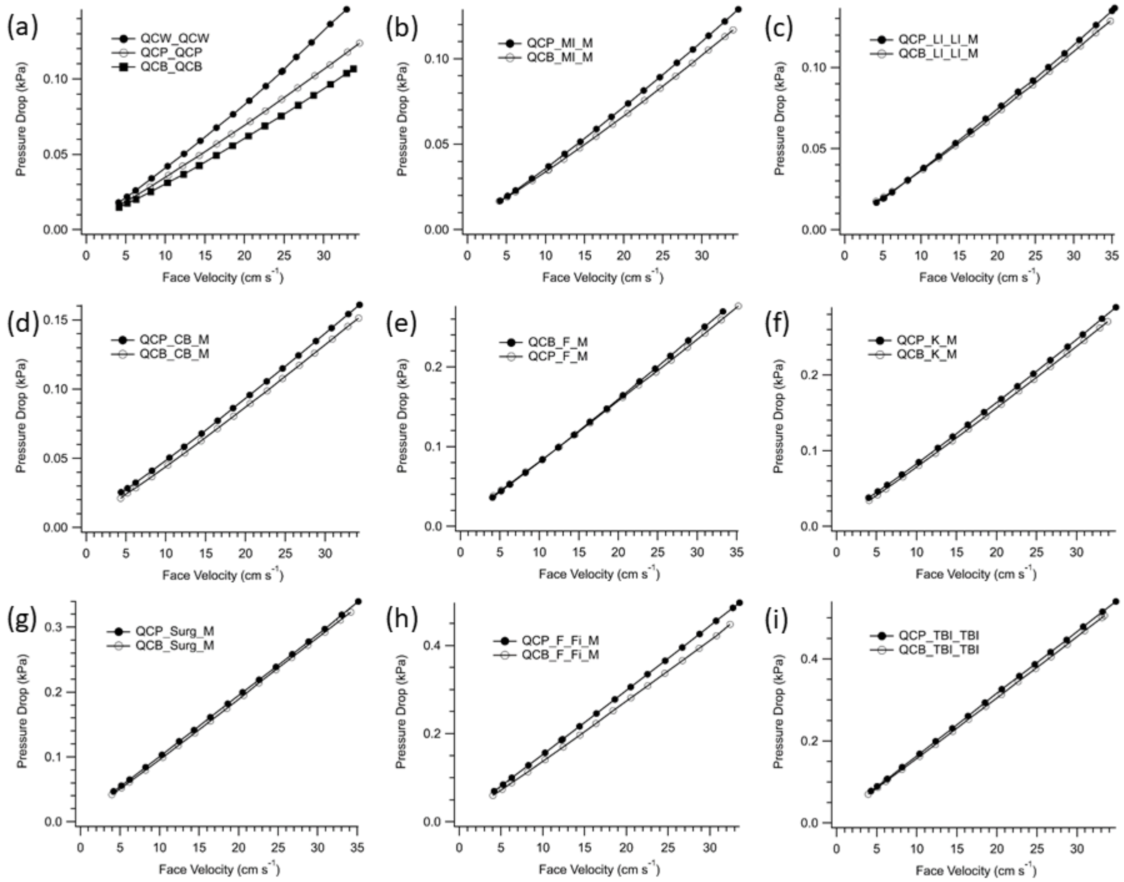

Figure S4. Comparison of pressure drop curves for material combinations that have different quilt cotton materials. Almost all of the material combinations with QCP have a slightly higher pressure drop as opposed to those with QCB, which indicates that material combinations with QCB are more breathable. However, there is not a noticeable trend of higher fit factors for masks with QCB material combinations, so it is assumed that the pressure drop difference is negligible.

Table S2: Fit test exercise descriptions (From OSHA Respiratory Protection Standard 29 CFR 1910.134 and the PortaCountPro manual).

Exercise Name	Description
1. Normal breathing	Remain still and breathe as usual.
2. Deep breathing	Take long deep breaths as if working hard. Do ***not*** overdo it.
3. Head side to side	Breathe normally while slowly turning the head from side to side. Turn far enough to each side to stretch the neck muscles. Each cycle from left to right should take several seconds, pausing momentarily at each side to take a breath.
4. Head up and down	Breathe normally while slowly alternating between looking up at the ceiling and down at the floor. Each up and down cycle should take several seconds.
5. Talking out loud	Read a prepared paragraph or count out loud to simulate the workplace.
6. Grimace	Grimace by smiling and/or frowning to create a leak in the respirator face seal. This exercise will often result in a failed fit factor, which is why the OSHA standard allows you to exclude that fit factor when computing the overall fit factor. When performing the grimace, you are intentionally creating a break in the face seal in order to see if the mask reseals itself afterwards. Successful re-sealing is proven by achieving a passing fit factor on the next exercise. ***Notes:*** *The OSHA protocol includes special provisions for the grimace exercise. It is allowed to be 15 seconds long and the resulting fit factor may be discarded (excluded) before calculating the overall fit factor. This is allowed because the grimace exercise is done to intentionally break the face seal in order to make sure the mask reseals itself before the next exercise.*
7. Bend and touch toes	Bend at the waist as if you were touching your toes while breathing normally.
8. Normal breathing	Remain still and breathe as usual.

S1. Mask Construction Specifications

Due to the scarcity of certain materials in March - May 2020, there were limitations in what materials could be purchased for testing, and cotton knit in particular was nearly impossible to find due to the CDC recommending cotton knit be used in face masks as a filtration layer. However, a large donation from an anonymous individual was secured, and the cotton knit was confirmed to not be a synthetic blend by a flame test. For quilting cotton, entire bolts were purchased. However, when those ran out, equivalent bolts from the same brand and fabric type were purchased to continue the experiments. Elastic was 6 mm (¼”), and ties were made from 5 cm (2”) wide strips of fabric folded and pressed to 1.25 cm (½”) width. “Stiff” nose wires were made from 11-gauge aluminum electric fence wire, and “soft” nose wires were obtained from disposable surgical masks that were cut up for testing and used inside of some masks.

S2. Clarification of Methods and Data Analysis

An automated valve with an on/off switch controlled by the participants alternated between sampling room air and air from behind the mask for preset amounts of time (60 seconds room air, 90 seconds behind the mask). A sampling delay in the tubing was assumed, for data analysis purposes, to be 5 seconds when starting a new exercise and 12 seconds when switching to measure room air. Tubing lengths were approximately the same for both behind the mask and room air sampling pathways, therefore the particle losses in the tubing were assumed to be equivalent for both pathways. The time difference between the CPC and the clock used to record the times of each measurement was routinely monitored and accounted for in data analyses because the two clocks were found to gradually drift apart over time. Although the ambient room particle concentrations were found to change throughout the testing sessions, the change was slow and not significant enough to influence the interpretation of the measurements.

A minimum of 6 exercises with data in a cycle was required in order for the cycle to be included in data analysis (for OFF with the grimace included).

$$\%\,particles\ filtered\ =\ 1\ -\ \frac{1}{Overall\ Fit\ Factor} \tag{S1}$$

$$Overall\ Fit\ Factor\ =\ \frac{n(\#\ exercises)}{\frac{1}{FF_1}+\frac{1}{FF_2}+\frac{1}{FF_3}+\ldots+\frac{1}{FF_{n-1}}+\frac{1}{FF_n}} \tag{S2}$$

Equation to calculate face velocity given flow rate and material area:

$$Face\ Velocity\ \left(\frac{cm}{s}\right)\ =\ \frac{L}{min}\cdot\frac{1000\ cm^3}{L}\cdot\frac{min}{60\ s}\cdot\frac{1}{area\ cm^2} \tag{S3}$$