Designing a Wearable Air Filtration Device to Block Coronavirus Transmission

By

Tyler Clark, Undergraduate Department of Biomedical Engineering
Gwanwoog Kim, Undergraduate Department of Biomedical Engineering
Kelly Waring, Undergraduate Department of Biomedical Engineering
Alexander Klibanov, Division of Cardiovascular Medicine, Biomedical Engineering

Word Count: 4,740
Number of Figures: 6
Number of Tables: 2
Number of Equations: 2
Number of Supplements: 3
Number of References: 23

Designing a Wearable Air Filtration Device to Block Coronavirus Transmission

Tyler Clark[a,1], Gwanwoog Kim[a,2], Kelly Waring[a,3], Alexander Klibanov[b], PhD

[a] Fourth Year Biomedical Engineering at the University of Virginia
[b] Division of Cardiovascular Medicine and Biomedical Engineering at the University of Virginia
[1] tc5vt@virginia.edu
[2] gk4zd@virginia.edu
[3] kw2eh@virginia.edu

Abstract

The Coronavirus Disease 2019, COVID-19, pandemic has had significant impacts on all aspects of our lives throughout the world. It primarily spreads through the air via respiratory droplets exhaled from an infected person. As a result, face masks have been utilized successively by all people in order to mitigate the spread of COVID-19. However, there are several limitations to current face mask designs, such as poor filtration and lack of comfortability. Therefore, our team set out to tackle limitations of current face masks by designing and building an affordable wearable air filtration system that offers superior filtration and comfortability. Preliminary research included testing of weights on our head to determine a level comfortable enough to not damage the user's head and neck. We also examined various fan-filter configurations by performing airflow testing to find the most optimal design that provides sufficient airflow and cooling effect for users. A comfortability survey to validate the overall comfortability of our apparatus compared to current face masks was also conducted. Lastly, a smoke test was used to validate the overall filtration efficiency of our four prototypes. The results of our tests indicate that our device provides superior comfortability and filtration compared to current face mask designs out today. This is important because it has far-reaching implications, such as high adoption of our device and increased user compliance, which can help to lower COVID-19 cases and deaths. To design our final prototype, the main components that we used were a baseball cap, an Aurora HEPA filter, two axial fans in series, a piece of cloth, a face shield, and a battery pack.

Keywords: COVID-19, face masks, wearable air filtration device, HEPA filter

Introduction

Coronavirus Disease 2019, also known as COVID-19, is an infectious disease that started in late 2019.[1] As of right now, there are about 150 million cases and over 3 million deaths worldwide from this virus, thus making it a global pandemic.[2] COVID-19 is caused by the virus, severe acute respiratory coronavirus 2 (SARS-CoV-2), where it primarily attacks the lungs and respiratory tract.[3] It does this by hijacking the healthy cells through the ACE2 receptors and can lead to symptoms such as fever, cough, shortness of breath, fatigue, chills, nausea, body aches, and loss of taste and smell.[4] It spreads from person to person through respiratory droplets when the infected person coughs, sneezes, talks, or touches their face and eyes. These droplets typically cannot travel more than six feet and remain in the air for a short period of time. However, the SARS-CoV-2 particles remain intact and contagious in droplets for up to three hours.[5] Because of this, face masks have been widely adopted to block the virus particles from entering the body through the mouth and nose.

Some of the most common face masks used today include cloth masks, surgical masks, and N95 masks as shown in Figure 1.[6] Cloth masks can be made from cotton, polyester, and even silk.[7] These masks are intended to trap droplets that are released when the user coughs, sneezes, or talks.[6] Surgical masks are loose-fitting, disposable, and also

Figure 1: Current face masks used by the public to reduce COVID-19 transmissions and their associated filtration efficiency.[6]

protect the users from droplets. They filter out large particles in the air and reduce exposure to saliva.[6] N95 masks are a type of respirator that offers the most protection because it can filter small and large particles when the user inhales. It is designed to block 95% of unwanted particles.[8]

Although these face masks have been shown to help slow the spread of COVID-19, there are many limitations with the current face mask designs. The two main limitations are poor particle filtration and lack of comfortability. Cloth and surgical face masks both lack a tight seal to the face, which gives access for small virus particles to reach the nose and mouth. A surgical mask can only filter 60% of 0.3 micron particles.[9] Some cloth masks, such as ones made of 100% cotton with a 60 thread count only filter about 10%.[10] N95 masks are defined as a tight-fitting respirator that can only filter 95% of particles if the user wears it properly with no facial hair. The efficacy of filtration is significantly reduced when a tight seal cannot be formed with the user's face due to the presence of facial hair.[11] Another limitation with all these face masks is the lack of eye protection. Because of this, the eyes lack proper protection which can lead to the transmission of the virus through airborne particles or even touching the eyes with contaminated hands.[12] Other than the lack of effective filtration and spread of the virus, these face masks also are very uncomfortable to wear. The constant covering of the mouth and nose makes it difficult to breathe, promotes skin irritation, and can even lead to overheating. Many people have also complained about their glasses fogging up due to all the moisture from breathing through a mask.[13] From all these reasons, many people wear their masks incorrectly, such as not covering their nose.

Some people have tried to develop new designs that provide better filtration, such as the powered air-purifying particulate respirator used to combat smoke particles for firefighters as shown in Supplementary Figure 1.[14] However, these designs are still bulky, uncomfortable, and expensive. Because of this, there is a critical need for an innovative device that not only provides better filtration, but also is comfortable for users at a low cost.

In order to overcome these limitations of the current designs and face masks, we developed three aims to follow through our process. The first aim is to design and build a wearable air filtration system. This consists of constructing a working prototype that uses various easy and accessible components. Some of the components we implemented in our design include: a baseball cap for its comfort and casual appearance, a face shield for eye protection and a way to block virus particles without touching the face, cooling fans to provide a constant airflow in front of the face for a cooling effect, a High Efficiency Particulate Air (HEPA) filter with 99.97% filtration efficiency to make sure the air entering is clean and filtered, a battery to power the fans, and lastly a bandana or piece of cloth to limit the virus from spreading. The second aim is to validate the device's comfortability and its air filtration system functionality. This includes comfortability testing to ensure our device has more comfort than cloth and N95 masks. Also, it consists of making sure the filtered air for the user to inhale is up to standards in regards to filtration efficiency. This includes a filtration test using smoke particles to ensure our device can filter out particles that have a similar size to COVID-19 particles. The last aim is to make our device accessible and share it to the world. We plan to post our design and instructions on how to construct it under Reddit channels.

Overall, our goal is to develop a wearable air filtration system that effectively blocks COVID-19 transmission while also providing superior comfort at a low cost. The following paper will discuss our process throughout the making of our device, as well as the results we have achieved from the experimentation.

Preliminary Research

Weight of Device Should be Limited to Less Than 0.6 Pounds

Prior to constructing the actual prototype, we needed to determine the constraint for the weight of the device. Therefore, a comfortability rating of 1 to 5 was given by each team member for each amount of weight placed on the top of the hat being worn. Real-world objects with equal weights of 0.2, 0.4, 0.6, 0.8, and 1 pound were utilized in the test. The ratings were averaged for each weight level and plotted on a graph. As shown in Figure 2, a linear relationship was determined with the x-axis being the rating and the y-axis being the weight.

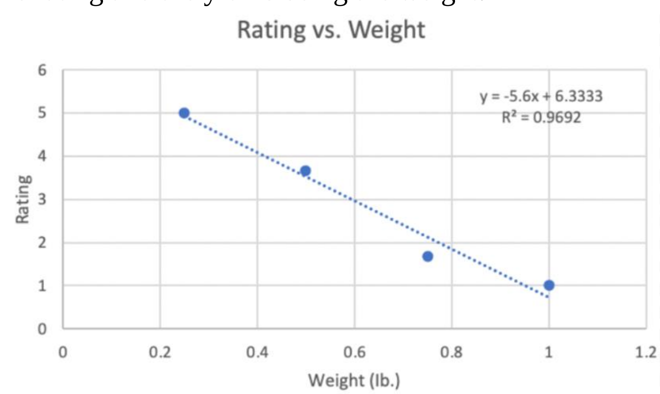


Figure 2: Graph showing the relationship between users' subjective discomfort and different weights. A line of best fit was performed to determine a linear relationship between user ratings and the weight on top of the brim of the hat. The R^2 value is 0.9692.

The equation of the line was determined to be:

$$y = -5.6x + 6.3333 \quad (1)$$

where x is the weight in pounds and y is the rating. In order to achieve a rating of 3, which is neutral comfortability, or better, it was determined from Equation 1 that the weight of the device should be limited to 0.6 pounds or less.

Results

Fan/Filter Configuration is Important for Optimal Airflow Rate

Different fan/filter configurations were tested with each team member due to circumstances revolving around the COVID-19 pandemic. This test was conducted in order to determine the best airflow rate that could be achieved with a set of fans and filters in various configurations. As illustrated in Table 1, for Setup A, the fan/filter assembly with the largest airflow rate was one 50 mm centrifugal fan mounted on the bottom of the Kenmore HEPA Filter, which was 77.22 L/min. For Setup B, the largest airflow rate configuration was two 60 mm axial fans in series mounted on top of the Aurora HEPA filter, which was 67.43 L/min. For Setup C, the largest airflow rate configuration was two 40 mm axial fans in series mounted on top of the Aurora HEPA filter, which was 41.63 L/min. For Setup D, the largest airflow rate configuration was one 50 mm centrifugal fan on bottom of the 3M 2091 HEPA filter, which was 70.85 L/min.

Table 1: Varying configurations of the Fan/Filter assemblies depending on the setup. Centrifugal represents a blower-type fan while axial represents a rotating fan. The configuration that yielded the maximal airflow rate is given for each setup.

Setups	Number of Fan	Type of Fan	Parallel/ Series	Type of Filter	Maximum Airflow (L/min)
Setup A	1	50 mm Centrifugal	N/A	Kenmore HEPA	**77.22**
Setup B	2	60 mm Axial	Series	Aurora HEPA	**67.43**
Setup C	2	40 mm Axial	Series	Aurora HEPA	**41.63**
Setup D	1	50 mm Centrifugal	N/A	3M 2091 HEPA	**70.85**

These results show that the increased power of the centrifugal fan (Setups A and D) led to a higher airflow rate compared to the axial fans, which use less power. In addition, the centrifugal fan had a large static pressure, which also contributes to its high airflow rate. Higher static pressure means more force exerted by the fans to overcome the filter's resistance. Setups B and C each had axial fans with low static pressures. To overcome this, the fans were put in series to accommodate the pressure drop, which resulted in airflow rates that exceeded the average human inhalation rate during walking of 41 L/min.[15] The parallel configuration of the axial fans did not perform as high as the series assembly due to their low static pressure.

Our Device Provides More Comfortability to Users Compared to Current Mask Designs

Each team member and their family and friends conducted comfortability testing with our device as well as current mask designs, such as cloth and N95 masks. The results of the survey forms filled out by the participants suggested that in terms of the overall comfortability, breathability, and cooling effect, our device performed better in these areas as shown in Figure 3. In terms of bulkiness and weight, the N95 and cloth masks performed better in these areas. The cloth mask had the highest score for the bulkiness component at 4, N95 mask at 3, and our device at 2. The cloth and N95 masks had the weight component rated at 4 while our device was rated at 3. This is expected given that the N95 and cloth masks only involve a very light material that covers the nose and face whereas our device involves a hat, fan/filter, face shield, and cloth that weigh more together and cover the whole head. That being said, our device performs better in the breathability and cooling effect aspects of comfortability. Our device had the cooling effect rated at 5 while the N95 and cloth masks were rated at 1. Also, our device had the breathability component rated at a 5, the N95 mask at a 3, and the cloth mask at a 2. This is because our device constantly provides a stream of air to the user to breathe in. This allows users to breathe in air more easily compared to N95 and cloth masks, especially in hot weather. Because our device excels in the breathability and cooling effect aspects of the

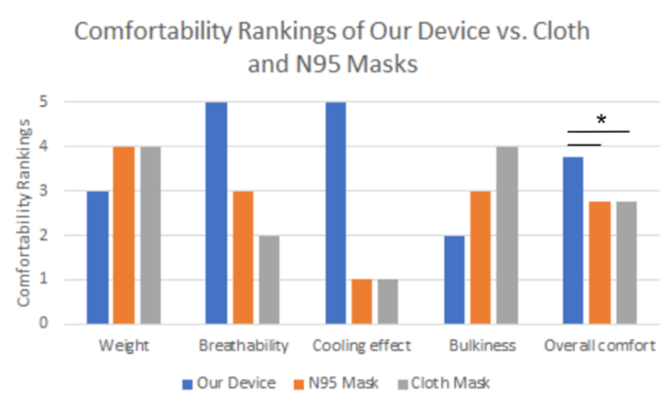


Figure 3: Bar graph representing the results from the comfortability survey. Overall comfort is based on the averages from the other comfortability factors. * denotes significance with p value < 0.05 between our device and a current mask design.

comfortability testing, it makes up for the deficiencies in weight and bulkiness, leading to an overall higher comfortability rating at a 3.75, compared to the score of 2.75 for both the N95 and cloth mask. In order to determine significance, we conducted a one-way ANOVA statistical test between our device, N95 mask, and the cloth mask with the independent variable being overall comfort. We had a sample size of 8. Based on the statistical testing, it was determined that our device had significantly higher comfortability compared to the N95 and cloth masks with a p-value of less than 0.05. Furthermore, the comfortability survey included a section for users to mention any additional comments that they had regarding our device, N95 mask, or cloth mask. Three people, who utilized glasses, mentioned that the N95 and cloth masks fogged their glasses, reducing their vision significantly. This can be discomforting as well as unsafe for people because they cannot see their surroundings effectively.

Wearable Air Filtration System is Able to Filter COVID-19 Droplets

Testing of the filtration functionality of our device through a smoke test illustrated whether our device is effective at blocking coronavirus transmission. The control test, which involved having the smoke detector only with a presence of a steady stream of smoke particles, resulted in the smoke detector going off in all 5/5 trials with all four models, A, B, C, and D. The experimental test, which involved placing the smoke detector in the protected volume of the device in the presence of a steady stream of smoke particles, resulted in the smoke detector going off in 0/5 trials for models A, B, and D and only 1/5 trials for Model C as shown in Table 2. The HEPA filter is able to filter out the smoke particles, causing the smoke detector to not go off. An explanation as to why Model C had the smoke detector go off in one of the five trials could be due to a possible leak in the apparatus where smoke got inside of the device. The results from this test illustrate how our device is able to block the smoke particles from entering the protected volume, which is where the user breathes in air. Because the smoke particles are similarly sized compared to COVID-19 aerosol particles and droplets, we can reasonably conclude that our device is able to block COVID-19 transmission for users. In addition, the cloth at the bottom of the face shield is also able to prevent smoke particles from entering the protected volume, suggesting that even if the user were to be infected with COVID-19, our device would prevent COVID-19 from spreading to other people who are not wearing our device.

Table 2: Results of Smoke Test with Different Models. Control represents the smoke detector only. Experimental represents our device with smoke detector inside protected volume

Model	Control (# of times smoke detector goes off)	Experimental (# of times smoke detector goes off)
A	5/5	0/5
B	5/5	0/5
C	5/5	1/5
D	5/5	0/5

Discussion

Optimizing Weight

One of our first tests included preliminary research to determine what the optimal total weight of our device should be based on comfortability rankings. A weight constraint on our device is important because it is crucial for the user's head to not be exerted with too much force. This may damage the head and neck region, causing our device to do more harm than good. In addition, people do not like to wear objects on their head that are heavy and uncomfortable. Therefore, we determined that based on the results of the test, our design choices would be made so that the device does not exceed 0.6 pounds, or a neutral comfortability rating of 3. An example of one of our design choices that take this into account is the face shield thickness. We utilized 0.3 mm for thickness even though there was a 0.5 mm option that was stronger. However, we believed that the increased weight would decrease comfortability. In addition, the increased weight of the face shield at the front of the hat would cause the hat to slip off. Optimizing the weight of the device has several implications, such as user compliance with our device as well as ensuring user safety by reducing risk of any unintended harm.

Airflow Testing

Based on the results from the airflow testing, we can conclude that Setup A produced the most airflow with a configuration of one centrifugal fan mounted on the bottom of the Kenmore HEPA. This is due to the fact that centrifugal fans have more power and higher static pressures. Setups B, C, and D also produced adequate airflow. These results were critical in our design process because it validated that all of our models provided sufficient airflow for users based on the human inhalation rate, which is about 41 L/min at a brisk walk.[15] Also, sufficient airflow can keep the face shield from fogging up and can reduce heat buildup. Providing sufficient airflow is crucial because certain agents like the National Institute for Occupational Safety and Health (NIOSH) require powered air-purifying systems like ours to supply adequate, fresh filtered air for the user to breathe in.[16] However, with this experimental testing, the centrifugal fans (Setups A and D) had drawbacks to producing more airflow, such as more noise or bulkiness on top of the hat. Also, the centrifugal fans required extra steps of constructing an air diverter to channel the filtered air through the brim of the hat. Therefore, for our selection of the fan/filter configuration for the final prototype, we chose the two 60 mm axial fans connected in series mounted on the bottom of the Aurora HEPA filter (Setup B) because this setup provided sufficient airflow while being one of the lightest and quietest configurations. It also was easy to construct while being less bulky than the other models. Overall, selecting the best fan-filter configuration that not only provides adequate airflow, but also falls in line with our other parameters of weight and comfort, allows for high user compliance, which subsequently helps to reduce COVID-19 transmission.

Comfortability Testing

Based on the results from the comfortability test, we can conclude that our wearable air filtration system is significantly more comfortable than some of the current face masks out today, such as cloth and N95 masks. These results were important in our design process because it validates that our device provides superior comfort as stated in our second aim. The different factors we looked at with regards to comfortability included weight, breathability, cooling effect, and bulkiness. We chose breathability and cooling effect because they are both limitations of current face masks out today. Also, we chose weight and bulkiness to ensure users adopt our device. Comfortability plays a critical role in face mask designs because it aids in user compliance. The more comfortable the face mask is, the more likely people are willing to wear it correctly when necessary. This is crucial, especially during a global pandemic, because everyone needs to comply with wearing a mask in public in order to protect themselves and the people around them. Another important aspect to consider with the comfortability in our design is the user's approval. If many people like our device because of its comfort, as well as its filtration capabilities, this could lead to a cascading effect of more people wearing our device, which in turn may cause an increase of mask-wearing in public. The overall effects of increased user compliance in wearing face masks and coverings include slowing down the spread of COVID-19, which is one of our main goals of this project. By reducing the number of COVID-19 cases, this leads to lower hospitalizations and fewer mortalities.

Filtration Testing

Based on our results of the filtration test, we were able to prove that our wearable air filtration system is able to provide superior filtration that is effective at blocking coronavirus transmission. These results have several implications. For one, it is necessary to ensure that our device is effective at blocking COVID-19 so that we ensure user safety. By supporting the conclusion that our device can stop COVID-19 transmission with data, we also increase adoption of our device by the public as well as user compliance. This has far-reaching consequences. When more people utilize our device in crowded areas, such as shopping malls, offices, grocery stores, etc., COVID-19 transmission is significantly reduced between people. This leads to less people getting infected, lower hospital admissions, which ensures hospitals are not overwhelmed, and a lower mortality rate. In addition, communities do not have to be locked down as much, improving the economy and the return back to "normal" life, which was pre-pandemic. The filtration data can also serve as preliminary testing data that can be utilized in future Food and Drug Administration (FDA) applications for medical device approval. This would allow usage in official settings, such as hospitals. Under FDA rules, our device would be categorized as Class II, similar to the N95 mask, which is currently used in hospitals and alike.

Variability in Design

Although most of the components of our device will be similar when built by other people using the do-it-yourself (DIY) steps and list of materials, we acknowledge that there may be some variability of certain components, such as the battery pack and/or the cloth that sits on the bottom of the face shield. Depending on their use scenarios, users should choose a battery pack that is larger or smaller if they plan on using the device for a long or short period of time per day, respectively. Furthermore, users should also potentially consider multiple battery packs so that they are able to continue to utilize the device in case a battery pack runs out. The cloth may also be variable as well. As illustrated in the different model prototypes built during this project, we utilized bandanas, old T-shirts, neck gaiters, and more. They are all capable of blocking the aerosol particles and droplets that are exhaled from the user.

Cost and Accessibility

Another major component of our design is affordability. All the materials we used, such as the baseball cap, cooling fans, HEPA filter, and face shield, were all chosen taking into account cost. The importance of low cost in our design allows for our device to be accessible to as many people across the world. At the beginning of the COVID-19 pandemic, personal protective equipment experienced a supply shortage, which led to the rationing of equipment and supplies for healthcare workers. Because of this, we wanted to develop a device that used widely available and low-cost components that could be easily ordered from online retailers.

Limitations

There were several limitations that our group encountered during this Capstone project. The main setback was the actual COVID-19 pandemic. We were restricted from working together and had to complete many components of the project while being isolated. Procuring the actual components also took much more time than expected due to logistical delays. The pandemic also limited the testing we could conduct on our device, since we were not allowed to use the University of Virginia's (UVA) laboratories, equipment, and resources. For example, we were unable to 3D print several parts to efficiently integrate our device's various components, such as the brim of the hat and the face shield. The project's initial goal was to mass manufacture the device, but we were unable to attain this due to no entity wanting to sponsor this idea, most likely due to COVID-19 circumstances and other financial limitations. Because of this, we opted into doing a DIY type design. Although our Reddit channel has been delayed due to COVID-19 circumstances, we are still planning to post our device and DIY instructions.

Materials and Methods

Materials Used in Prototype

For the construction of our prototypes, several components were obtained. Polycarbonate sheets ranging in thickness of 0.15 to 0.5 mm were purchased from Grainger because we could get large sheets for affordable prices. Thermoplastic material was selected based on literature reviews highlighting this material's ability to withstand heat, impact, chemicals, or other hazards while still providing optical clarity and reduced glare.[17] In addition, it is the most common plastic material used in the medical and motorcycle industries.[17,18] We chose a thickness of 0.3 mm because it provides stiffness and clarity without being too heavy. The baseball cap obtained from Amazon was the main support structure used to house and attach specific components to. It was chosen because it has a brim with a large surface area for the fan, filter, and face shield to be mounted on. The fans provide airflow for our system. We chose centrifugal and axial fans pictured in Supplementary Figure 2 obtained from Amazon because of their small dimensions, minimal noise, and low price, while still outputting a sufficient amount of airflow for the user to inhale. The filters, which were obtained from Amazon, are used to filter the incoming air into our system. We chose to use NIOSH certified or equivalent filters, as shown in Supplementary Figure 3, which were 3M 2091 P100, Kenmore HEPA filter, and Aurora HEPA filter because they provide superior air filtration to block coronavirus transmission. The 3M 2091 filter is denoted with a P100 rating, which means that this filter met NIOSH P100-series test criteria. The P means the filter is strongly resistant to oil (oil proof) and the 100 means the filter collected at least 99.97% (essentially 100%) of the challenge aerosol during the test.[19] We selected the Kenmore filter because it is certified by the Asthma & Allergy Friendly Certification Program (ASP), which deemed this HEPA filter met the ASP:03:02 standards for vacuum cleaners.[20] In addition, this filter is tested by using dispersed oil particulate (DOP), mineral oil, and other materials that generate mono-dispersed particles that are all 0.3 microns or smaller in size.[21] The Aurora HEPA filter is a Japanese H13 HEPA filter, which is a medical-grade filter that is tested to remove all particles of 0.21 microns and larger.[22,23] The cloth obtained from Amazon was utilized in order to filter the exhaled air from the user in the incidence that the user was infected. The battery pack obtained from Amazon provides power for the fans.

Building the Four Model Prototypes

From the airflow test results, we used the fan-filter setups A, B, C, and D with the maximum airflow rate to construct our prototype models A, B, C, and D, respectively, as shown in Figure 4. The procedure for building our prototypes consists of mounting either two axial fans in series on top of the Aurora HEPA filter (Models B and C) or one centrifugal fan on the bottom of the Kenmore HEPA filter (Model A) and 3M HEPA filter (Model D) via hot glue or screws. This allowed the air to either blow or suck through the filter to yield filtered air. A small opening for the filtered air to flow through was made into the baseball cap brim using a Dremel or utility knife. The fan-filter assembly was then mounted to the opening in the brim using hot glue or screws. Next, the polycarbonate sheets were trimmed to the optimal shape and size for the face shield. We made sure to trim it to its optimal length and width so that the edges touch the side of the user's head and the bottom of the user's chin. We secured the face shield to the brim of the hat by using zip-ties. The fans were wired to USB connectors and routed down from the hat's brim, and plugged into a USB battery pack that could be stored into the user's shirt or pants pocket. The cloth material was trimmed and attached to the bottom of the face shield via zip-ties or a stapler. Figure 4 shows the end products of this build process.

Figure 4: Four physical prototype designs that were built by each team member. (1) Model A used one 50 mm centrifugal fan mounted on bottom of the Kenmore HEPA filter, (2) Model B used two 60 mm axial fans connected in series mounted on top of the Aurora HEPA filter (3) Model C used two 40 mm axial fans connected in series mounted on top of the Aurora HEPA filter, and (4) Model D used one 50 mm centrifugal fan mounted on the bottom of the 3M 2091 HEPA filter.

Testing Procedures

NIOSH specifies that the fans on a powered air-purifying system must provide a sufficient airflow rate of 41 L/min when installed in the housing.[16] Airflow can be measured in several ways, but in our case, the airflow rate was measured in a more accessible manner by using our device to fill a known volume, a trash bag. The device was sealed into the opening of a polyethylene bag with a manufacturer-listed volume of 49.2 L. All openings were sealed, leaving the air inlet as the only path for air to enter or leave the bag. The setup is pictured in Figure 5. Prior to connecting the device to the bag, all air possible was squeezed out of the bag by hand. Then, the bag was clutched to block airflow into the bag. The fan-filter assembly was attached to the fitting on the bag. A stopwatch was started as the bag was released, allowing air to flow into the bag. The fill was timed from the release of the bag until it became taut, indicating it was 'full' with air, meaning it was filled to 49.2 L ± 10%. Utilizing Equation 2, the measured time was used to estimate airflow, Q, by dividing the volume of the bag, V, by the fill time in minutes, t.

$$Q = \frac{V}{t} \quad (2)$$

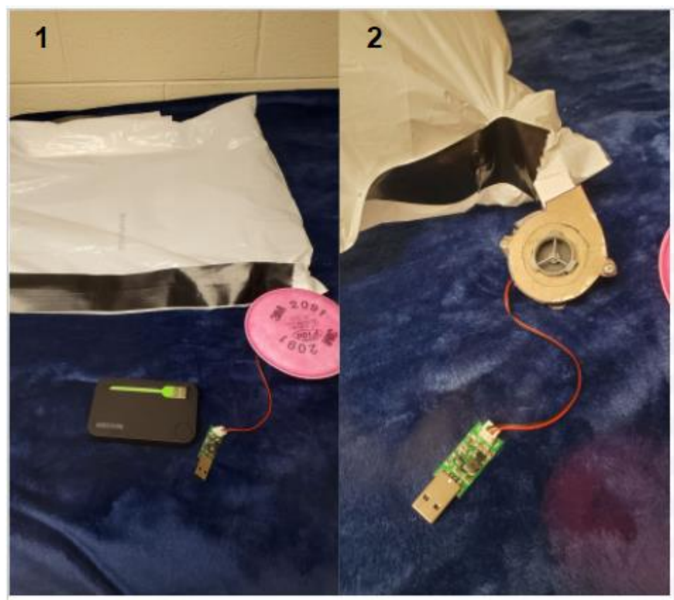


Figure 5: Airflow test setup where the left image (1) shows the trash bag sealed and flattened before the test begins and the right image (2) shows how the centrifugal fan outlet was sealed to the inlet of the trash bag.

In order to validate the comfortability of our device, we conducted a survey to compare our device's comfort to the comfort of cloth and N95 masks. This survey was filled out by us and several friends and family members who could try on our device. In the survey, we asked questions related to comfort with regards to different aspects, such as bulkiness, weight, cooling effect and breathability. We selected a rating on a scale of 1 to 5. A rating of 1 indicated the worst performance in the respective comfortability aspect while a rating of 5 indicated the best performance. We compared these ratings to other mask designs out today, such as N95 and cloth masks.

For the filtration testing, we placed a smoke detector inside the protected volume area where the user’s mouth and nose would be. Also, we sealed the sides of the hat with a trash bag to eliminate possible leaks. We lit a fire stick that produced smoke (simulating COVID-19 particles) and we placed a large container over the device and fire stick in order to create a tight seal enclosure. We let the smoke particles accumulate in the enclosure, and we waited two minutes to see if the smoke detector would be triggered. If the smoke detector went off, that indicated a failure of the fan-filter configuration. The control was the smoke detector placed in the container alone in the same location with the smoke source, which was expected to set off the smoke detector every trial. Images of this setup can be seen in Figure 6.

Figure 6: The smoke test materials and setup. The left image (1) is the materials used for the experiment and right image (2) shows how the back of the hat was sealed and the smoke detector was placed within the protective volume.

End Matter

Author Contributions and Notes

T.C., G.K., K.W., and A.K. designed research, T.C., G.K., and K.W. performed research, T.C., G.K., and K.W. analyzed data; and T.C., G.K., and K.W. wrote the paper.

The authors declare no conflict of interest.

Acknowledgments

We would like to thank our Capstone advisor Alexander Klibanov, as well as Dr. Timothy Allen, Dr. Shannon Barker, Taylor Eggertsen, Delaney Fisher, and Kareem El-Ghazawi for their supplemental support.

References

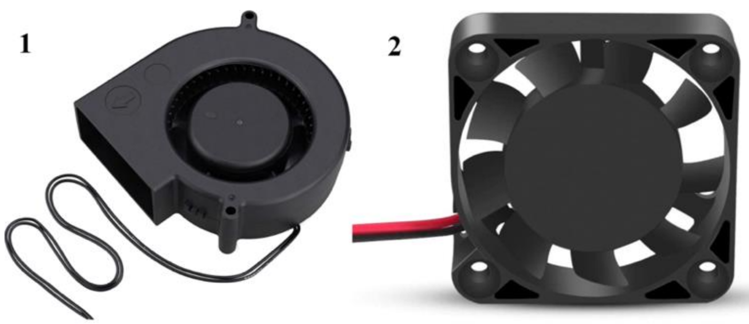
1. World Health Organization. Coronavirus disease (COVID-19) Update. https://www.who.int/bangladesh/emergencies/coronavirus-disease-(covid-19)-update.
2. COVID-19 Map. Johns Hopkins Coronavirus Resource Center. https://coronavirus.jhu.edu/map.html.
3. How Does COVID-19 Affect the Heart? - Cardiac / Heart Health, COVID-19, Featured, Health Topics. Hackensack Meridian Health. https://www.hackensackmeridianhealth.org/HealthU/2020/08/13/how-does-covid-19-affect-the-heart/ (2020).
4. Bhargava, H. D. Coronavirus: What Happens To People's Body If They Get Infected. WebMD (2021). https://www.webmd.com/lung/coronavirus-covid-19-affects-body#1.
5. Lotfi, M., Hamblin, M. R. & Rezaei, N. COVID-19: Transmission, prevention, and potential therapeutic opportunities. Clinica Chimica Acta 508, 254–266 (2020).
6. COVID-19: How much protection do face masks offer? Mayo Mayo Clinic. https://www.mayoclinic.org/diseases-conditions/coronavirus/in-depth/coronavirus-mask/art-20485449.
7. Robertson, P. The Ultimate Guide to Homemade Face Masks for Coronavirus. Smart Air. https://smartairfilters.com/en/blog/best-diy-coronavirus-homemade-mask-material-covid/(2020).
8. Qian, Y., Willeke, K., Grinshpun, S. A., Donnelly, J. & Coffey, C. C. Performance of N95 respirators: filtration efficiency for airborne microbial and inert particles. Am Ind Hyg Assoc J 59, 128–132 (1998).
9. Nick Fox. How Effective Are Masks and Other Facial Coverings at Stopping Coronavirus?
10. Konda, A. et.al. Aerosol Filtration Efficiency of Common Fabrics Used in Respiratory Cloth Masks. ACS Nano (2020) doi:10.1021/acsnano.0c03252.
11. Sandaradura, I. et.al. (2020). A close shave? Performance of P2/N95 respirators in healthcare workers with facial hair: results of the BEARDS (BEnchmarking Adequate Respiratory DefenceS) study. The Journal of Hospital Infection, 104(4), 529–533. https://doi-org.proxy01.its.virginia.edu/10.1016/j.jhin.2020.01.006

12. Maragakis, L. L. Eye Protection and the Risk of Coronavirus Disease 2019. JAMA Ophthalmology 138, 1199 (2020).
13. Metz, N. Many of us are trying to figure out how to deal with this new normal. Maybe part of that process is acknowledging the yuck factor of masks. chicagotribune.com (2020). https://www.chicagotribune.com/coronavirus/ct-coronavirus-the-misery-of-masks-0512-20200512-nz3nuv7uyngl7mczdmz2hjll2e-story.html.
14. Hubbard, B. R. & Pearce, J. M. Conversion of Self-Contained Breathing Apparatus Mask to Open Source Powered Air-Purifying Particulate Respirator for Fire Fighter COVID-19 Response. (2020). doi:10.20944/preprints202006.0207.v1
15. Measuring the Energy of Ventilation and Circulation during Human Walking using Induced Hypoxia | Scientific Reports. https://www.nature.com/articles/s41598-017-05068-8.
16. Liverman, Catharyn T., Sarah B. Domnitz, and Margaret A. McCoy. *The Use and Effectiveness of Powered Air Purifying Respirators in Health Care: Workshop Summary*. Washington, DC: National Academies Press, 2015.
17. Surgical Face Shields | Polycarbonate Sheet | PET Sheet. https://www.piedmontplastics.com/applications/surgical-face-shield.
18. What are motorcycle helmets made of? *Overdrive* https://www.overdrive.in/news-cars-auto/features/what-are-motorcycle-helmets-made-of/.
19. N95 Respirators and Surgical Masks | | Blogs | CDC. https://blogs.cdc.gov/niosh-science-blog/2009/10/14/n95/.
20. Science Behind the Certification | The Asthma & Allergy Friendly® Certification. *Allergy Standards Ltd* https://www.allergystandards.com/the-science-behind-the-certification/.
21. MERV vs. HEPA: How Air Filters Work. *Sy-Klone International* https://www.sy-klone.com/merv-vs-hepa-how-air-filters-work.html.
22. Aurora Electric Smart Face Mask Air Filter Material Roll With Purifier For Virus PM2.5. https://www.aurora-ex.com/powerful-portable-air-purifier-99-99-filtration.html.
23. The 7 Best H13 HEPA Air Purifiers in 2021 (medical-grade). https://reviewsofairpurifiers.com/best-h13-hepa-air-purifiers/ (2020).

Supplemental Material

(a) (b)

Supplementary Figure 1: Fully assembled open-source powered air-purifying particulate respirator (PAPR) completed by the individuals at Michigan Technological University, USA (a) the device and (b) in use.[14]



Supplementary Figure 2: Different types of cooling fans used in prototypes (1) Centrifugal Fan and (2) Axial Fan

Supplementary Figure 3: The three filters: (1) 3M 2091 P100, (2) Kenmore HEPA, (3) Aurora H13 HEPA that are NOISH or equivalent certified that we chose to use in our team prototypes.