Bio-Inspired 3D printable face masks

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Abstract. *During the ongoing COVID-19 pandemic, using respirators is one of the preventive measures to avoid contamination from the deadly virus. Most of these effective face masks rely on very fine filter materials which can be expensive. Similarly, due to the high demand, the shortage of these respirators in medical facilities, pharmacies, as well as to the general public is a great concern. Here, we are adopting a unique approach inspired by the complex nasal anatomy of animals to design 3D printable filters. The mask also consists of features that reduce air gaps with the nose and the chin whereas the filter includes tortuous or bifurcating pathways to capture particles. This concept of focusing on the airflow to trap the particles can be a new approach to develop highly efficient air filters along with the material used. All the designs of the face mask and the filters are made available to the public free-of-cost which would help people with technology to print and use the mask during a global crisis.*

1. Introduction:

Face masks have been used to prevent the spreading of diseases, avoiding dust, as well as in industries dealing with harmful chemicals. Most of these masks rely on the material by which the mask or the filter is made. The surgical mask material is layers of thin thread fabric that can prevent droplets greater than 5 μm (Fennelly, 2020). More effective face masks such as 3M™ Aura™ N95 Particulate Respirator is made out of synthetic materials like polyester with the filter containing polypropylene (3M, 2019). These materials are very fine which are known to filter out at least 95% of particles of 0.3 μm (CDC, 2020). Similarly, other researches involve experimentation of readily available materials to filter particles better. Konda et al. presented that the hybrid-masks containing cotton-silk had an efficiency of > 80% for particles less than 0.3 μm. However, these masks can be costly to buy or manufacture especially during the pandemic (Rosalsky, 2020). The shortage of respirators and surgical masks during the pandemic has also led to people adapting to more local solutions such as using homemade fabrics/materials as filters whose efficacy is unknown (Ong et al., 2020). There are also problems associated with the leaking of air through the gaps of surgical face masks as well as other efficient respirators such as N-95. Yu et. al concluded that only 10% of the participants were able to pass the fit-test for N-95 as required by the standard (2014).

In this paper, we present a completely new bio-inspired approach to design respirator filters which considers air-flow when trapping particles and simple design of a foldable face mask which provides a tight seal preventing air leakage. Animals with high smelling senses like dogs are known to have complex nasal structures with a lot of compartments unlike that of humans (Craven et al., 2009; Caravan et al., 2007). This involves several curved passages within the nasal through which the air flows. The curved structure gives rise to a secondary airflow in addition to the primary flow which creates a vortex motion

(Taylor, 1986). Therefore, filters were designed consisting of several twists and turns which would give rise to numerous secondary flows resulting in a vortex trap. This would prevent the particles from leaving the filter thus, effectively protecting the user from breathing the particles in. In addition to the filter, a face mask where the filter could be attached was also designed with specific features including pin/holes and belt adjustment to avoid air leakage from the nose as well as the chin. This consists of a flat mask that can be 3D printed very easily without printing any supports and can be readily folded to adjust to the face shape.

2. Methods and Materials:

Autodesk® Inventor™ Professional 2020 (Autodesk, 2020) was used to design the face mask whereas Fusion 360™ (Autodesk, 2020) was used to design the tortuous filters.
The dimensions of the facial structure were taken into consideration when designing the face maks. The average size of the jawline (~18 cm), as well as the length and width of the nose (5.2cm and 2.2cm respectively), was taken as a rough reference to make the mask fit this size when folded (Olayemi, 2011; Uzun, 2006). The dimensions of the air passage in the filters were considered based on the minimum resolution for general Fused Deposition Modelling (FDM) 3D printers available in the market i.e. 0.1 mm (PinShape Blog, 2017). This is the minimum width of the filament that can be extruded using the 3D printers. The face masks and the filters were both modified based on trial and error by 3D printing. The face masks were printed using Longer LK4 3D Printer whereas the tortuous filters were printed using Creality 3D Ender-3 pro. The face masks were printed using two filaments: Polylactic Acid (PLA) and Thermoplastic Polyurethane(TPU). This was to compare the flexibility, comfort, and the ability of the mask to stay in shape once folded. PLA has a Young's Modulus of 1280 MPa whereas that of TPU is 26-35 MPa (Farah, Anderson, & Langer, 2016; Lee, Eom, & Lee, 2019). PLA and TPU were melted at a temperature of $210° C$ and $225° C$ respectively. The following custom settings were used for both filaments: extrusion speed: 50 mm/s, bed temperature: $65° C$ and layer height: 0.25mm. The default print setting of Ultimaker Cura was used for all the other quality features (Ultimaker, 2020).
The average printing time was recorded for each filter and the flat-foldable face mask in the settings mentioned above. The cost of the 3D printed face masks and filters based solely on the filament used was calculated and compared with the commercial respirators available (Goldschmidt, 2019).

For this research project, I designed and 3D printed the flat-foldable face masks. Karl worked on modifying the 3D mask design of Dr. Christopher Wiles to adjust our filter. A total of 7 filters was designed by Ben, Daniel, and Karl. Ben designed 2 tortuous pathways filters which consisted of numerous twists and turns for the air-flow. Daniel designed 4 Triply Minimal Periodic Surfaces (TMPS) design filters. Karl also designed 1 highly-bifurcating filter. Jisoo analyzed the tortuous pathways in the nasal cavity of animals and experimentally tested the flow-rates and pressure drops in the filter designs of Ben and Daniel.
In this report, the flat-foldable mask design and one of the tortuous designs will be explained in-depth. Other filter designs will also be briefly discussed.

3. Results:

Filter designs:

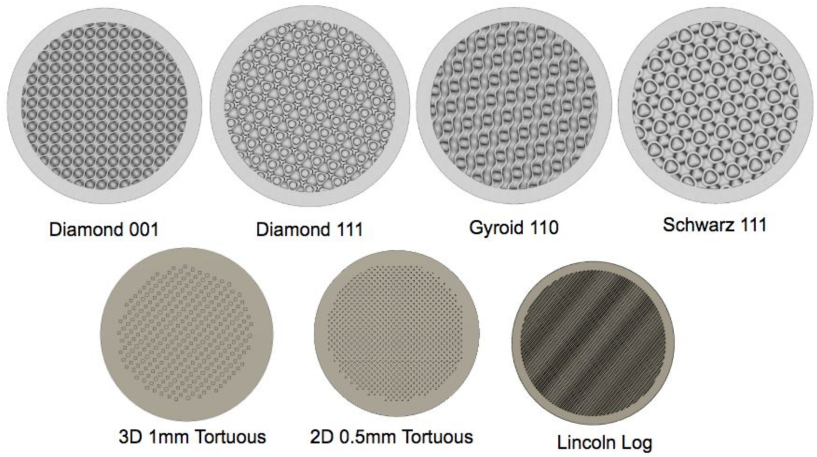
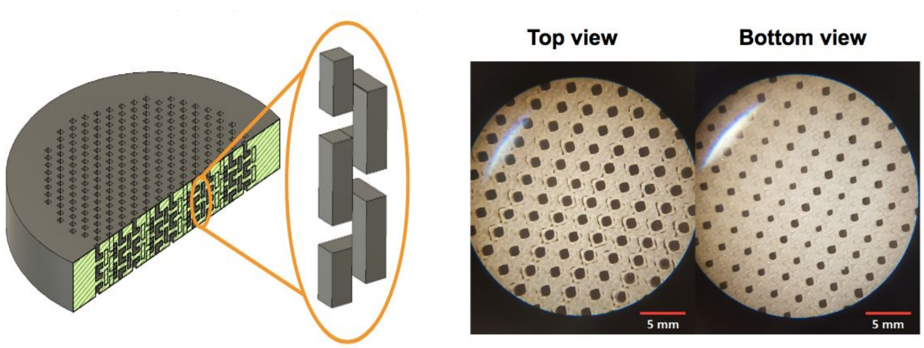


Figure 1. Cross-section of all the filter designs

The cross-section images of all the filters designed are shown in Figure 1. The outer diameter of all the filters to fit with the flat-folding mask is 5.5 cm and the height is 1cm.

3.1. 3D 1mm Tourtous Filter

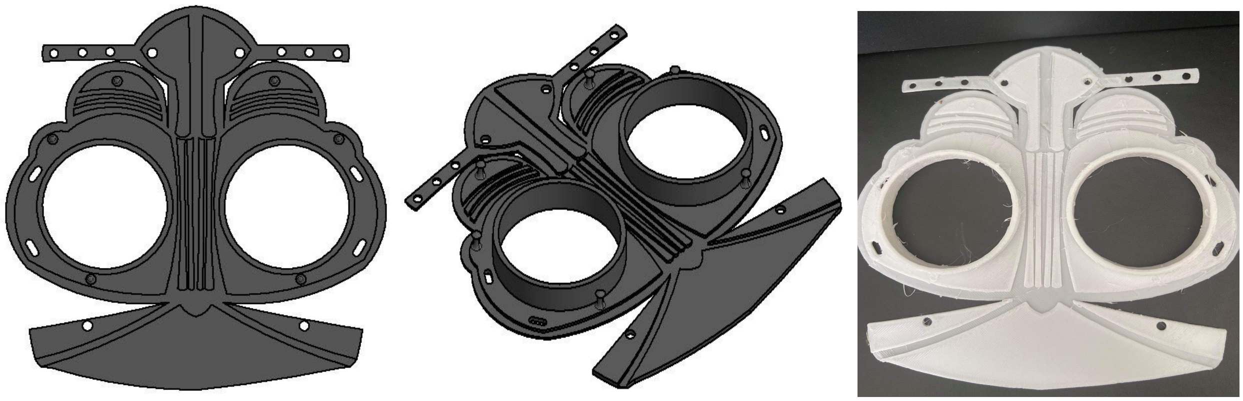


a) b)

Figure 2. a) Tangential plane of the 3D 1.0mm tortuous path design filter with a close-up view of the airflow pathway. b) Top and bottom layer of the filter after 3D printing.

The airflow pathway size on the outer layer for this filter after 3D printing is 0.94 * 0.94 mm and the inner layer is 0.70 * 0.70 mm as shown in Figure 2 b). There are a total of eight 90° turns from inlet to the outlet.

3.2. Flat-foldable mask design:



a) b) c)

Figure 3. a) Top view of the face mask. b) Top-side view of the face mask. c) 3D printed mask

Figure 3. shows the final design of the flat-foldable mask. The overall height of the mask is 16.5 cm whereas the width is 16.2 cm. The diameter of the open cylinder to attach the filter is 5.5 cm and its height is 1 cm.

There are 3 specific features included in this foldable mask design which allows it to be stable and provides a better seal with the face. They are listed as:

1) Ridges
2) Pins and holes
3) Adjusting belt

Ridges are included vertically at the center and the top of the nose curve as shown in Figure 4 a). There are 2 pins on the nose flap and 2 right below the filter cartilage fitter on both sides (vertical symmetry) as shown in Figure 4 b). The belt is an extension of the nose flaps with 3 holes as shown in Figure 4 c) which is inserted in the pin located on the side of the filer cartilage fitter.

a) b) c)

Figure 4) a) Ridges. b) Nose flap hole inserted in its respective pin. c) Belt for adjustment

Table 1. shows the approximate print time, the mass of filament, and the cost required to 3D print the prototype.

Table 1. shows the approximate print time of the prototype, the mass of filament used, and the cost.

Prototype	Approximate Printing Time (hours, minutes)	Average Mass of filament (g)	Cost ($)
Flat Face mask	3 hrs, 50 mins	31.0	2.79
3D 1 mm Tourtous Filter	5 hrs, 5 mins	23.0	0.46
Diamond 001	2 hrs, 26 mins	15.0	0.30
Diamond 111	3 hrs, 41 mins	17.0	0.34
Gyroid 110	3 hrs, 26 mins	18.0	0.36
Schwarz 111	3 hrs, 54 mins	18.0	0.36

The results obtained from flow analysis showed that the pressure drop in our filters was lower than that of commercial N-95 and surgical face masks. The TPMS filters and the tortuous filter had pressure drops of approximately 5 Pa and 15 Pa respectively when the flow rate increased from 0 Litres per Minute (LPM) to 120 LPM. The N-95 and surgical mask had the pressure drops of 30 Pa and 25 Pa respectively in the same flow rate change.

4. Discussion:

4.1. Filter printing and analysis

The 3D 1mm tortuous filters printed using PLA had a great quality. Although there were few filament strings that could be noticed on the inner holes, it was found that it had a minor effect on the airflow. This model consists of approximately 64 flow paths and 8 right-angled turns through-out the path. It is known that the velocity of the particles decreases when it hits the wall in each turn. Therefore, increasing the number of turns can also decrease the chances of particles flowing through the filter. TPMS filters have a minimum possible area for a surface spanning the boundary of the filers. This maximizes the airflow by minimizing the boundary thickness. Therefore, this thickness should be set in such a way that it is still larger than the resolution of the printer and could be printed without any problems.

4.2. Features of the flat face mask

The design of the face mask was chosen to be flat for several reasons. This mask requires no support to 3D print which makes it easily printable with minimal technical knowledge in 3D printing. The specific features included in the design of the flat mask also makes it unique. The ridges allow the mask to be easily foldable and give users the flexibility on the degree to which they can fold the mask. The holes and pins help to hold the folded mask together. The pins are wider on the top and the bottom so that once they are inserted in the pins, they are held together strongly. This design is also very easy to 3D print and it allows us to attach different parts of the mask together without requiring any additional adhesive materials. The belt allows for additional adjustment to the nose flaps in order to prevent any air from leaking. It is pulled away from the nose and one of the three holes located at a different distance is inserted in the respective pin. As the belt is tightened, there is a formation of an inner curve along the nose guided by the ridges which help to seal the mask better.

4.3. Comparison of the filaments for the face mask

Filament TPU provided us with the best results when 3D printing the foldable face masks. The flexible nature of TPU at room temperature allowed an easy folding of the mask, unlike PLA which required the mask to be heated up to $60° C$. This is because its glass transition temperature is $55° C$ (PLA, N.A.). Once the adjustments were made to the hot mask, it again turned rigid. The brittleness of PLA was another issue that came up which led to the breaking of parts of the mask when folding continuously. This was not experienced when using TPU because of its low glass transition temperature and lower young's modulus. TPU was also found to be more comfortable when wearing as it is softer than the PLA. To further increase comfort, it is recommended to use a thin layer of soft material (fabric/silk) to cover up the area that comes in contact with the face.

4.4. Cost comparison

As shown in Table1. the total cost of the filament used to 3D print the flat-foldable mask with 2 filters is < $4.00. The cost of 2 filters is as low as $0.80. During the pandemic, the average cost of reusable face masks ranged from $10 - $30 (Meyers, 2020). Although our cost analysis does not include printing labor and electricity costs, the expense can still be made lower through mass production or resuing the foldable-face masks.

4.5. Pressure Drop Analysis

The pressure drop results showed that our filters had lower values than that of the commercial face masks available. This means that it is easier to breathe in and out through our filters. The reason behind this is the design of filters to conserve the cross-sectional surface area of the flow region throughout the path. This can be done by keeping the surface area of the inlet and outlet to be the same. Pressure drop is very important factor to be considered in mask design. Due to the uneven surface areas in the inlet and the outlet of the filters, the pressure difference increases. This causes difficulty in breathing as well as increases the chances of air leaking out of the weak gaps from around the mask.

5. Future Directions

The team is continuing to work on the mask to include additional features to make the mask smarter. One of such features is adding an active component. The active component would allow an option for mask users to control the resistance of the airflow. There would be an extra rotating cylinder that can be attached to any filters as shown in Figure 5.

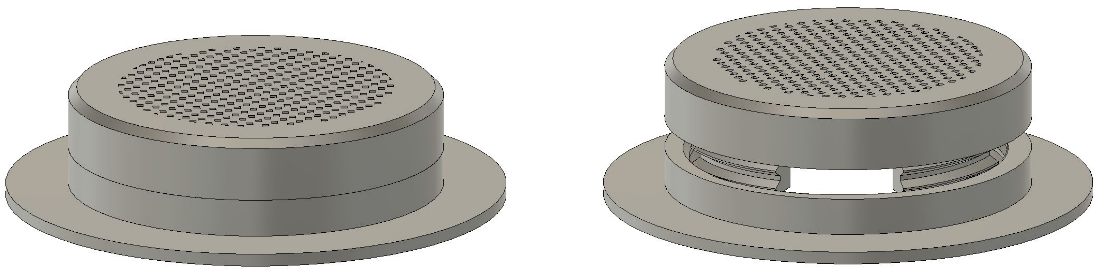


Figure 5. a) Closed filter b) Rotated open filter

Rotating the filter allows for air to pass through low resistance side ports. This can be used when in a less-crowded area. This rotation can either be controlled manually or electrically through an Arduino. For controlling the filter electronically, we are planning to include a sensor which can detect coughing sounds and responds by sending a signal to the rotating portion which contains an actuating motor to tighten the filter. Similarly, the extra space in the rotating cylinder could also be filled with fine mesh, or even fine filter materials to increase the protection. Currently, we have the design for the actuating part ready and we are working on programming the Arduino to detect coughing sound through its unique characteristics like frequency, time interval, and amplitude.

6. Conclusion

Overall, this project describes a bio-inspired approach to design face masks filters whose mechanism relies on the vortex trap created due to the tortuous pathway within the filters. This concept can be applied to develop face mask filters as well as other air filters which can still trap the particles without the requirement of very-fine filtering material. The filters along with the flat-foldable mask are made available online. This allows people with access to 3D printers an option to print these for themselves and their family during a scarcity to keep them safe. In the future, additional modifications could be made to the face masks and the filter to increase comfort and efficiency. Similarly, testing the flow of the particles in the filter remains our top priority to observe the trapping capacity of the filters.

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