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Modified full-face snorkel mask as COVID-19 personal protective equipment: quantitative results

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April 14, 2020

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1.0 Background

The COVID-19 crisis has resulted in a shortage of personal protective equipment (PPE) [1]. COVID-19 is currently the leading cause of death in the United States[2]. Health care providers caring for COVID-19 patients or at high risk of being exposed to the SARS-CoV-2 virus benefit from a face shield to protect against aerosol droplets that could hit the face and minimize the chance of inadvertently touching the face with contaminated hands, and air filtration to filter out aerosolized SARS-CoV-2. Adapting commercially available full-faced snorkel masks has been proposed as an alternative to narrow the gap in PPE [3]. Here we explore a full-faced snorkel mask with commercially available particulate filters.

2.0 Methods and materials

The testing equipment consisted of a PortaCount 8030 Respirator Fit Tester (TSI, Minnesota, USA), Particle Generator 8026 Tester (TSI, Minnesota, USA), Surface Pro (Microsoft, Redmond, WA), Nellcor OxiMax N-65 Pulse Oximeter (Medtronic, Minnesota, USA) (**Figure 1**), and a gauge manometer (Instrumentation Industries, Inc., Pennsylvania, USA). The PortaCount 8030 was calibrated March 6, 2020 by TSI.

Testing was done in an approximately 9 ft. x 9 ft. room with the particle generator on. A 3M 6800 series (3M, St. Paul, MN) full-faced mask served as the benchmark.

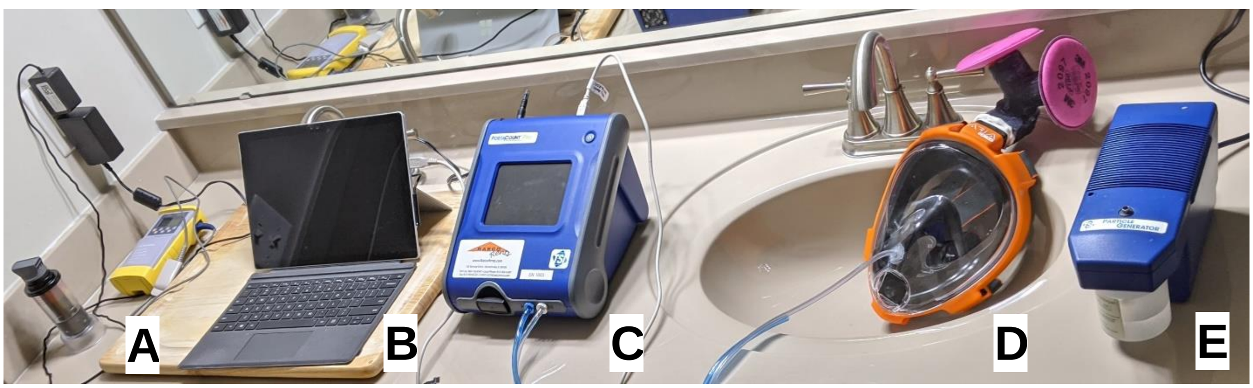

Figure 1. From left to right: A) pulse oximeter, B) SurfacePro, C) PortaCount 8030, D) ARIA QR+ snorkel mask, and E) particle generator 8026.

Full face snorkel-mask

An Aria QR+ (Ocean Reef, Inc., California, USA) Medium/Large full-faced snorkel mask was tested since the design minimizes fogging problems and CO_2 rebreathing.

A hole was drilled into the mask and a PortaCount grommet for testing N95 masks was inserted (**Figure 2**). Silicone was added to seal the external and internal surfaces. Superglue was used to secure and seal the contact between the metal grommet and plastic tube to reduce air leaks that can impair accurate quantification of the fit factor.

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Figure 2. Metal grommet covered with silicone on its outside and inside flat surfaces and extending beyond the grommet's edge to eliminate potential air leaks. The PortaCount's testing clear tube was secured with superglue.

Filter

For filtration we selected a 3M P100 particulate filter with 99.97 % filter efficiency meeting NIOSH P100-series test criteria.

3D printed adapter

The adapter was a modification of the APA – Aria Protection Adapter available at the Ocean Reef website (https://oceanreefgroup.com/covid19/). The original adapter was designed to accept a 40 mm particulate air filter with 1/7 inch thread. The design was modified to accept two 3M P100 filters. We made an earlier prototype with a single filter but found it required too much breathing effort to use for long durations. **Figure 3** shows a CAD drawing of the adapter. The CAD design is available here: https://www.tinkercad.com/things/7dZnjwUKZRr The design reduced the printing material required compared to a vertical alignment of the filter. **Figure 4** shows the finished product.

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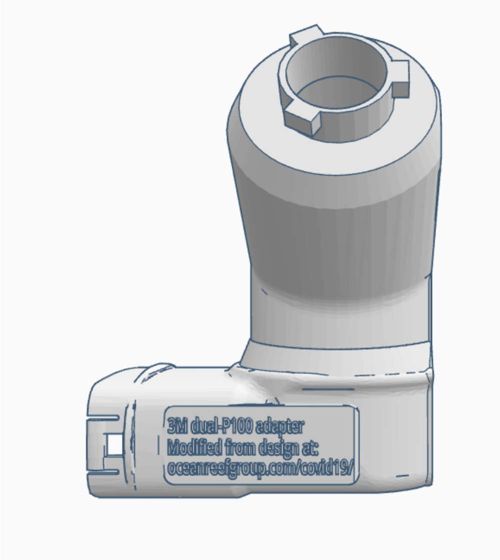
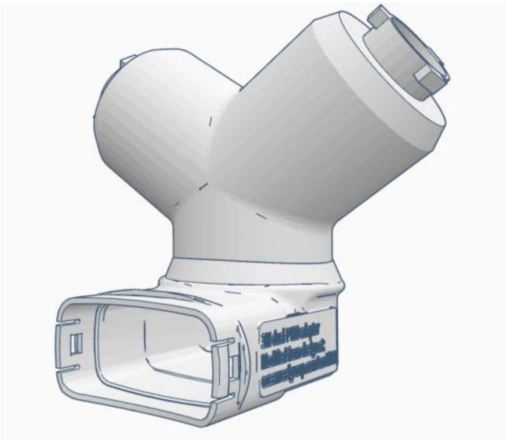
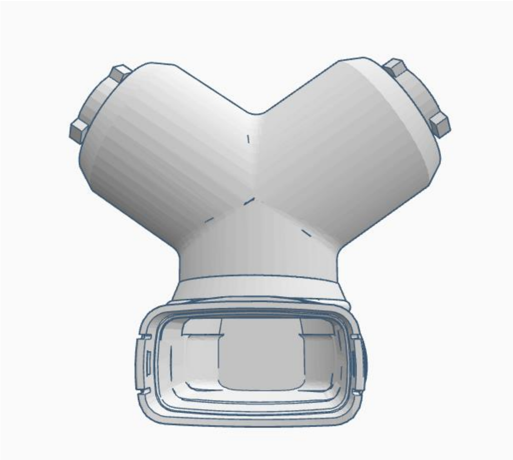


3A



3B



3C

Figure 3. CAD drawing A) Lateral view B) Oblique view C) Front view.

The adapter prototype was a black polylactic acid (PLA) print (**Figure 4**). PLA prints are porous and without an airtight coating they will not work in an air filtration application. Two coats of XTC-3D (Smooth-On, Inc., Pennsylvania, USA) were applied to make it airtight. One 3M 3PRG7 (3M, St. Paul, MN) inhalation port gasket was placed at each of the two inhalation ports. Finally, one P100 filter was attached at each of the two inhalation ports. Sticky putty (Alcolin, Cape Town, South Africa) was used to ensure an airtight seal between the mask and the snorkel connector. Additional information on the 3D printing and assembly can be found at the Hackaday website: https://hackaday.io/project/170772-ocean-reef-snorkel-face-mask-emergency-ppe

4A

4B

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4C

Figure 4. A) Snorkel mask with adapter and filters B) PLA adapter with filters attached C) View of the inhalation port with 3M gasket.

Fit testing

Fit testing was performed using the OSHA 29CFR1910. 134 protocol in the PortaCount 8030. The fit test exercises include normal breathing, deep breathing, turning the head side to side, moving the head up and down, talking, grimace, bending over, and normal breathing. Each test exercise lasts one minute except for the grimace exercise which is 15 seconds. A passing fit factor for full face masks like this design is 500, while for half face masks is 100. The fit factor is expressed as the challenge aerosol concentration outside the respirator divided by the challenge aerosol concentration that leaks inside the respirator during a fit test. Therefore, the higher the number the better.

Test scenarios

Daily QA for the PortaCount with the particle generator active was performed and passed. We tested the 6600 series 3M mask as our benchmark and three experimental configurations of the snorkel mask. These four experimental setups were named as follows:

1. 3M 6800 series mask: benchmark
2. Snorkel mask duct tape: In this setup the front plastic cover was removed as shown in this video (skip to 1 minute):
   https://www.youtube.com/watch?v=ewrsJ4lTgj4&feature=emb_logo
   The mushroom valve by the mouth was also removed. Two square pieces of duct tape covered the resulting opening to seal the port's opening.
3. Snorkel mask no modifications: This setup preserves the original configuration of the snorkel mask including the mushroom valve and protective cover in front of it.
4. Snorkel mask mouth cover removed: This setup preserves the mushroom valve, but removes the plastic protective cover in front of it as shown in the previous video.

3.0 Results

3M 6800 series mask

The 6800 series 3M mask served as our benchmark and reached its maximum fit factor in 1:15 minutes. O_2 Saturation remained stable. Real time test results can be seen here:

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https://drive.google.com/file/d/1hY2ZT3B8HeySWEC7M7wPVEo2ACfaUtaZ/view?usp=sharing

The 3M mask passed the fit test results with a fit factor of 333867 (see **Table 1**). Fogging or humidity were not an issue.

Snorkel mask duct tape

This configuration reached its maximum fit factor in approximately 2:11 minutes. O_2 Saturation remained stable. Real time test results can be seen here:

https://drive.google.com/file/d/1ETWlNk0VjiZnSMaRXsm5R3HmVk0Zrd-M/view?usp=sharing

This configuration passed the fit test results with a fit factor of 32281 (see **Table 1**). Increased humidity decreased the comfort of the mask although fogging was minor.

Snorkel mask no modifications

This configuration reached its maximum fit factor in approximately 1:56 minutes. O_2 Saturation remained stable. Real time test results can be seen here:

https://drive.google.com/file/d/1Hpwc90kCozlu2EnfLrXCWGt5bk2bqQw8/view?usp=sharing

This configuration passed the fit test results with a fit factor of 15448 (see **Table 1**). Fogging or humidity were not an issue. Further evaluation of this configuration generated during inspiration a negative pressure of 2 cm of water and no positive pressure during exhalation.

Snorkel mask mouth cover removed

This configuration reached its maximum fit factor in approximately 1:08 minutes. O_2 Saturation remained stable. Real time test results can be seen here:

https://drive.google.com/file/d/1kPSIH0cFRrhGwltuDOD-RODMJAn9U_OG/view?usp=sharing

This configuration passed the fit test results with a fit factor of 1105 (see **Table 1**). Fogging or humidity were not an issue.

Table 1. Fit testing results for the different mask configurations

	3M 6800 series mask	**Snorkel mask duct tape**	**Snorkel mask no modifications**	**Snorkel mask mouth cover removed**

Normal breathing	297913	44910	18511	1123
Deep breathing	288127	40394	27612	1412
Head side to side	442017	63628	38360	1541
Head up and down	349546	66749	63259	1234
Talking	266729	21200	7933	1953
Bending over	326150	12676	7534	929
Normal breathing	454406	76511	16065	593
Overall fit factor	333867	32281	15448	1105
Fit Test*	Pass	Pass	Pass	Pass

*OSHA fit factor passing value is 500 or greater

Subjective user experience

A radiation therapist wore the non-modified snorkel mask from 9 AM to 3 PM while performing daily work activities which require an increased level of exertion while positioning and moving patients to the treatment couch of the linear accelerator. She took off the mask for lunch and for a break to have a drink. She treated between 25 and 30 patients that day. Visibility was great and comfort better than other PPE she had used. Near the end of the daily with increased physical activity she felt some breathing discomfort. She measured the O_2 sat at the time which was 100 %. Overall her feedback was that it was a comfortable option she could tolerate for prolonged periods of time. The only negative feedback was that the patients and the other therapists had a hard time hearing her, requiring speaking up or using hand gestures. Talking on the phone revealed no issues.

4.0 Discussion

Although subjective qualitative fit testing can reveal promising PPE air filtration solutions, quantitative testing will ultimately reveal the effectiveness of any given solution. Our results are comparable to results obtained from commercial systems[4]. An advantage of the full-faced snorkel mask design is that it serves two critical purposes: eye and face protection, and high quality air filtration to protect against SARS-CoV-2. Multiple snorkel mask solutions have been circulated online, but none to our knowledge have undergone and passed rigorous quantitative testing [5-7]. One of the snorkel mask modifications explored using a ventilator filter, and although promising failed the quantitative testing [7]. Due to the smaller size of ventilator filters, it is unknown the long term breathability of these filters without the assistance of a ventilator. Others have proposed custom-made 3D-printed face masks to substitute N95 masks [8, 9]. The full-face snorkel mask in its original configuration (snorkel mask no modifications) offered the optimal balance between comfort and fit factor. The plastic cover of the mushroom valve has a support that helps push the valve in at the center and make a better seal improving the fit test. Users should pay attention to facial hair, eyeglasses, and other factors that could affect the mask's seal.

We experimented with several prototypes in the development of this setup. Critical modifications were sealing the 3D printed PLA adapter to make it airtight, and sealing the connection between the 3D printed adapter and the mask with putty. These steps may not be necessary if different manufacturing processes or materials are used to create the adapter. We also found it important to leave the plastic part covering the mouth of the mask as shown in the product

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website video, and use the manufacturer's inhalation port gasket and a high quality filter. Other design considerations should minimize dead space in any adapter, especially in hermetically sealed systems. Some full face snorkel masks have dead space which can result in CO_2 rebreathing and adverse symptoms. The manufacturer has a clear sizing guide to ensure an optimal fit.

One key difference between a commercial mask with air filters connected to the mouth compartment is that the volume of air that needs to be purged is relatively small compared to the snorkel mask volume where the filters are attached superiorly to the face compartment. Therefore, it takes longer for the snorkel mask to reach particle equilibrium. When testing the snorkel masks, assuming ideal conditions, we recommend wearing it for at least one minute before initiating any fit testing or it may falsely fail the initial normal breathing test.

The snorkel mask manufacturer has various models as the one tested here sharing the same basic design, but various price points ($50, $70, $90). All models retain the same basic features in the design components relevant to this application. Additional costs include the two 3M inhalation gaskets ($1.25 each), a pair of filters (retail for $10.32 a pair), putty, sealant, and the 3D printing costs. This is a cost-effective and environmentally effective solution for creating a full-face PPE mask replacement. The masks are effectively a reusable face shield, and the industrial P100 filters should last for a long time in the relatively clean air in most hospitals. The generated waste is minimal and the effectiveness exceeded OSHA standards.

The main barriers to implement this solution at the moment are obtaining the filters due to the current high demand, price gouging, and counterfeit filters. The snorkel masks are readily available as well as other materials required to implement this project. One limitation of our recommended non-modified configuration of the mask is that it is not a hermetically sealed system so an infected user could inadvertently infect a patient. The alternative is the configuration sealed with duct tape, but this may not be as comfortable for extended periods depending the ambient conditions. One limitation of the study is that due to resource and time constraints we only tested one mask model on one user. In the future, we plan to test this solution on two models of the mask and three mask sizes. We are also exploring ways to do the quantitative fit testing without drilling the mask.

Finally, the adapter and mask need to be able to be sterilized. Snorkel masks are robust and can be cleaned with soap and water. Other methods of disinfection need to be tested so that the mask's seal is not compromised or harmful fumes are inhaled by the user. For disinfection, UVC light with a 254 nm wavelength may be an option worth exploring. A UV sterilization system the delivers at least 1 J/cm^2 is reportedly sufficient to eliminate SARS-CoV-2 [10]. PLA cannot be heat sterilized as it deforms at ~60°C, although other 3D printed materials can withstand much higher temperatures. However PLA is able to withstand alcohol, bleach and other hospital disinfectants. One potential advantage of the snorkel mask tested is that as more 3D printed adapters are validated, users may have multiple filter choices depending on the current supply.

Finally, we want to emphasize that potential users should do quantitative testing before assuming their prints will achieve similar results. Users should understand that this is an off label application that is not FDA cleared and should be used at your own risk. We release the design files as open-source so users are able to modify this design to fit filters from different manufacturers, depending on the current supply.

5.0 Conclusion

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The modified full-faced snorkel mask tested solved two critical PPE problems in the current COVID-19 crisis: eye and face protection, and high quality air filtration to protect against SARS-CoV-2. The solution exceeded the OSHA requirements for a full faced mask in quantitative testing, and should be further evaluated as a PPE alternative in the current COVID-19 related PPE shortage.

6.0 Acknowledgments

We want to acknowledge Mark Abshire and Nick Zeid at Computer Aided Technology for their help with printing.

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