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David Ballard
Washington University School of Medicine in St. Louis

Alex Scott
Washington University School of Medicine in St. Louis

Broc Burke
Washington University School of Medicine in St. Louis

Jason Morris
Washington University School of Medicine in St. Louis

Connie Gan
Washington University School of Medicine in St. Louis

See next page for additional authors
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Authors
David Ballard, Alex Scott, Broc Burke, Jason Morris, Connie Gan, Jesse Hu, Udayabhanu Jammalamadaka, Sena Sayood, Stephen Liang, Bruno Maranhao, J. Tyler Bertroche, Nirah Shomer, Pamela Woodard, Kathleen Meacham, and et al

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Protection levels of N95-level respirator substitutes proposed during the COVID-19 pandemic: safety concerns and quantitative evaluation procedures

David H Ballard, Audrey J Dang, Benjamin M Kumfer, Patricia B Weisensee, J Mark Meacham, Alex R Scott, Mary Ruppert-Stroescu, Broc A Burke, Jason Morris, Connie Gan, Jesse Hu, Bradley King, Udayabhanu Jammalamadaka, Sena Sayood, Stephen Liang, Shruti Choudhary, David Dhanraj, Bruno Maranhao, Christine Millar, J Tyler Bertroche, Nirah Shomer, Pamela K Woodard, Pratim Biswas, Richard Axelbaum, Guy Genin, Brent J Williams, Kathleen Meacham

ABSTRACT

Objective The COVID-19 pandemic has precipitated widespread shortages of filtering facepiece respirators (FFRs) and the creation and sharing of proposed substitutes (novel designs, repurposed materials) with limited testing against regulatory standards. We aimed to categorically test the efficacy and fit of potential N95 respirator substitutes using protocols that can be replicated in university laboratories.

Setting Academic medical centre with occupational health-supervised fit testing along with laboratory studies.

Participants Seven adult volunteers who passed quantitative fit testing for small-sized (n=2) and regular-sized (n=5) commercial N95 respirators.

Methods Five open-source potential N95 respirator substitutes were evaluated and compared with commercial National Institute for Occupational Safety and Health (NIOSH)-approved N95 respirators as controls. Fit testing using the 7-minute standardised Occupational Safety and Health Administration fit test was performed. In addition, protocols that can be performed in university laboratories for materials testing (filtration efficiency, air resistance and fluid resistance) were developed to evaluate alternate filtration materials.

Results Among five open-source, improvised substitutes evaluated in this study, only one (which included a commercial elastomeric mask and commercial HEPA filter) passed a standard quantitative fit test. The four alternative materials evaluated for filtration efficiency (67%–89%) failed to meet the 95% threshold at a face velocity (7.6 cm/s) equivalent to that of a NIOSH particle filtration test for the control N95 FFR. In addition, for all but one material, the small surface area of two 3D-printed substitutes resulted in air resistance that was above the maximum in the NIOSH standard.

Conclusions Testing protocols such as those described here are essential to evaluate proposed improvised respiratory protection substitutes, and our testing platform could be replicated by teams with similar cross-disciplinary research capacity. Healthcare professionals should be cautious of claims associated with improvised respirators when suggested as FFR substitutes.

INTRODUCTION

Personal protective equipment (PPE) is critical for limiting infectious disease risk to clinicians. During the COVID-19 pandemic, the WHO noted in February 2020 that the global stockpile of PPE was insufficient, particularly for masks and filtering facepiece respirators (FFRs). In a survey in March 2020 by the Association for Professionals in Infection Control and Epidemiology, nearly half of respondents reported that their healthcare facility’s N95 FFR supply was nearly or...
completely depleted. To address these shortages, many institutions developed alternatives to commercial FFRs to provide immediate stopgap solutions. Some of these proposed substitutes were publicly disseminated, often with limited testing of key attributes including filtration, breathability, fit and liquid fluid repellency.

Key functional attributes of N95 FFRs

In the USA, surgical N95 FFRs used by healthcare personnel are regulated by both the National Institute for Occupational Safety and Health (NIOSH) and the Food and Drug Administration. The surgical N95 respirator serves to protect wearers by filtering fine particles, providing a tight seal around the face, and repelling fluid splatter, while ensuring ease of breathing (figure 1).

Particle filtration efficiency is dependent on the size of the particle, the material properties of the respirator and the face velocity at which the particle approaches the material; the face velocity depends on the user’s instantaneous respiratory rate and the shape and size of the respirator itself. Respirator form must ensure that all breathed air passes through the filtration medium and does not leak from an edge. Lower flow resistance (larger surface area, material with lower pressure drop) reduces the work of breathing, mitigating wearer fatigue. The respirator must be comfortable, and respirator materials cannot pose health risks to the wearer (ie, should not shed hazardous particles or fibres that can be inhaled). During crises, the respirator may need to function over periods of extended use and be reused; therefore, the respirator should be suitable for sterilisation and maintain structural integrity. More specifically, supply of commercial N95 respirators has been conserved during the COVID-19 pandemic by multiple sterilisation methods including hydrogen peroxide vapour, chlorine dioxide vapour, steam, ultraviolet radiation, heat and isolation over time. Finally, in the patient care environment, the filter material and/or an outer covering should repel high-velocity fluid splatter.

Due to the critical shortage of N95 respirators during the early COVID-19 pandemic, many institutions resorted to using locally improvised masks which have not undergone appropriate safety testing. As such, a discrepancy may exist between the respiratory protection actually provided by an improvised design and that the level of protection which healthcare workers would expect of a commercial respirator. Testing recently developed, open-source designs intended as proposed substitutes for N95 respirators, we present our framework of establishing an institutional platform for evaluating these improvised designs and materials, including fit, filtration and fluid repellency testing. This framework could be replicated by collaborative teams with similar cross-disciplinary expertise and laboratory capabilities.

METHODS

Overview

Five open-source, improvised respirator designs were selected for testing based on their wide public dissemination (during the early COVID-19 pandemic, March–April 2020) in order to demonstrate testing procedures and identify efficacy and potential limitations (figure 2): a cloth-based respirator (‘Sewn Sterilization Wrap’), three 3D-printed respirators (‘P100 Adaptor’, ‘Self-Moldable 3D Printed’ and ‘Multi-Part 3D Printed’) and one repurposed from medical supplies (‘Elastomeric’). These were produced as detailed in online supplemental data document. A commercial NIOSH-approved N95 respirator (disposable 3M 1860 Health Care Particulate N95 FFR Respirators, 3M, St Paul, Minnesota, USA) served as control. Experiments were performed in laboratories at our institution. Testing included Occupational Safety and Health Administration (OSHA)-standard quantitative fit testing, filtration testing in an aerosol laboratory and liquid repellency testing in a surface chemistry laboratory.

Several of these designs could be fabricated using different filtration media, and we evaluated several candidates that have been proposed for use in these open-source designs. Filtration efficiency and liquid repellency
were evaluated for Halyard H600 sterilisation wrap (O&M Halyard, Alpharetta, Georgia, USA) and Filti Face Mask Material (Filti, Lenexa, Kansas, USA). In addition, filtration efficiency was also evaluated for a second Halyard sterilisation wrap (H500, O&M Halyard, Alpharetta, Georgia, USA), material from a commercial N95 respirator (3M VFlex Healthcare Particulate Respirator and Surgical Mask 1804, 3M, St Paul, Minnesota, USA), and commercial HVAC material (MERV16 rating), and other configurations of the sterilisation wrap materials (two layers of H600, single layers of H600 with stitching).

**Patient and public involvement**
The authors (including those who originated the study) and fit testing volunteers include intended users (ie, healthcare workers) of the improvised respirator designs studied in this work. No patients were involved in this research.

**Quantitative respiratory fit testing**
Respirators were quantitatively tested via OSHA 7-minute standardised fit test\(^{17}\) using a PortaCount Respirator Fit Tester Model 8048 and TSI Model 8026 Particle Generator with TSI FitPro Ultra software. A 4 mm metal grommet was punched through each respirator at a location not in direct contact with skin and connected with 4 mm tubing to the PortaCount device. To facilitate testing of 3D-printed respirators, the grommet was inserted through the filter material. To permit passage of a grommet into the filter of the Multi-Part 3D Printed respirator, a soldering iron was used to create a hole in the thermoplastic cap overlying filtration material. Three adult volunteers served as standard faces (two regular, one small). The Self-Moldable 3D Printed respirator was moulded using hot water as described in design instructions (online supplemental data document). Each user adjusted respirator placement and strap tightness during real-time fit testing to achieve the best possible fit prior to the 7-minute OSHA standard test. Each design was tested on faces calibrated to small-sized and regular-sized surgical N95 FFRs.

**Materials testing: filtration and breathability**
Particle filtration performance was evaluated for several materials including commercial filtration materials and fabrics intended for other medical uses. Additional information about testing procedures and a sampling diagram

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**Figure 2** The six designs are displayed with an image of them on a user in the second column, and the filter material used in the third column. The last two columns present the respirators stratified by standardised face size of the user. Radial bar plots display overall fit factor from the OSHA 7-minute standardised fit test for each design as well as the 3M N95 for regular and small size standardised users. Green bars represent passing scores, 100 or greater, while red bars indicate failing scores. Areas noted by users to leak air were highlighted. OSHA, Occupational Safety and Health Administration.
can be found in online supplemental data document, figure 1. Sample discs of 47 mm were cut directly from the mask or the sourced material sheet and placed in an inline filter holder during filtration testing (online supplemental data document, figure 2). A polydisperse NaCl aerosol was produced using a Collison nebuliser, dried to remove water content, and then passed through a charge neutraliser and an electrostatic classifier (TSI, Model 3080 with long differential mobility analyser column), which selected particles based on their mobility in the electric field with a single-charge diameter setpoint of 300 nm (online supplemental data document for additional discussion of the particle size). The size-classified aerosol was then charge-neutralised a second time and diluted using HEPA-filtered air to achieve a final particle number concentration in the range of 3000–4000 #/cc. As per our intention to evaluate how these improvised designs compare with the N95 respirators in short supply, this selected size is consistent with similar filtration studies of N95 respirators. Though this diameter is somewhat larger than the size of an isolated SARS-CoV-2 viral particle (approximately 75–105 nm), the virus would most likely be in a larger respiratory particle consisting primarily of water, proteins, salts and surfactants.

To determine filtration efficiency, particle concentrations upstream and downstream of the filter were measured via continuous condensation particle counter (TSI, Model 3022A). Concentrations were measured in immediate succession to mitigate impact of drift in nebuliser output over time. The NIOSH N95 protocol demands a flow of 85 L/min through the entire respirator, reported to yield a face velocity in the range of 10–13 cm/s for surface areas typical of commercial N95 respirators. We report results here for tests at 7.6±0.1 cm/s, based on the calculated face velocity for the N95 FFR in this study. Particle filtration efficiency values reported here are the average of the three to four different filter samples tested every test session.

RESULTS

Quantitative respirator fit testing

All but one potential N95 respirator substitute evaluated failed to reach the OSHA half-mask respirator overall fit factor minimum of 100; only the Elastomeric substitute (which uses a commercial HEPA filter for particle filtration) passed quantitative fit on both small and large face standardised users. Common points of fit failure between respirators were air leak around the nose and difficulty with strap tightening. For 3D-printed respirators, users experienced discomfort due to respirator contact at the chin and bridge of the nose. Individual fit factors and points of failure are noted in figure 2 and online supplemental data document. Components of the quantitative fit test for each potential N95 respirator substitute are noted in figure 3.

The Sewn Sterilization Wrap design failed to reach OSHA specifications (fit factor >100) for both small and regular respirator size (overall fit factor 20 and 17, respectively). A poor seal was noted around the nose and chin and the rigidity of the straps complicated proper tightening. A fit test was not completed for the P100 filter respirator on small size standardised users due to grossly inadequate seal. Poor fit was additionally noted for regular size standardised users, overall fit factor 17. The Self-Moldable 3D Printed respirator additionally failed to meet OSHA fit standards, overall fit factors 11 and 12, respectively, after heat moulding. The overall fit factor for the Self-Moldable 3D Printed respirator was not improved by heat moulding to users’ faces, although it improved subjective user perception of fit with no subjectively noticeable air leak during normal breathing. The Multi-Part 3D Printed respirator additionally achieved poor-quality seal, overall fit factor 4 and 15, respectively. Users noted circumferential air leak as well as potential air leak surrounding the filter screw threads. The Elastomeric respirator passed fit testing for both small and regular size standardised users, overall fit factor 110 and 108, respectively; however, the respirator had inconsistent performance across sections of the fit test and users noted discomfort with the weight of the filter, work of breathing and strap tightness at which good fit was achieved.
Quantitative fit factors reflect infiltration of particles through both face seal leakage and material penetration, though typical N95 FFRs have such high average filtration efficiency that poor fit is the more likely cause of failed tests (online supplemental figure 3). For improvised designs and materials, particle penetration through the filter media itself could contribute a larger fraction of particles which infiltrate the FFR, as these materials typically have poorer filtration performance. In addition, the 3D-printed designs have a lower filter media surface area, and the resulting higher air face velocities would decrease filtration performance.

**Material filtration and air resistance testing**

Only the commercial N95 mask material (3M VFlex Healthcare Particulate Respirator and Surgical Mask 1804, 3M, St Paul, Minnesota, USA) filtered more than 95% of 300 nm particles at a face velocity of 7.6 cm/s (figure 4). In addition, the commercial N95 material had
a modest pressure drop of 50 Pa (95% CI: 32 to 69) at this face velocity.

The quality factor (Q) enables evaluation of the trade-off between filter media filtration performance and pressure drop:

\[ Q = \frac{\ln(1/(1-E))}{\Delta P} \]

where E is filtration efficiency, and ΔP is pressure drop. The HVAC (MERV16) and Filti materials had higher quality factors than the sterilisation wrap materials, though their performance was more variable (a range of 12% among four punches of Filti and 13% among three punches of the HVAC material). Two sterilisation wrap materials (H500 and H600) were tested in a variety of arrangements. As a single layer, H500 and H600 performed similarly, with slightly higher filtration efficiency (70% (95% CI: 67% to 72%)) and pressure drop (50 Pa (95% CI: 34 to 66)) for H600. A double layer of H600 (with the flat, less textured sides of the two layers facing inward) improved the filtration efficiency to 89% (95% CI: 86% to 91%), though the pressure drop increased. The filtration efficiency measurement for two layers of H600 sterilisation wrap was within 5% of that measured by Ou et al who also evaluated the impact of dry heat, steam and alcohol decontamination cycles at additional particle diameters.

To evaluate the impact of stitching Halyard material, two lines of stitches (between 6.5 and 7.0 cm total length) were made with a sewing machine in the centre of 47 mm discs of H600 material (online supplemental data document). The impact of stitching was a decrease in the filtration efficiency from the single-layer H600 of 70% (95% CI: 67% to 72%) to 65% (95% CI: 60% to 71%) for the stitched H600, which also had more variable performance.

A summary of the filtration efficiency and pressure drop measurements is provided in online supplemental table 1.

### Breathability of improvised designs

At the test face velocity in this study (7.6 cm/s), none of the materials exceeded the maximum pressure drop across the filter in the NIOSH standard for N95 respirators (343 Pa H2O during inhalation and 245 Pa during exhalation) to avoid discomfort and detrimental physiological effects. However, the actual face velocity of a respirator undergoing this test (at a flow rate of 85 L/min) would depend on the sur area of filtration material (online supplemental figure 4). For fibrous filters, pressure drop and face velocity are proportional, such that we can use our measurements at a single face velocity to model the pressure drop of each material at the face velocity at which 85 L/min of air would flow through the surface area of each design (online supplemental figure 5).

For all materials, the modelled pressure drop of the Sewn Sterilization Wrap mask is lower than the maximum standard for inhalation and exhalation. By contrast, only the HVAC material is modelled to meet this breathability standard for any of the 3D-printed designs. If the closed area of the mesh grid of the Multi-Part 3D Printed mask is not counted as available filtration surface area, then not even the HVAC material is predicted to meet the NIOSH air resistance standard when used with this design.

### Liquid repellency and splatter testing

Test results and optical images of the fabric surfaces (figure 5) show that both H600 and Filti are repellent towards deionised water and milk (part A: advancing contact angles ≥120°), but pose potential liquid penetration points due to millimetric holes in their design. For Halyard, these holes appear sealed, whereas for Filti, the composite fabric consists of a very thin continuous layer sandwiched between two outer layers with the holes in vertical alignment. Both fabrics passed the textile absorbency test with no visible liquid penetration even after multiple minutes. Furthermore, while receding contact angles of milk on both fabrics are zero, milk stains were easily removed by wiping the surface with a wet cloth. When subject to the high-velocity milk jet (part B), however, both fabrics failed splatter testing for a single layer, as confirmed by liquid penetration (part C, bottom image ‘layer 1’). When used in a double layer, H600 was able to prevent liquid breakthrough for all jet velocities, whereas Filti failed even as a double layer at higher impingement velocities. Whereas liquid penetration for the top layer happened uniformly at the location...
design, in that an improvised design that performed well for individuals with only small and regular faces would still have large benefit in alleviating crisis shortages such as those encountered during the COVID-19 pandemic. In one cohort, medium and large sizes were grouped together and only represent 50 of 229 (21%) of the cohort.31 Even with appropriate sizes, fit testing is further complicated with the shape of users’ faces.32 In addition, with the same protocols required for individuals using a commercial N95 respirator in an occupational setting, fit testing could be used to verify that a particular design had adequate fit for a given individual’s face.

Apart from the commercial N95 FFR, only the Elastomeric design passed quantitative fit testing. This design leverages key attributes of its commercial components, including high-quality fit of a commercial anaesthesia mask and high filtration efficiency of HEPA filter. While we did not directly test the air resistance of a single HEPA filter, the manufacturer’s specification (35 mm H2O at 60 L/min) indicates that it exceeds the NIOSH standard (25 mm H2O for exhalation) even at a flow rate (60 L/min) lower than that of the NIOSH test (85 L/min).33 Thus, a bifurcated adapter for simultaneous use of two filters is recommended for adequate breathability (modelled as 24.8 mm H2O at 85 L/min). Although the Elastomeric design did pass, its basis off an existing commercial design may limit its implementation for mass production and distribution, as it depends on the availability of the product compared with the manufacturing capabilities of sewn masks or 3D-printed designs.

The Sewn Sterilization Wrap mask was well tolerated by users, and its larger surface area results in a modelled pressure drop (for all materials) which among the improvised proposed substitutes is most similar to the commercial N95 FFR. Both material filtration testing and quantitative fit testing indicate that its respiratory protection is not equivalent to that of an N95 FFR, though it is likely superior to that of a surgical mask (online supplemental figure 3). Two layers of sterilisation wrap also demonstrated fluid resistance in a test with a high-velocity jet of milk, though this was not strictly equivalent to the regulatory test method. Filti face mask material would not be an appropriate alternate material for improvised surgical masks or FFRs, unless combined with an additional layer that provided fluid resistance. We note that use in masks is an off-label application of sterilisation wrap.

The 3D-printed designs yielded 5 of the 6 poorest quantitative fit scores. Quantitative fit testing does not discriminate between particles which infiltrate through leaks in the face seal (or through defects) and particles which penetrate the filtration media itself. The rigidity of the 3D-printed designs compromised fit (as well as comfort), and the limited surface area likely exacerbated penetration through the filtration media itself. Though some reports have suggested the use of individual-specific 3D-printed masks based on their facial topography, this may not be practical for a mass production standpoint.34 35 At the face velocity calculated for the N95 FFR...
in this study at the flow rate of a NIOSH particle filtration test, none of the alternate materials filtered more than 95% of particles. Since their lower surface area would result in a higher face velocity in an NIOSH particle filtration test, the 3D-printed masks would likely have lower filtration efficiency than reported here for these materials. Only the HVAC material was modelled to have low enough air resistance for the 3D-printed designs at these high face velocities, such that we recommend pressure drop measurements of specific filter media proposed for these designs. More specifically, measuring or modelling air resistance at the face velocity which would be encountered in an NIOSH test (at 85 L/min) enables a direct comparison of an improvised design with the N95 standard.

Even without direct filtration testing of full prototypes (which is experimentally more demanding), we demonstrate how quantitative fit testing and material filtration testing can be combined to screen proposed improvised designs together with consideration of air and fluid resistance. These results point to a fundamental need to improve facial fit in future respirator designs, and even more acutely, to an ongoing need during this pandemic for end users to be equipped and educated for some measure of fit testing. In addition, evaluating designs at the conditions of regulatory test methods (eg, appropriate face velocity for filtration and air resistance) enables direct comparison to the performance expected of an N95 FFR.

There are several limitations to the present study. Our working group identified designs based on designs in the published literature, designs in the mainstream media and designs that were proposed to the Washington University hospital system. Although these designs were by no means exhaustive and their selection represented a degree of media bias, they nevertheless represented a sufficiently diverse sampling of improvisation and innovation to illustrate the need to evaluate efficacy and to demonstrate the protocols that are the focus of this paper. Although this study does not evaluate improvised respirator designs as a category (in which case sampling bias would be of concern), we did not attempt to test all of the large number of potential N95 respirator substitutes. The improvised respirator-proposed substitutes were reproduced to the best understanding of posted instructions; however, the tested designs may not reflect interval improvements. To demonstrate these protocols, fit testing was carried out with a limited number of individuals who passed fit testing of analogous small-sized and regular-sized N95 respirators. For designs such as the elastomeric design, which was the only one to pass the fit test for any of the seven volunteers, additional testing would be warranted for each individual who used this design. Although this limited testing was not designed to develop statistically significant datasets on the proportion of the population that might be able to use each mask design effectively, it did serve to both demonstrate repeatable protocols and to establish limitations of the designs that were not sufficiently pliable to pass fit testing for any of the volunteers.

While filtration testing of material patches at relevant conditions can inform material selection for further development, filtration tests of a mask prototype in its complete form are necessary for evaluation against N95 NIOSH standards, and we continue to develop in-house capacity for these tests. A complication is that the face velocity of a mask depends on a user’s minute ventilation, respiratory rate, inspiratory time and the mask surface area, complicating comparison of masks and protocol standardisation. Whole milk was used to test the splatter resistance of the fabrics, as artificial blood was not readily accessible. While the measured surface tension is within the range of surface tension of typical body fluids and blood at body temperature, it is slightly higher than that of synthetic blood as prescribed by F1862, which could result in favourable test results, as fluids with lower surface tension are known to wet surfaces more easily. The potential N95 respirator substitutes tested here were attempts to meet immediate needs of the COVID-19 pandemic frontline. However, our data indicate the majority of these proposed substitutes do not have equivalent respiratory protection and breathability to an N95 FFR. The majority of masks tested revealed inherent design issues such as inadequate filtration capabilities of the base materials and poor ergonomic facial fit to a variety of facial shapes and sizes. Our experience has highlighted the importance for institutions to be equipped and educated to perform appropriate qualitative and quantitative testing prior to novel mask implementation. This study reveals that rapid creation of an improvised respirator with N95 performance using readily available materials and simple manufacturing methods is extremely challenging, and consequently there is an emergent need for in-house testing platforms to better understand the degree to which protection is being provided. Healthcare professionals requiring this high level of respiratory protection should be cautious of claims associated with improvised respirators when suggested as N95 replacements without quantitative evaluation.

Author affiliations
1 School of Medicine Mallinckrodt Institute of Radiology, Washington University, Saint Louis, Missouri, USA
2 Department of Energy, Environmental and Chemical Engineering, Washington University in St Louis, St Louis, Missouri, USA
3 Department of Mechanical Engineering & Materials Science, Washington University in St Louis, St Louis, Missouri, USA
4 School of Medicine, Washington University in St Louis, St Louis, Missouri, USA
5 Sam Fox School of Design and Visual Arts, Washington University in St Louis, St Louis, Missouri, USA
6 Department of Anesthesiology, Washington University in St Louis, St Louis, Missouri, USA
7 Department of Environmental Health & Safety, Washington University in St Louis, St Louis, Missouri, USA
8 Division of Infectious Diseases, Washington University in St Louis, St Louis, Missouri, USA
9 Department of Anesthesiology, Memorial Hospital Belleville, St Louis, Missouri, USA
10 Department of Otolaryngology-Head & Neck Surgery, Washington University in St Louis, St Louis, Missouri, USA
11 Department of Otolaryngology – Head & Neck Surgery, Washington University in St Louis, St Louis, Missouri, USA
1 Division of Comparative Medicine, Washington University in St Louis, St Louis, Missouri, USA
2 NSF Science and Technology Center for Engineering Mechatanobiology, Washington University in St Louis, St Louis, Missouri, USA
3 Bioinspired Engineering and Biomechanics Center, School of Life Sciences and Technology, Xi’an Jiaotong University, China, Xi’an, China

Twitter David H Ballard @DavidBallardMD
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Competing interests None declared.

Patient consent for publication Not required.

Ethics approval The Washington University Human Protection Research Office determined that this study (which included fit testing of respirator designs by adult volunteers without collection of personal data) was designated non-human subjects research and was exempt from Institutional Review Board oversight (reference ID #202000144).

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ORCID iD David H Ballard http://orcid.org/0000-0001-7470-3364

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Supplementary Mask Fabrication Methods

For 3D printed respirator designs, a number of different 3D printers and materials were used depending on availability. For sewn respirators, traditional sewing machines were used by experienced sewers. In all cases, fabrication followed the process defined in the online instructions. Detailed fabrication procedures for the five designs, named as follows in the main text: P100 Adaptor, Multi-part 3D Printed Mask, Sewn Sterilization Wrap, Commercial Elastomeric Respirator, Self-Moldable 3D Print. All links were retrieved on May 1, 2020.

Sewn Sterilization Wrap

The Florida mask pattern and instructions were downloaded from the University of Florida Department of Anesthesiology website.\(^1\) Two layers of Halyard 600 sterilization wrap (Halyard, Alpharetta, GA) was cut according to the pattern downloaded and printed from the website. The masks were assembled with a Janome Memory Craft (Janome, Tokyo, Japan) home sewing machine according to the detailed instructions provided. Spandex elastic 3/8 inch (0.952 cm) wide was attached at the specified locations.

P100 Adaptor

Manufacture of the “P100 Adaptor” mask followed open source instructions created at the Barrow Innovation Center (Phoenix, AZ).\(^2\) Mask parts were produced by fused deposition modeling 3D printing and silicone casting for fit. Parts were printed in PLA (grey stock 1.75 mm from Prusa) with 20% infill and a shell thickness of 4 perimeters using a .4 mm nozzle on a Prusa i3 MK3s. The print layer height was .2 mm thickness. Print temperature was 200°C with a print bed temperature of 70°C. A soldering iron was used to melt perforations in 3D printed mask perimeter. A mold was created from a production staff member’s face, encasing the printed...
shell of the mask with clay. This clay mold was then removed, and a silicone seal was cast. Assembly of the mask required manually clearing the holes in the plastic shell and trimming clearance for elastic head straps to pass silicone seal. An O-ring seal was applied prior to attachment of a p100 filter.

Specifications were followed as described in the document from the Barrow Innovation Center, with a few exceptions as follows. The silicone mold as described was observed to be too thick to obtain a completed seal, so the edge of mold was sculpted back for a better fit. Moreover, the seal as described did not stay adhered to the mask shell on first casting and had to be glued after removal from mold. Although the end user would ideally be present for mask production to ensure personalized fit, this was not possible in our fabrication process, and masks were molded to the face of a production staff member.

**Self-Moldable 3D Print**

“Self-Moldable 3D Print” masks designs were obtained from open source instructions provided by Make the Masks.\(^3\) 3D printer files were formatted in Simplify3D (Simplify3D, Cincinnati, OH) for use on the Fusion3 F410 (Fusion 3D, Greensboro, NC) single filament printer with a 0.4 mm diameter print head and standard 1.75 mm PLA. Head temperature was set at 240°C. Test prints priors were conducted at infills of 10%, 15%, 20% and 25% with aspect ratios of 90%, 95%, and 100%, corresponding to small, medium, and large face sizes. These test prints were sanded, cleaned, and test fit to gauge pliability under heat molding as outlined by the designers. Lower infills yielded more pliable masks but ran the risk of allowing perforations in the print layers that compromised the integrity of the mask. After these preliminary test prints, prototype
samples were printed with a print head temperature of 230°C, with extrusion and print speeds lowered to 90%, and monitored for the duration of the print to ensure quality of layer adhesion at an infill of 15% in aspect ratios of 90% and 100%. Masks were individually molded to user faces using a hot water dip and adequate molding was established by forcibly exhaling against a blocked filter to identify points of air leak prior to quantitative testing.

**Multi-part 3D Printed Mask**

Manufacture of the “Multi-part 3D Printed Mask” closely followed open source instruction provided online by River City Labs. Parts were printed in PLA (grey stock 1.75 mm from Prusa, Prague, Czech Republic) with 20% infill and a shell thickness of 3 perimeters using a .4 mm nozzle on a Prusa i3 MK3s. The print layer height was .2 mm thickness. Print temperature was 200°C with a print bed temperature of 70°C. Notably, a deviation in the printing process from the instructions was use of PLA rather than Polyethylene Terephthalate Glycol-modified (PETG) due to supply availability. For filtration material, Merv 13 (AAF International, Doraville, GA) was substituted for Merv 16 due to local supply limitations. After 3-D printing from the file provided and testing the seal mold, adjustments to the external geometry were needed to enable fitting. To address this, an alternative seal mold external geometry was developed to allow for better closure, but this still failed to yield a perfect seal. Seals did not self-retain on the contoured mask shell due to low elasticity of the seals, requiring gluing to the shell edge. Additionally, extensive hand finishing was not performed on exterior parts or on threads of articulating parts due to increasing thread tolerance and worsening seal.

**Commercial Elastomeric Respirator**
Instruction for fabrication were obtained from open source documents provided on the Boston Children’s Hospital Website. The “Commercial Elastomeric Respirator” was fabricated by mounting a Ultipor 25 Ventilator Inline Bacterial/Viral Filter (Pall Corporation, Westborough, MA) on an anesthesia face mask with one end open to the environment. A face piece-filter adapter with integrated sampling port was 3D printed of polylactic acid (PLA) using fused deposition modeling (Prusament PLA; Prusa i3 MK3S, Prusa Research, Prague, CZ). The sampling port was tapped to receive a 1/4 inch-28 compression fitting to seal around fluorinated ethylene propylene (FEP) tubing with an outer diameter of 1/8 in (3.12 mm). The mask was then secured using elastic straps attached to the 4-pronged ring surrounding the inflow and outflow tract.

**Supplementary Splatter testing Methods**

For splatter testing, a Nordson EFD ValveMate 8000 (Nordson Corporation, Westlake, OH) with a 741V pneumatic valve generated the liquid jet. Fabrics, either as a single or a double layer, were secured using a 1/16 inch (0.159 cm) rubber cuff over a polyethylene terephthalate (PET) 3D printed backing form with the standard-specified dimensions. A 0.25 inch (0.635 cm) centering hole, drilled into an acrylic sheet, was placed approximately 0.5 inches (1.27 cm) from the respirator surface, and the valve with an 18 gauge needle was placed at a distance of 12 inches (30.5 cm). After impingement, fabrics were visually inspected for liquid penetration.

**Supplementary Filtration Methods**
A flow diagram of the particle testing station is provided in Figure S1. Sample discs of 47 mm were extracted directly from the mask or the sourced material sheet and placed in a stainless steel in-line filter holder (Pall #2220, Pall Corporation, Westborough, MA), which exposed a circular area of 35 mm diameter during filtration testing. A polydisperse NaCl aerosol was produced from a 1.0 %wt. NaCl solution in DI water using a Collison Nebulizer (CH Technologies) and an in-line custom diffusion dryer, with a pressure of 8 psig (55.2 kPa) and a flow rate of 6 liters per minute (LPM). The aerosol was then passed through an electrostatic classifier (TSI Inc., Model 3080, Shoreview, MN, with long differential mobility analyzer (DMA) column, operated with a sheath flowrate of 5 LPM and an aerosol flow rate of 1.46 LPM ± 0.04, which was set by controlling the pressure at the exit of the DMA by continually adjusting the needle valve to vacuum) to select particles based on mobility in the electric field with a peak mobility size of 300 nm mean diameter. Electric mobility is proportional to the ratio of particle charge and aerodynamic diameter (equivalent to diameter for spherical particles), such that for a given diameter setpoint, a set of particles of increasing diameter and discrete charge (i.e. +1, +2, etc.) will be selected by the DMA. Since the mode of the nebulizer size distribution is less than the 300 nm setpoint and since the aerosol is neutralized prior to the DMA, the singly charged particles (with 300 nm diameter mode) will predominate. After the classifier, the aerosol was neutralized a second time by flowing through a tube with two imbedded Po-210 strips (NRD Staticmaster 2U500, Grand Island, NY) and then diluted with HEPA-filtered house air. In the case of samples at 4.38±0.05 LPM (corresponding to 7.6±0.1 cm/s face velocity to the exposed filter area), an additional 2.92 LPM of using HEPA-filtered house air was added to achieve a final particle number concentration in the range of 3000 - 4000 particles per cubic centimeter. To determine the filtration efficiency, the concentrations of particles upstream and downstream of the filter were measured using a
continuous condensation particle counter (TSI Inc., Model 3022A). Upstream and downstream particle concentrations were measured in immediate succession to mitigate impact of drift in nebulizer output over time. The flow through the filter material was varied to achieve a range of face velocities. The pressure drop across the filter material was measured with a magnehelic differential pressure gauge (Dwyer, Michigan City, IN) and the temperature and relative humidity of the gas passed through the filter was measured with an industrial probe (Dwyer HHT Series). Relative humidity and temperature were not actively controlled and were within the range of 8 and 21 % relative humidity and 19.4 and 21.1°C for the results presented here.

**Methods of calculation**

Particle filtration efficiency for a single punch was calculated from the unfiltered and filtered particle concentrations \( C_{\text{Unfiltered}} \) and \( C_{\text{Filtered}} \) respectively:

\[
\text{Filtration Efficiency} = 1 - \frac{C_{\text{Filtered}}}{C_{\text{Unfiltered}}}.
\]

\( C_{\text{Unfiltered}} \) and \( C_{\text{Filtered}} \) were calculated as the mean of replicate measurements through the bypass line and filter respectively for the same punch:

\[
C = \frac{1}{J} \sum_{j=1}^{J} \bar{x}_j
\]

where \( \bar{x}_j \) is the \( j^{\text{th}} \) replicate measurement (of a total of \( J \)) for a given condition (filtered or unfiltered) and is calculated from the mean concentration (#/cc) recorded by the condensation particle counter (CPC) (for at least 30 s at 1 s time resolution):
\[ \bar{x}_j = \frac{1}{n_{CPC}} \sum_{i=1}^{n_{CPC}} x_i \]

where \( x_i \) is the \( i \)th raw concentration datum (of a total of \( n_{CPC} \) data) recorded by the CPC.

\( C_{\text{unfiltered}} \) was also corrected for particle penetration (99.4% ± 2.4) through the empty filter holder relative to the bypass line:

\[ C_{\text{unfiltered}} = (99.4\% \cdot \frac{1}{\bar{x}_j} \sum_{j=1}^{n_{CPC}} \bar{x}_j) \]

The uncertainty in filtration efficiency is the combined uncertainty of the two measurements as well as the uncertainty in the measurement of particle penetration through the empty filter holder:

\[ S_{\text{Efficiency}} = (1 - \text{Filtration Efficiency}) \sqrt{\left(\frac{2.4\%}{99.4\%}\right)^2 + \left(\frac{S_{\text{unfiltered}}}{C_{\text{unfiltered}}}\right)^2 + \left(\frac{S_{\text{filtered}}}{C_{\text{filtered}}}\right)^2}. \]

The uncertainty of the unfiltered or filtered particle concentration (\( S_{\text{unfiltered}}, S_{\text{filtered}} \)) for a punch was calculated as the combined error from the maximum relative CPC variability (\( S_{\text{CPC}} \)) observed for that condition and punch and the variability between replicate measurements of the filtered or unfiltered particle concentrations (\( S_{\text{Punch}} \)):

\[ S = \sqrt{S_{\text{CPC}}^2 + S_{\text{Punch}}^2} \]

\[ S_{\text{CPC}} = \max \left( \frac{s_{\text{CPC,j}}}{\bar{x}_j/n_{CPC}} \right) \times C \]

where \( n_{CPC} \) is the number of CPC measurements and \( s_{\text{CPC,j}} \) is the standard deviation of the raw CPC data.
Given the evolving and urgent demand for this data, the number of replicates of measurements of $C_{\text{unfiltered}}$ and $C_{\text{filtered}}$ for a single punch ($n_{\text{condition,unfiltered}}$ and $n_{\text{condition,filtered}}$) varied from one unfiltered and one filtered measurement to three unfiltered and two filtered measurements (with the mean of each condition used to calculate filtration efficiency). These replicate measurements were always performed in immediate succession to mitigate any long-term nebulizer output drift. In cases where the unfiltered or filtered particle concentration $\bar{x}_j$ was measured multiple times for a single punch (with the mean value $C$ used to calculate the particle capture efficiency), $S_{\text{Punch}}$ was calculated as the standard error of the mean of these replicate measurements:

$$S_{\text{Punch}} = \frac{\sqrt{\sum (y_j - \bar{y})^2}}{\sqrt{n_{\text{condition}} - 1}} \sqrt{n_{\text{condition}}}$$

where $n_{\text{condition}}$ is the number of replicate measurements for that condition and punch.

As discussed previously, for several punches, only a single unfiltered or filtered measurement were taken. Since a standard error cannot be computed for a single replicate, we estimated $S_{\text{Punch}}$ using the standard error of an estimate calculated for the regression of repeat measurements ($n=16$ for unfiltered measurements, $n=13$ for filtered measurements) versus time in a separate test with the same sample flowrate and diameter setpoint. This approach yields estimates of $\frac{S_{\text{Punch,filtered}}}{c}$ of 1.43% and $\frac{S_{\text{Punch,unfiltered}}}{c}$ of 0.93%.
Supplemental Figure 1. Flow diagram of the aerosol filtration testing station.

Supplemental Figure 2. 47 mm discs were cut from H600 sterilization wrap fabric sheets (Halyard Health, Alpharetta, GA) and stitched with two straight lines using a sewing machine. The total length of stitching on each of the three filters was 6.7, 6.5, and 7.0 cm.
Supplemental Table 1. Filtration efficiencies and mean pressure drop of filtration efficiencies.

<table>
<thead>
<tr>
<th></th>
<th>Filtration Efficiencies of Replicate Punches (%) (Standard Uncertainty)</th>
<th>Mean Filtration Efficiency (%) (95% Confidence Interval)</th>
<th>Mean Pressure Drop (Pa) (95% Confidence Interval)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Punch #1</td>
<td>Punch #2</td>
<td>Punch #3</td>
</tr>
<tr>
<td>VFlex™ (N95)</td>
<td>99.659% (99.649% - 99.669%)</td>
<td>99.67% (99.65% - 99.69%)</td>
<td>99.600% (99.590% - 99.610%)</td>
</tr>
<tr>
<td>HVAC (MERV 16)</td>
<td>83.8% (83.3% - 84.3%)</td>
<td>79.7% (79.2% - 80.3%)</td>
<td>70.3% (69.5% - 71.1%)</td>
</tr>
<tr>
<td>Filti™</td>
<td>81% (80% - 82%)</td>
<td>90.9% (90.7% - 91.2%)</td>
<td>93.2% (93.0% - 93.4%)</td>
</tr>
<tr>
<td>H600 (2 Layers)</td>
<td>87.5% (87.1% - 87.8%)</td>
<td>89.0% (88.7% - 89.3%)</td>
<td>89.7% (89.4% - 89.9%)</td>
</tr>
<tr>
<td>H600 (1 Layer)</td>
<td>69.6% (68.8% - 70.4%)</td>
<td>70.7% (69.8% - 71.6%)</td>
<td>68.4% (67.6% - 69.2%)</td>
</tr>
<tr>
<td>H600 Stitched</td>
<td>62% (60% - 63%)</td>
<td>65% (64% - 67%)</td>
<td>68.3% (67.4% - 69.2%)</td>
</tr>
<tr>
<td>H500</td>
<td>66.9% (66.0% - 67.7%)</td>
<td>65.9% (64.9% - 66.9%)</td>
<td>68.4% (67.6% - 69.2%)</td>
</tr>
</tbody>
</table>

Replicate intervals represent standard uncertainty, and mean intervals represent 95% confidence intervals.
Supplementary Discussion of Individual Discussion of Respirators

Sewn Sterilization Wrap

The sewn sterilization wrap was well tolerated by participants who noted its breathability and easily understandable speech. Nevertheless, the respirator presented a poor seal with multiple points of air leak including the nose, chin and cheeks. The respirator surface area is small compared to many currently marketed duckbill respirators and these leaks may be improved by extending the material outward across the cheeks and further below the jawline. Additionally, users noted difficulty with tightening the respirator straps due to lack of elasticity, with additionally restricted head motion when the lower strap was tightened with the head in a neutral position and the participants were instructed to look upward. Circumferential seal can be potentially improved with more elastic straps to provide additional tension to the sides of the respirator.

P100 Adaptor

Due to fabrication limitations users were not present for silicone molding and fitting and consequently the respirator was unable to be tested on a small sized user due to gross mismatch in size and circumferential lack of seal. Users noted easy breathability, but the hard-plastic design contacting the chin created discomfort while talking and acted as a lever during upward head motion reducing perceived seal. The strength of the straps was also insufficient to support the weight of the respirator with the attached filter and caused pulling away from the face during downward movements. While ideally respirators would have been molded individually to the end users this highlights a crucial challenge in widespread implementation.
Self-Moldable 3D Print

The Self-Moldable 3D Print respirator was well tolerated with easy breathability and speech comprehension. Users performed fit testing prior to individualized heat molding (described in supplementary methods) and noted that perceived air leaks were resolved with molding, however fit factor was not improved. Without fit testing this may lead to a false assurance of respirator fit and underscores the importance of proper fit testing. Additionally, users found the heat molding process to be difficult and cumbersome and a potential challenge to widespread implementation.

Multi-part 3D-Printed Mask

The multi-part 3D-printed respirator was poorly tolerated by users due to discomfort at the nose bridge and cheek bones from the hard-plastic fit as well as highly muffled and near incomprehensible speech. The multi-part design introduced several potential locations for air leak, most notably the lack of an O-ring rubber seal between the threads of the 3D respirator shell and filter housing. On forceful exhalation users noted potential air leak around the filter. Material and fabrication constraints are discussed in the supplemental methods and represent challenges with wide implementation of the potential N-95 respirator substitutes.

Commercial Elastomeric Respirator

The Commercial Elastomeric Respirator was poorly tolerated by users, both commented on discomfort at the bridge of the nose which may be attributable to greater tension on the upper strap necessary to achieve good fit. This was partially relieved by increasing inflation of the respirator, however fully inflating the respirator for user comfort compromised fit during real-
time testing. Additionally, users noted difficulty with talking due to tension placed on the jaw. Speech was highly muffled and difficult to understand. Furthermore, the weight of the filter caused subjective difficulty with fit during head motion and may explain the inconsistency in fit across fit test segments. Additionally, users commented on the difficulty of adjusting respirator tightness due to the high elasticity of the straps, which was necessary to counteract the high weight of the respirator. Iterations of this respirator with a single filter were found to be significantly more difficult to breathe through compared to those with a bifurcated adaptor that allowed for attachment of two separate filters.

REFERENCES


**Supplemental Figure 1.** Flow diagram of the aerosol filtration testing station.
Supplemental Figure 2.

**Supplemental Figure 2.** 47 mm discs were cut from H600 sterilization wrap fabric sheets (Halyard Health, Alpharetta, GA) and stitched with two straight lines using a sewing machine. The total length of stitching on each of the three filters was 6.7, 6.5, and 7.0 cm.
**Supplemental Figure 3.** Lines represent combinations of material filtration efficiency performance (%) and leakage (ie. around the face seal or through defects; % of flowrate) which result in a given fit factor.
Supplemental Figure 4. Face velocity of 85 L/min as a function of filtration surface area.
Supplemental Figure 5. For several materials, pressure drop is modeled as a function of face velocity. Vertical lines represent the characteristic face velocity for 85 L/min flowrate through the filtration area of the improvised designs.