An Emergency Powered Air-Purifying Respirator From Local Materials and its Efficacy Against Aerosolized Nanoparticles

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Abstract

We describe an approach used by a rural healthcare provider to convert surgical helmets into emergency powered air-purifying respirators (PAPRs) at the onset of the COVID-19 pandemic. The approach uses common materials and efficacy was demonstrated against aerosols measuring 7 nm to 25 μm in diameter.

Keywords

aerosols, COVID-19, head protective devices, healthcare, health personnel, infection control, intubation, nanoparticle, pandemics, powered air-purifying respirators, respiratory protective devices, surgical helmet

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What do we already know about this topic?

Various research groups have attempted to construct Powered Air-Purifying Respirators (PAPRs) from surgical helmet systems during emergency Personal Protective Equipment (PPE) shortages, such as during the COVID-19 pandemic, but the majority of these modifications are impractical and have not been verified for efficacy against nanoscale aerosols.

How does your research contribute to the field?

Our approach to modifying surgical helmets as PAPRs is practical, easy to implement in resource-constrained healthcare settings such as rural communities or developing countries, and was verified against a highly concentrated SiO_2 nanoaerosol—this has never been reported.

What are your research's implications towards theory, practice, or policy?

Our research has practical implications for helping healthcare workers in resource-constrained emergency situations, particularly in rural settings and developing countries, create effective emergency PPE from locally available materials.

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Introduction

During the COVID-19 pandemic, shortages in personal protective equipment (PPE) were especially severe in resource-constrained areas.[1] Overcoming such shortages, particularly in healthcare and public safety settings, became an urgent global priority. In the United States, the National Institute for Occupational Safety and Health (NIOSH) published an interim final rule establishing a new class of powered air-purifying respirators (PAPR) that aimed, in part, to help alleviate strains on respirator supplies.[2] Healthcare professionals in rural Virginia sought to alleviate such shortages by converting surgical helmets into emergency powered air-purifying respirators (PAPRs). Similar efforts have been reported[3,4] but efficacy against sub-micron particles associated with airborne transmission of SARS-CoV-2[5] is largely unknown. We demonstrated an approach for converting surgical helmets into emergency-use PAPRs with readily available materials and verified its efficacy against nanoscale aerosols using an improvised PAPR evaluation method. The PAPR was originally intended for non-sterile use. Practical modifications to the donning and doffing procedure could theoretically allow for sterile use but were beyond the scope of the present work. While makeshift solutions present numerous risks and are never recommended by authorities such as the US Centers for Disease Control and Prevention (CDC), the PPE shortages and supply chain disruptions encountered during the early phase of the COVID-19 pandemic, prior to the issuance of NIOSH's interim final rule for PAPRs[2], presented healthcare providers with especially dire choices and no viable alternatives.

Materials and Methods

The emergency PAPR is achieved by adding supplemental filter media over the air intake of a surgical helmet and then compressing the media into the groove of a machined polyvinyl chloride (PVC) ring mounted to the underlying surgical helmet. Assuming that most healthcare settings already have access to surgical helmets and sterile wrapping, the remaining materials (i.e., PVC pipe and cable ties) can be acquired from a local hardware store for less than $30 USD (excluding ring machining costs, which will be locally variable) and used to modify a dozen or more surgical helmets. Assembly consists of the following four steps (Figure 1A) which are demonstrated in an online video[6]:

1. Prepare PVC ring: Cut a 1.25" length of 12" diameter PVC pipe; using a suitable cutting tool (e.g., bandsaw, router), cut a central groove measuring .25" deep by .75" wide around the ring's outer margin;
2. Mount PVC ring to helmet: Mount the ring around the crown of a Stryker T4 (Stryker Instruments, Kalamazoo, MI) surgical helmet (Velcro® fasteners placed at the front/rear of the helmet help secure the ring); don the helmet/ring assembly per routine helmet donning procedure;
3. Position toga over helmet: Place an AAMI Level 4 Flyte Toga comprised of tri-laminate breathable viral barrier (BVB) with PeelAway Lens System (Stryker) over the ring/helmet assembly per routine toga donning procedure;
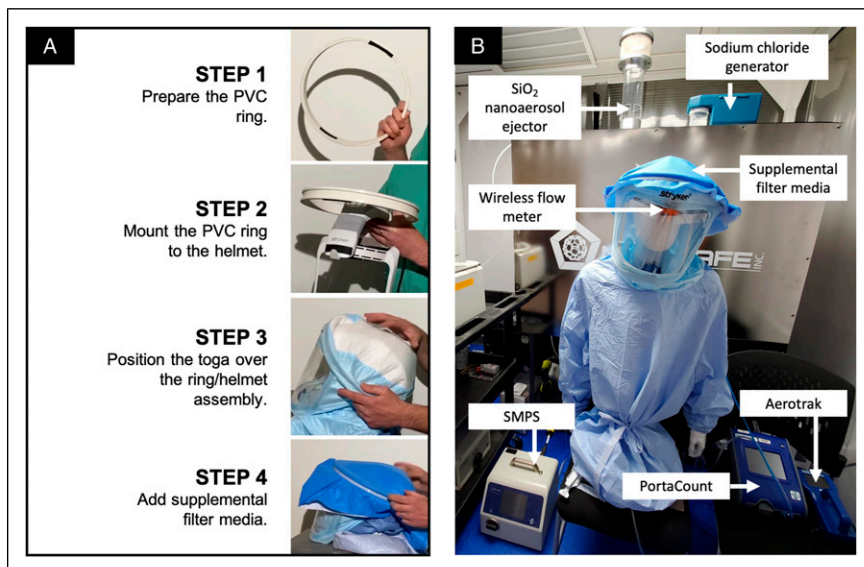
Figure 1. PAPR assembly and test setup used to evaluate the filtration efficiency of different media. A, A summary of the four general steps needed to achieve the emergency PAPR solution. B, An image of the test set-up used to evaluate the efficacy of the emergency PAPR and supplemental materials against aerosol challenges comprised of sodium chloride and silicon dioxide nanoparticles; all aerosol challenges were performed inside a Class 1000 cleanroom.

4. Add/secure supplemental filter media: Place a 24" x 24" piece of filter media, externally, over the toga/helmet air intake and secure it to the internal helmet-mounted PVC ring using a 48" cable tie to compress the filter/fabric layers into the machined groove (use a tensioning tool to securely tighten the cable tie).

Methods for evaluating the performance of PAPRs are limited,[7] so we devised an improvised procedure. We used the ring-mounted surgical helmet to outfit two types of supplemental filter media plus a negative control onto an instrumented test manikin. Filter media included sterilized surgical wrap (Halyard H600, Owens & Minor Global Products, Mechanicsville, VA) and vacuum HEPA media (ShopVac®, Williamsport, PA). We then evaluated the filtration efficiency of each media type against two aerosol challenges: 1) a sodium chloride (NaCl) aerosol generated using a Particle Generator Model 8026 (TSI, Shoreview, MN) and 2) a silicon dioxide (SiO_2) nanoaerosol generated as described by Ostraat et al.[8] and applied to PPE evaluation as described by Hill et al.[9] The size distribution and concentration of each aerosol challenge was monitored outside and inside the experimental PAPR in triplicate one-minute averaged samples using a TSI NanoScan Model 3910 Scanning Mobility Particle Sizer and a TSI AeroTrak Model 9306. Additionally, a TSI Model 8030

Portacount Pro Respirator Fit Tester was used to collect tandem measurements both inside and outside of the PAPR.[10] The effect of filter media on airflow through the helmet was evaluated using a Model ABM-200 Wireless Airflow and Environmental Meter (CPS Products, Inc., Miramar, FL) mounted to the helmet's exhaust. The test apparatus was assembled and all challenges performed within a cleanroom to reduce background particles to <10 particles cm^{-3} (Figure 1B). Carbon dioxide (CO_2) within the breathing zone of a volunteer wearing the PAPR and walking on a treadmill was measured using an ExplorIR®-W 20% CO_2 Sensor (CO2Meter.com, Ormond Beach, FL) for the negative control and the 2x H600 treatment, as these test conditions were expected to have the least and greatest impact, respectively, on airflow resistance and CO_2 levels.

Results

Average (±SD) geometric mean size distributions and concentrations for the aerosol challenges were 52±1.8 nm and 7,100 (±1,040) particles cm^{-3} for the NaCl challenge and 35 ± 1.9 nm and 87,000 ± 14,000 particles cm^{-3} for the SiO_2 nanoaerosol (Table 1). Without modification, the surgical toga removed >60% of the challenge aerosol fraction measuring 0.3–25 μm; filtration efficiency was especially poor for

Table 1. Effect of Supplemental Filter Media on Measured Parameters Including: Helmet Airflow and Differential Pressure, Breathing Zone CO_2, Filtration Efficiency and Fit Factor Against 2 Types of Aerosol Challenges (NaCl and SiO_2). Filtration Efficiency is Based on (%) of Particles (by Number), Mean (SD), of the Particle Size Range Indicated (7–420 nm and 0.3–25 μm in Diameter).

Supplemental Filter Media	Flow Rate (FPM) and Differential Pressure (mbar)[a]	CO_2 (%)[b]	Challenge Aerosol	Filtration Efficiency (%)		Fit Factor[e]
				7–420 nm[c]	0.3–25 μm[d]	
None	741 (1.2)	0.5	NaCl	67.8 (6.3)	75.7 (2.7)	2.6
	0.11 (.00)	(0.1)	SiO_2	1.4 (5.0)	61.5 (1.7)	0.4
2x H600[f]	473.3 (2.2)	2.3	NaCl	98.5 (0.4)	99.9 (0.01)	2,229
	.62 (0.01)	(0.3)	SiO_2	99.1 (0.6)	99.9 (0.01)	28,942
1x H600	541 (0.6)	n/a	NaCl	96.9 (0.6)	99.7 (0.01)	135
	0.32 (.03)		SiO_2	96.4 (0.4)	99.1 (0.01)	81
2x ShopVac®	507.0 (3.2)	n/a	NaCl	82.6 (0.8)	99.7 (0.04)	72
	0.32 (0.02)		SiO_2	79.0 (2.3)	99.6 (0.01)	45
1x ShopVac®	548.0 (0.6)	n/a	NaCl	86.7 (2.1)	97.8 (0.4)	8.3
	0.20 (0.01)		SiO_2	67.8 (3.5)	97.4 (0.1)	8.6

[a]Flow Rate measured using CPS Products, Inc. Model ABM-200 Wireless Airflow and Environmental Meter. Pressure differential measured using HHP886 differential manometer (Omega) and cartridge-mounted swatches (37 mm diameter) of supplemental filter media. Reported values are subtracted from a blank cartridge containing no filter media.
[b]Measured using CO2Meter.com Model ExplorIR®-W 20% CO_2 Sensor. CO_2 measurements were made only on the unmodified Stryker helmet (control) and the 2x H600 modification as these two test conditions represented the least and greatest reduction in airflow rate, respectively. Further, modifications other than 2x H600 displayed poor performance against 7–420 nm aerosols and were therefore not considered viable solutions.
[c]Measured using TSI NanoScan Model 3910 Scanning Mobility Particle Sizer (SMPS).
[d]Measured using TSI AeroTrak Model 9306.
[e]Measured using TSI Model 8030 Portacount Pro Respirator Fit Tester (range: 0.02 μm to greater than 1 μm) and calculated as the ratio of the average aerosol challenge (salt or SiO_2) concentration to the concentration measured inside the experimental PAPR worn by the stationary manikin (i.e., no activities were performed by a live wearer as per normal respirator fit testing procedure).
[f]For clarity, one layer of H600 consists of two thinner layers of material that are readily separated (one blue layer and one white layer). That is, "2 layers H600" equates to four total layers of material (two separate blue/white layers).

the smallest particulate fraction (7–420 nm) of the concentrated SiO_2 nanoaerosol (1.4%). In all cases, filtration efficiency improved by adding a layer of H600 or vacuum HEPA material and improved further upon adding a second layer of the same material. Two layers of H600 achieved the greatest level of filtration, but also the greatest pressure differential. Consequently, two layers of H600 reduced airflow by the greatest margin (36%) and increased the breathing zone CO_2 concentration by nearly 2%.

Conclusions

Without modification, the Stryker Flyte helmet system is unsuitable for use as a PAPR, confirming warnings provided by the manufacturer and Derrick and Gomersall[3]. However, when modified as described herein, infiltration of particles measuring 0.3–25 μm in diameter was reduced by 99.9%. Particles measuring 7–420 nm were reduced by >98.5%. The greatest reduction in particles of all sizes was achieved using two layers of H600 material, a sterilization wrap found in hospital settings and used to demonstrate an N95-equivalent facemask.[11] The added material reduced airflow through the helmet, however, and allowed CO_2 inside the PAPR to stabilize at $2.3 \pm 0.3\%$ when worn by a volunteer. The increased differential pressure resulting from adding filter layers over the air intake of the PAPR helmet is expected to reduce the operational lifetimes of the helmet blower motor and battery, which further emphasizes the temporary emergency nature of the solution described. While healthcare providers should always seek PPE authorized for given tasks, the solution described offered a relatively simple approach to achieve enhanced protection against sub-micron particles during the earliest stages of the COVID-19 pandemic when supply chains were disrupted, and emergency PPE alternatives were critically needed. The solution was used by healthcare providers in the US who had no alternative PPE during treatment of COVID-19-positive patients. Further, our approach to develop and validate the experimental PAPR informs a need for new PAPR evaluation methods.[7]

While the impact of the COVID-19 pandemic on PPE and supply-chains caught many healthcare providers off-guard, including the medical personnel who initiated and participated in the work described here, they can be better prepared for similar scenarios in the future based on the provisions of the NIOSH PAPR100[2] rule. The PAPR100 rule specifies test criteria and acceptable performance criteria for components and attributes of air-purifying particulate respirators. Provisions are included and/or modified for quantifying airflow resistance, exhalation valve leakage, filter efficiency, fit, total noise level, and related parameters. The silica dust loading test typically required for PAPRs has been excluded for the PAPR100 designation and may allow for PAPR designs that are better suited for healthcare settings. Additionally, a new low-flow warning device is designated only for PAPR100 class respirators and must alert users when breathing airflow falls below a certain threshold.[2]

This work illustrates one of the many examples of innovative collaborative efforts that transpired between hospitals, institutions of higher learning, businesses, and state/federal government during the earliest phase of the COVID-19 pandemic in the US, when PPE shortages persisted and supply chains were critically disrupted. As resources were directed to population centers, healthcare providers in small rural areas with increasing COVID-19 caseloads faced especially dire choices. Makeshift PPE solutions are never advisable and more innovative testing frameworks, such as the NIOSH PAPR100 rule, can help healthcare providers and public safety workers confront PPE shortages more effectively during future pandemics and public health emergencies.

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