Ultra-portable low-cost improvised powered air-purifying respirator: feasibility study

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Editor—The coronavirus disease 2019 (COVID-19) pandemic, subsequent worldwide disruptions, and increased demand for personal protective equipment (PPE) have forced healthcare providers to ration or improvise, even in developed countries.[1] Healthcare workers have fallen victim to disease at a time that it could least be afforded. This echoes past outbreaks such as severe acute respiratory syndrome coronavirus (SARS-CoV) and influenza A virus subtype H1N1 (A/H1N1).[2–4] Powered air-purifying respirators (PAPRs) offer crucial protection, especially if used together with N95 masks.[5,6] PAPRs are respirators that filter out air contaminants and use battery-operated blowers to deliver clean air through a tight-fitting respirator, loose-fitting hood, or helmet.[6,7] They are currently in high demand, with significant waiting times for procurement, and the price may be prohibitive. Except for the CleanSpace® Halo (CleanSpace Health, Sydney, Australia), they are bulky with significant dead space in long tubing. Despite these limitations, PAPR use is well accepted among healthcare workers (HCW).[6,8] We converted a full-face snorkel mask into an ultra-portable PAPR using cost-effective equipment and 3D printed adaptors. This was tested using an adapted version of the National Institute for Occupational Safety and Health (NIOSH) guidelines for PAPR.[7]

The overall concept was to link an actuator to a high-efficiency particulate air (HEPA) filter and a full-face snorkel mask via 3D printed adaptors (Fig. 1). The total weight is 800 g. We tested our concept using the Subea Easybreath™ snorkelling mask by Decathlon (Villeneuve-d'Ascq, France) for its reasonable pricing, quality, sizes, full-face protection, silicone seal, and option of lens inserts. We chose Medtronic mechanical DAR™ ventilator filters (Medtronic, Salt Lake City, UT, USA) for their widespread use in hospitals, and bacterial and live viral filtration efficiency of >99.99999%. The heat moisture exchanger (HME) electrostatic HEPA filter version may incur undue airflow resistance from the non-filtering HME portion. A commercially available, inexpensive, and portable centrifugal DC blower fan (Model 9BMB12P2F01; Sanyo Denki, Tokyo, Japan) was used. Operating at 12 V and a power rating of 10.8 W, this actuator achieves a peak post-filter airflow of >30 L min^{-1} with the impeller rotating at 4500 rpm, generating a maximum noise of 56 dB. It has a small footprint of 9.5×9.7×3.3 cm (height × depth × width) and weighs 190 g. A portable 12 V lithium ion (Li-ion) rechargeable battery with a 9800 mA h capacity and dimensions of 13×6.7×2.3 cm (height × depth × width) was selected to provide a battery life of >10 h. Ducted 3D printed adaptors interfaced with the mask's air inlet to concentrate the actuator output into the mask. Acrylonitrile butadiene styrene (ABS) filament was used for its durability, strength, and limited flexibility. The total cost of the prototype device was £107 (mask £17, battery £45, actuator £28, 3D printed parts £17). In comparison, a conventional PAPR can cost from £600 to £2000.

The study volunteers comprised seven clinicians working in a public hospital that manages COVID-19 patients. A National Healthcare Group Domain Specific Research Board waiver was obtained. The participants first performed a fit test to determine the best fit. We assumed some degree of air leakage, hence are not classifying it as a tight-fit mask; neither is it loose-fitting. Second, a battery, airflow and HEPA filter check was performed.

Fig 1. User wearing prototype device.

Table 1 Results of breath gas concentration testing. Median (Range) given for all applicable categories. For conditions 1–3, results are based on the final 1 minute of testing; For condition 4, results are based on the per minute average of the whole interval of testing. $ETCO_2$, end-tidal carbon dioxide; $FiCO_2$, inspired concentration of carbon dioxide; FiO_2, inspired concentration of oxygen; SpO_2, peripheral capillary oxygen saturation n = 7.

	Condition 1: Standing (with mask and HEPA filter on, no actuator attached) – 10 min	Condition 2: Standing (with mask, HEPA filter and actuator attached and turned on) – 10 min	Condition 3: Jogging on the spot at a speed of at least 6 km h^{-1} (with mask, HEPA filter and actuator attached and turned on) – 10 min	Condition 4: Performing CPR (100 compressions min^{-1}, depth of 5 cm on manikin) for 2 min, rest for 2 min, CPR for 2 min, rest for 2 min (with mask, HEPA filter and actuator attached and turned on) – 8 min
Lowest SpO_2 (%)	97 (95–98)	97 (95–99)	97 (93–99)	96 (95–99)
Highest ventilatory frequency (min^{-1})	18 (16–28)	19 (14–23)	25 (22–28)	26 (23–31)
Lowest FiO_2 (%)	18 (16–20)	19 (19–21)	19 (18–20)	19 (18–20)
Cumulative time of FiO_2 ≤19% (s)	50 (0–59)	3 (0–5)	10 (0–52)	6 (0–13)
Highest $FiCO_2$ (mm Hg)	13 (7–24)	2 (0–3)	4 (1–5)	7 (4–8)
Cumulative time at highest $FiCO_2$ (s)	4 (2–13)	3.5 (1–50)	4 (2–60)	0.88 (0.375–2)
Cumulative time of $FiCO_2$ ≤2 mm Hg (s)	1.5 (0–15)	60 (55–60)	51 (24–60)	53 (50–57.9)
Highest $EtCO_2$ (mm Hg)	38 (36–44)	22 (16–30)	28 (10–38)	35 (20–38)

A performance evaluation of breath gas concentrations was carried out. Per the NIOSH Certification Standards for Human Testing of PAPR,[7,9,10] we monitored peripheral capillary oxygen saturation (SpO_2), ventilatory frequency, inspired concentration of oxygen (FiO_2), and carbon dioxide ($FiCO_2$) and end-tidal carbon dioxide ($ETCO_2$) inside the PAPR sampled 1 cm away from the face midway between the nose base and the upper lip at room temperature (25°C [5°C]). Measures included FiO_2 ≤19.5% and $FiCO_2$ ≤ 2.0% during the inhalation portion of the breathing cycle. Participants performed varying conditions of physical activities occurring in clinical care while wearing the device: condition 1 – standing position for 10 min with only HEPA filter, no actuator connected; condition 2 – same as condition 1 but with actuator turned on; condition 3–10 min of jogging on the spot at ≥6 km h^{-1} with actuator on; and condition 4 – two rounds of chest compressions on a manikin to a depth of 5 cm at a rate of 100 compressions min^{-1} for 2 min, per Basic Cardiac Life Support (BCLS) guidelines. Users evaluated the presence of dizziness, headache, inability to focus, drowsiness, breathlessness, flushing, palpitations, muscle twitches, seizures, fogging inside mask, ease of assembly and wear, comfort, noise, weight, subjective feeling of airflow, and safety. Study subjects were all familiar with established PAPR models 3M™ Jupiter™ Powered Air Turbo and Bullard EVA™ (3M Company, Maplewood, MN, USA).

Performance evaluation

We looked at the last 60 s for conditions 1–3, and per minute average for condition 4. Condition 1 resulted in longer periods (median 50 s) of breathing a hypoxic mixture (FiO_2 ≤19.5%), compared with conditions 2–4, which avoided prolonged hypoxic mixtures even on strenuous exertion (3, 10, and 6 s, respectively). The lowest FiO_2 in condition 1 was 16%, compared with 18% in the other conditions. Condition 1 resulted in the highest $FiCO_2$ (3.2 kPa), compared with conditions 2–4 (0.4, 0.67, and 1.1 kPa). $FiCO_2$ was ≤2 0.27 kPa for longer periods of time (60, 51, 53 s) in conditions 2–4 compared with condition 1 (1.5 s) (Table 1).

User evaluation

There were no adverse symptoms reported when the actuator was on. On a scale of 1–5 (where 1 denotes least favourable and 5 most favourable), subjects gave the following mean scores: ease of assembly, 4.4; ease of wear, 4.3; comfort, 3.7; noise level, 3.4; weight, 3.6; and subjective safety, 4.

We propose this adaptation as a potential low-cost and ultra-portable PAPR device, which may help ameliorate supply shortages and provide healthcare workers exposed to aerosol-generating procedures with additional protection. The airflow rate of this mask needs improvement, but we note the NIOSH criteria are written for high-intensity industrial and mining use, not specific to healthcare, where the activity, environment, and workload differ.

Declarations of interest

The authors declare that there are no conflicts of interest.

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