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Case Report

The design and manufacture of 3D-printed adjuncts for powered air-purifying respirators

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Summary

Spurred in part by literature published in the immediate aftermath of the severe acute respiratory syndrome epidemic in 2003, powered air-purifying respirators have seen increased use worldwide during the COVID-19 pandemic. Whereas these devices provide excellent protection of the user, there is an added element of risk during doffing and cleaning of the device. An additional layer of barrier protection, in the form of a polypropylene gown, to be worn over the hood and motor belt, can be used to minimise this risk. However, the device entrains air perpendicular to the lie of the gown, resulting in the impermeable material being sucked into the air intake, and partial occlusion of flow. In this report, we describe a clinical-academic partnership whereby a bespoke filter guard was designed to disrupt airflow and prevent gown entrainment, thereby enabling full barrier protection of both the device and user. This intervention was simple, cheap, scalable and able to be mass produced.

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Introduction

Caring for patients with coronavirus disease 2019 (COVID-19) may put healthcare workers at a risk of infection. This is especially true during aerosol-generating procedures, where standard droplet and contact personal protective equipment (PPE) is inadequate to prevent contamination. In order to reduce this risk, staff are required to utilise aerosol precautions, which requires adequate protection of mucosal membranes. This can be accomplished with a separate respirator (rated to removed 95% of particles 0.3 μm in diameter), face shield and eye protection. Alternatively, a full-face or hooded powered air-purifying respirator (PAPR) is able to perform all these functions [1] and create a positive-pressure air barrier between the wearer and the external environment [2].

Our institution procured several of these devices, only to discover the positioning of the fan intake resulted in an unacceptable airflow occlusion when covered with an impermeable gown. Wearing the PAPR motor on the outside of the gown, as has been performed in other centres, was felt to carry a risk of accidental user contamination during doffing and cleaning [3]. We describe the formation of a clinical-academic collaboration to develop a simple, cheap, scalable solution to this problem that could be manufactured rapidly.

Report

In late February 2020, our institution began to investigate various options for PPE. Given the limitations of disposable N95 respirators [2, 4–6], we determined that PAPRs would be provided to staff performing high-risk aerosol-generating procedures in patients with suspected or confirmed disease. We selected the Sundström SR700 PAPR motor unit (Sundström Safety Ab, Stockholm, Sweden) as the preferred device. These were fitted with two 0.3 μm particle filters and paired with a polyvinyl chloride hood and Perspex visor to provide coverage of the head and shoulders. We opted to cover the hood and motor with a further disposable layer of PPE (impermeable surgical gown and hood, also with inbuilt Perspex visor) to minimise the risk of accidental contamination of staff during doffing and cleaning.

A problem emerged quickly during testing and simulation. Although a standard surgical gown provided adequate coverage, the high air flow through the filter led to the impermeable fabric being entrained and obstructing the particle filter. This resulted in a motor alarm and a reduction in airflow. Clinicians determined that a standoff to maintain separation between the gown and the filter intake was required to mitigate the problem. A clinical-academic collaboration, with direct input from design engineers was formed.

The filter and pre-filter cap were imaged using a computed tomography scanner (Biograph128 mCT, Siemens AG, Munich, Germany) and a three-dimensional (3D) reconstruction was created. Using the rendered model, small project teams were able to design and present several virtual prototypes to clinicians. The most promising design was selected and 3D printed using non-toxic, polylactic acid filament (Makerbot Replicator+, MakerBot Industries LLC, Brooklyn, NY). This solution consisted of a cage, inserted into the pre-filter cap via a compressible split-ring design that allows secure but reversible fastening in order to displace the gown and maintain airflow to the intake filter cartridge (Fig. 1). We measured airflow through the PAPR using a pneumotachograph. Airflow was preserved when the device was active and with the filter guard in-situ (Table 1).

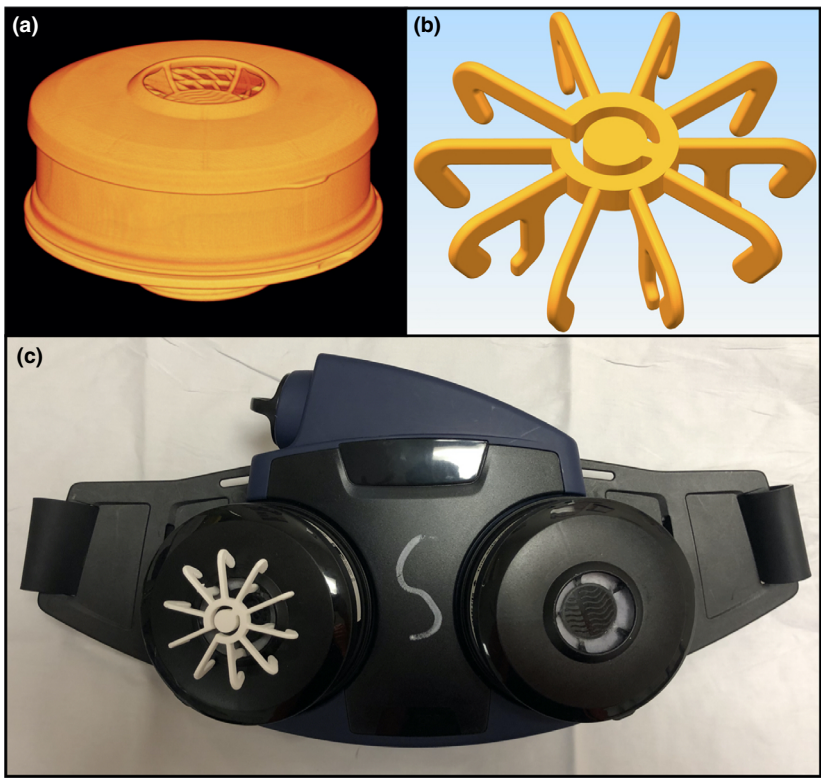

Figure 1 Design process for the powered air-purifying respirator filter guard: (a) 3D reconstruction of filter and pre-filter cap; (b) Computer assisted design schematic of the final design; and (c) Sundström SR700 PAPR motor with (left) and without (right) filter guard in-situ

Table 1 Comparison of airflow with various materials obstructing the filter both with and without the filter guard in situ. Maximum flows were above the upper measurable limit of the clinical pneumotachograph used. Complete obstruction was not attempted for fear of damaging the motor unit

	Air flow ($l.min^{-1}$)	
	No filter guard fitted	**Filter guard fitted**
Unobstructed	> 140	> 140
Polypropylene	131[a]	> 140
Plastic	52[a]	> 140

[a]Obstruction alarm sounded during test.

Discussion

Powered air-purifying respirators provide a higher level of protection than an N95 respirator. However, the use of PAPR is not without risk, and requires careful, facilitated doffing to avoid accidental contamination of the user or other staff [7, 8]. We were concerned that the wearing of PAPR motor units on the outside of disposable protective equipment placed the wearer at risk of contamination during doffing and cleaning, as the device is vulnerable to droplet and aerosol contamination. However, the problem described here demonstrates why other clinicians may not adopt this approach. This issue is heightened for PAPR models where the air intake is located on the dorsal surface of the motor belt, resulting in airflow directed perpendicular to the lie of gown fabric, partial occlusion when the motor is running and the immediate sounding of a persistent alarm. The solution engineered here demonstrates the ability of clinical-academic collaborations to generate a scalable, cheap and readily deployable solutions.

Physical modelling of medical consumable items for redesign can be undertaken using manual measurement, photogrammetry and laser scanning. In this case, a human computed tomography (CT) scanner with optimised software for acquisition and processing was selected due to availability of imaging facilities. Whereas standard human diagnostic computed tomography (CT) scanners can be used, changes to the standard human acquisition, reconstruction and exporting software need to be made for optimal 3D printing.

This report highlights an additional point about the adoption of devices commonly used in industry to medical environments. Only some PAPR models are able to maintain air intake from the lateral aspect of the motor belt. Unfortunately, we did not discover this drawback until simulated training with the device after purchase.

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References

1. Cook TM. Personal protective equipment during the COVID-19 pandemic - a narrative review. *Anaesthesia* 2020; **75**: 920-927.
2. Tompkins BM, Kerchberger JP. Personal protective equipment for care of pandemic influenza patients: a training workshop for the powered air purifying respirator. *Anesthesia and Analgesia* 2010; **111**: 933–45.
3. Ahmad I, Wade S, Langdon A, et al. Awake tracheal intubation in a suspected COVID-19 patient with critical airway obstruction. *Anaesthesia Reports* 2020; **8**:28-31.
4. Zamora JE, Murdoch J, Simchison B, Day AG. Contamination: a comparison of 2 personal protective systems. *Canadian Medical Association Journal* 2006; **175**: 249–54.
5. Peng PWH, Wong DT, Bevan D, Gardam M. Infection control and anesthesia: lessons learned from the Toronto SARS outbreak. *Canadian Journal of Anesthesia* 2003; **50**: 989–97.
6. Livingston E, Desai A, Berkwits M. Sourcing personal protective equipment during the COVID-19 pandemic. *Journal of the American Medical Association* 2020; **323**: 1912–4.
7. Suen LKP, Guo YP, Tong DWK, et al. Self-contamination during doffing of personal protective equipment by healthcare workers to prevent Ebola transmission. *Antimicrobial Resistance and Infection Control* 2018; **7**: 157.
8. Meng L, Qiu H, Wan L, et al. Intubation and ventilation amid the COVID-19 outbreak: Wuhan's experience. *Anesthesiology* 2020; **132**: 1317–32.

