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Correspondence and Communications

A customized 3D printed N95 respirator analogue to face crisis capacity scenarios in pandemics such as the COVID-19 and to support surgical personnel during PPE shortages

Dear Sir,

The expansion of the global economy in the last century has been a wide enabler for rapid economic growth and technological development. It can however be said that this interwoven economic fabric has rendered most modern-day societies closely interdependent to one another, rendering them able to function normally only under a very delicate set of conditions. The ongoing COVID-19 pandemic has shown how extraordinary surges in patient morbidity and mortality can result in healthcare crises which manifest to severe economic, social and political disruptions.[1] During the ongoing pandemic, the shortage of Personal Protective Equipment (PPE) has been of alarming concern with medical professionals expressing concern with regards to shortage of surgical masks and N95 respirators.[2]

For a respirator mask to work efficiently, the operator's respiration system has to be physically separated from the surrounding environment via a semi-permeable barrier. As such, air-tight sealing needs to be achieved in the application of this type of mask for it to work effectively. The current recommendation for PPE equipment for health care professionals is to use N95 class masks, defined as being able to retain particles of average size 300 nm at 95% or above retention rate.[3] In the last two month, the authors have noted the emergence of over 30 respiratory designs in various three dimensional (3D) printing repositories all of which fail to fulfill this requirement.[4] Currently adopted reusable respirators that fulfill the requirements are bulky and Plastic Surgeons are frequently faced with inability to use their loupes or other personal equipment with those, causing serious implications on the fluency of the surgical performance.

In our work, we employed 3D printing via Fusion Deposition Modelling (FDM) in order to create a rigid mask body and a filter protective cap (Figure 1). This was built upon a previous design by Lukas Budinsky distributed under an open source license (Attribution 4.0 International license, CC BY 4.0) We built upon the design by designing a 3D printed mold which serves to imprint the contact points of the mask to

Figure 1 Successful application of our 3D printed customised respirator with the use of magnification loupes during hand surgery.

the face of the operator. A silicone layer was then cast upon the mold and fitted to the mask thereby serving as a sealing gasket. In order to achieve good contact of the mask to the silicone, the mold bears a 4.5 mm mid-plane indentation in order to fit tightly to the rigid mask body. The respirator was designed usingfree open-source Computer Aided Design (CAD) software and can be customized in dimensions. Typical prints of the respirator with the settings provided in Table 1 are completed within three hours.

We chose to use segments from a 3 M tie-on surgical mask for the semi-permeable filter. Previous studies have shown that such masks are able to block up to 96.4% of aerosolized Bacillus atrophaeus (diameter distribution: 925-1250 nm) and up to 89.5% of aerosolized MS2 Bacteriophage (mean diameter: 23 nm).[3] Despite the virus particle size being smaller than the pore size of the N95 or surgical mask filters, both are capable of blocking aerosols and performing at the prescribed rate. This is because filtering is achieved by several mechanisms in semi-permeable membranes. For instance, in HEPA filters which employ pore diameters of 300 nm, a NASA study on the 'Submicron and nanoparticulate matter removal by HEPA-rated media filters and packed beds of granular material' suggests that 99,5% of particles of 100 nm in size are filtered.[3]

Based on the quantities of source material used we estimate the cost of mask production to be 2.3 GBP per mask. Provided the mold for the silicone parts is reusable however, PLA filament costs can be reduced for subsequent mask pro-

Table 1 Material type, printing settings and cost of manufacturing the customized N95 analogue respirator. Printer and software cost is excluded from this estimate.

	Respirator body	Filter cap	Mold	Silicone sealing
Material	SUNLU, Transparent PLA, 1.75 mm	SUNLU, Transparent PLA, 1.75 mm	SUNLU, Transparent PLA, 1.75 mm	Prepolymer by DecorRom 10 g
Temperature	210 °C	210 °C	210 °C	60 °C
Infill	20%	20%	20%	-
xy speed	68 mm/s	80 mm/s	80 mm/s	-
Time to print	60 mins	30 mins	90 mins	30 min
Cost	1.58 GBP			0.5 GBP

ductions to 1.4 GBP per mask (Table 1). We do however caution that if third parties are to use or adapt masks that the necessary contamination control measures are taken, masks are sealed in sterile packaging and allowed to sit for the prescribed timeframe for the virus to be rendered inactive.

In summary, the recommended respirator is customized, ergonomic, reusable, has been validated by fit testing and is especially applicable for surgeons that require the use of loupes for their surgical technique, making it especially useful for Plastic Surgeons and microsurgeons.[5] Recognizing that inter-societal dependency is a one-way street, having a system in place able to rapidly respond and adapt to such spikes of high demand seems necessary. Recent technological advancements such as the advent of 3D printing, printed circuit boards as well as modular mechanical and biological parts have all been enablers to the rise of the 'citizen-led science' movement whereby individuals can make notable contributions to technology from the leisure of their own homes, no longer necessitating access to centralized facilities. In times of global crisis such as pandemics, this movement of individuals could potentially adapt and rise to the challenge in a manner resembling industry 4.0, whereby smart manufacturing of high demand goods can be spearheaded in a joint effort to aid to the cause.

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Ethical approval

Not required.

Declaration of Competing Interest

Dr Papavasiliou and Dr Chatzimichail are co-Founders of Stelth, a company that specialises in 3D printing. The authors declare no interest in commercialising the device described in this article.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.bjps.2020.08.111.

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