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RAPID RESEARCH IN COVID-19 PROGRAMME

3DPPE: Rapid 3D printing of personalised protective facemasks and visors to WHO standard for healthcare workers treating SARS-CoV-2 patients.

AIMS

COVID-19 is a highly contagious viral infection that spreads through small droplets when an infected person coughs or exhales. Healthcare workers are at particular risk of infection due to frequent and high dose exposure. The ongoing global pandemic has highlighted the shortage and difficult procurement of personal protective equipment, particularly 'Filtering Facepiece' (FFP3) masks, as a major weakness in preparedness to wide-scale infectious crises.

In this project we aimed to test two questions:

1.) Can clinically available 3D scanners and printers be repurposed to rapidly scan and generate customised WHO standard facemasks within hospitals?

2.) Can these masks be easily cleaned and reused?

Our specific aims were:

- To design fitted, comfortable and reusable FFP3 masks which are customised to an individual's facial anatomy,
- To create this FFP3 mask using remotely acquired 3D photography files,
- To manufacture the design using 3D printing and silicone over-moulding,
- To examine the intrinsic antiviral properties of commonly used 3D printer and silicone materials and to test if these materials could be disinfected by commonly available disinfectants,
- To explore sources of filter material that are resilient to supply-chain disruption.

KEY FINDINGS

- Accurate 3D files of individual faces can be safely and securely acquired by a healthcare worker by uploading three smartphone images onto a cloud platform (provided in our case by a third party).

- Templates of 3D facemasks can be digitally designed, and 3D printed to produce a negative mould for a customised silicone-based face mask.
- Exchangeable FFP3 spirometry filters (a low-cost and resilient source of appropriate filter material) can be incorporated into the facemask allowing the wearing protection equivalent to commercially available FFP3 respirator masks.
- A pilot trial on volunteer healthcare workers demonstrated equivalence to available FFP3 masks using PortaCount™ Respirator Fit testing.
    - 76% of participants wearing Alpha Solway 3030v masks passed face fit testing.
    - 88% of participants wearing our 3D printed bespoke masks passed face fit testing.
    - Bespoke 3D printed masks were successfully fitted to individuals who had previously failed multiple assessments with available FFP3 masks.
- Virology analysis demonstrated that the materials used can be safely decontaminated using readily available household detergents and hypochlorite-based detergents routinely used in public hospital settings.
    - Significantly, household washing up liquid showed slightly higher cleaning efficacy than NHS standard detergents.

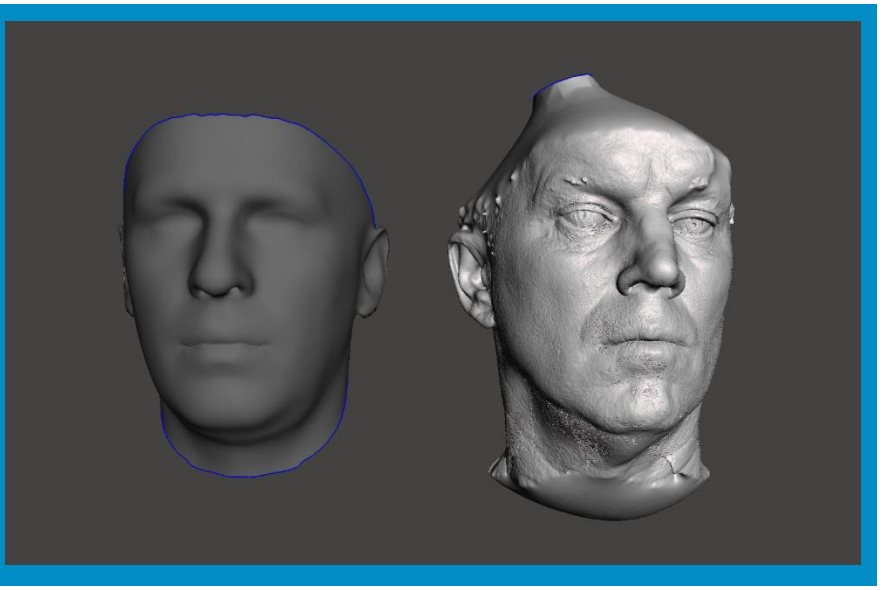
WHAT DID THE STUDY INVOLVE?

Mask Design and Manufacture

Volunteer healthcare workers recruited for NHS Lothian and randomised to the acquisition of 3D images either via an Artec Spider™ scan performed by a medical photographer or remote upload of three smartphone images to the Crisalix™ platform.

Figure (1).

On the left of the figure a 3D scan from Crisalix is shown while on the right a 3D scan taken using an Artec Spider Scanner

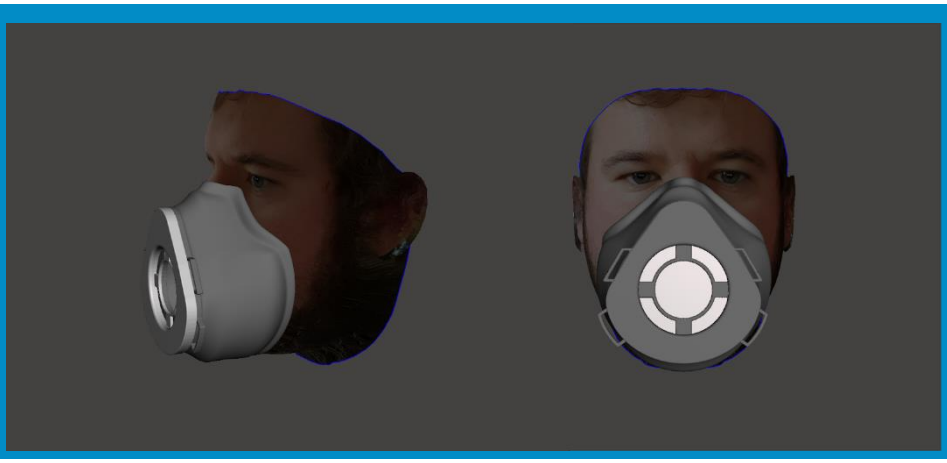


A standard mask template was produced using a computer-aided design package (CAD), Solid Edge™, as well a filter holder section and a push-fit filter cover. Each filter holder took five hours to print while the push-fit filter covers took approximately three hours each.

These 3D files were manipulated using another standard CAD package (AutoDesk Meshmixer™) to produce a negative 3D printed plastic template customised to individual facial anatomy.

Figure (2).

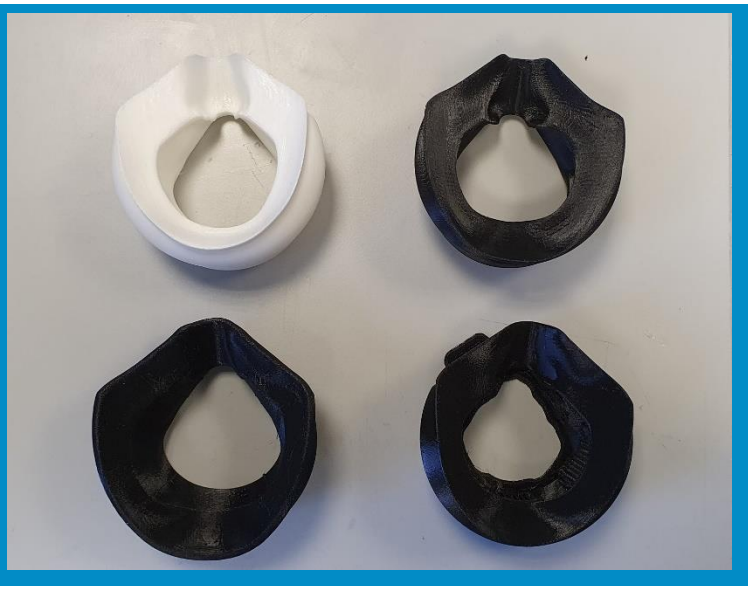
On the right is a front view of the full mask mounted on to a head and on the left an approximately 45 degree view of the mounted mask



Each of the 3D templates was then 3D printed. This process took between five to eight hours per template depending on the printer used.

Figure (3).

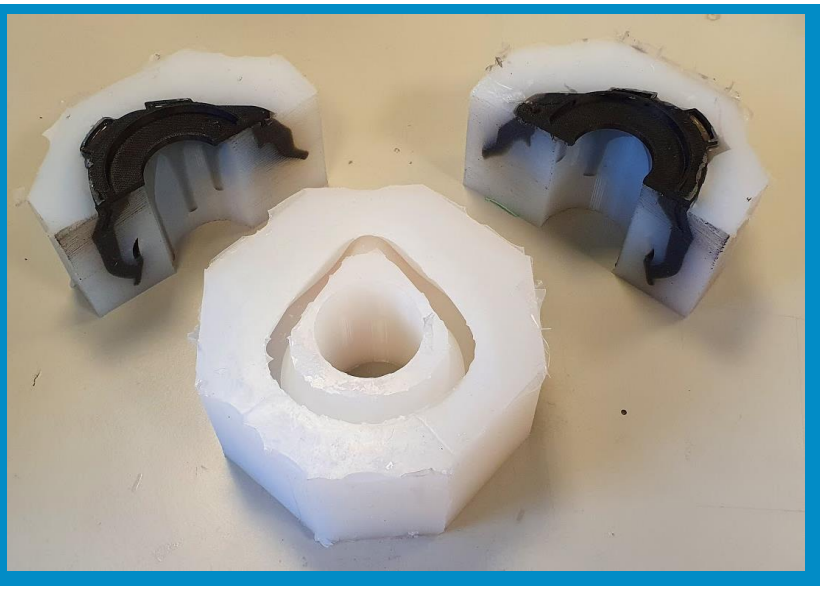
Four separate 3D printed templates are shown here, all are printed in PLA plastic. The top left template was printed using a RAISE 3D Pro2™, the other three were printed on a MakerBot Replicator +™. The bottom right template shows the structural support material required to complete each print



Each 3D printed template was then placed in a laser-cut acrylic box complete with spacers which were then filled with EcoFlex30™ to create a negative mould. Each negative mould took approximately four hours to cure. The negative moulds were then coated with a mould release spray and then filled with silicone Ecoflex50™. After a curing period of three hours, the negative mould would be peeled away to reveal the facemask sections, which are uniquely contoured to the individual's anatomy. Each of the negative moulds could then be cleaned and, if required, reused to create another mask if the individuals involved in the project required it.

Figure (4).

An example of a negative mould is shown in the middle of this figure surrounded by a cut-through of a negative mould with a mask incorporated into it



A 3D printed PLA plastic filter housing was incorporated into the Ecoflex50™ during the curing process. This inclusion allowed the subsequent insertion of a replaceable FFP3 spirometry filter and was secured via a push-fit filter cover mounted on to the mask.

In the development process, 25 different series of prototypes were made by the team and multiple modifications were made, using participant feedback, to enhance fit and comfort. Multiple iterations of different straps were designed to test for: comfort, durability, adjustability, ease of manufacture and use of readily available material. Numerous solutions were developed and tested. The final strap designs were built to avoid any interference with eyesight or interaction with the user's ears and to displace the weight of the mask over a large area of the head.

A pilot randomised trial was undertaken with 66 healthcare worker volunteers. All participants were tested with Alpha Solway 3030V™ masks to establish a baseline. After a gap of several weeks subjects were retested with a bespoke fitted ("3DPPE") trial mask. Outcome measures were:

1. Standardised quantitative PortaCount™ Face fit testing (set to N95 standard).

2. R-COMFI mask comfort scoring after the volunteer had worn the mask in simulated cardiac arrest management in a clinical simulation suite and after wearing each mask for a four-hour trial active in their home environment.

3. Modified Rhyme Test (MRT) speech samples were collected for all individuals in a standardised environment when wearing no mask, an Alpha Solway and a trial mask. These were assessed and marked for intelligibility by two qualified speech therapists using the standardised MRT scoring system.

Figure (5).

Bottom left shows the standard plastic section universal to all of the mask, bottom right is the push-fit filter cover, top left shows the standard mask sections and filter with test valve stamped all assembled and the top right image is a final prototype of all of the mask including the straps assembled

Figure (6).

On the left is a side-on view of the mask being worn and on the right is front on view

Virology Tests

The project was prompted by the Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2) but for biosafety, cost and time constraints we used a vaccine strain of influenza A virus (IAV) as a surrogate. Like SARS-CoV-2, IAV is an enveloped virus with a lipid envelope spread by respiratory and contaminated surface transmission routes and is thus likely to show similar sensitivities to SARS-CoV-2. It is also a medically important pathogen in its own right that has caused multiple pandemics over the last century.

Materials and methods

Viral stock: H1N1 strain influenza A virus A/Puerto Rico/8/1934 (PR8) was grown in embryonated eggs, diluted in Dulbecco's modified Eagle's medium (DMEM; D5796, Sigma) supplemented with 1% bovine serum albumin (BSA) to a titre of around 108 plaque forming units (PFU)/ml and snap frozen in aliquots at -80 °C. On the day of experiment, virus was thawed on ice.

Tissue culture and plaque assays: Madin Darby canine kidney (MDCK) cells were maintained in DMEM supplemented with 10% foetal bovine serum (10500, Gibco), 1x Penicillin/Streptomycin (15140122, Life Technologies), and 1x L-Glutamine (25030024, Life Technologies) at 37°C in 5% CO_2. For plaque assay, MDCK cells were plated in 6-well plates and allowed to grow to confluency. Before virus inoculation, medium was removed and cells washed with phosphate-buffered saline (PBS). Viral samples were serially 10-fold diluted (down to 10^{-7}) in serum-free DMEM, before 500 µl of the 10^{-2} to 10^{-7} dilutions were added to the plates. After 1h incubation at 37°C, cells were overlaid with 2 ml of SFM supplemented with 1.2% Avi-cell RC-581, 0.14% BSA, and 1µg/ml L-(tosylamido-2-phenyl) ethyl chloromethyl ketone (TPCK)-treated trypsin and incubated for 48 h to allow viral plaques to develop. Cells were then fixed in 10% formaldehyde in PBS and stained with toluidine blue dye to visualise plaques. For each plate, the well with between 10-100 plaques was counted, and the corresponding viral titre (in PFU/ml) was calculated.

Material testing: Plastic disks were sterilised by soaking in 70% ethanol for five minutes followed by air-drying overnight. For time course assays, 10 µl of viral stock was spotted on each disk, and at 0, 4, 8, 12 and 24 hours after spotting, recovered by the addition of 990 µl of SFM supplemented with 1% BSA, snap frozen and stored at -80 °C prior to titration by plaque assay. To test disinfectants, 10 µl of viral stock was spotted on each disk as before and allowed to dry for ~1.5 hours. Following this, 50 µl of disinfectant: Chlor-Clean™, 70% ethanol, hand sanitizer (Purell), shower-gel (diluted 1:10 with PBS), wash-up detergent or SFM (to serve as a negative control) was deposited on top of the dried viral spot. Five minutes after incubation, 940 µl SFM plus 1% BSA was used to recover the virus and the samples processed as before. Assays were set up in a minimum of triplicate.

Data analysis: Numeric data were plotted as $\log_{10}$-transformed values (assigning a value of 10 minutes to the "0" h time point) and analysed by linear regression (for visual display), while the raw data were analysed by non-linear regression and a one phase decay model to directly estimate half-lives. All analyses were carried out in Graphpad Prism 5.

WHAT WERE THE RESULTS AND WHAT DO THEY MEAN?

3D Imaging Technique Results

We used both files generated from an Artec Spider Scanner and from using images loaded via smartphone to the Crisalix software. Whilst each generated a standard 3D data file that could be used there were noticeable differences in quality and usability.

The Artec produced a file which was made up of an average of 400,000 data points. The Crisalix scan file had around 8000 data points. Typically, the higher the vertex count the more detailed a 3D data file is. This additional detail, however, comes at the cost of greater computational power required when working with the files.

Visually the Artec scanned file showed extensive detail from facial hair and moles to pore indentations. Each Artec scan required extensive post-processing such as smoothing of the face, wireframe reductions, removal or repair of artefacts from the scan in an attempt to reduce the complexity and data size of the file. Even after the post-processing was completed the Artec file would still have a greater number of data points and excessive detail compared leading to a longer and more complicated merging process for the masks.

The fit tests showed no discernible difference between the masks generated using the Artec scanner when compared to the Crisalix software.

Fit Tests Results

The fit testing that was carried out on the Alpha Solway 3030V™ masks showed a failure rate of 24% across the range of volunteers with the majority of failures occurring on female participants (62.5%).

50 participants have been tested, each wearing a custom made 3DPPE mask, and 44 have passed. We found a technical error in early testing and corrected the protocol. Since making this change, and after retesting participants, we have established an 88% pass rate for the new 3DPPE masks.

Preliminary statistical analysis shows that the novel 3DPPE mask is at least as good as the industry standard and NHS-approved FFP3 mask. Summary results are tabulated in Figure 7.

R-COMFI scores reported by participants are shown in Figure 8. Our analysis shows that the 3DPPE masks were significantly more comfortable than the controls. The aggregate comfort score of the new mask also compares favourably with other standard masks reported in previous trials.

We will report further technical analysis of the R-COMFI and MRT data in a future academic publication, but some subjective observations that were common to many participants were that the 3DPPE masks were more comfortable than the control mask, but there was some pinching to the bridge of the nose. We can fix this in a future design revision.

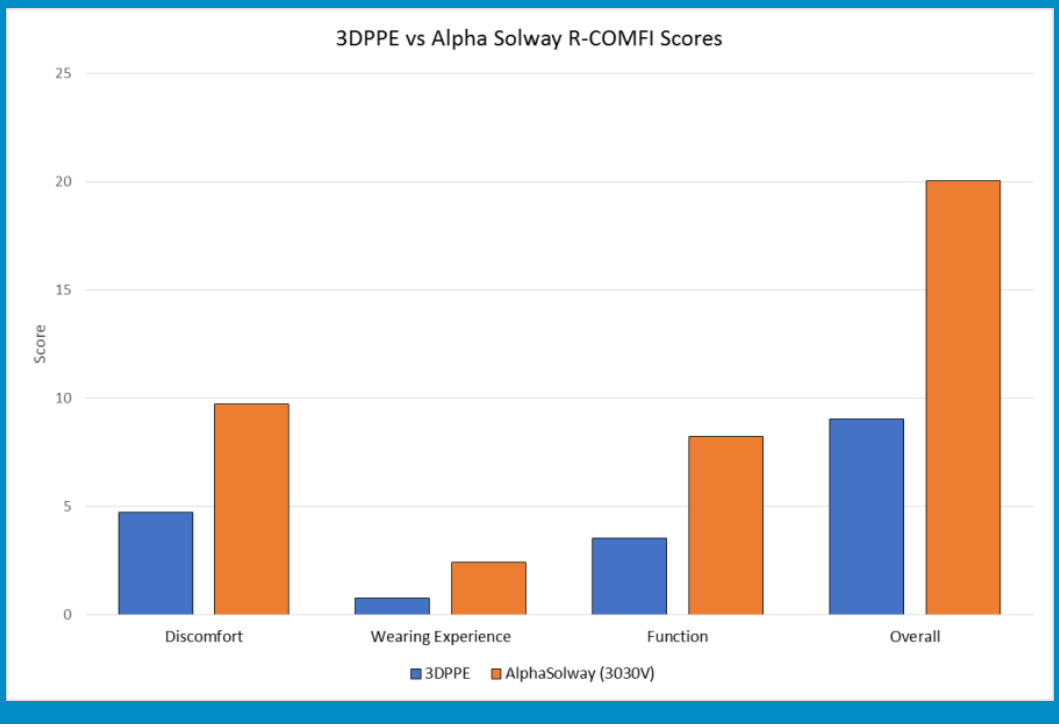
	3DPPE	Alpha Solway			
Pass	44	38		3DPPE Pass Proportion	0.88
Fail	6	12		Sample Size 3DPPE	50
				Alpha Solway Pass Proportion	0.76
Sample Size (N)	50	50		Sample Size Alpha Solway	50
				Pooled sample proportion	0.82
Fail Rate	12.0%	24.0%		Test statistic	1.5617
Pass Rate	88.0%	76.0%		P-value (two tailed)	0.1183
				P-Value (one tailed)	0.0592

Figure (7). Fit Test Results

Figure (8).

R-COMFI Scores

Lower is better



Virology Results

We tested a total of ten different 3D printed materials and three different surface coatings for effects on virus survival in the absence of disinfectants, all in comparison to the polystyrene surface found in tissue culture plastic ware; a material we have previously found to not be notably antiviral.

Virus survival was assayed by sampling virus deposited on the various surfaces across a time course, from 0 hours (actually around 10 minutes) to 24 hours. As expected, virus viability dropped off with time, following an exponential decay curve, so that when data are plotted in log-log format, a straight line can be fitted to provide a visual guide to decay rate (Figure 9).

The likely influence of environmental conditions (e.g. temperature, humidity) could be inferred from variability between experiments; the estimated half-lives of virus on polystyrene varied between 1 h in the first experiment (Fig 9A), 1.2 h (Fig 9B) and 2.6 h (Fig 9C). However, none of the various 3D printer plastics or the coatings applied to them showed any major differential effect on virus viability, with the log-transformed data showing similar slopes and half-lives not varying substantially from the baseline polystyrene material.

In summary, no material that we tested showed any significant difference in the viability of virus survival and this means that we were able to freely choose the most appropriate materials for manufacture based on their mechanical, rather than anti-viral, properties.

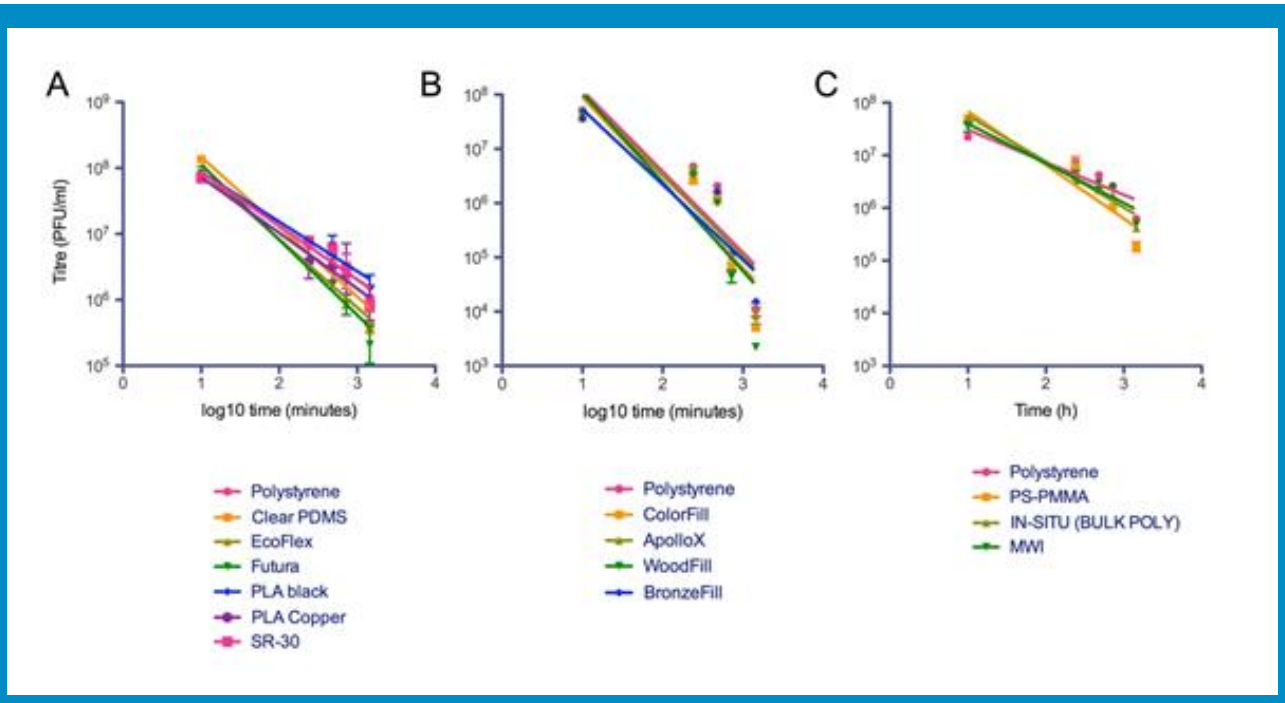
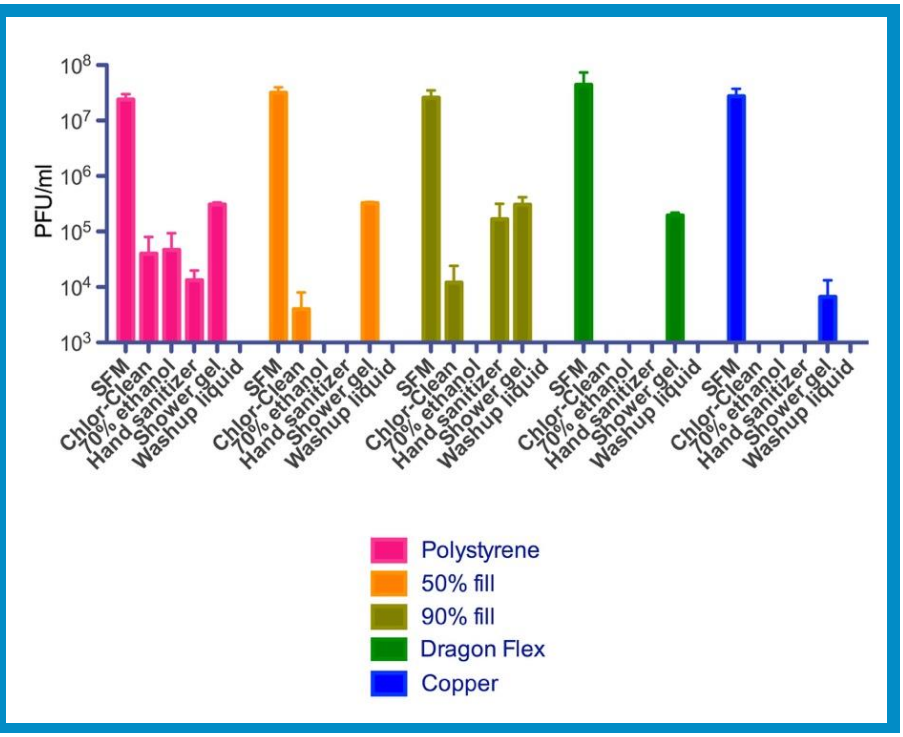


Figure (9). Effect of plastic type on virus viability. Samples of the indicated plastic materials were inoculated with IAV and virus viability measured by plaque assay at 0, 4, 8, 12 and 24h. Data are the Mean± SEM of 3-5 replicates plotted as log10-transformed values and analysed by linear regression.

To assess the ability of the materials to be disinfected by common cleaning agents we tested four materials and five cleaning agents. The latter were: Chlor-Clean (the NHS standard disinfectant), 70% ethanol (as a readily available laboratory disinfectant) and hand sanitiser, shower gel and washing up detergent as disinfectants likely to be widely available in professional and domestic settings. Controls were polystyrene as a neutral surface and tissue culture medium (SFM) as a non-virucidal liquid. In general, diluted shower gel was the least effective disinfectant on all surfaces, but even this reduced viable virus load by over 90% (Figure 10).

Figure (10).

Decontamination of 3D printer plastics. Samples of the indicated plastic materials were inoculated with IAV, allowed to dry and then viable virus measured after treatment with the indicated cleaning agents, or a non-virucidal control (SFM). Data are the Mean± SEM of 3-5 replicates.



Washing up liquid was the most effective agent, removing virus below the limit of detection in all cases. All other cleaning agents worked effectively; Chlor-Clean removed over 99.9% of virus from all 3D printed plastics tested, for instance.

WHAT IMPACT COULD THE FINDINGS HAVE?

Simply put our proposed system would allow each healthcare workers to be fitted with a single re-usable mask at the beginning of an epidemic. The mask can be worn comfortably and safely decontaminated in home and work settings. Remote acquisition of face shape on a normal mobile phone eliminates the burden on hospital administration and allow this system to be used anywhere. Ease of production and elimination of the waste from single use would allow widespread use of FFP3 masks (e.g. medical wards with non-ventilated patients) thus reducing staff infection rates, reducing staff shortages and minimising hospital acquired infection.

Procurement of FFP3 standard single-use facemasks was extremely challenging in the first wave of the pandemic. Fitting healthcare workers to FFP3 masks was a significant resource-heavy burden to the NHS. Fluctuating stock counts of various mask types necessitated the repeated fitting of vulnerable workers to available masks. For some healthcare workers, it was very difficult to find a mask that fitted and in a smaller number, no FFP3 respirator could be provided. Those individuals either had to rely on PAPR (powered air-purifying respirator) hoods or were simply

unable to work in red COVID areas or to perform aerosol generating procedures. Anecdotally female individuals with slim faces were particularly difficult to fit.

Our proposed system of remote image acquisition, remote computer-aided design and 3D print facilitated the manufacture of a bespoke reusable face mask has the potential to 'game change' the efficient and effective provision of appropriate protection for both health care workers and others from viral transmission. Individuals can upload standardised three photographs using the Crisalix™ system. This platform was initially designed to allow visualisation and virtual manipulation of patient images as an aid to plastic surgeons and their patients undergoing cosmetic surgery such as rhinoplasty. Our volunteers found the software is very user friendly.

The trail facemasks were found to be very comfortable to use and by virtue of their bespoke contour have the potential to reduce the incidence of pressure induced discomfort on the nose and cheeks of healthcare workers.

The materials utilised were demonstrated to be essentially impenetrable to viral particles. In addition, we have demonstrated the materials to very effectively decontaminate utilising readily available detergents.

Reusable face masks are potentially more environmentally friendly, more economic and more practical to utilise for example during foreign travel. The COVID-19 pandemic has generated billions of contaminated single-use plastic masks to be sent to incineration and landfill. Waste masks have been found in every global ecosystem.

The designed trial masks relied entirely upon a viral filter for inhalation and exhalation. The elimination of an exhalation valve means that the mask both protects the wearer and those nearby from viral transmission.

Trial masks resulted in similar communication issues as all FFP3 masks. The 'hard casing' welded to the silicone base plate of our mask offers the potential to incorporate communication aids such as microphones, bone conduction hearing aids and external-facing cameras.

HOW WILL THE OUTCOMES BE DISSEMINATED?

Our multidisciplinary research team included a unique combination of engineers, plastic surgeons, speech therapists, virologists, entrepreneurs and simulation suite staff. Each academic discipline in the team has plans to present the work conducted in this project both internally in their respective departments and institutions and at relevant scientific conferences.

We will submit two separate journal papers, one aimed at an engineering audience and one with a more medical angle.

Once our papers have been peer-reviewed and published we will contact media outlets to disseminate the work undertaken, and to showcase how different sectors can work together successfully in the midst of a pandemic.

The team aim to commercialise this work and we are having discussions with a commercial partner and manufacturer who have shown interest. There are also opportunities to talk to and engage with local Maker Spaces and community groups that contributed during the pandemic to show the effort that went into this project and theirs.

The next piece of research from this work is the design of a sensor system for monitoring a constant fit as the current standards only require a fit test to be done once prior to the usage of the mask while we believe there is a lot to be gained from a mask that could both monitor its current fit and also self-adjust to reduce and eliminate any leaks that may occur. Masks designed with an active filter that could be sterilised and reused would also reduce the wastage to a bare minimum.

CONCLUSION

There have been hundreds if not thousands of mask designs created and posted online over the course of the COVID-19 pandemic, few if any of these masks have gone through the rigorous design process, and testing in a clinical environment, that our 3DPPE Mask has done.

We successfully showed that by using either a 3D video scanner or smartphone to generate a 3D model of a participants' head combined with our custom mask we could manufacture individual, reusable, face fitted masks that passed R-N95 standards and could be readily disinfected using commonly available materials.

The ability to remotely acquire images, produce reusable, individually fitted masks which can be readily disinfected has the potential to significantly enhance the rapid provision of FFP masks in future COVID waves and future pandemics.

A team of clinicians and engineers set out to exploit 3D imaging and 3D printing technologies to produce bespoke individually reusable fitted face masks for healthcare workers. We have had success in producing a viable mask prototype.

The efficacy of remote smartphone image upload as a means of producing 3D files for CAD modelling and printing has been proven. Healthcare workers found these masks comfortable to wear in simulated clinical environments, and speech intelligibility scores were similar to comparative FFP3 masks confirming that communication in masks is an issue and making communication aids a further area for development.

The 3D printed plastics that were chosen to be taken forward on the basis of materials science testing could all be effectively disinfected by common cleaning agents and, importantly, washing up liquid can be used to completely disinfect a reusable 3D printed mask.

Our virology testing showed that all of the mask sections could be easily decontaminated and the one part that could not be is the filter, which can be replaced.

There is scope for further improvement, as shown by the subjective evidence on the weight of the mask and the tightness around the nose. To advance the mask further and increase the flexibility of its use we could incorporate communication aids such as microphones, bone-conduction hearing aids and respiratory monitors.

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ADDITIONAL INFORMATION

The project was completed on the 31st October 2020.

We received a grant of £84,000 from the CSO for this work.