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Innovative Face Shields Help Frontliners Face-off COVID-19 Pandemic

Dear Editor,

The COVID-19 outbreak has presented unique challenges[1] and opportunities for innovations towards effective response and overcoming operational constraints.

Personal protective equipment (PPE) is critical to mitigate the risk of infection faced by healthcare workers (HCWs)[2,3] in care settings. Prolonged use of goggles can cause discomfort, pain and facial imprints. Moreover, the lenses tend to fog up, reducing visibility and even resulting in giddiness at times. In response to discomfort, HCWs may be compelled to adjust the goggles, inadvertently exposing themselves to the risk of contamination with blood, bodily fluids and other potentially infectious materials.

Face shields may be a more comfortable alternative to these goggles. Acute shortages due to global supply-chain disruptions in the early course of the pandemic presented our innovation team with an opportunity to swiftly design and develop an ideal face shield for HCWs, to provide robust protection with better fit and comfort. For ease of use and viability, disposability and low-cost factors were noted. Expedited production would address the potential acute shortages.

In response to this challenge, an interdisciplinary team consisting of a design team from the Centre for Healthcare Innovation (CHI), and clinical leads comprising infectious diseases physicians and infection control nurses from the National Centre for Infectious Diseases (NCID) and Tan Tock Seng Hospital (TTSH), came together to develop a low-cost, robust and disposable face shield. Most importantly, the product should be desirable and usable.[4]

The project was initiated on 1 February 2020. The team conceptualised and produced 10 prototypes over a weekend. More than 100 iterations were generated in the subsequent 2 weeks. The team tested prototypes with our clinical leads while concurrently making the necessary iterations.

The team conducted a literature review of face shields used in infection control and identified potential materials such as polycarbonate, polyvinyl chloride (PVC), and polyethylene terephthalate glycol (PETG)[7] to prototype a face shield. After testing the possible plastics available, the team took reference from the design requirements (Table 1) and decided upon the optically clear biaxially oriented polyethylene terephthalate (BoPET) for the prototype's shield.

Table 1. Key design requirements in designing and developing the face shield

Design Requirements	Specific Concerns	
Protective fit	Shield the face with N95 mask on while securely fitting varying head sizes, and not dislodging during usage	
Good visibility	Clear and does not fog up; low refraction and low reflection	
Hygienic	Disposable or easy to wipe down	
Wearability	Easy to don and remove	
Accessibility	Made of materials that are easy to procure	
Scalability	Easy to manufacture in large quantities via die-cutting manufacturing process for plastic shields	
Cost-effectiveness	1. Iterative 3D printing technology incurs lower manufacturing costs compared to traditional injection moulding (up to 5-figure cost savings). 2. Unit cost price is comparable to or cheaper than commercially available options	
	Design 1: **Disposable Face Shield** Cheaper by at least 30% compared to commercially available options	**Design 2: Spectacle Face Shield** Lower running cost with savings of >50% after the 10th use

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The team utilised different prototyping tools and techniques like 3D printing to produce the face shield frame. This reduced turnaround time and facilitated quick customisation to fit users' needs, and allowed continuous testing and refinement of design iterations without incurring costly tooling and moulding expenses.

A user-centric design process based on the 4 phases of the British Design Council's Double Diamond approach of discover, define, develop and deliver, was employed to rapidly design and develop the face shield prototype. This creative process utilises a combination of divergent and convergent thinking that enabled the team to target pertinent issues. By delving into the issues collaboratively through concurrent user interviews and testing, a design prototype that effectively addressed user needs was created.[5] Through internal trials at the NCID screening centre, NCID wards and TTSH general wards, the prototypes were used to validate requirements, reveal critical design concerns,[6] collect instant feedback and encourage openness to alternative design suggestions by end users.

Further key design requirements were identified through an understanding of user's needs. These were taken into consideration during selection of materials for the prototyping and design process. For example, in view of wearability, infection control staff on the team ensured design iterations were within their guidelines for safe removal. The result was a design that allowed shield detachment without skin contact and seamless incorporation of shield removal (and safe disposal) within the established TTSH PPE removal procedure.

Face shields offer sufficient protection against splash incidents but can still cause facial imprints, especially if they are uncomfortable to wear. The team resolved this issue by introducing an elastic band (Design 1, Fig. 1) and a flexible 3D-printed frame (Design 2, Fig. 1).

Two high fidelity[8] prototypes were selected after user testing and usability testing. User testing validates the user's demand for the face shields, and usability testing was conducted using the mask fit test to ensure that the face shields offer splash protection without compromising the safety offered by N95 masks.

A pilot trial of the two prototypes was initiated in week 2 and completed by the end of week 3, with a total of 75 responses from user testing surveys conducted with clinical staff from NCID and TTSH.

Overall, the selected designs received positive comments of being more comfortable and easier to wear than goggles. The proof-of-value trial revealed that 78.5% of users were "likely" and "very likely" to recommend the 2 prototypes to their colleagues, based on the Net Promoter Score.[9] A small percentage commented that reflection and refraction of light caused discomfort and vision limitations. The tasks at hand, duration and environmental factors like lighting were

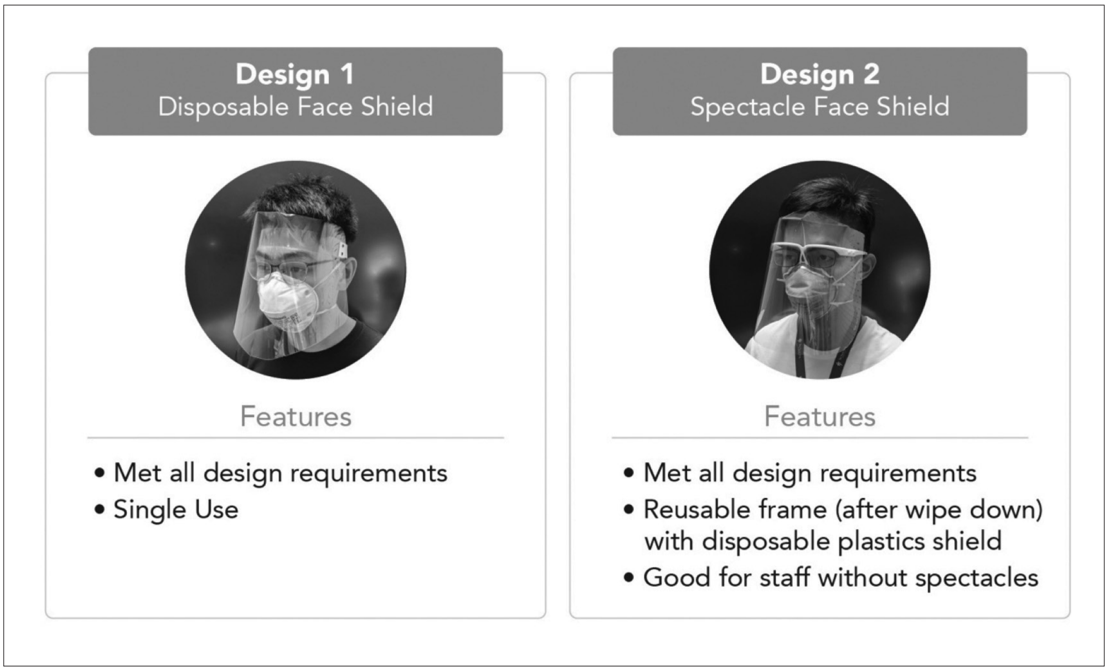

Fig. 1. Prototypes selected for internal use and trial

identified as key influencers. In response, the team further explored ways of blocking light through material selection and design enhancement to reduce the refraction and reflection issues faced by users.

We further established that the Disposable Face Shield (Design 1, Fig. 1) was more suitable for HCWs in routine clinical care in inpatient settings, as a disposable product per patient use. On the other hand, the Spectacle Face Shield (Design 2, Fig. 1) was more suitable in ambulatory settings, such as the screening centre, where more extended use of the face shield is desired.

The team applied a systematic prototype selection for preproduction by evaluating prototype desirability, feasibility and viability.[10] A successful design prototype has to meet the end-user needs (desirability), be ready for scaling-up through ease of manufacture (feasibility), be cost effective to the organisation (viability), and be made of environmentally friendly material (sustainability). The team also adhered to the principles of "good design" as defined by the industrial designer Dieter Rams by keeping the form simple and avoiding unnecessary complexity.[11]

After evaluation, both Design 1 and Design 2 were selected for production and use within defined areas of TTSH and NCID, based on user preferences and usage needs.

From user feedback, protection offered by our in-house face shield prototypes are comparable to commercially available goggles and visor masks for splash protection. These prototypes provide greater comfort and better fit, as evidenced by HCWs' feedback from the pilot trial.

We consider the success of our rapid innovation to be possible due to a combination of factors. Firstly, we adopted an inter-disciplinary approach with input from the TTSH and NCID clinical teams and support from the design team at CHI Living Lab (CHILL). Secondly, we applied an agile user-centric design process with each prototype development phase driven to meet users' needs. Thirdly, the team had access to CHILL, a purpose-built maker space within CHI, which supports ground-up innovations in collaboration with in-house service, industrial designers and engineers. The design team was able to make full use of the facility and its equipment, such as workshop tools and 3D printers, to quickly fashion face shield components and assemble the pieces. Lastly, the use of 3D printing technology[12] allowed demand-driven manufacturing with less material waste and real-time prototype development and evaluation.

As continuous improvement is part of TTSH's innovation culture, the face shield prototypes will continue to be iterated based on feedback from end users. Through our initial testing processes, the current prototypes have proven capable of providing sufficient protection to HCWs on the frontline.

One possible area to target for future improvement is visibility. While design changes were made to reduce the mild discomfort and limited vision experienced by some users due to the reflection and refraction of light through the plastic, choice of material and curvature of the shield could be further improved.

Using a lean, iterative user testing approach, at least 10 users were recruited from each site to validate the design features and uncover potential usability issues. While our trial sample size was relatively small, it was deemed sufficient as it has been shown there is minimal value in recruiting a large number of users when collecting qualitative feedback, due to a saturation point where feedback from the sixth user onwards typically becomes repetitive.[13] Testing with a small group of users after each iteration allowed the team to efficiently and continuously gain new insights. Moving forward, the team could obtain user feedback after scaling across to users in other industries (such as surveillance staff at border control checkpoints). This would add greater credibility to the viability of the innovation for a wider market.

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