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Original Article

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Evaluation of Face Shields, Goggles, and Safety Glasses as a Virus Transmission Control Measure to Protect the Wearer Against Cough Droplets

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Abstract

Face shields (also referred to as visors), goggles and safety glasses have been worn during the COVID-19 pandemic as one measure to control transmission of the virus. However, their effectiveness in controlling facial exposure to cough droplets is not well established and standard tests for evaluating eye protection for this application are limited. A method was developed to evaluate face shields, goggles, and safety glasses as a control measure to protect the wearer against cough droplets. The method uses a semi-quantitative assessment of facial droplet deposition. A cough simulator was developed to generate droplets comparable to those from a human cough. The droplets consisted of a UV fluorescent marker (fluorescein) in water. Fourteen face shields, four pairs of goggles and one pair of safety glasses were evaluated by mounting them on two different sizes of breathing manikin head and challenging them with the simulated cough. The manikin head was positioned in seven orientations relative to the cough simulator to represent various potential occupational exposure scenarios, for example, a nurse standing over a patient. Droplet deposition in the eyes, nose and mouth regions were visualised following three 'coughs'. Face shields, goggles, and safety glasses reduced, but did not eliminate exposure to the wearer from droplets such as those produced by a human cough. The level of protection differed based on the design of the personal protective equipment and the relative orientation of the wearer to the cough. For example, face shields, and goggles offered the greatest protection when a cough challenge was face on or from above and the least protection when a cough challenge was from below. Face shields were also evaluated as source control to protect others from the wearer. Results suggested that if a coughing person wears a face shield, it can provide some protection from cough droplets to those standing directly in front of the wearer.

Keywords: cough; COVID-19; droplets; exposure; face shield; goggles; safety glasses; virus transmission.

What's important about this paper?

Face shields, goggles, and safety glasses have been worn during the COVID-19 pandemic as one measure to control transmission of the virus, but their effectiveness in controlling facial exposure to cough droplets is not well established and standard tests for evaluating eye protection for this application are limited. Using simulated coughs, this study demonstrated that these devices can decrease, but not eliminate exposures. The best performing face shields had larger than average visor areas, and wrapped around the face.

Introduction

Background

Face shields (also referred to as visors), goggles, and safety glasses have been worn during the COVID-19 pandemic as one measure to control transmission of the virus. There are a number of studies that advise the use of eye protection to prevent contamination from external droplets and aerosol (Napoli *et al.*, 2020; Scalinci and Battagliola, 2020) and associate eye protection with a lower risk of infection (Chu *et al.*, 2020; Singh *et al.*, 2021).

A medical face mask is considered a medical device and its primary intended use is to protect others from infective agents emitted by the wearer (BSI, 2019). A particle filtering half mask (respirator) is considered personal protective equipment and is worn to protect the wearer against solid and liquid aerosols (BSI, 2009). A face covering is broadly defined as something which safely covers the nose and mouth and is not considered a medical device or PPE (MHRA, 2021). Face shields have many advantages when compared to other face masks or coverings. They are robust, more comfortable, make it less likely for the wearer to touch their face, ease breathing, can be disinfected, reused, and communication is easier than when wearing a face mask or covering (Li *et al.*, 2020; Verma *et al.*, 2020; Salimnia *et al.*, 2021; Singh *et al.*, 2021). In public and occupational settings, individuals are wearing face shields in place of, or in conjunction with, respirators, medical face masks, or face coverings.

Some studies have concluded that face shields alone do not provide an adequate level of protection to the wearer against an infectious aerosol and that they should be worn in conjunction with other personal protective equipment (PPE) or a medical face mask (Lindsley *et al.*, 2014; Roberge, 2016; Samaranayake *et al.*, 2020; Salimnia *et al.*, 2021). Although the use of face shields can substantially reduce the short-term exposure of the wearer to larger infectious aerosol particles and reduce contamination of a face mask or respirator worn underneath, face shields are less effective against smaller particles, which can remain airborne for extended periods and can easily flow around a face shield to be inhaled (Lindsley *et al.*, 2014).

Some studies have considered the effectiveness of face shields as source control to protect others from the wearer (Anon *et al.*, 2020; Verma *et al.*, 2020; Li *et al.*, 2021). Face shields were found to prevent the forward motion of the expelled droplets, deflecting them downwards with smaller droplets remaining suspended. Grinshpun and Yermakov (2021) found that wearing a face shield caused reduction in the forward travel of a simulated cough aerosol from a manikin, but substantially elevated levels occurred sideways and backwards. Pan *et al.* (2021) found droplets smaller than 0.7 µm travelled around the face shield but the face shield exhibited overall protection efficiencies of ~75% (as source control) and ~25% (to wearer) for 5 µm particles. Wendling *et al.*, (2021) found that for short, close range exposure scenarios, when the receiver alone wore a face shield rather than a medical face mask (type I), there was a significant reduction in the number of particles, even with small particle size emission (~ 0.3 µm). Conversely however, Lindsley *et al.* (2021) found that while an N95 respirator blocked 99% of the total mass of a simulated cough aerosol from a manikin from being released into the environment, a face shield blocked only 2% of the total aerosol.

Anon *et al.* (2020) and Ko-Keeneya *et al.* (2020) considered the effect of a modified face shield design on the protection it provided. Both studies found a modified design that was more enclosed around the base of the chin provided more effective protection. Anon *et al.* (2020) found that when wearing a familiar single-use standard face shield design, a simulated cough from the wearer was scattered along the side and lower parts of the visor and spray was observed across a significant part of the wearer's shirt. Ko-Keeneya *et al.* (2020) also considered the relative head orientation of the wearer to the source of the cough and determined that there is inadequate protection provided by face shields of the common design particularly when leaning over the coughing person, exposing areas of the face and neck.

Performance testing of face and eye protectors and the aim of this study

Eye protectors are tested to the European standard BS EN 166:2002 (BSI, 2002a) before being placed on the UK market. This standard considers the basic optical and non-optical requirements applicable to all eye protectors and lists particular and optional tests specific to particular applications.

BS EN 166:2002 does not include a test to evaluate protection afforded to the eyes against biological hazards. However; it does reference Clause 12 of BS EN 168:2002 (BSI, 2002b) as a method for testing against droplets and fluids. Here, the tests vary according to whether the eye protector is goggles (providing protection against droplets) or a face shield (providing protection against larger splashes of liquid). There is no standard test to determine the splash protection of safety glasses. Face shields are not challenged by splashes in the standard test. As a surrogate, the face shield is required to cover a rectangular region around the eyes of a standard head form. The area of coverage is assessed by directing a laser towards this region whilst rotating the head form in various orientations to ensure the face shield continually intercepts the light.

Since the start of the COVID-19 pandemic, there has been an increase in the research published in this field. Throughout the COVID-19 pandemic, decisions, and guidance have been based on best available evidence which, particularly at the outset, has been limited. The Health and Safety Executive (HSE) is the market surveillance authority for PPE in Great Britain. HSE worked with public health regulatory bodies in the UK and industry to publish PPE guidance for workplaces and the public. However, as new evidence emerged, this has needed to be reviewed and updated regularly. Early in the pandemic, it was broadly believed that the main transmission vectors did not include airborne virus, therefore control measures were designed to protect individuals from cough droplets when working in close contact and where social distancing was not possible. Evidence latterly confirmed that the virus could be spread via airborne transmission. One such example is the guidance in Great Britain for close contact services such as hairdressers and barbers, spas, beauty salons, tattoo, and photoshoot studios (BEIS and DCMS, 2021). In July 2021, it advised that workers should 'wear further protection' against the COVID-19 risk. The guidance specified that this should be a face shield to provide a barrier between the wearer and the client from respiratory droplets caused by sneezing, coughing, or speaking and there was no requirement for the client or practitioner to wear any additional protection or source control such as a mask or face covering, when the practitioner was wearing a visor. This suggested that the face shield was being worn to protect the worker but may also provide some protection to the client in this instance. Throughout the pandemic, this guidance has had many iterations, including the requirement for the client to wear a face covering, the addition of face masks for the practitioner then the easing of restrictions meaning that face coverings were no longer required by law (BEIS and DCMS, 2021).

This paper describes how HSE researchers developed a method to evaluate the protection afforded to the wearer of safety glasses, goggles, and face shields against droplets in such a way that is appropriate and proportionate to the risks associated with COVID-19. The method builds on BS EN 168:2002 with fluorescence visualisation techniques. It uses a human cough simulator adapted from an existing design for influenza and a manikin head. The paper also describes the findings from the use of this method to evaluate a range of safety glasses, googles, and face shields procured by the UK Government. The research findings have informed HSE decision making and the development of evidence-based guidance for the control of COVID-19 transmission in workplaces.

Methods

A cough simulator was adapted from an existing design (Lindsley *et al.*, 2013) which was based on flow rate measurements of coughs from 47 human subjects with influenza (Lindsley *et al.*, 2010). The simulator used in this study had a 'drive cylinder' that ejected 4.2 litres of air from a 'lung cylinder' through a 'mouth' outlet (Fig. 1). The flow rate against time profile matched the target profile presented by Lindsley *et al.* (2010). The outlet was connected perpendicularly to a plastic pipe (1.1 m length × 0.04 m diameter). One end of the pipe was connected to a Badger 200 Airbrush (Badger Air-brush Co, USA) used to spray an aqueous solution of 0.1% fluorescein into the pipe to prime it with airborne droplets. The drive cylinder was drawn to the back of the simulator and both sides of the drive cylinder were pressurised in equilibrium before depressurising the piston rod side to initiate the cough. The simulated human cough thus generated was directed towards a breathing manikin head.

A bespoke test rig on which to mount the manikin heads was constructed following the design described in BS EN166 (BSI, 2002b). The rig enabled the head to be tilted forward, backward, and rotated side to side and locked in the required position. Tubing joined a connection beneath the neck of the head to a breathing machine (Inspec International Ltd). This was operated at a breathing frequency of 20 breathing cycles per minute

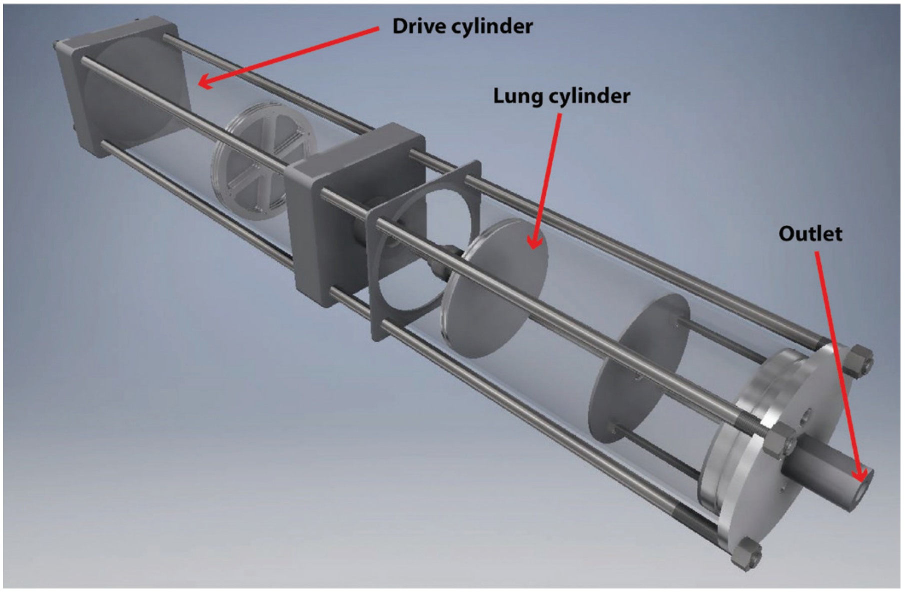

Figure 1. Design of the HSE cough simulator with the barrels transparent.

and a tidal volume of 2 l to give a ventilation setting of 40 l min^{-1} as described in BS ISO 16900-5 (BSI, 2016).

Tests were conducted in a wooden test room (Supplementary Fig. SF1, available at *Annals of Occupational Hygiene* online) with internal dimensions of 3 m *H* × 4 m *W* × 4 m *D*.

Fourteen face shield models were tested. These were sourced from the stockpile of PPE that had been centrally procured by the United Kingdom Government for supply to the National Health Service (NHS) and wider health and social care. All models were evaluated within the context of European Commission recommendation 2020/403 to meet the increased demand for PPE during the COVID-19 pandemic (EU, 2020). According to the stockpile database, twelve of the fourteen face shields were CE marked, i.e. they conformed to European health, safety, and environmental protection standards as affirmed by the manufacturer or importer. Each face shield was removed from its packaging and assembled where applicable. The face shield's dimensions (Supplementary Fig. SF2 and summary Table ST1, available at *Annals of Occupational Hygiene* online) were measured with a steel ruler or flexible tape measure, where appropriate, before mounting the face shield on a manikin head. There was a broad variation in the dimensions and design across the fourteen face shields e.g. the overall length of the face shield ranged 139–310 mm and the distance from the face shield to the ear ranged from an overlap of 25 mm to a gap of 70 mm. Ten of the face shields had foam headbands; four required self-assembly which involved adhering a foam headband to the clear visor material in two instances and clipping a plastic headband to the clear visor material and attaching elastic straps for the other two. Twelve were made all from plastic material; two had cardboard headbands and straps, with one of these having a cardboard surround to the clear visor material.

Two manikin heads were used (Supplementary Fig. SF3, available at *Annals of Occupational Hygiene* online). The smaller head size is described in BS ISO 16900-5 (BSI, 2016) and the larger head was based on the 'Sheffield head' (Inspec International Ltd). Both were chosen by the authors to represent male and female head forms. The larger manikin head had a circumference of approximately 59 cm and the smaller head had a circumference of approximately 52 cm.

Sampling templates were laser-cut from laboratory Cytiva Whatman Benchkote Surface Protector (Fisher Scientific UK Limited), an absorbent paper fibre-based material with a plastic backing, which had previously been shown to be non-UV fluorescent. The dimensions of both templates are shown in Supplementary Fig. SF4 (available at *Annals of Occupational Hygiene* online). Two templates, one for each manikin head size, were designed to capture deposit of fluorescein droplets on the face of the manikin head, the templates being delineated into three regions: eyes, nose, and mouth. The templates were pre-labelled according to the face shield model, manikin head size, and position. The appropriately sized template was placed over the face of the manikin head, an example shown in Fig. 2, and secured in place using adhesive tape over tabs at the sides of the eye and mouth sections.

An ultraviolet (UV) light (Titan365 UV LED, UV Light Technology, Birmingham, UK) was used to confirm that the sample was devoid of any fluorescence before proceeding. The face shield was then mounted on the head following the manufacturer's instructions, where provided and the manikin head was adjusted to the required position. The distance between the edge of the face shield and the base of the ear was measured on each side to determine the extent of coverage of the face. Any other observations were also noted.

The test set-up is shown in Fig. 3. The cough simulator was positioned 60 cm in front of the manikin head and level with the eyes consistent with distances in challenge tests described in BS EN166 (BSI, 2002b) (Fig. 3). Preliminary experiments delivering a cough to the manikin heads without face shields in place confirmed the even distribution of droplets across the templates.

Each 'cough' was synchronised with the inhalation phase of the breathing cycle and repeated three times as quickly as possible, which in practice was approximately 30 s due to the time required to re-prime the cough mechanism. After three consecutive 'coughs', the face shield was removed and the template was taken off the manikin head, handling only the tabs/tape to avoid cross-contamination of the deposition areas, then replaced with a new sample. Exposed samples were removed from the test area and stored in a clean space ready for further analysis.

Each test was conducted with the following manikin head positions described in BS EN166 (BSI, 2002b), using a new absorbent material sample template but the same face shield, taking care not to cross contaminate the sample:

- Position 1: Facing forwards with the head face on.
- Position 2: Facing forwards and rotated 45° backwards (front and looking up).
- Position 3: Facing forwards and rotated 45° forwards (front and looking down).
- Position 4: Rotated 90° to the left and rotated 45° backwards (left and looking up).
- Position 5: Rotated 90° to the left and rotated 45° forwards (left and looking down).
- Position 6: Rotated 90° to the right and rotated 45° backwards (right and looking up).
- Position 7: Rotated 90° to the right and rotated 45° forwards (right and looking down).

Once all sample positions had been tested for each face shield, the room, which was fitted with a HEPA filtered horizontal displacement system, was ventilated at a flow rate 1.2 m^3 s^{-1}, previously calculated to clear the room

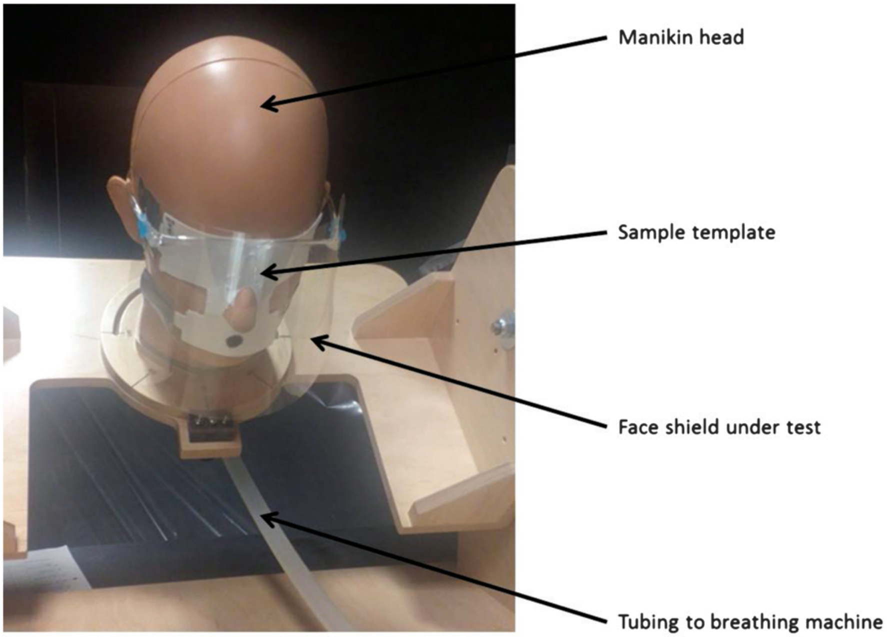

Figure 2. A sample template fixed to the manikin head whilst attached to the test rig. The manikin head is attached to the breathing machine via tubing at the neck.

of airborne particles in 40 s, but was done for 2 min. This was as a precaution against build-up of airborne fluorescent particles that could over time have led to cross-contamination.

The protocol was undertaken in triplicate with both the large and small manikin heads attached to the manikin rig and using each of the test face shields.

Four different models of goggles, also sourced from the NHS stockpile of PPE, and one pair of safety glasses, as used in the authors' laboratories, were also tested following the same method but with an adapted template (Supplementary Fig. SF5, available at *Annals of Occupational Hygiene* online). A description of each pair of goggles can be found in Supplementary Table ST2 (available at *Annals of Occupational Hygiene* online).

A set of tests were undertaken to observe the ability of a face shield to contain a cough. The large manikin head on the test rig used in previous tests (Fig. 2) was fitted with a standard template as shown in Supplementary Fig. SF4 (available at *Annals of Occupational Hygiene* online). For these tests, this head was referred to as the 'receiver'. The outlet of the cough simulator was then fitted to a second large manikin head at the cough delivery point as shown in Fig. 4. This manikin head was referred to as the 'wearer'. The same template was fitted to the receiver with a larger cut out at the mouth to ensure that the cough simulator's outlet was unobstructed. The 'mouth' of the 'wearer' was positioned 60 cm in front of the 'receiver' level with the 'eyes'. Tests were run as before with three consecutive coughs but only using sample position one. Five face shields were chosen for testing which covered a range of visor lengths and widths.

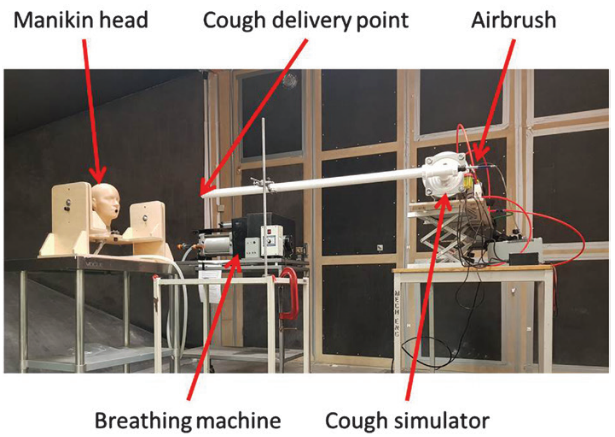

Figure 3. Cough simulator positioned in front of the manikin head rig and breathing machine to the side.

Figure 4. Cough simulator cough delivery point attached to the 'wearer' manikin head.

Sample analysis

Detection of fluorescent deposition on all of the sampling templates in this study was done by a single analyst. This was based on their ability to visualise small deposited fluorescent droplets with the unaided eye. While it is acknowledged that to some extent this method of detection is subjective compared, for example, to elution and chemical detection of fluorescein as described by other researchers (Weber *et al*., 2019), semi-quantitative visual detection enabled larger numbers of replicate tests to be conducted within the resources available. Each sample was viewed under UV light and the presence or absence of fluorescent deposits in each region of the sample, i.e. the facial areas surrounding the eyes, nose, and mouth as covered by the sampling template, was recorded separately. In addition, the level of contamination in each of the three regions was classified as 'Low', 'Medium' or 'High' by visual comparison to templates previously prepared with fluorescent deposits. This semi-quantitative method of classification is comparable to that used for example in reading dip slides for detection of microbial contamination in water samples. Examples of each of the three categories are shown in Supplementary Fig. SF6 (available at *Annals of Occupational Hygiene* online). To aid analysis, each classification was also assigned a numerical score. Undetectable contamination = 0, low = 1, medium = 2, and high = 3.

Results

Tables 1–3 show the mean levels of contamination in the eyes, nose, and mouth regions respectively when the manikin head was wearing each face shield. The mean levels of contamination in the eyes, nose, and mouth regions of an exposed manikin head and a coughing manikin head when the coughing head was wearing five of the face shields is shown in Table 4. Mean levels of contamination in the eye region when wearing each of the four goggle types and one safety glasses type (G1–G4 and SG1 respectively) is shown in Table 5.

Discussion

In this study, face shields covering a range of different designs were tested. While all offered some level of protection from a simulated cough challenge, none eliminated exposure. Tables 1–3 rank the face shields tested in order from best to worst for eyes, nose, and mouth regions respectively. As may be expected, for both head sizes, the face shield offered the greatest overall protection when the manikin head was either face on (orientation 1) or looking down (orientation 3 front on; orientation 5 turned to the left and orientation 7 turned right). The face shield offered the least protection when the manikin heads were looking up (orientation 2 front on; orientation 4 turned to the left and orientation 6 turned to the right).Overall, the greatest challenge to the level of protection afforded by face shields was in the mouth region. In this region UV fluorescence deposition was highest, as depicted by the darkest grids, totalling 88 out of a possible 196 (44.9%), compared to 50 at the eye region (25.5%) and 36 at the nose region (18.4%). This data supports the need for a further level of protection in the mouth region when working in close contact with patients and not undertaking aerosol generating procedures.

In summary, for any face region, face shields offer the greatest protection when a cough challenge is face on or from above (when the manikin head was tilted forward) and offer least protection when a cough challenge is from below, (when a manikin head is tilted backward). This has implications for situations where face shields are typically worn, for example in healthcare if the wearer is standing over an infected patient providing treatment, the angle of exposure is likely to come from below.

Across all three face regions (eyes, nose, and mouth), the face shield designs that offered greatest protection against a cough challenge tended to be those with the most wrap around the face. This is exemplified by the width of the gap between the edge of the visor and the ear, that is, the smaller the gap the more the face shield wraps around the head. For example, face shield 6 had a gap from visor edge to ear of 9 mm on the large head and 8 mm on the small head (Supplementary Fig. SF7a, available at *Annals of Occupational Hygiene* online). With this face shield, only three instances of high level contamination were recorded in the mouth region with the small head and none with the large head. Conversely, the poorest performing face shields had wrap around less than many of the other face shields tested. For example, face shield 14 had a gap from visor edge to ear of 72 mm on the large head and 70 mm on the small head (Supplementary Fig. SF7b, available at *Annals of Occupational Hygiene* online). With this face shield, five instances of high level contamination were recorded with both small and large head. This emphasises the importance of being able to choose a face shield size and design that matches the wearer.

The two most protective face shields (6 and 11) were ones with larger than average (width and length) visor areas, while the worst performing ones in this study (13 and 14) both had smaller than average visor areas.

Table 1. Face shields ranked best to worst based on the level of contamination in the eye region on small and large manikin heads: lightest—low, to darkest—high, none (–).

Ranking*	Face shield	Head orientation														Total High/ Medium/low contamination	
		1		2		3		4		5		6		7			
		Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large
1	11		–													0/1/6	1/1/4
2	6					–					–				–	2/0/4	0/0/5
3	7															1/1/5	2/2/3
4	9		–													1/3/3	1/1/4
5	8															1/2/4	1/3/3
6	2															0/4/3	2/1/4
7	1						–				–					3/3/1	0/4/1
8	12									–						2/1/3	2/2/3
8	10					–										2/2/2	2/1/4
10	4						–				–					2/1/4	3/0/2
11	3		–			–	–			–	–					3/1/1	2/1/1
12	5					–										2/2/2	3/0/4
13	14	–				–										3/1/0	3/2/2
14	13		–													3/3/1	3/2/1
Total high contamination		0	0	5	8	0	0	9	7	1	0	10	9	0	1		
Total medium contamination		6	2	5	5	3	0	4	4	1	3	1	3	5	3		

Head orientations: 1—facing forwards, 2—facing forwards looking up, 3—facing forwards looking down, 4—facing left looking up, 5—facing left looking down, 6—facing right looking up, 7—facing right looking down.
*Ranking criteria is the highest frequency of high level contamination, followed by the highest frequency of medium level contamination, followed by the highest frequency of low level contamination.

Table 2. Face shields ranked best to worst based on the mean level of contamination in the nose region on small and large manikin heads: lightest—low, to darkest—high, none (–).

Ranking*	Face shield	Head orientation														Total high/ medium/low contamination	
		1		2		3		4		5		6		7			
		Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large
1	6									–	–				–	1/1/4	0/1/4
2	2		–											–		0/2/4	1/1/4
3	11						–					–	–	–		0/1/4	1/3/1
4	1						–									1/3/3	0/2/4
5	9		–			–							–		–	1/3/2	1/0/3
6	8															1/1/5	1/2/4
7	4		–								–					0/3/4	2/1/2
8	7		–													1/1/5	1/4/1
9	10					–										1/4/1	1/2/4
10	3					–					–				–	1/2/3	2/1/2
11	5					–				–						1/3/1	3/1/3
12	14	–														2/2/2	2/3/2
13	13	–				–	–									2/1/2	3/3/0
14	12		–													3/1/3	3/2/1
Total high contamination		0	0	7	8	0	0	1	6	0	0	7	7	0	0		
Total medium contamination		1	3	5	4	0	0	10	6	4	5	4	3	4	5		

Head orientations: 1—facing forwards, 2—facing forwards looking up, 3—facing forwards looking down, 4—facing left looking up, 5—facing left looking down, 6—facing right looking up, 7—facing right looking down.

*Ranking criteria is the highest frequency of high level contamination, followed by the highest frequency of medium level contamination, followed by the highest frequency of low level contamination.

Table 3. Face shields ranked best to worst based on the mean level of contamination in the mouth region on small and large manikin heads: lightest—low, to darkest—high, none (–).

Ranking*	Face shield	Head orientation														Total high/medium/low contamination	
		1		2		3		4		5		6		7			
		Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large
1	6		–								–		–			3/1/3	0/1/3
2	11															2/2/3	1/5/1
3	2					–										1/5/0	2/3/2
4	9															3/4/0	1/3/3
5	3															3/3/1	3/1/3
6	1															4/2/1	2/3/2
7	4		–				–									4/1/2	3/2/0
8	5															4/1/2	3/2/2
9	7															2/5/0	5/0/2
10	8															2/5/0	5/2/0
11	12															4/1/2	4/1/2
12	10															5/0/2	4/1/2
13	13															5/0/2	4/3/0
14	14					–										5/0/1	5/2/0
Total high contamination		0	1	13	12	0	0	12	10	5	4	11	10	5	5		
Total medium contamination		6	4	1	2	5	4	2	3	5	8	2	2	9	6		

Head orientations: 1—facing forwards, 2—facing forwards looking up, 3—facing forwards looking down, 4—facing left looking up, 5—facing left looking down, 6—facing right looking up, 7—facing right looking down.
*Ranking criteria is the highest frequency of high level contamination, followed by the highest frequency of medium level contamination, followed by the highest frequency of low level contamination.

Table 4. Mean level of contamination in the eye, nose, and mouth regions when the coughing manikin head wore a face shield and the receiver did not: lightest—low, darkest—medium, none (–).

Face shield	Contamination on face of wearer			Deposition on face of receiver		
	Eyes	Nose	Mouth	Eyes	Nose	Mouth
1						
2		–				
6				–		
10						
14						

Face shields 6 and 11 had cardboard headbands and straps, which tended to be less pliable than those with flexible plastic headbands. Their close fit meant they either touched or pressed heavily against the nose on both manikin heads, suggesting discomfort during normal wear. As a result, it is possible that they would be tipped backward when worn and likely to afford less protection than was achieved during testing. The close fit may also make these models incompatible with some respirators that may need to be worn when undertaking aerosol generating procedures in healthcare. Of the poorly performing face shields, face shield 13 had a foam headband, however, rather than an elastic strap it had two notched plastic straps that slotted together. Face shield 14 had a plastic headband and thin rubber bands in place of a strap, with a noticeable gap between the headband and the forehead when worn on both manikin heads.

Greater protection was probably more influenced by the overall shaping of the visor. While it was assumed that the presence of a foam headband would provide greater protection, especially to the eyes and nose, this was not borne out as both best and worst performers had foam headbands. However, one of the poorer performers did have an obvious gap between the headband and the forehead.

With the cough simulator was configured to deliver a cough through a manikin head wearing five representative face shields (wearer), it was found that all those tested mitigated exposure to a manikin directly in front (receiver), with only one (face shield 10) allowing medium level deposition (Table 4). There were only two instances of self-contamination of the face inside the face shield, face shield 1 in the nose region and face shield 14 near the eyes, the latter possibly due to a funnelling effect due to the gap between the headband and the forehead as previously discussed. This suggests that wearing a face shield can provide some protection from cough droplets to those standing directly in front of the wearer. This was consistent with the findings from previous studies (Grinshpun and Yermakov, 2021; Pan *et al.*, 2021; Wendling *et al.*, 2021), while our data indicated greater exposure mitigation was possible than that suggested by another recent study (Lindsley *et al.*, 2021).

All the goggles tested allowed medium level exposure; even the best performing goggles (G4) allowed on average four medium level exposures across the seven orientations on the small head and five medium level exposures across the seven orientations on the large head (Table 5 and example in Supplementary Fig. SF8a, available at *Annals of Occupational Hygiene* online). Deposition was detected in every test; there were only seven instances where low deposition was detected across the 56 data points for the small head (12.5% of the total number) and five out of 56 (8.9%) for the large head.

In measuring the eye protection afforded by goggles there was some similarity to the face shield with regard to manikin orientation. For example, the manikin head orientations in which goggles provided greatest eye protection were with the head looking down (orientation 5; left looking down) for both head sizes but with slightly greater protection on the large head; and orientation 7 (right looking down) on both size heads. Also consistent with face shields, orientations that were least protective were looking up; orientation 6 (right looking up) yielded two high level and two medium level depositions on each size head, as did orientation 4 (left looking up) on the large head. However, no firm conclusions could be drawn about the level of deposition on the face in relation to the presence of vents in the goggle design, although gaps when fitted to the manikin heads could have contributed (see example in Supplementary Fig. SF8b (available at *Annals of Occupational Hygiene* online) with worst performing goggle G3). While the best performing goggles (G4) were observed to achieve a good seal around the forehead and cheeks, which may have improved performance.

Safety glasses were much less protective than goggles (Table 5), allowing high level exposure in five out of seven orientations and lesser exposure only with the

Table 5. Goggles and safety glasses ranked best to worst based on the mean level of contamination in the eye region: lightest—low, to darkest—high.

Ranking*	Goggles/ safety glasses	Head orientation														Total high/ medium/low contamination	
		1		2		3		4		5		6		7			
		Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large
1	G4															0/4/3	0/5/2
2	G2															0/5/2	0/5/2
3	G1															1/6/0	0/6/1
4	G3															0/5/2	2/5/0
5	SG1															5/1/1	5/1/1
Total high contamination—goggles		0	0	0	0	0	0	0	1	0	0	1	1	0	0		
Total medium contamination—goggles		4	4	3	4	1	4	3	2	4	2	2	2	3	3		
Total high contamination—safety glasses		1	1	1	1	1	1	1	1	0	0	1	1	0	0		
Total medium contamination—safety glasses		0	0	0	0	0	0	0	0	0	0	0	0	1	1		

Head orientations: 1—facing forwards, 2—facing forwards looking up, 3—facing forwards looking down, 4—facing left looking up, 5—facing left looking down, 6—facing right looking up, 7—facing right looking down.
*Ranking criteria is the highest frequency of high level contamination, followed by the highest frequency of medium level contamination, followed by the highest frequency of low level contamination.

manikin looking down and left or right, presumably due to protection from the brow of the manikin and the wider part of the arm of the glasses.

A key limitation of this study was that, although the cough simulator was configured by mathematical and physical parameters to ensure the size pattern of droplets represented a human cough, the authors were unable to measure the size distribution of the droplets. Despite attempts being made using an airborne spray detection device (Spraytec, Malvern Instruments), it is believed that difficulties in detection were due to the low concentration and relatively high velocity of the droplets being expelled from the cough simulator.

Conclusions

This study has contributed to the evaluation of face protection by developing methodology to simulate a human cough, and to visualise and provide a semi-quantitative assessment of droplet deposition. This semi-quantitative assessment has enabled a comparison to be made of the protection afforded by a range of face shield designs. It has also highlighted real world circumstances where the protection afforded by face shields may be compromised, for example with a cough challenge from below and angled up at the wearer. Previous studies have demonstrated protection with a face shield compared to without, but only used a single generic face shield (Lindsley *et al.*, 2014; Verma *et al.*, 2020; Salimnia *et al.*, 2021), or reviewed information on face shield design and performance, sometimes with illustrated examples (Roberge, 2016; Singh *et al.*, 2021) but without measured levels of protection. One study (Ko-Keeneya *et al.*, 2020) used fluorescence visualisation and looked at improvements afforded by amending a face shield design and addressed orientation, but again tested only a single style and limited orientations. Compared to previously published data, our study therefore offers a more comprehensive evaluation of face shield designs and protection afforded, as well as that from goggles and glasses.

The face shields, goggles, and safety glasses reduced but did not eliminate the risk of exposure to the wearer from droplets such as those produced by a human cough. The level of protection differed based on the design of the eye protector and the relative orientation of the wearer to the cough e.g. face shields and goggles offered the greatest protection when a cough challenge was face on or from above and the least protection when a cough challenge was from below. Wearing a face shield can provide some protection from cough droplets to those standing directly in front of the wearer. Awareness of the advantages and limitations of different face shield designs can offer the user an informed choice as to how much protection they will provide, as part of a PPE ensemble, against droplet-borne transmissible infection.

Supplementary Data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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Conflict of Interest

The authors declare no conflict of interest relating to the material presented in this article.

Data Availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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