Examining the protection efficacy of face shields against cough aerosol droplets using water sensitive papers

A. Ronen[1], H. Rotter[2], S. Elisha[1], S. Sevilia[1], B. Parizer[1], N. Hafif[2], A. Manor[1]

Israel Institute for Biological Research. 1- Environmental Physics Department, 2- Physical Chemistry Department

Abstract

Simple plastic face shields have many advantages compared to regular medical masks. They are easily cleaned for reuse and comfortable to wear. In light of the spreading COVID-19 pandemic, the potential of face shields as a substitution for medical masks, as a recommendation to the general population, was tested. Testing the efficacy of the protective equipment utilized a cough simulator that was carefully tuned to replicate human cough in terms of droplet size distribution and outlet velocity. The tested protective equipment was worn on a manikin head simulating human breathing. An Aerodynamic Particle Sizer (APS) was used to analyze the concentration and size distribution of small particles that reach the manikin head respiration pathways. Additionally, Water sensitive papers were taped over and under the tested protective equipment, and were subsequently photographed and analyzed. For droplets larger than 3μm by diameter, the efficiency of shields to block cough droplets was found to be comparable to that of regular medical masks, with enhanced protection on face parts the mask does not cover. Additionally, for finer particles, of the order 0.3 to few microns, a shield was found to perform even better, blocking about 10 times more fine particles than the medical mask. This implies that for the general population that is not intendedly exposed to confirmed infected individuals, recommending the use of face shields as an alternative to medical masks should be considered.

Introduction

Transmission of diseases by means of pathogen-laden aerosol transport, created by expiratory events such as coughing, sneezing or talking, fundamentally contributes to the spread of the disease and its potential of becoming an epidemic. The study of the processes involved in such expiratory events and the efficiency of related personal protective equipment (PPE) is therefore essential.

The global COVID-19 pandemic that has spread worldwide in just a few months has challenged public health policy makers in many different aspects. The ultimate objective for controlling the pandemic in the nation level is to lower the rate of infections such that, in average, every infected person will subsequently infect not more than a single susceptible to make the disease endemic. In this respect, altering the rate of spread even modestly, can greatly contribute to the overall control over the spread of the disease. For that reason, personal protective equipment that is considered insufficient in the occupational context, focusing on the well-being of individual workers (i.e., healthcare workers) operating in a highly contaminated environment, can make a considerable difference when the problem at hand involves epidemic control in mass-population scales.

The advantages of face shields over regular medical masks are numerous. While medical masks have limited availability and are disposable, face shields can be reused and are easily cleaned. They are comfortable to wear, less retained dermal facial heat, and they have no impact on breathing resistance, less claustrophobic and inexpensive [1]. They reduce the potential for autoinoculation by preventing the wearer from touching their face, and potentially protect all the face and not only expiratory pathways [2].

Also, the importance of cooperation by a large fraction of the population leads to the fact that, in the public health context, protective equipment which is less effective but more comfortable or simple to wear, may be beneficial compared to more effective equipment which is less comfortable or cumbersome. Considering the above, a face shield, although protecting the users only partially, can reduce the rate of infections, and be adopted by more users thanks to its relative comfortableness [3].

Motivated by these concepts, this work examines the potential of face shields as a sole protective equipment used by the entire population. It is important to emphasize that for health-care workers face shields are generally not used alone, but rather in conjunction with other protective equipment and are therefore classified as adjunctive personal protective equipment [1].

A former comprehensive work which studied the level of protection provided by face shields [4-6] used a coughing simulator, a breathing simulator and an optical particle counter to estimate the amount of spray inhaled by a susceptible in the vicinity of a cough event. The inhaled, droplet-laden air was transferred into the particle analyzer, and the total inhaled mass was reported as a function of time. The study concludes that wearing a face shield substantially reduces the number of inhaled particles in the short term, but in the longer term, very small particles bypass the shield and are inhaled.

Droplet formation during an expiratory event like coughing, sneezing, talking or even breathing is a complicated process which involves complex flow through the different expiratory pathways. When a fast airflow passes over a wet boundary, stripes of liquid are lifted from the boundary, and are consequently shredded and ripped into droplets. The final droplet size distribution depends upon the fluid velocity, the pathways topology, the boundary wetting, and physical attributes of the mucus. Spray created by different expiratory events has been studied in different aspects. Yang et al. [7] measured the cough droplets size distribution by asking volunteers to cough into airbags, and subsequently sucked its content into a droplet size analyzer. Their measurements yield a droplet number size distribution with a mode at 8.35 µm. More controlled experiments conducted by Morawska et al. [8] took into account the droplet dynamics between exhalation and measurement and attained a different size distribution. The size distributions observed for different expiratory events were measured, and the authors suggest that every observed distribution is a combination of four distinct distributions, each of them characterized by a specific mode. Specifically, a cough event involves two main modes, at 0.8 µm and at 1.8 µm. Face shields are more efficient in blocking larger droplets, above a few microns. Smaller droplets evaporate extremely fast and reach the vicinity of the susceptible as sub-micron aerosol which follows the flow and easily bypasses the shield. The droplet size distribution created by the cough simulator used here admits the latter of the two modes specified.

The ejected air stream during a cough event creates a jet. The velocity immediately after the mouth is the greatest, and it decreases further downstream. Specifying a jet velocity is therefore a matter of definition. The common way of defining and measuring the velocity related to coughing and sneezing events is to estimate arrival times for a given distance using some imagery technique. Tang et al. [9] used a shadowgraph imaging technique combined with high speed photography and reported velocities around 4.5 m/s for coughs.

The current study utilizes a cough simulator and additionally to monitoring of inhaled fine particles, provides further insight into the subject in a few aspects. First, infected droplets can impinge on other parts of the face and subsequently be inhaled by the susceptible. To address this, water papers (see below) were taped on the breathing simulator and the protecting shield. The droplet patterns formed on the papers were subsequently quantitatively analyzed. Second, different mutual configurations of the simulators were tested. Finally, a shield was placed on the coughing simulator itself to assess the amount of protection the surrounding is provided when an infected individual is wearing the shield. This issue is very important in the current context since COVID-19 can be transmitted by non-symptomatic infected individuals.

Methods

A controlled experiment was held inside an IIBR aerosol chamber, a facility which allows the controlled formation of artificial aerosol under monitored conditions. An “Airbrush” diffuser [Iwata Eclipse SBS] was used as a source of droplets spray, due to its characteristic droplet size distribution that meets the requirements (see below). Controlling the diffuser pressure and operation duration enabled to calibrate the amount of released liquid. Tuning the jet direction and estimating the spray exit velocity were achieved by high-speed photography using a Photron high-speed digital camera applied in a frame rate of 4500 Frames/sec. The jet velocity was estimated by measuring the average velocity over 40 cm. The instantaneous size distribution of airborne droplets was monitored by a laser diffraction system, “Spraytec” [Malvern], located 30 cm from the source.

The susceptible person was represented by a breathing simulator located downstream from the diffuser. The breathing mechanism is required in order to simulate the increased droplets penetration during inhalation as a result of lower pressure. A standard medium-sized breathing manikin head [Dräger] was connected to a mechanical breathing machine (self-production) which is a piston pump maintaining a sinusoidal respiratory rate, with a maximal flow rate of 21 liters per minute (1.1 liter per a single breath).

At the first stage, the experimental setup was aimed at monitoring the concentration of the inhaled very fine particles. The experimental setup included 2 APS 3321 [TSI] instruments, sampling the air very close to the mouth of the breathing simulator through thin 40 cm long tubes. The APS instruments yield continuous monitoring, with a time resolution of 1 second, of the particle number concentration and size distribution between 0.3 to 20 μm. To ensure sufficient concentration of very fine particles, the cough simulator was used with 0.25 gr/L NaCl solution.

A subsequent phase was designed to study the distribution of larger cough droplets on different face parts. Indication of droplets reaching different areas on the manikin head was achieved by yellow water sensitive papers [Quantifoil] that change their color upon contact with liquids. The papers were taped over the manikin face, above and below the tested face shield, at six representative regions: forehead, nose, chin, left chic, right chic and neck. Following former work [4] which determines that about 90% of the total spray mass affecting the susceptible accumulates during the first few seconds, the papers were collected right after each trial, and analyzed not more than one hour later.

Some figures that show the experimental setup are presented in Fig. 1.

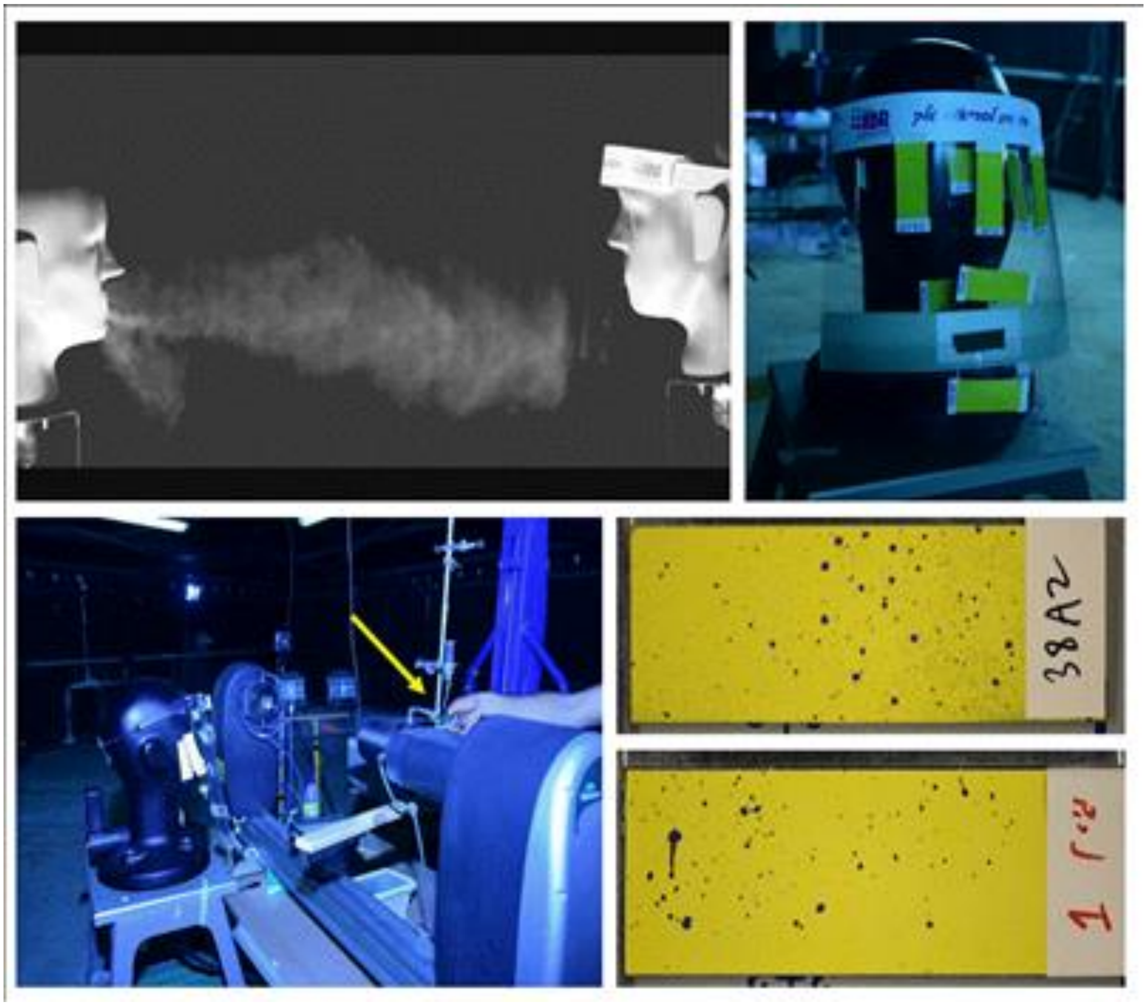

Fig. 1: Experiment Setup. Up left: diffuser was located behind the left manikin head, releasing the jet toward the right. Down left: An Airbrush diffuser (indicated by an arrow) is located facing the manikin head, while the "Spraytec" analyzer measures the droplet size distribution along the jet. Up right: Water sensitive papers taped on top of and below a face shield. Down right: Water sensitive papers marked by droplets stains of Airbrush spray (up) compared to real human sneeze (down).

After the absorption of droplets onto the water sensitive papers, they were photographed using a digital camera (Nikon D810) with macro lens (Nikon Macro D 105 mm). Image analysis of each figure (by Image Pro Plus Version 10.0, [Media Cybernetics]) included the number of droplets, area and appropriate diameter of each droplet. Finally, each droplet aerodynamic size (Y) was calculated from the stain droplets on paper (X) by the known paper spread factor as follows [10]:

$$Y = -4.42 + 0.583X - 0.000132X^2 \tag{1}$$

Relation Eq. (1) can be used to determine the smallest pre-impact diameter that could be identified on the water sensitive papers. In our case this value was around 3 μm.

The protection efficiency of a face shield was assessed by testing its ability to block the droplets from reaching the face below the shield. This is achieved by counting the droplets below and above the shield for every specific run. Equation (2) defines the *blocking efficacy*, evaluated separately for each run, as the ratio between the number of droplets deposited on the shield, and the total number of droplets, on shield and face together.

$$E = 100\frac{N_{above}}{N_{above}+N_{below}} \tag{2}$$

It is worth elaborating here on the utilization of eq. (2) in the current work. The straight forward way of evaluating the total mass of fluid impacting the face and shield is through addressing the size distribution of the droplets staining the papers. A simpler, alternative way was followed here. It is reasonable to assume that a smaller, flow-tracing droplet has a greater chance of reaching the face compared to a bigger, inertial droplet flung at the shield. Therefore, the blocking efficacy, Eq. (2), provides a lower bound for the fraction of **mass** of contaminated fluid blocked by the shield. In other words, for the evaluation of shield efficacy, it is sufficient to show high values of blocking efficacy.

Relaying on water-sensitive papers for the evaluation of the effectivity of face shields in preventing infection, involves a few assumptions:

1. The distribution of pathogens among different droplet size populations is yet unknown for the novel coronavirus. So is the minimal infective dose. Therefore,

these factors are not taken into account in our analysis. In other words, we assume that pathogens are uniformly distributed in the volume of liquid ejected during the expiratory event, and that the protection efficacy is proportional to the mass fraction of liquid blocked by the shield.

2. During its flight, droplets evaporate, and their diameter is reduced. This process is affected by the temperature and relative humidity in the close proximity of the droplet [11] (which can deviate from environmental background values due to the local impact of the droplet cloud itself). Studying this effect demands careful monitoring and control on the environmental parameters along the droplets path. This was left out of the scope of the current work. The same applies for other environmental conditions which affect the droplet spray dynamics such as ambient wind speed and direction.

Results

The scenario tested is designed to challenge the shield, but at the same time to be feasible. The released mass in each of the cough simulating events was set to 100 μl, which is the upper limit expected from a real cough. The proximity of the breathing simulator was set to 60 cm, which is a typical distance of mutually interacting individuals. In order to take into account height differences between the infected and the susceptible individuals, some trials were conducted where, aside from the 60 cm horizontal distance, a vertical distance of 30 cm is kept between the cough and the breathing simulators. The pressure of the diffuser was tuned to guarantee a jet speed typical for a cough event (about 5 m/s [9]) that was measured using fast photography.

The diffuser was selected and tuned to meet representative distributions of droplet sizes. Mass and number distributions as measured 30 cm from the diffuser are shown in Fig 2, where different colors indicate different repetitions. Minor differences between repetitions arise mostly as a result of the unsteady flow generated by the jet. It should be noted that converting the measured volume distribution results to number distributions can be followed by errors, thus the number distributions is used as an indication only. The spray number distribution is characterized by diameters of 1.29, 1.76 and 6.51 μm for the 10th, 50th and 90th percentiles, respectively. Additionally, the volume distribution diameter is characterized by the diameters 8.87, 22.25 and 280.64 μm for the 10th, 50th and 90th percentiles, respectively.

It is worth noting, that observed distributions of cough-generated droplets include sizes of up to a few hundreds of micrometers [12]. In contrast, our cough simulator is limited to droplets smaller than 100 μm. However, such large droplets are very inertial and ballistic, and their increased presence in real cough events would therefore enlarge the actual blocking efficiency.

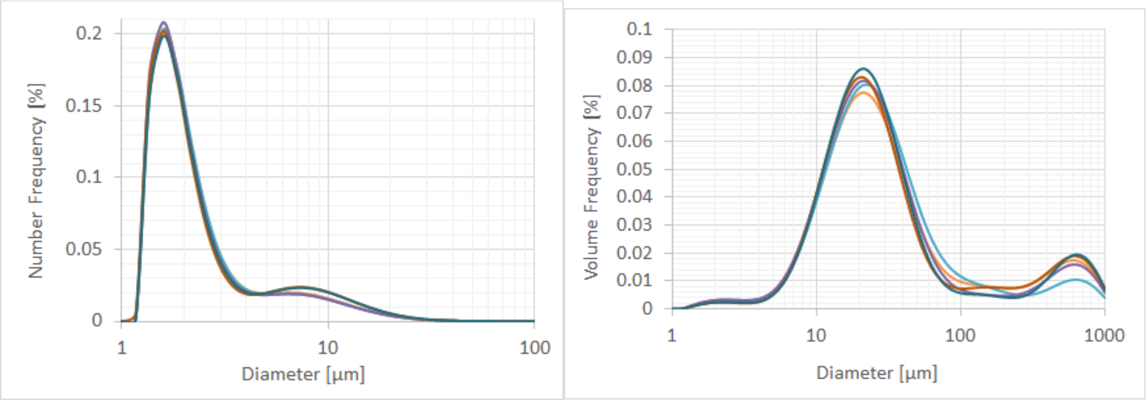

Fig. 2. Spraytec measurements number (left) and volume (right) size distribution of jet droplets, measured 30 cm from source. The different line colors indicate different repetitions.

APS measurements were conducted with a 60 cm horizontal distance between the breathing and the coughing simulators (no vertical distance was introduced). Several tens of repetitions were conducted, with a medical mask [Shengguan LTD.], a face shield (28 cm width and 23 cm long) and a N95 mask (MOLDEX LTD.) were tested. Additionally, some repetitions were conducted with no protection.

The typical time interval after a simulated cough event when a concentration higher than the room's background could be identified is around one minute. Maximal concentrations were observed around 10 seconds after cough event onset.

Fig. 3 shows statistics of the measured number size distributions during multiple repetitions, where for each repetition the time of maximal total number concentration was selected. As indicated by different bar colors, measurements are grouped into tests with no protection, with a medical mask or with a face shield. The bars show the average of different repetitions and the error bars indicate the standard deviation. The leftmost bar is exceptional as it is associated with a wider diameter range (0.3-0.523 µm) compared to the other bars.

Up to a particle diameter of about 2.2 µm, the different distributions look qualitatively similar in shape, with a slight decrease in amplitude moving from no protection to medical mask, and a more significant decrease moving further to the face shield tests. For larger particles, the medical mask and the face shield cases exhibit similar performance, with substantially lower concentrations, up to about two orders of magnitude, compared to the case of no protection.

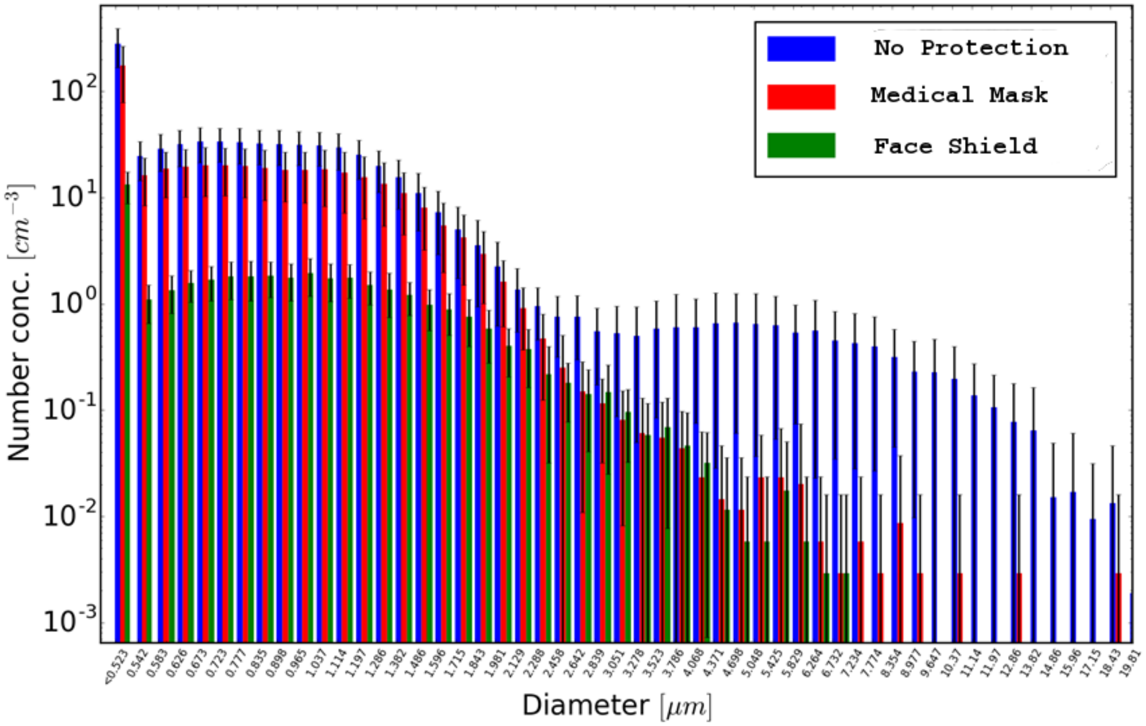

Fig. 3: APS measurement statistics of inhaled particles Number concentration. The horizontal axis specifies the aerodynamic particle diameter. Repetitions are grouped into three different cases as indicated by the different colors. For each repetition, a single representative size distribution is taken at the moment of highest total number concentration. The bars reflect the average of different repetitions, and the variability between different repetitions is indicated by error bars.

Considering the total number concentration measured by the APS across all repetitions, the median value of maximal concentration available to be inhaled (Fig. 4) is around 750, 450,100 and 40 particles per cubic centimeter for cases with no protection, a medical mask, a N95 mask and a face shield, respectively. Also, despite the considerable scatter among different repetitions, the clear advantage of face shields in comparison to medical masks is evident. While the medical mask reduces the number of inhaled particles by roughly a factor of two, the face shield provides better protection and blocks more than 90% of the otherwise inhaled particles.

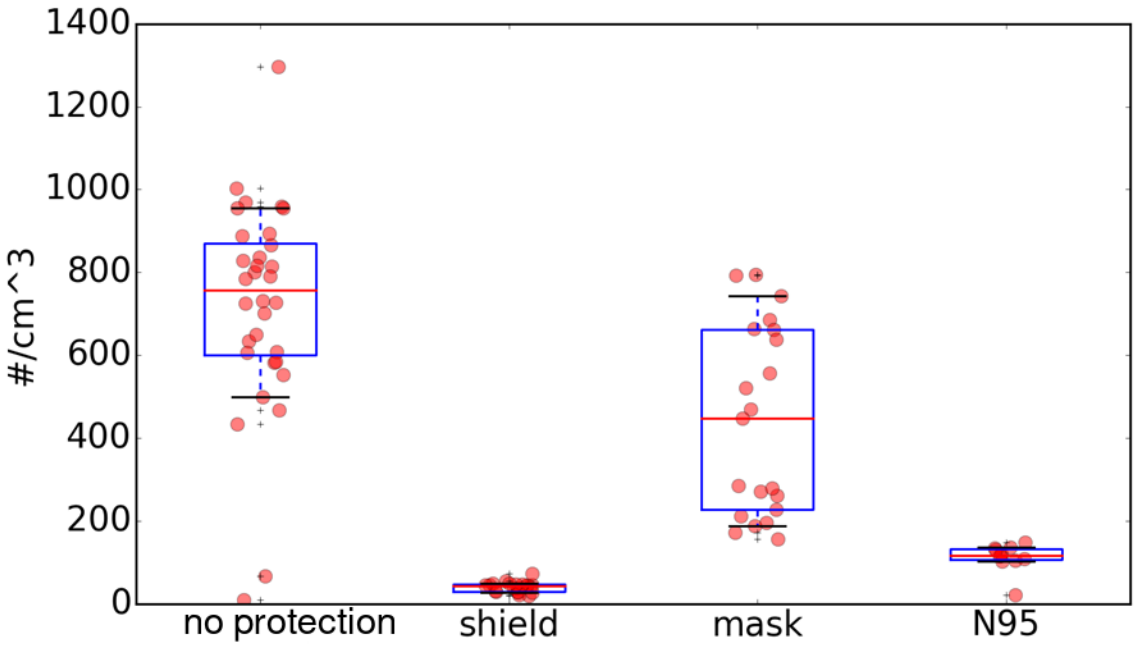

Fig 4: Total maximal particles number, measured by an APS instrument, comparing unprotected scenario, plastic shield, medical mask and an N95 mask. The horizontal red line marks the median, the blue square indicates the second and third quarter, and the extreme horizontal lines describe the first and ninth decile. Individual values are depicted by red circles.

For the second phase, that included the use of water sensitive papers, four face shields with plastic visors from different manufactures were examined. Their sizes were in the range of 23-35 cm width and 23-28 cm long. For reference, a medical mask was also tasted.

The total number of droplets deposited by the cough simulator on the shield and simultaneously on the face, at different test configurations, can be seen in Fig. 5. Two repetitions were conducted for each configuration. The bars indicate the average number of droplets for the two repetitions, and the difference between each pair is indicated by the error bars. High repeatability is reflected by small deviations from the average where in cases of lower number of droplets are associated with larger variation between identical measurements, due to bad droplets statistics.

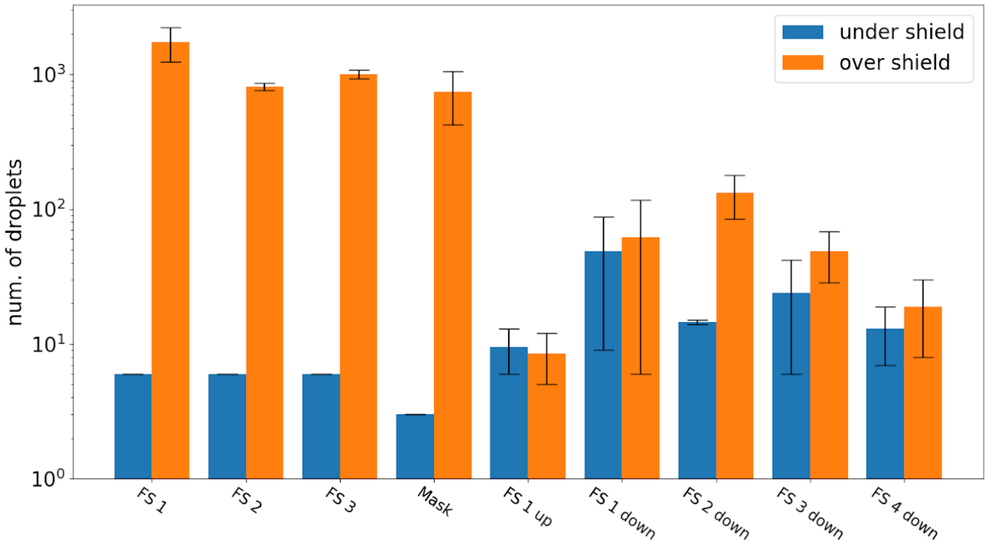

Fig 5: Overall number of droplets (logarithmic scale) over and under the face shield (FS), for different kinds of shields (FS 1 to 4), a medical mask and different configurations 'up' and 'down' refer to cases in which a vertical distance was introduced, where in the former, the breathing simulator was positioned 30 cm above the cough simulator and the opposite for the latter. For all repetitions a horizontal distance of 60 cm was kept.

Fig. 6 presents the overall average blocking efficacy (as defined by Eq. 2) for each tested scenario. The plastic shield did not cover the neck area completely and therefore, the neck droplet counting is omitted from the calculation of blocking efficacy.

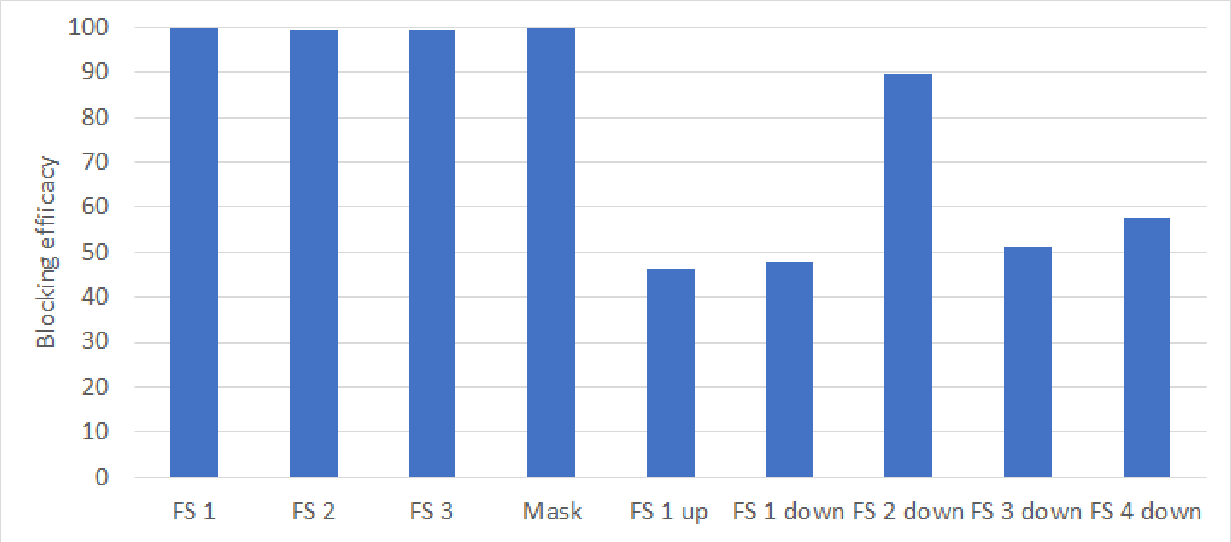

Fig. 6: The Blocking efficacy of different face shields (FS). See last caption for information about the different cases and configurations.

As evident from Fig. 5, when the breathing simulator and the cough simulator were at the same height, the overall number of droplets is high and relatively constant, with low dependence on shield type. For these cases, the face shield significantly reduced the droplets number under it in two orders of magnitude, and the corresponding blocking efficacy is 98%-100%. This applies equally for a medical mask, which provides similar protection for the face parts it covers. As noted above, these findings apply to droplets larger than 3 µm by diameter. This is consistent with the APS observations (see Fig. 3) showing similar blocking capabilities of the medical mask and the face shield for large particles.

In contrast, in experiments which include a vertical distance between the simulators, the number of droplets that are deposited on the face is not much less than the number of droplets over the shield, and in some cases the two are comparable, which results in blocking efficacy as low as about 45%. However, one should take into consideration that for such events, the overall number of deposited droplets is low by up to two orders of magnitude. This applies, that the chances of infection following such events is relatively low, and thus, these cases are practically less important in evaluating the overall efficacy of shields.

It is interesting to compare the number of droplets deposited on the shield and below it, for different face parts. Fig. 7 presents the ratio between the number of droplets that were deposited over the shield\mask and the total number of droplets (i.e., over and under the shield) for specific face parts. For each face part, only the droplets in its vicinity were taken into account. Values close to unity reflect good protection for the specific area of the face, whereas lower values indicate less effective blocking of droplets. For cases without vertical separation, this ratio depends on the region of the face. For the center of the face, the forehead, the nose and the chin, that ratio is close to 1. In contrast, at the cheeks and neck it falls to a range of 0.4-0.5. This observation can motivate the designing of more advanced shields that allow less penetration from the marginal gaps which exist at the bottom and at the sides of the shield.

Introducing a vertical distance of 30 cm above and below, results in an increase in the relative penetration of the droplets, regardless of the face part. The droplets penetrate through the shield openings, and affect all parts of the face, not only those close to the openings.

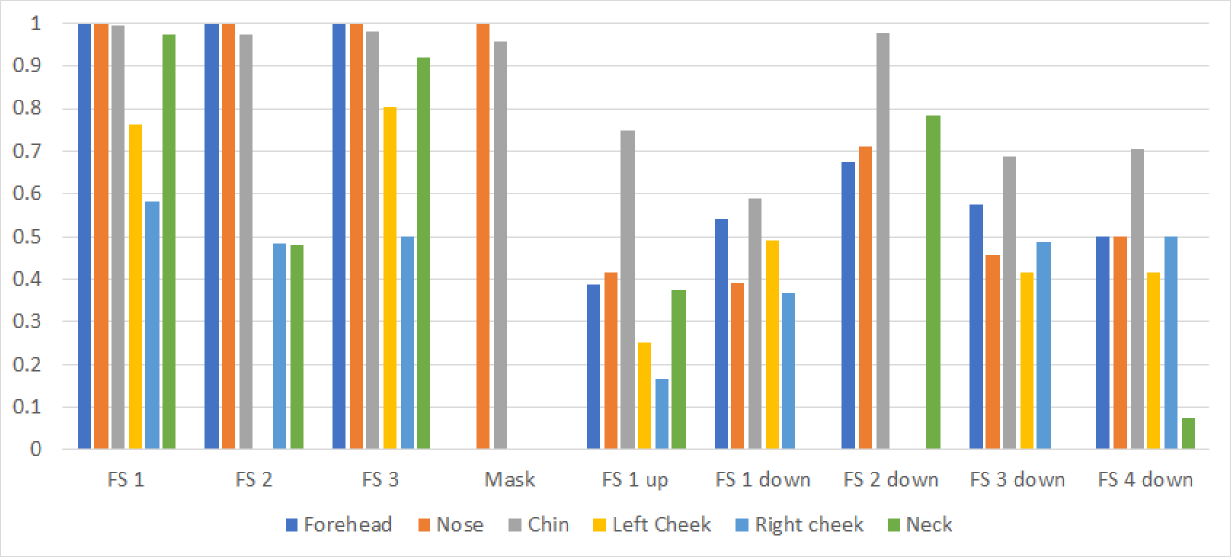

Fig. 7: Ratio of the number of droplets blocked by the shield to their total number, for different face shields and configurations and for different face parts.

The potential of a shield worn by an infected individual to prevent transmittance was tested by placing the shield on the diffuser in the right distance and location to simulate usage by an infected person. In this configuration, no indication of droplets could be found in the close vicinity of the breathing simulator, positioned 60 cm apart, not by the water sensitive papers, nor by the APS instrument. This implies that a shield worn by an infected individual can effectively block the infected spray emitted in an expiratory event.

Discussion

Motivated by the potential of mass-use of face shields to control the spread of COVID-19, various face shields were tested. A carefully calibrated Airbrush diffuser, with a median number droplet size of 1.76 µm, a 100 µl of liquid per cough and a characteristic ejection velocity of 5 m/s was used to simulate human coughs. A manikin head fitted with a breathing simulator was used to test different protective equipment including medical and N95 masks, and different kinds of face shields. Different configurations were tested, the air penetrating the protection was monitored for fine particles, and droplets deposited on water sensitive papers were counted. Each tested case was repeated to ensure statistical significance.

An APS instrument monitored the air inhaled by the breathing simulator for the concentration of fine particles. Cough events were repeated several tens of times where the manikin head is fitted by turns with a medical mask, an N95 mask, a face shield and, for the sake of reference, no protection at all. While the medical mask lowered the number of inhaled particles by a factor of around 2, the face shield performed much better and blocked 10 times more particles than the mask. A spectral analysis of the aerodynamics particle diameter reveals that this effect is related to the finer particles, smaller than 2 μm by diameter.

The protection provided from larger particles was subsequently examined using water sensitive papers. For that part of the measurements, different kinds of face shields were tested, which all exhibited similar blocking efficacies. For configurations where the breathing simulator is located directly in front of the cough simulator, high blocking efficacy of close to 100% was attained, which is comparable to the blocking efficacy measured for a regular medical mask, for the face parts it covers. In contrast, when a vertical difference between the simulators also exists, the blocking efficacy drops markedly and reaches typical values of 40%-60%. It is however important to note that for such configurations, the total number of arriving droplets also drops by up to two orders of magnitude, which lowers their relative practical significance.

The droplet counting for the different face parts yields that the shield performs the best in protecting the central and upper parts of the face. The other marginal parts of the face are less protected. Extending shields toward covering a wider part of the face, especially the neck and the cheeks, may improve their protection. This is consistent with the recommendations of the Centers for Diseases Control and Prevention (CDC) [2].

Other scenarios we examined included locating the shield over the coughing simulator itself. This is done to assess the protection provided to the surrounding when an infected individual is wearing a shield. For this configuration, no particles could be identified in the vicinity of the manikin head, by neither the APS nor the water sensitive papers. The important conclusion is that wearing a face shield can protect the surrounding from exposure to an infected person.

Conclusions

Overall, our results imply that blocking efficacy of face shields is similar, and for some parts of the face, even higher, than the efficacy of medical masks. This is even more true for fine particles, which are blocked much more efficiently by a shield compared to a medical mask. Considering other advantages of shields over medical masks, public health policy makers may consider, for the general population, the usage of face shields as an alternative to medical masks.

References

[1] Roberge, R.J. Face shields for infection control: A review. J. Occup. Environ. Hyg., 13, 235–242, (2016).

[2] Centers for Disease Control and Prevention (CDC): "Workplace Safety & Health Topics. Eye Protection for Infection Control." Available at http://www.cdc.gov/niosh/topics/eye/eye-infectious.html (accessed July 15, (2015).

[3] Perencevich, E.N., Diekema, D.J., Edmond, M.B., Moving Personal Protective Equipment into the Community: Face Shields and Containment of COVID-19, JAMA (2020).

[4] Lindsley W. G., Noti J.D., Blachere F. M., Szalajda, J.V., Beezhold, D.H. “Efficacy of face shields against cough aerosol droplets from a cough simulator”. J. Occup Environ Hyg. 11(8): 509-518, (2014).

[5] Lindsley W. G., Blachere F. M., Thewlis R. E., Vishnu A., Davis K. A., Cao G., Palmer J. E., Clark K. E., Fisher M. A., Khakoo R., Beezhold D. H. “Measurements of airbourne influenza virus in aerosol particles from human coughs”. PLOS ONE (2010).

[6] Lindsley, W. G., Reynolds J. S., “A cough aerosol simulator for the study of disease transmission by human cough-generated aerosols”. Aerosol Science and Technology 47.8 (2013).

[7] Yang, S., Lee, G. W. M., “The size and concentration of droplets generated by coughing in human subjects”. Journal of Aerosol Medicine, 20(4), (2007).

[8] Morawska L., Johnson G. R., Ristovski Z. D., Hargreaves M., Mengersen K., Corbett S., Chao C. Y. H., Li Y., Katoshevski D., “Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities”. Aerosol Science. 40 (2009).

[9] Tang J. W., Nicolle A. D., Klettner C. A., Pantelic J., Wang L., Bin Suhaimi A., Tan A.Y.L., Ong G. W. X., Su R., Sekhar C., Cheong D. D. W., Tahm K. W., “Airflow dynamics of human jets: Sneezing and breathing – potential sources of infectious aerosols”. PLOS one (2013).

[10] Hoffman WC., Hewitt AJ. “Comparison of three imaging systems for water sensitive paper”. Applied engineering in Agriculture. 21: 961-964, (2005).

[11] Bouroubia L., “Turbulent gas clouds and respiratory pathogen emissions: potential implications for reducing transmission of COVID-19”. JAMA (2020).

[12] Xiaojian Xie, Yuguo Li, Hequan Sun and Li Liu, Exhaled droplets due to talking and coughing, J. R. Soc. Interface (2009).