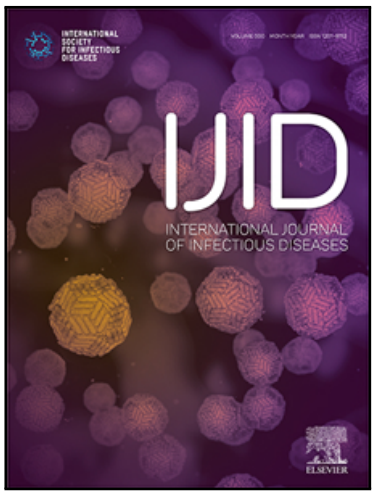
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Effectiveness of different types of Masks in Aerosol Dispersion in SARS–CoV-2 Infection

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PII: S1201-9712(21)00518-X
DOI: https://doi.org/10.1016/j.ijid.2021.06.029
Reference: IJID 5499

To appear in: *International Journal of Infectious Diseases*

Received date: 25 March 2021
Revised date: 10 June 2021
Accepted date: 12 June 2021

Please cite this article as: Gokhan Tanisali , Ahmet Sozak , Abdul Samet Bulut , Tolga Ziya Sander , Ozlem Dogan , Cagdas Dag , Mehmet Gönen , Fusun Can , Hasan Demirci , Onder Ergonul , Effectiveness of different types of Masks in Aerosol Dispersion in SARS–CoV-2 Infection, *International Journal of Infectious Diseases* (2021), doi: https://doi.org/10.1016/j.ijid.2021.06.029

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Effectiveness of different types of Masks in Aerosol Dispersion in SARS–CoV-2 Infection

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Highlights

- No difference between single and double surgical masks in spread of aerosols
- Fitting of the mask is crucial in preventing the spread of aerosols
- Cloth masks could be used, although a standardization of the textile is necessary.

Abstract

Objective: We aimed to compare the effectiveness of different masks in limiting the dispersion of coughed air.

Method: We employed the single-curved mirror Schlieren method. Coughed air with a slightly higher temperature than the ambient air generates a refractive index gradient. We used a spherical mirror with a radius of curvature of 10 m and a diameter of 60 cm. The spread of the cough wavefront was investigated among five subjects wearing (1) no mask, (2) single surgical mask, (3) double surgical masks, (4) cloth mask, 5) valveless N95 mask or 6) valved N95 mask.

Results: All mask types significantly reduced the magnitude of the dispersion of the contaminated region. The percent reduction in the cross sectional area of the contaminated region for the same mask types but different subjects revealed by the normalized data suggests that the fitting of the masks play an important role.

Conclusions: We observed no significant difference between using either a single or a double surgical mask for the exhalation spread. Cloth masks could be effective, depending on the quality of the cloth. The valved-N95 mask type exclusively protects the user. Fitting of the mask is an important factor to minimize the contaminated region.

Introduction

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COVID-19 is an acute respiratory illness caused by the novel coronavirus SARS-CoV-2. The World Health Organization (WHO) identified COVID-19 as a pandemic on March 11, 2020. The basic reproductive rate (R0) of SARS-CoV-2 was determined as 2.5, higher than influenza and its close species SARS-CoV and MERS-CoV (Petersen et al., 2020). One of the most effective ways to prevent the spreading of SARS-CoV-2 is proper use of masks. Although there was extensive research about mask type usage (Simha and Rao, 2020, Tang et al., 2009) there was not a comprehensive study about the usage of double masks ~~number of masks~~. ~~There is an urgency of quantitative measure of dispersion by the most commonly used surgical mask type vs its number.~~ There is an urgent need to measure the dispersion of a cough when two surgical masks are worn together.

Coughed air having higher temperature than the ambient air generates refractive index variations. Schlieren's method is a useful tool to image transparent fluids exhibiting such refractive index variations across the imaged area. It has been used in different applications in many engineering fields as well as in biology, including investigation of flow visualization generated by insects (Liu et al., 2018), human thermal plume (Gena et al., 2020), and protein crystal formation (Poodt et al., 2006, Warkentin, 2007). Recent COVID-19 pandemic has turned attention to transmission ways of respiratory diseases via droplets generated during coughing. Although studies suggested slightly different droplet size distributions in exhaled cough air, it can be safely said that the droplet sizes are on the order of microns. Previous works using a laser diffraction system (Zayas et al., 2012) or an aerodynamic particle sizer and scanning mobility particle sizer (Yang et al., 2007) measured that the majority of the produced droplets are less than 5 microns in size. Using face masks reduces the number of virus-laden droplets spread to the surrounding; nevertheless, some droplets still emitted through the mask due to their small sizes (Asadi et al., 2020, Johnson et al., 2011) or leak due to improperly placed masks. Consequently, infection risk increases when the coughed air travels greater distances. Schlieren imaging can help to determine the effectiveness of different mask types by employing the refractive index variations in the coughed air

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due to the temperature difference between the exhaled and the ambient air. We aimed to compare and measure the ~~exhalational effectiveness~~ ~~of~~ effectiveness of the masks in limiting the dispersion of coughed air using either single or double surgical (Mumu, made in Turkey), valved and valveless N95 (3M), and cloth masks (from organically grown cotton). Therefore the outcome of this research is not considering the protection of the wearer but of others.

Materials and Methods

Schlieren Imaging

A schematic representation of the Schlieren imaging can be seen in **Fig. 1**. In a simple Schlieren setup discussed here, a light source (either a point source or an extended source such as slit) is placed slightly off-axis (a few cm), 2f away from the curved mirror where f is the focal length of the mirror. The light source is imaged next to itself where a knife edge is placed (**see Supplementary Fig. 1**). Knife-edge can move perpendicular to the optical axis so that it blocks the desired percentage of the incoming beam reaching to the camera. When refractive index variations exist in the transparent medium between the light source and the curved mirror, the propagating beam experiences a slight change in its propagation direction in accordance with the Snell's law (**Supplementary Fig. 2**). This is illustrated in **Fig. 1** as the beam (shown with red) entering the test area at point A would reach point B if there were no refractive index changes in the test area. However, slight variations in the refractive index induced by the temperature changes bend the propagation direction of the beam by angle θ and direct it to point C (the deflected beam shown with blue). As a result, the incoming beam that would reach the camera is deflected downward toward the knife edge and blocked by it (as illustrated in **Fig. 1**) or the beam that would propagate toward the knife edge could have been deflected away from it and reached the camera. This, in turn, generates brighter and darker regions in the image carrying information regarding the refractive index gradients in the test area.

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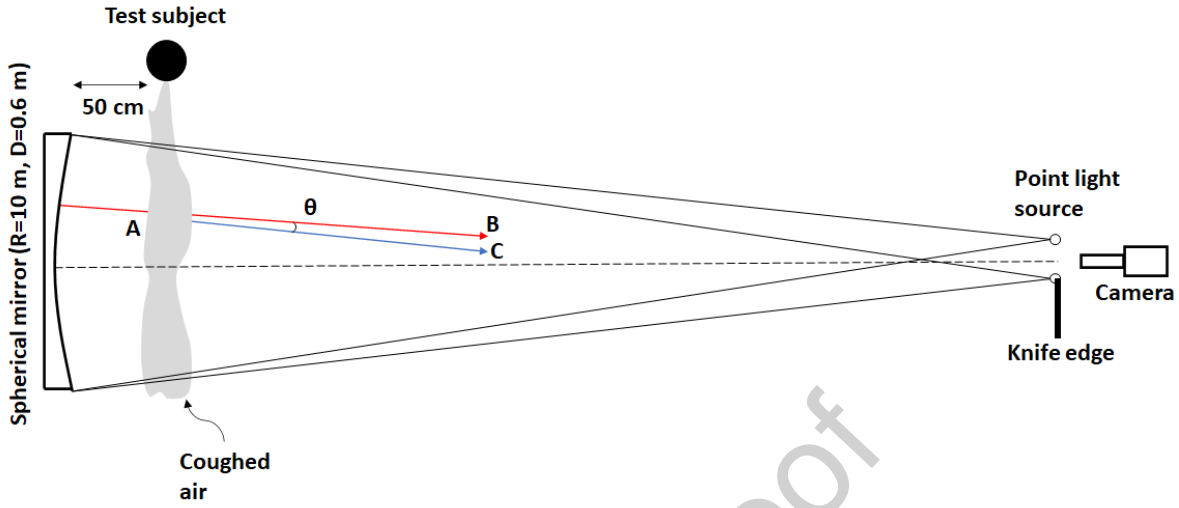


Figure 1. Schematic representation of the single-curved mirror schlieren setup.

Single-spherical mirror Schlieren setup was assembled at Koç University Isbank Research Center for Infectious Diseases (KUISCID), Istanbul. For our experiments, the spherical mirror with a radius of curvature of 10 m and a diameter of 60 cm was manufactured by Aselsan optical unit. The optomechanical design of the mirror was done by using parametric optimization with finite element techniques for light weighting. The light weighting pattern of the back surface and flexure design at mounting interface are so crucial for the performance of a 60 cm diameter mirror under gravity and mounting force to eliminate the surface deformation. Aluminum alloy was chosen as a mirror material and single point diamond turning was the manufacturing technique. On the other hand, the manufacturing process was developed specifically to obtain required surface quality and precision because the 60 cm diameter is so close to the limit of a single point diamond turning machine **(Supplementary Fig. 3 & 4)**. The feed rate and rotation speed of machining were optimized to improve the surface irregularity and roughness.

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A 21V, 150W fiber optic illuminator (Bel Engineering SRL, Italy) was used with an attached optical aperture in front of it as a point light source. The light coming out of the aperture was imaged 3 cm next to itself, where a carpet blade was placed vertically as a knife-edge to visualize horizontal refractive index variations in the test area due to the warmer coughed air. Finally, the camera (Canon EOS 800D) was placed along the optical axis of the mirror, 5 cm behind the knife edge (**Supplementary Fig. 1)**.

Experiment of Masks

Verbal consent of the test subjects were taken before starting the experiments.The test subjects were then ~~initiall~~ seated 50 cm in front of the mirror, next to the imaged area while they faced perpendicular to the optical axis (see **Fig. 1** and **Supplementary Fig. 5**). The field of view (60 cm), which is limited by the diameter of the mirror, was enough to investigate the propagation of the cough wavefront, defined as the interface between the warmer coughed air and the ambient air (Simha and Rao, 2020).

We define the contaminated region as the region surrounded by the cough wavefront. The effectiveness of the masks was determined based on the size and shape of the contaminated region. To investigate the effectiveness of masks we studied 6 different scenarios. 1) no mask, 2) surgical mask, 3) double surgical mask, 4) cloth mask, 5) valveless N95 mask, and 6) valved N95 mask. For each scenario, five individual test subjects were initially instructed to cough while they were placed facing parallel to the mirror. They were advised to take their deep breath and cough at expiration..The exact distances changed +/- 5 cm during the experiments because the test subjects were not fully-restrained when they produced voluntary coughs. The lower body of the test subjects were covered with a sheet of nylon as an insulator to minimize the interference of the warm air dissipated by the test subjects.

Results

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Analysis of data

The videos were recorded at 50 ~~fps~~ frames per second throughout the experiments. In each recording, the first frames were designated as the frames in which the coughs were initiated. The cough wavefronts in the fourth frames, which correspond to time 60 ms after the initiation of the coughs, were manually drawn as closed polygons. In each frame, in order to determine the area of the contaminated region, the area of the closed polygon was calculated ~~together with the width and height of the minimum enclosing rectangle~~. A frame with no obstacle in front of the mirror was used as the reference frame, in which the mirror was manually annotated as a closed polygon. Using the mirror dimensions, the areas ~~and dimensions~~ calculated in other frames were converted into metric units. ~~From the cough wavefront, the contaminated regions were determined.~~ The propagation of the contaminated region for no mask case can be seen in **Fig. 2**. Furthermore, the contaminated regions at 60 ms after the initiation of the coughs are shown in **Fig. 3** for each of the six cases for the same test subject. In the case of no mask the mean cross sectional contaminated region of the five subjects was 291 cm^2, representing the largest contaminated area among all recorded scenarios as expected (**see Fig. 4a**). The mean areas are reduced to 61 cm^2, 67 cm^2 and 63 cm^2 when the subject's face is covered with a single mask, double mask or cloth mask respectively. Valveless N95 masks performed the best among all with allowing a contaminated region of 52 cm^2 (**Fig 4a**). However, valved N95 masks were the least successful of all types of masks tested with a contaminated region of 113 cm^2 (as seen in **Fig. 4a**). To compare the percent reduction in the contaminated region with different mask types, the areas were normalized by dividing them with the area of the unmasked case for each individual, respectively (see **Fig. 4b**). The variance in the normalized values is, among other factors, due to the improper fitting of the masks for some of the test subjects (see **Fig. 4b**). This can also be seen in **Fig. 3b-d**, where there was leakage of coughed air above the nose.

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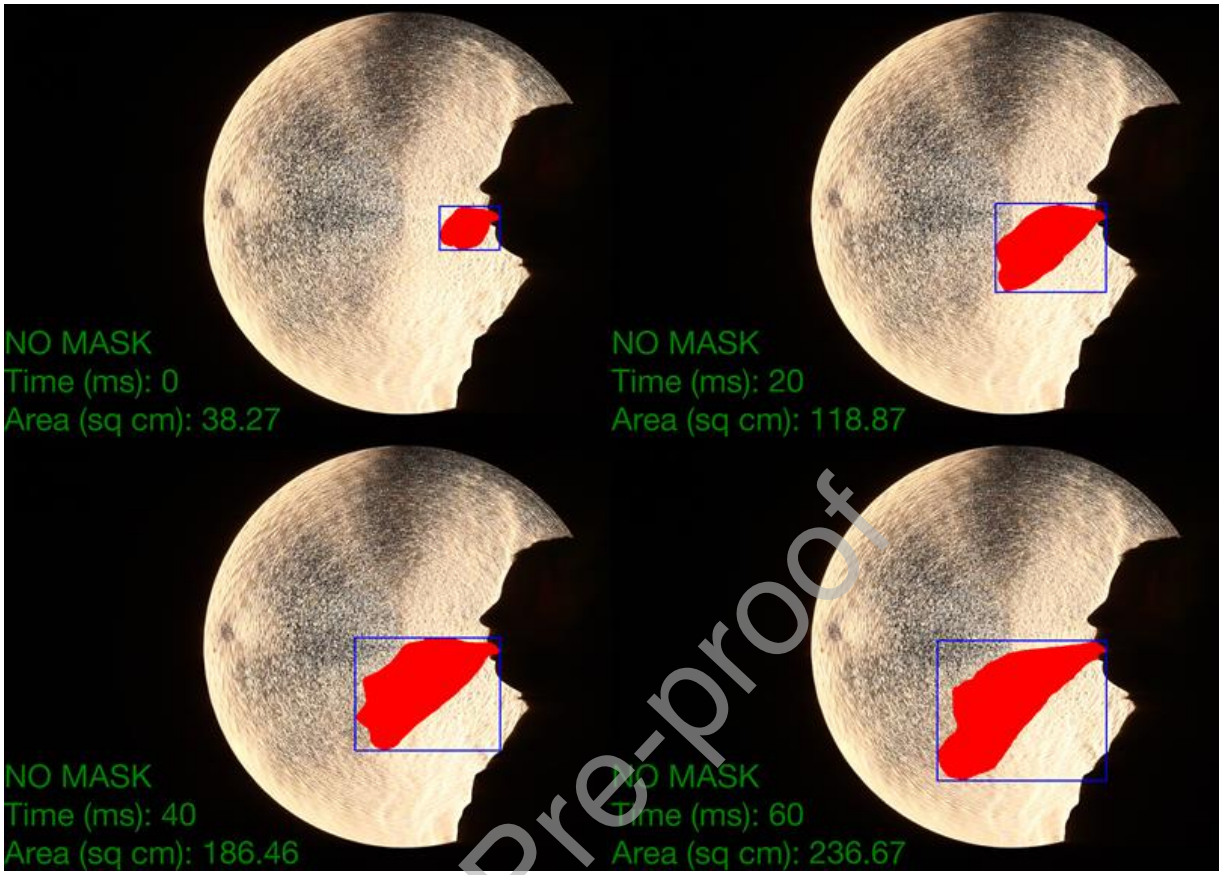


Figure 2. The propagation of the contaminated region for no mask case from the initiation of the cough to 60 ms.

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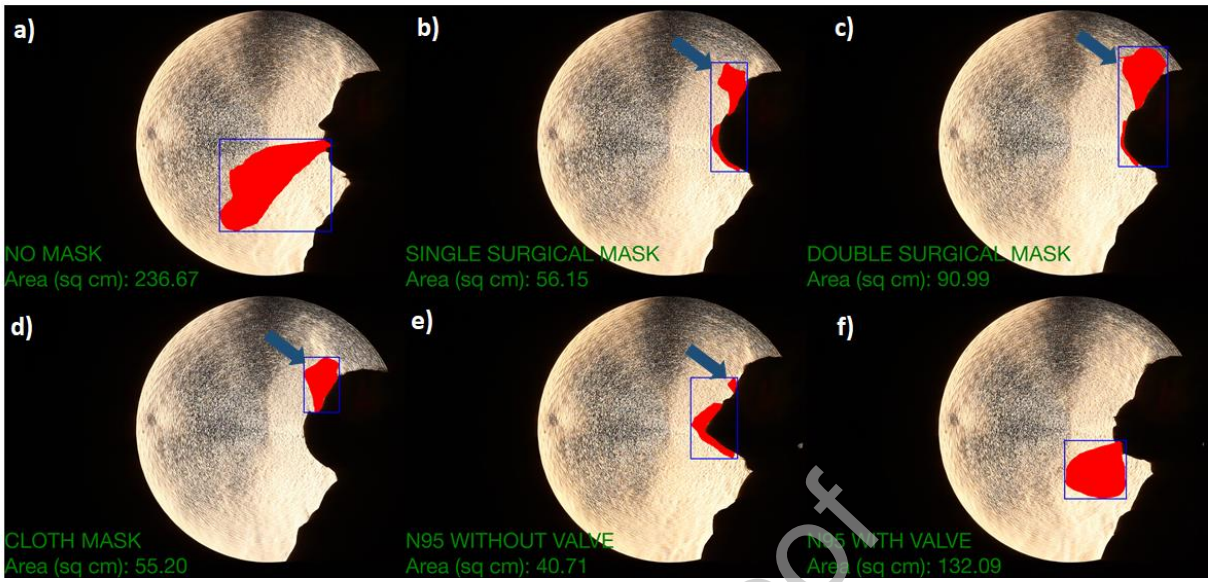
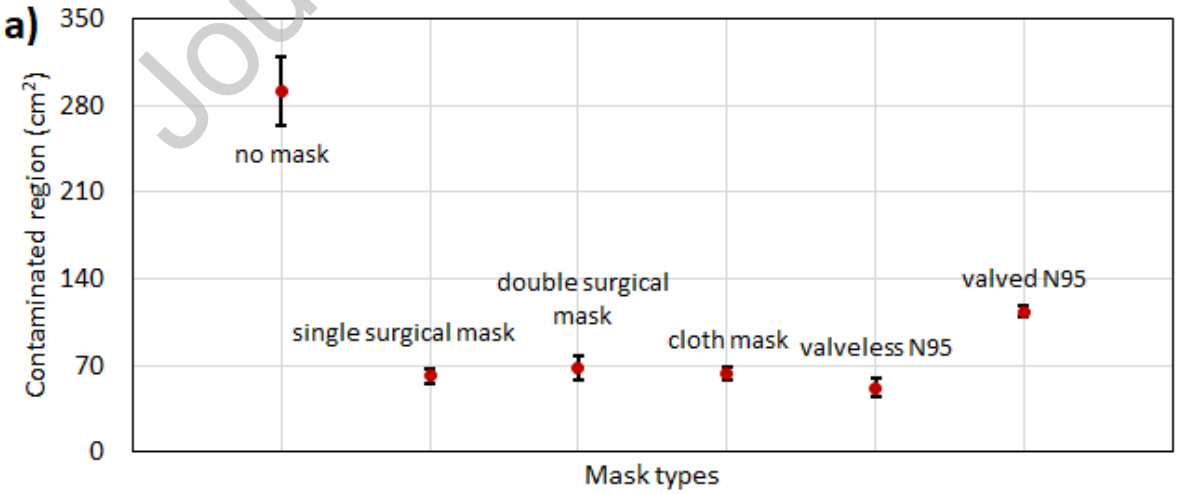


Figure 3. The contaminated regions at 60 ms after the initiation of the coughs for cases of (a) no mask, (b) surgical mask, (c) double surgical mask, (d) cloth mask, (e) valveless N95 mask, (f) valved N95 mask. Note the leakage of air above the nose indicated by the arrows.



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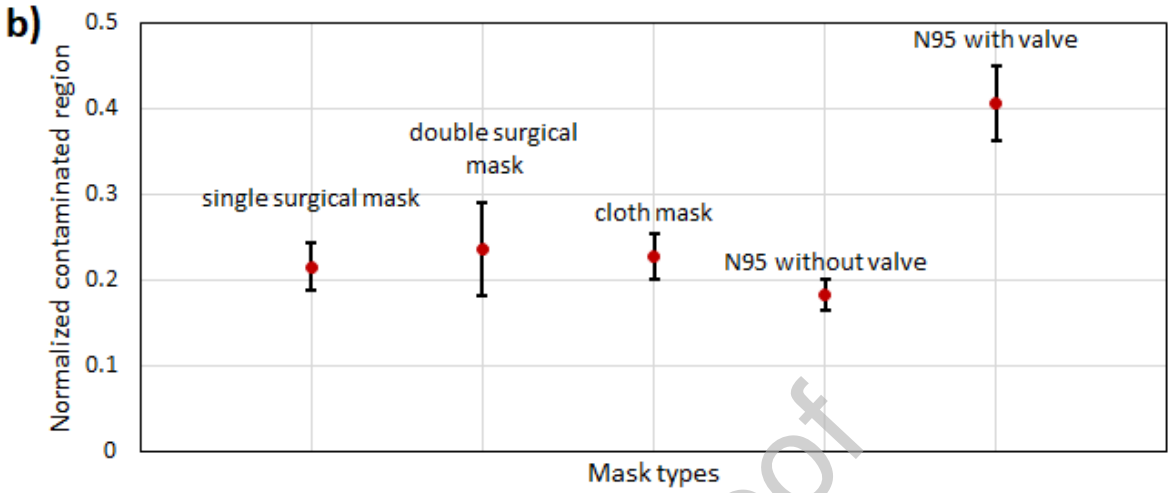


Figure 4. (a). The mean cross sectional area of contaminated regions at 60 ms after the initiation of coughs. **(b).** The mean normalized cross sectional areas of contaminated regions for different mask types with respect to the unmasked case.

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Discussion

As the new SARS-CoV-2 variants emerged, extra cautions became trending and using double masks became standard in many countries. However, we observed similar results for the exhalational spread when a single or double surgical masks are used.. Cloth masks could be effective, depending on the quality of the cloth. Our wavefront measurements confirm that the valved-N95 mask type exclusively protects the user. Fitting of the mask is another important factor to minimize the contaminated region.

~~It can be safely said that~~ The majority of the mask types were quite successful in preventing the spread of the contaminated region by about 80% while this prevention for valved N95 masks was about ~~%60~~

60% (**Figure 4b**). Lower reduction in the contaminated regions for valved N95 masks is expected since these masks permit the leakage of airflow through their valves. In our experiments, the leakage is observed along the direction of the valves (**Supplementary Fig. 6**). This findings regarding valved N95 masks agrees with the previous studies (Staymates, 2020). Therefore, the discouragement of valved N95 mask usage in public places is appropriate. Instead, valveless N95 mask usage should be preferred since they exhibit extraordinary protection against inhalational exposure to viruses and they were quite successful in minimizing the contaminated region as can be seen from the (**Fig. 3e, and Fig. 4)**. Another important point is that single and double surgical masks performed similarly in reducing the areas of the contaminated regions (Fig. 3b, c, and Fig. 4). Although most of the coughed air escaped through the gap around the nose in Fig. 3b, this was not the case for each test subject (**Supplementary Fig. 7**). We believe a plausible explanation is that differences in fitting of the masks among different test subjects become more pronounced in double masking. As a result, this leads more coughed airflow above the nose in some test subjects as in Fig. 3b. The larger variation in double masking in Fig. 4b also supports the differences in fitting among test subjects in the case of double masking.The major limitation of the current study is that schlieren technique only images the warmer coughed air not the individual aerosols and droplets. ~~due to high risk of contamination we have not used aerosols which contain real viral particles.~~ Therefore, although the dispersion of the coughed air for a single mask and double surgical masks are quite similar, it should be noted that there may be possible differences between them ~~single and double surgical masks~~ in terms of the number of virus-laden particles emitted and their success in preventing the inhalational exposure to viruses (Brooks et al., 2021, Konda et al. 2020). Furthermore, the concentration of droplets can be expected to be higher in the leaked air through the gaps (shown by the arrow in Fig. 3b-e) as opposed to the leaked air through the masks since it is not filtered.The effectiveness of the cloth mask in reducing the contaminated region is also noteworthy.

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Schlieren imaging is a very robust method and allows direct testing of the real life scenarios. Our data suggests people must wear the mask appropriately, and that means it conforms to the person's face at the nose, under the chin, and on the cheeks rather than gaping and letting air in. Despite double layering it adds extra filtration, most of the benefit comes in making sure to cover those gaps around the mask, because not every mask fits equally. Although double surgical masks are recommended in many countries, the increased emphasis should be on "better masking" and better mask use, as the next phase of the pandemic may well be dominated by the fight against emerging respiratory pathogens.

Supplementary: https://drive.google.com/file/d/1Srka3ckY1p7AQPXEXss50UByek4CVRQ-/view?usp=sharing

Figures: https://drive.google.com/file/d/1q2LlJjPF7EfKshGdPrN3nx9vT_C8X316/view?usp=sharing

Declaration of Competing Interest

We, the authors of "Effectiveness of different types of Masks in Aerosol Dispersion in SARS–CoV-2 Infection", declare that we do not have any conflict of interest. This study is original and was not published elsewhere.

Ethical Report

Verbal consent of the test subjects were taken before starting the experiments. Koç University Institutional Review Board approved the study (2021.255.IRB1.087)

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Acknowledgement

The authors gratefully acknowledge use of the services and facilities of the Koç University Isbank Research Center for Infectious Diseases (KUISCID). HD acknowledges support from National Science Foundation (NSF) Science and Technology Centers grant NSF-1231306 (Biology with X-ray Lasers, BioXFEL). This publication has been produced benefiting from the 2232 International Fellowship for Outstanding Researchers Program of TÜBİTAK (Project No: 118C270). However, the entire responsibility of the publication belongs to the owner of the publication. The financial support received from TÜBİTAK does not mean that the content of the publication is approved in a scientific sense by TÜBİTAK. CD acknowledges support from TÜBİTAK (Project No: 120Z594).

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