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HOLOGRAPHIC METHOD TO EVALUATE THE FACE MASK EFFICACY

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ABSTRACT

The pandemic of the Corona virus has increased demand for face masks to prevent the virus from spreading from one person to another. Due to the shortage of medical masks in many circumstances, numerous public health organizations have approved the use of other types of masks as suitable alternatives. Cotton masks are low-cost alternative masks that are popular in developing countries because they can be washed and dried several times and used for up to months. The cotton masks can be one or two layers thick with stretchy earloops. However, if this type of mask is used for an extended period of time, its quality decreases and its capacity to filter out released particles is compromised. Although wearing a mask is partly intended to shield others from inhaled and virus-containing particles, few research have looked into the emission of particles from a face mask into the surrounding air. In this paper, we investigate the emission of micro particles using a micro-dispensing device that simulates exhale while using various masks. The filtering efficiency of cotton masks was found to be lower than that of surgical masks as the study proved that surgical masks minimize external particle emission rates and sizes compared to cotton masks, which confirms the power of medical masks' efficiency. The study was made using the digital in-line holography which could image the emitted particles for digital analysis. The number of particles emitted within a given area allowed us to determine the particle emission rate.

KEYWORDS: Face mask efficacy, droplets emission, Holography, Digital construction.

INTRODUCTION

Since the start of the Corona pandemic, hand hygiene has become an essential way to reduce transmission of the disease (Gralton, J. and McLaws, 2010; Bartoszko et al, 2020). This is in addition to the face masks that provide great protection to those who put them to achieve the desired protection (Rengasamy et al., 2010). The demand for face masks has increased all over the world with attention to their effectiveness with the spread of Corona virus disease in early 2020. Hence, several studies have been published highlighting the striking differences in the effectiveness of different face masks and their alternatives in preventing the transmission of respiratory particles or drops during normal speech. As it is known, the most common application of face masks is to protect those who wear them from the surrounding people. But surgical face masks have also been used to protect the surrounding people from the wearers, who may be sick with Corona but without symptoms, and yet they are a source of infection for several days (Klompas et al, 2020). Thus, wearing a face mask will reduce the spread of respiratory droplets that contain viruses. Studies show that wearing face masks limits the spread of the Corona virus globally and suspends the curve of the epidemic (Chu et al., 2020; Leung et al, 2020). The determination of the effectiveness of the mask is the subject of many complex studies, especially since the infection pathways are not completely recognized and include several factors. The lack of surgical face masks and N95 in several countries (Ong et al, 2020), has led to the general use of a range of homemade cotton masks, which have little known efficacy, especially as they are made of different textiles. This calls for the need to evaluate the efficacy of these masks in a practical environment. On the other hand, face masks reduce the transmission of infection from the infected individuals to surrounding people (Allen and Marr, 2020). Studies have shown that carriers of the Corona virus may not show any symptoms. Despite this, they remain a source of infection to the others (He et al., 2020; Rothe et al., 2020), which increases the necessity of wearing the convenient face masks to control the transmission of the disease. It has been demonstrated in (Liu et al., 2020) that non-respiratory particles flying from surfaces contaminated with the Corona virus, such as animal fur or paper tissues, can cause infection with the virus. Even personal protective equipment may represent a source of flying dust, which can be a cause of infection with the Corona virus. Therefore, it has become important to take into account the effectiveness of the face masks when manufacturing them to limit the external transmission of air or spray during breathing, speech, etc. Epidemiological and clinical studies in evaluating the effectiveness of the masks have found that wearing masks reduces disease transmission, especially in the early stages (MacIntyre and Wang, 2020; Chu, 2020). It has also been able to measure the efficiency of filtration of materials and its relationship with the effectiveness of the mask in preventing external filtration of particles generated by coughing (Shah et al., 1983). Investigations have shown that the concentration of particles transported through face masks ranges between (0.02 –1) µm and decreases according to the type of mask. Therefore, surgical masks reduce the internal cell transfer to the outside by a large and effective rate (Davies et al., 2013; Green et al, 2016). Studies are still dealing with the effectiveness of certain types of masks in preventing the transmission of infectious respiratory diseases among humans by preventing the emission of respiratory system particles. The clinical trials have reported the effectiveness of KN95 respirators, N95 respirators, surgical masks, and homemade masks in reducing the rate of droplet emissions from breathing, speaking and coughing (Asadi et al., 2020). However, the investigations proved the effectiveness of the face masks in reducing the transmission of the particles causing respiratory diseases, especially viral diseases such as corona, and which are believed to be transmitted through exhaled particles issued directly from the respiratory system of infected individuals (Killingley and Nguyen, 2013). Researchers in (Emma et al., 2020) demonstrated an optical method to investigate a variety of common masks with speakers to extract a relative comparison between different face masks and their transmission of droplets.

In this paper, we introduce a simple holographic method to evaluate the efficacy of the surface mask in preventing the transmission of particles.

Digital in-line holographic microscopy-DIHM

DIHM has the ability to track, identify, and distinguish a target particle due to the order of the laser wavelength used in the investigation. It became possible to track micro-organisms such as bacteria, biological samples, and tissues by this simple method (Sucerquia et al., 2006). One of the advantages of DIHM that distinguishes it from other techniques is its simplicity of installation as it does not require a magnifying lens, while all that is required to install DIHM is a laser source, an optical fiber, and a CCD camera to create a three-dimensional image of the object that includes the available information related to it. The accuracy of the system can be controlled by choosing a laser with an appropriate wavelength. This system is characterized by its ability to track a large number of particles simultaneously within a short period of time.

The idea of DIHM is based on imaging the interference between the object waves and the reference waves by the CCD, and then the interference images are processed to extract the required information about the object.

On line measurement is of a great importance for many applications, but it was difficult to implement with traditional imaging means. Therefore it witnessed limited practical applications until the traditional holographic imaging was replaced by electronic recording processes besides visual reconstruction with numerical computation by computer software followed by the suitable printing method. The reconstruction is then done by visual aids (Brown and Lohmann, 1966). Through direct electronic recording of holographic interference, a complete and accurate representation of the visual field as an array of complex numbers is allowed for many imaging and processing possibilities that are difficult (Jueptner and Schnars, 2005). With the development of many useful and special technologies the capabilities could be enhanced to expand the range of the applications. Both number of pixels and the resolution of imaging devices are important limitations of digital holography.

Hologram of the flying particles

The present work uses the in-line Fresnel holographic setup in figure 1 to image the transmission of external particles passing through different types of face masks.

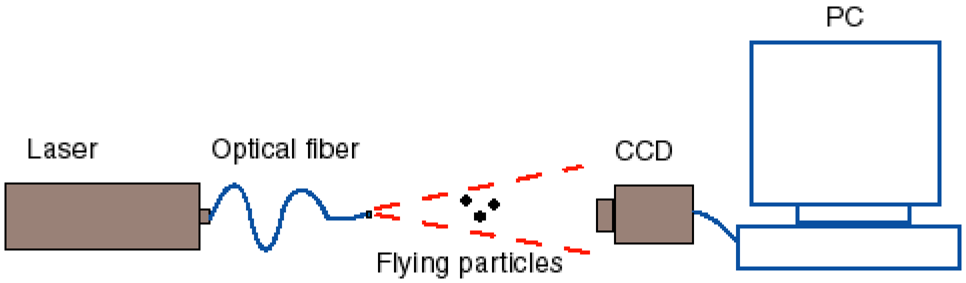


Figure 1: In-line Fresnel holography composed of optical fiber laser producing a point source that emerges divergent beams to illuminate the flying particles.

The linearly polarized light falls on the particles where the optical fiber creates a virtual point source that acts as a linearly polarized spherical reference waves as in figure 2. When the beams fall on the small particles, they in turn form another spherical source of light. The accuracy can be controlled by adjusting the angle and distance between the light source, the location of the particles, and the camera. When the reference waves interfere with the waves originating from the particles, a hologram is produced and the interference fringes are formed.

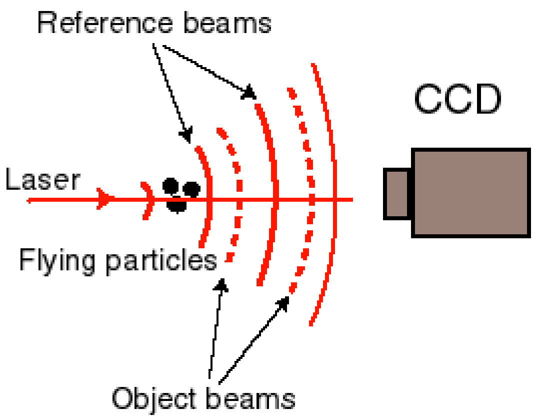


Figure 2: Flying particles are illuminated with laser beams, and both reference and flying particles beams interfere on the receiver.

The interference of the reference and object waves is represented in (Ayoub and Tokés, 2003) as:

$$I(x,y) = \left|I_{\mathrm{Re}f}^{2}\right| + \left|I_{Obj}^{2}\right| + I_{\mathrm{Re}f}^{*} I_{Obj} + I_{Obj}^{*} I_{\mathrm{Re}f}$$

where $I_{\mathrm{Re}f}$ is the intensity of the reference wave, I_{Obj} is the intensity of the object wave, and $I_{\mathrm{Re}f}^{*}$, I_{Obj}^{*} are the complex conjugates of the two waves interference. The hologram interference patterns are recorded by the camera. For the classical reconstruction of the hologram, a plane wave W illuminates the hologram to form the reconstructed wave front H that is given by the formula:

$$H(x,y) = W\, I(x,y) = WI_{\mathrm{Re}f} + WI_{Obj} + WI_{\mathrm{Re}f}^{*} I_{Obj} + WI_{\mathrm{Re}f} I_{Obj}^{*}$$

where $WI_{\mathrm{Re}f} + WI_{Obj}$ forms the diffraction zero order, both $WI_{\mathrm{Re}f}^{*} I_{Obj}$ and $WI_{\mathrm{Re}f} I_{Obj}^{*}$ represent the virtual and real images of the object. The virtual image is a replica of the multiplication of object wave and the reference intensity, while the real image is a replica of the multiplication of conjugate object wave and the reference intensity.

The total automation of the particles hologram reconstruction is an advantage of the current work. It also allows for the location and size of each droplet to be determined.

To replicate Fresnel diffraction for a certain distance z_0, the holograms will be simply convolved with the spatial impulse response in the digital reconstruction (Poon, 2007). The following equation will be applied to get a real image reconstruction in front of the hologram:

$$H(x,y) * h(x,y;z_0)$$

where $H(x,y)$ represents the hologram. The reconstructed real image at a distance z_0 can be obtained digitally using the above equation, which is implemented in the Fourier domain as:

$$F^{-1}\left(F(H(x,y)H\left(k_x,k;z_0\right)\right)$$

where $H\left(k_x,k;z_0\right)$ is the spatial frequency response, knowing that the two-dimensional spatial *Fourier transform* of a signal $f(x,y)$ is:

$$F_{xy}(f(x,y)) = F\left(k_x,k_y\right) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\exp\left(jk_x x + jk_y y\right)dxdy$$

and the inverse Fourier transform is:

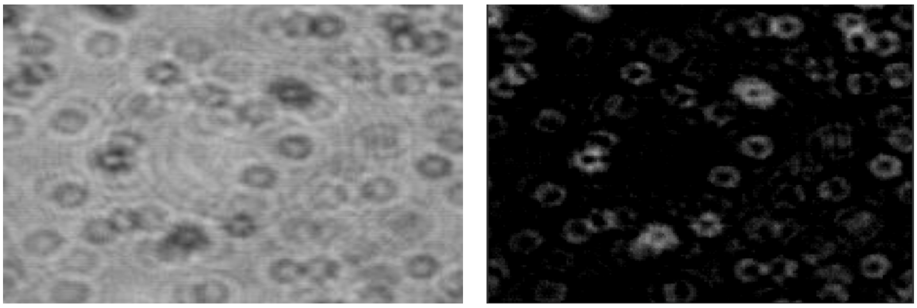
$$F_{xy}{}^{-1}(F(k_x,k_y)) = \frac{1}{4\pi^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} F(k_x,k_y)\exp\left(-jk_x x - jk_y y\right)dk_x dk_y = f(x,y)$$

MATERIALS AND METHODS

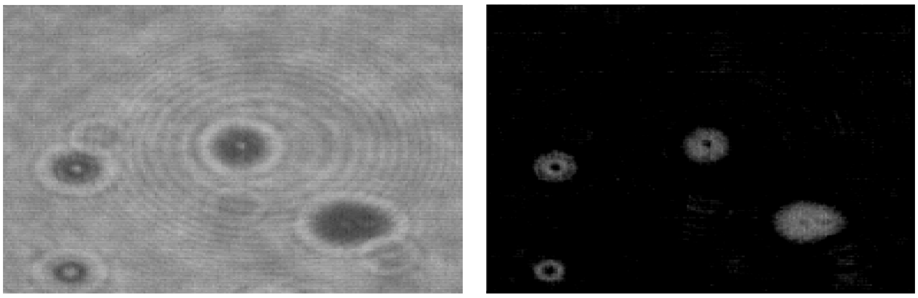
The experimental work focuses on recording the holograms of the flying particles (droplets) penetrating the face mask. We have used different types of commonly used masks (single layer cotton mask, two layers cotton mask, surgical mask), where we put the masks next to the light source at the exit of the optical fiber. We generated droplets by micro dispensing device which can allow control on the droplets diameter by changing the pressure applied to the reservoir. In this case, the generated droplet size is dependent on the pressure, while the penetrated droplet size is dependent on the mask material. The dispensing device is adjusted to generate constant droplet volume. By this, the change in the penetrated droplet size is only caused by the mask material.

In systems with low particle density and relatively large sizes, digital in-line holography can be a very good solution for particle characterization. The in-line holographic setup is appealing because it requires minimal optical equipment and laser coherence length. It can adapt any droplet size by adapting the magnification.

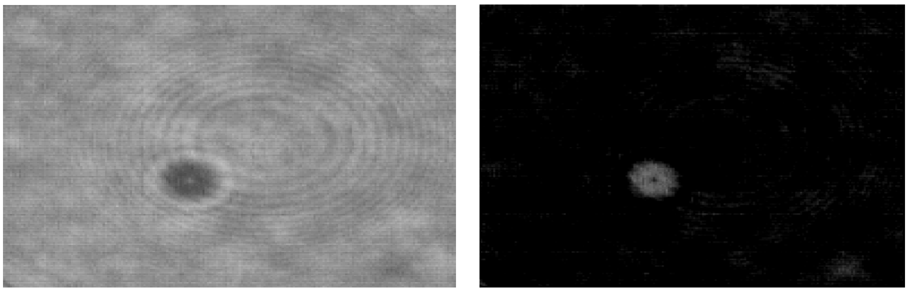
The penetrated droplets scatter laser light that interfere with the reference beams in the CCD camera. The droplet holograms are recorded and reconstructed in different conditions of no mask use and different masks use, and the holograms are then constructed mathematically (Figure 3).



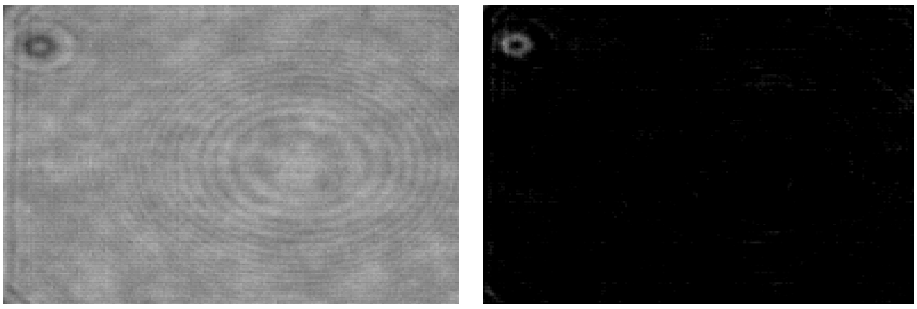
(a) Droplets hologram and its reconstruction for no mask show large number of droplets of mean size ~200µm.



(b) Droplets hologram and its reconstruction for single layer cotton mask shows reduced number of the droplets of mean size ~167µm.



(c) Droplets hologram and its reconstruction for two layer cotton mask shows fewer droplets of mean size ~159µm.



(d) Droplets hologram and its reconstruction for surgical mask shows the least number of droplets of mean droplets size ~77µm.

Figure 3: The droplets holograms and the reconstruction for (a) No mask, (b) Single layer cotton mask, (c) Two layer cotton mask, and (d) Surgical mask.

RESULTS AND DISCUSSION

Initially, the size of the droplets was adjusted by adjusting the dispensing device's pressure. The size of the droplets, on the other hand, is determined by the viscosity of the fluid and the cleanliness of the fluid. Generally, it was assumed that the droplet sizes would differ significantly as the droplets start out small, but as they fall down, they can collide and agglomerate, resulting in larger size droplets. However, number of holograms can help in finding the relationship between the droplets size and the type of the mask for the accurate determination of the position of the particle.

Focusing on figure 3a, the holographic system detected largest droplets size (mean diameter ~200µm) in case of no mask is used. To measure the particle size, the field of view of the measured image was calibrated by using a reference slide of 5 mm, and particles size was estimated based on the pixel size and number of pixels.

In contrast, using a single layer cotton mask in figure 3b significantly reduced the outward number of particles, representing an approximately 10% penetration rate compared to no mask case, and the droplets mean diameter becomes ~167µm.

In figure 3c, two layer cotton mask reduced the number of particles by 25%, and the mean particle size was found to be ~159µm, suggesting no statistically significant influence on particle size comparable to that observed with the single layer cotton mask.

In figure 3d, the overall trend of the surgical mask type influence on particle emission rate was qualitatively similar to that of the two layer cotton mask although it reduced the mean droplets size to ~77µm.

Figures 4 and 5 demonstrate the size and emission rate of the droplets when no mask is used, as well as for the three mask types considered in this work: single layer cotton mask, two layer cotton mask, and surgical mask. The logarithmic trend may be seen on both scales.

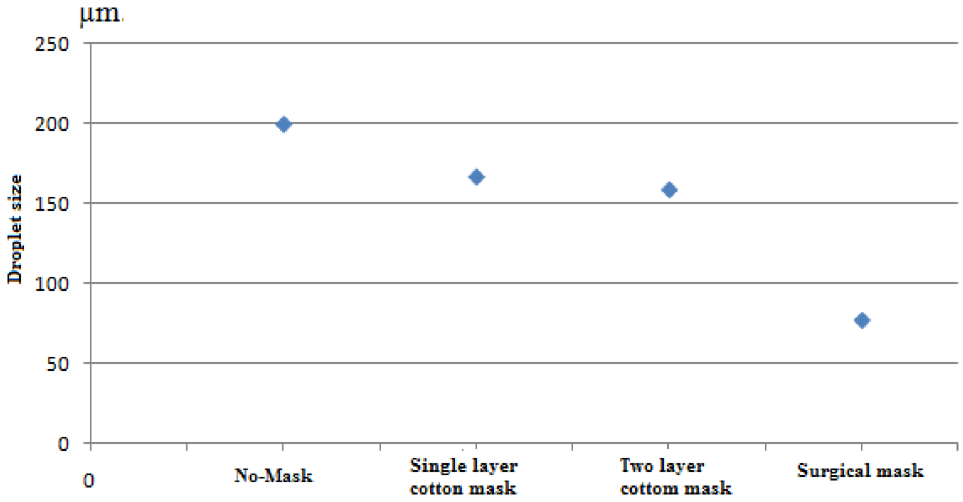


Figure 4: The droplets size measured from the constructed hologram for: No-mask, single layer cotton mask, two layer cotton Mask, and Surgical mask.

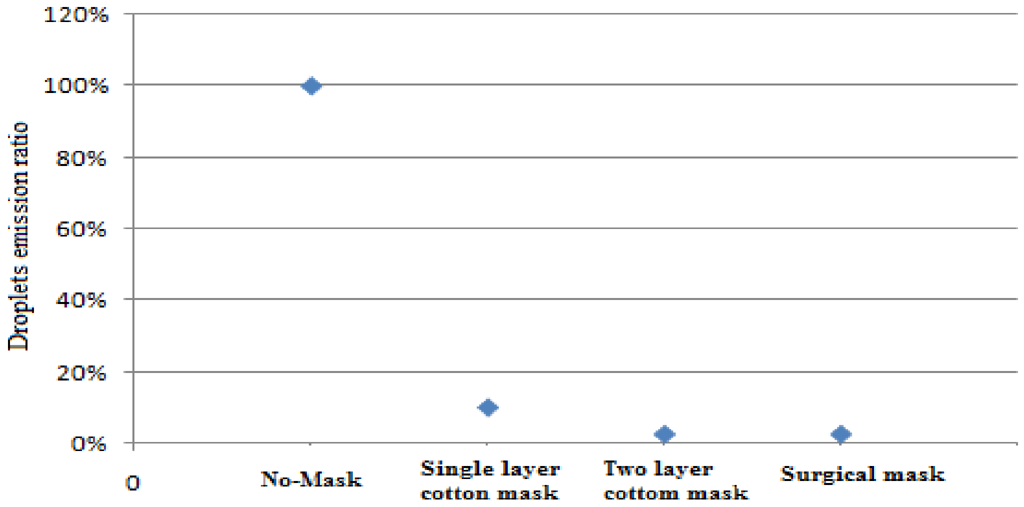


Figure 5: The droplets emission ratio from the constructed hologram for: No-mask, single layer cotton mask, two layer cotton Mask and Surgical mask.

CONCLUSION

Digital in-line holography was used to analyze the released droplets formed by a micro dispensing device to determine the efficacy of several types of face masks. The diameter of the mean droplets and the rate of emission are observed to vary depending on the mask type. In systems with low particle density and relatively large sizes, digital in-line holography can be a very good solution for particle characterization. The in-line holographic setup is appealing because it requires minimal optical equipment and laser coherence length. The results obtained with the selected mask types agree reasonably well based on either number of mask layers and mask type. The results show that wearing surgical masks or two layer cotton masks reduces the number of particles emitted from the dispenser, however single layer cotton masks are ineffective but do reduce the ratio of particles emitted. We did not evaluate virus emission, but our findings clearly suggest that wearing a mask reduces droplet emission. Our findings support the notion that wearing a mask can help in the prevention of pandemics caused by respiratory diseases. Our findings emphasize the significance of replacing disposable masks and washing cotton masks on a regular basis, as well as the need for extra caution when removing and cleaning the masks.

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