Quantitative Performance Analysis of Respiratory Facemasks using Atmospheric and Laboratory generated Aerosols following with Gamma Sterilization

Amit Kumar (amitpatel@igcar.gov.in)  
Indira Gandhi Centre for Atomic Research

D.N. Sangeetha  
Indira Gandhi Centre for Atomic Research

Ramani Yuvaraj  
Indira Gandhi Centre for Atomic Research

M. Menaka  
Indira Gandhi Centre for Atomic Research

V. Subramanian  
Indira Gandhi Centre for Atomic Research

B. Venkatraman  
Indira Gandhi Centre for Atomic Research

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Abstract

The emergence of the recent Covid-19 pandemic has rendered mandatory wearing of respiratory masks by infected persons, frontline workers, security personnel and members of the public. This has caused a sudden shift of focus and significant demand on availability, effectiveness, reuse after sterilization and development of facemask. Toward this, three types of masks viz. N95, nonwoven fabric and double layer cotton cloth are being used by the majority of the population across the world as an essential inhalation protective measure for suppressing the entry of virus-laden respiratory droplets. The Filtering Efficiency (FE) of these masks are tested for atmospheric and laboratory generated aerosols of size 1.0 µm and 102.7 nm particles before and after sterilisation and for the two flow rate conditions corresponding to normal breath rate and during sneezing/coughing. Sterilisation is carried out using a gamma irradiator containing Co-60 source for the two-dose exposures viz. 15 kGy and 25 kGy. The FE of surgical and cloth masks is found to be in the range of 15.76±0.22 to 22.48±3.92%, 49.20±8.44 to 60±7.59% and 73.15±3.73 to 90.36±4.69% for aerosol sizes 0.3<5.0, 1.0<5.0 and 3.0<5.0 µm atmospheric aerosols respectively. The FE of cloth and surgical masks ranges from 45.07±6.69% to 63.89±4.44% and 56.58±1.69% to 83.95±1.04% for 1.0 µm laboratory generated aerosol for two flow rate, control and irradiated conditions. The FE of N95 mask is found to be more than 95% for atmospheric aerosol and 1.0 µm laboratory generated aerosol. However, FE reduced to about 70% for most penetrating particle size after sterilisation. Further, FE reduced to 84% for the particle >0.3 µm and to 87% for the particle <0.3 µm after sterilisation. The reduction in FE for N95 mask after sterilization is associated with reduction of electrostatic interaction of filter medium with particles laden in the air stream. Instead of disposing of N95 masks after single use, they can be reused a few times as N70 mask during this pandemic crisis after sterilisation. The use of cotton cloth masks in the general public serves fit for the purpose than surgical masks.

Introduction

The corona virus disease (COVID-19) is a new type of disease that started spreading from December 2019 and presently, affected more than 200 countries across the territories around the globe. As of now (26 June 2020), more than 9 million positive cases and more than 0.4 million deaths indicate the severity of the current pandemic (https://www.worldometers.info/coronavirus/). In general, the spread of the corona virus infection can occur through contact (direct and/or indirect), droplet spray in short range (for droplet diameter greater than 5 µm) and long range by airborne transmission of aerosols (aerosol diameter less than 5 µm) when infected person coughs, sneezes and talks. Further, the transport of droplet and aerosols depends on airflow velocity, temperature and relative humidity of the environment (Moriyama et al., 2020). According to the latest findings, the entry of Covid-19 virus into human tissue and from sneeze/cough droplet ballistics suggests that the major transmission mechanism is not via the fine aerosols but by large droplets. This warrants the wearing of facemasks by everyone and maintaining good social distance (more than 2 m) to reduce the spread of the virus (Eikenberry et al., 2020; Cheng et
Further, the particles generated from coughing/sneezing ranges from 0.1 to 100 µm (Yang et al., 2007; Gralton et al., 2011; Lindsley et al., 2012) and these aerosols are principal carrier of virus. In general large droplet settle in a small distance about 1-2 m due to gravity (Morawska, 2006) however, aerosols remain suspended in air for longer time due to their small size, which play a key role in spreading the infection (Morawska, 2020; Wang and Du, 2020; Santarpia et al., 2020). It is to be understood that inhalation hazard is the important means of getting infection; hence, in order to avoid or mitigate the spread of respiratory infection, the physical barrier such as facemask is highly necessary.

The facemask offers protection against infectious respiratory droplets, aerosols and corona virus-laden aerosols from the contaminated conditions (Feng et al., 2020; Ho et al., 2020). As millions of masks are being used daily and currently there exists a shortage of N95 masks (Juang et al., 2020). Hence, it has become necessary to reuse the masks in this pandemic crisis by the public, the staff on the frontline workers in health-care, and security personnel in order to avoid any shortages in supply of N95 masks and prevent infection. It is often considered as good practice to sterilize the masks by killing the secondary pathogens before reusing. Many authorities (governments, manufacturers, scientists and experts) are looking to expand the availability facemask by sterilizing them with effective methods. Under these premises, multiple potential methods for sterilization have begun to be explored. Some are based on chemical methods (hydrogen peroxide, chlorine dioxide, bleach, alcohol, soap solution, ethylene oxide and ozone decontamination etc.) and physical methods (dry/steam heat treatment, UV light sterilization, electron beam and gamma irradiation etc.) (Kumar et al., 2015; Liao et al., 2020). All above sterilisation methods having advantages and disadvantages from one than others (Cramer et al., 2020; Juan et al., 2020). Among the different methods, the available literature seems to point out that, the most promising methods are those that use hydrogen peroxide vapour, ultraviolet radiation, moist heat, dry heat, ozone gas and gamma irradiation. The methods that are not recommended for disinfection or sterilization such as cleaning with soapy water, alcohol, bleach immersion, ethylene oxide, microwave, high temperature, and autoclave or steam because they can significantly degrade the filter due to degradation of solidity of filter, alteration of the electrostatic properties of the filter fibre and affect particle penetration levels (Juan et al., 2020). Ozone gas appears to be effective in decontaminating respirator masks without damaging them, although it presents risks for the safety and health of workers who carry out the process if it is not handled properly (Zhang et al., 2004; Juan et al., 2020). In the case of dry or moist heat, at what temperature and how much time the mask should be heated, so that corona virus can be deactivated without affecting the filtering efficiency, filtering material, strap and strap attachment etc. is not known satisfactorily. Among all the sterilisation methods, the gamma irradiation is found to be safe, reliable and highly effective towards treating a wide variety of products with varying densities.

Radiation sterilization has been commonly used since the mid-nineteenth century to eliminate microorganisms, such as bacteria, fungi and spores, from medical equipment. Currently, almost half of the of healthcare products, such as gloves, syringes and single use protective clothing, are sterilized using gamma irradiation, electron-beams or X-rays prior to use (IAEA, 2020). The gamma sterilisation has been extended to disinfect cloth masks and textile masks, which offer sizeable protection from respiratory droplet (IAEA, Technical report). The gamma radiation has the ability to penetrate products while sealed
in their final packaging, supports manufacturing and distribution process by facilitating final packaged products as well as raw materials, by ensuring full and homogeneous sterility of the product (IAEA, 2020). It is found in some of the recent work on the Covid-19 pandemic scenario to determine whether radiation could be used for sterilization of facemasks (Cramer et. al., 2020; Tzu et al., 2020; Man et al., 2020; Liao et al., 2020).

Towards these objectives, three types of masks, which are being mostly used across the world include, N95, non-woven fabric masks (often called as surgical mask), self-made two-ply double layer cotton masks are tested for filtering efficiency by atmospheric aerosols and laboratory generated aerosols. The laboratory generated aerosols are 102.7 nm (the approximate size of the virus) and 1.0 µm (the approximate size of droplets generated during sneezing and coughing). These masks are being used by the general public and are being worn in the open/office environment where they encounter aerosols available in the atmosphere. Hence these masks were tested by general ambient/atmospheric aerosols. The testing was carried out in accordance with two breath conditions (normal breathing and during sneezing/coughing). As millions of masks are being used per day, in order to prevent the spread of secondary pathogens, cross contamination and continue to use the irradiated N95 face mask after sterilisation at par with surgical and cloth masks, filtering efficiency tests were conducted before and after sterilisation using gamma irradiation for the three types of masks. A comparison is made on the filtering efficiency of the current work and with the results available in literature for N95 masks, in particular, in the present work, highlighting flow rate conditions, where, there is practically no data available. The detailed experimental methodology, results and discussion, conclusion and recommendations are described in this paper.

**Materials And Methods**

The evaluation of filtering efficiency of these masks are carried out in a test facility consisting of stainless steel cylindrical duct which have provision for fixing the facemask without any air leakage. The upstream and downstream aerosol number concentrations are counted and the efficiency is determined before and after sterilisation of the masks. The details of the experimental setup, types and quantity of masks, necessary data acquisition system and generation of test aerosols are explained in this section.

**Experimental setup**

All the tests were conducted at HEPA Filter Testing Laboratory, Radiological and Environmental Safety Division. The filter-testing rig was installed as per British Standards (BS-2831). The lab was accredited by NABL (National Accreditation Board for Testing and Calibration Laboratories), India and follows test procedure for HEPA filters used in nuclear industries as per IAEA technical document series 122. The schematic of experimental filter test apparatus is shown in Fig.1. It consist of a cylindrical tube of 8.5 cm internal diameter and 180 cm length connected with sampling ports in the upstream and downstream (60 cm upstream and 30 cm downstream of the test specimen), aerosols generator, aerosols diagnostic
instruments, air velocity meter, differential pressure monitor, relative humidity and temperature monitor of air stream. The facemask specimen (without cutting the facemask) is fixed in the test rig using flange and O-ring set-up and it is perfectly found to be fitted without any air leakage (the mask edges were completely sealed). The desired airflow rates are achieved through suction by using an air displacement pump (Make: M/s. Rotovac and CG commercial motor) and flow meter (M/s. Weiser). The aerosols are sampled before (upstream) and after (downstream) of specimen when aerosol-air suspension passes through the facemask. The effective area of the various masks during the test was 56.74 cm².

Aerosol generator and standard test aerosols

All three types of masks are tested for filtering efficiency with atmospheric and laboratory generated aerosols. The standard test aerosols are generated using an aerosol generator (Model and Make: 7.811 and M/s Grimm Aerosol Technik, Germany). The aerosols suspended in air are continuously introduced at the inlet of the test rig. The polystyrene latex (PSL) particle sizes 1.0 ± 0.1µm (M/s MAGSPHERE Inc., USA) and 102.7 ± 1.3 nm (M/s Polyscience Inc., USA) are used as monodispersed test aerosols.

Aerosols diagnostic instruments

The aerosol sampling is carried out from the upstream and downstream simultaneously using of Optical Particle Counter (OPC) (Model and Make: 1.108 and M/s Grimm Aerosol Technik, Germany) and Scanning Mobility Particle Spectrometer (SMPS) (Model and Make: 5.416 and M/s Grimm Aerosol Technik, Germany). The OPC works on the principle of light scattering and measures the particles in the range of 0.3 – 20 µm and SMPS works on electrical mobility and measures particles in the range of 10 – 1100 nm. The details of the both instrument working principle and specification can be found elsewhere (Usha et al., 2019 and Subramanian et al., 2019). The reproducibility of the OPC and SMPS are ± 3% and ± 5% respectively for the entire measuring range of OPC (0.3 to 20 µm) and SMPS (10 to 1100 nm). The total upstream and downstream aerosols counts of the test rig were measured by OPC and SMPS without face mask for 20 and 90 L min⁻¹ flow rate. The filter test rig was tested for zero efficiency (without face mask) condition using ambient aerosols and found less than 3% for OPC and ranges from 4 - 6% for SMPS.

Gamma sterilisation

The sterilization of various type of masks is achieved by using Gamma irradiation chamber (Model and Make: GC500 and M/s BRIT, India) where the masks are irradiated using Co-60 source (gamma energy 1.17 and 1.33 MeV) for the desired dose level. The gamma irradiation chamber is cylindrical in shape with approximately 17.2 cm in diameter and 20.5 cm height and the dose throughout the chamber is uniform by using pencil sources. All facemasks were irradiated at a dose rate of 1.94 kGy h⁻¹ (current activity 2.5 kCi as of May 2020). The dose variability was ≤10%, based on most recent calibration by
using Fricke dosimeter. It is noted from the recent study, the corona virus (SARS-CoV and MERS-CoV) are inactivated with cumulative radiation dose of 2.0 Mrad (Feldmann et al., 2019; Kumar et al., 2015). It is pointed out form the IAEA technical report (https://www.iaea.org/newscenter/pressreleases/radiation-effective-in-sterilizing-personal-protective-equipment-except-for-respiratory-masks), a high level disinfection with the dose in the range of 12-18 kGy would be enough to reduce 99.99% of infectious agent. However, the sterilization is carried out as per the Technical document, BRIT, 2015, for the medical product with the cumulative dose in the range of 15-25 kGy.

**Types of facemask and quantity**

The three types of facemasks viz. N95 (NIOSH N95 TC -84A-6969, Manufacturing date: 01-02- 2020), non-woven fabric (surgical mask) and self-made double layer cotton cloths (general public choice during the pandemic) have been tested for particulate filtering efficiency. The cotton masks are stitched from a bundle cloth made of 2/2 twill weave (two warp threads crossing every two weft thread) having 80 x 80 counts per square inch. The surgical masks are made of 3 layered gauze having high count gauze (40 x 24) at the outer side and two layers of normal gauze (28 x 24 counts) on the inner side. The tests are conducted at two constant flow rate conditions at 20 and 90 L min\(^{-1}\) corresponding to breathing rate during light activity and sneezing/coughing respectively (Adams, 1993; Lee et al., 2019). The number of masks tested in each type are summarised in Table 1. The image of nonwoven fabric, double layer cotton cloth and N95 facemask is shown in Fig. 2. A set of three N95 facemasks and 10 numbers of each of surgical and cloth masks are irradiated in gamma irradiator. The duration of irradiation is 7.75 and 12.75 hrs and total cumulative doses received by the masks are 15 kGy and 25 kGy respectively.

**Data for differential pressure, Air velocity, relative humidity and temperature**

The pressure drop or differential pressure (\(\Delta P\)) was measured using a manometer (Make and model: TSI, USA and 9565P143003) across the test mask at 10 cm away on either side. The measuring range and error in reading in \(\Delta P\) is -3736 to +3736 and ±2 pascal respectively. The differential pressure is an indicator and condition for comfort and breathability of facemask. The face velocity in the test section is measured with a velocity meter (Make and model: Velocicalc, TSI, USA and 9565P143003). The measuring range and error in reading in air face velocity is 0 – 50 m s\(^{-1}\) and ±3% respectively. The face velocity of aerosols in the upstream is measured at 45 cm before the test specimen. The K type thermocouple and Humidity monitor are used for the measurement of temperature (T) and relative humidity (RH) of air stream respectively. The measuring range along with error in the measurement of T and RH are -10 to 60 °C± 0.3 °C and 5 to 95% ± 3% respectively.

**Filtration efficiency**
The filtering efficiency ($FE$) of three different mask are calculated using the following formula:

$$\text{Filtering efficiency } (FE) = \frac{(Cu - Cd) * 100}{Cu},$$  

(1)

Where, $Cu$ and $Cd$ are the average aerosols concentration of upstream and downstream respectively for each size bin. The sampled data of each mask has been recorded for about 2-3 min in interval of 6 s from OPC (total sample record 20-30) and for 2L/min in interval of 7 min from SMPS (total sample record 3). The $FE$ is computed by taking the average of the collected data of upstream and downstream for the tested period and for each filter. The $FE$ of the three type of mask is calculated for atmospheric aerosols and mono dispersed PSL aerosols of 1.0 µm. Further, the N95, cloth and surgical mask has been tested for 102.7 nm laboratory generated PSL aerosols and reported.

**Data Analysis**

In the present study the aerosols number concentration is used to quantify the filtering efficiency of masks. The aerosols concentration recorded by instruments are analysed for each mask (N95, non-woven fabric (surgical mask) and self-made double layer cotton cloths) and $FE$ were averaged for all similar type masks and tested conditions (like flow rate and both gamma sterilization). Furthermore, the uncertainty associated in $FE$ of facemask has been calculated. Type A uncertainty has been arrived at for repeated measurement and number of face masks tested and Type B uncertainty has been calculated based on the following individual uncertainty (accuracy in measurement, resolution and calibration of instrument). The combined uncertainty has been calculated and then expanded uncertainty has been derived from combined uncertainty by multiplying the coverage factor (95% confidence level). The average $FE$ was subjected to one iteration of the Grubbs test with a 95% confidence interval to remove most one outlier in filtering efficiency. This improves the statistical variation of the data for the calculation of $FE$.

**Results And Discussion**

The masks being tested is fixed into an air duct and ambient particulates are flown through the facemask with a face velocity of 0.058±0.002 and 0.264±0.009 m s$^{-1}$ corresponding to 20 ± 0.2 and 90 ± 1.0 L min$^{-1}$ flow rates respectively. The measured ambient air temperature is 26±0.3ºC and RH% is 65±3. The measured average aerosol concentration for the upstream ($Cu$) and two flow rates 20 and 90 L min$^{-1}$ is presented in Fig. 3(a) (SMPS) and 4(a) (OPC) respectively. Similarly, the average aerosols concentration measured for the downstream ($Cd$) for two flow rate, with and without gamma sterilisation of N95 mask is shown in Fig. 3(b) (SMPS) and 4(b) (OPC) respectively. It is observed from Fig. 3 (a) and 4 (a) that, a significantly lower aerosol concentration in the upper size distribution for both the data sets, that is, for aerosol greater than 300 nm for the data measured by SMPS and greater than 5 µm for the data measured by OPC. The data were excluded above these thresholds (300 nm for SMPS and 5µm for OPC) for all results presented in the paper due to the extremely low concentration and this may increase statistical error. The pressure drop across the all facemask is measured before and after sterilisation and
it is given in Table 2. The average pressure drop of surgical masks was found to be 2.45±2.03 pascal for 20 L min\(^{-1}\) flow rate and 7.36±2.08 pascal for 90 L min\(^{-1}\) flow rate, which is much less than the reported value (approximately 20 pascal at flow rate 90 L min\(^{-1}\)). The average pressure drop of cloth masks was found to be 11.57±2.12 and 73.55±2.74 pascal for 20 and 90 L min\(^{-1}\) flow rate respectively. The average pressure drop of N95 mask was 31.32±2.31 pascal for 20 L min\(^{-1}\) flow rate and 258.9 ± 4.59 pascal for 90 L min\(^{-1}\) flow rate. The average pressure drop of cloth masks is more than surgical masks and less than N95 masks. It is to be mentioned that the pressure drop across all the three types of decontaminated facemask showed that there is no measurable change observed i.e. change appears within the error bar values, i.e. there is no physical change in bulk density of face mask fibres/threads after decontamination. The pressure drop indicates the condition for usage during breathing and is found to be in the accepted range (inhalation and exhalation resistance limit is 343 and 245 pascal respectively) (Lin et al., 2020).

Efficiency evaluation with ambient aerosols size 0.3 – 5 µm using OPC

The average \(FE\) of the cloth masks, surgical masks and N95 masks for the two-flow rate condition and before and after gamma sterilisation (15 and 25 kGy) is tabulated in Table 3. Table 3 is drawn with three particle size bins viz. 0.3 – 5.0, 1.0 – 5.0 and 3.0 – 5.0 µm. An average \(FE\) of cloth masks vs aerosol optical diameter is shown in Fig.5 for control and decontaminated mask for two flow rates. It is observed from Fig. 5 and Table 3, in the case of cloth masks, average \(FE\) is found to be more or less same after sterilisation and found to vary from 18.84±0.33 to 20.28±1.49%, 49.20±8.44 to 60±7.59% and 80.66±4.28 to 89.41±5.63 % for both flow rate and irradiated conditions for atmospheric aerosols of size 0.3–5.0, 1.0–5.0 and 3.0–5.0 µm respectively. Similarly, from Table 3, the average filtering efficiency for the surgical mask found to vary from 15.76±0.22 to 22.48±3.92%, 49.89±7.63 to 59.22±9.25% and 73.15±3.73 to 90.36±4.69% for the atmospheric aerosols of size 0.3–5.0, 1.0–5.0 and 3.0–5.0 µm respectively. The surgical masks are found to be performed with slightly decrease in efficiency after sterilisation when compared to without gamma sterilized condition for the same particle ranges. In the case of N95 masks, the filtering efficiency is found to be reduced to 69.78±1.07% from 99.68±0.05% and about 63.12±2.22% from 94.98±1.98% for the two irradiated conditions for 20 and 90 L min\(^{-1}\) respectively. The uncertainty in \(FE\) is significantly more for cloth and surgical masks in case of 1.0–5.0 and 3.0–5.0 µm aerosols compared to N95 masks probably indicating the texture/material quality of masks in the manufacturing stage. Further, the masks showed no measurable changes in fit or measurable structural changes when exposed up to 25 kGy dose of radiation. The International Atomic Energy Agency (IAEA) has recently indicated the same observation that, there is no significant change in the texture of the mask with respect to fit factor of the mask at 24 kGy radiation dose, which is needed to kill viruses and bacteria (IAEA, 2020).

Efficiency evaluation with PSL aerosol size of 1.0 µm
The performance evaluation of mask for atmospheric aerosols may give more statistical error due to low aerosols number concentration (less than $10^1 \div 10^2 \text{ L}^{-1}$) for 1.0 µm and above. In this regard, all three types of masks are tested for laboratory generated PSL aerosols of size 1.0 µm. This kind of added information may be very useful for some specific context and application. For example, the average number of aerosols generated per cough by Influenza patient is $7.5*10^4$ and count median diameter (CMD) of cough generated aerosols/droplet were in between 0.6 to 0.9 µm with Geometric Standard Deviation (GSD) 1.53 to 2.28 (Lindsley et al., 2012). Similarly, another recent study suggests that, the average number of droplet/aerosols expelled per cough by a person having respiratory infection is $4.9*10^6$ with most of the aerosols are less than 5.0 µm and aerosol number becomes less when person recovered from the infection (Lee et al., 2019). Another study shows that 80% of droplets/aerosols are centred in the range of 0.74 ± 2.12 µm during coughing and sneezing (Yang et al., 2007). Further, the detailed transmission of SARS-CoV-2 virus is not well understood till now; aerosols less than 5.0 µm are considered as the primary source of transmission of respiratory infection (Doremalen et al., 2020; Wang et al., 2020). In this context, the filtering efficiency of the mask needs to be tested for high aerosols concentration ($10^5 \div 10^6 \text{ L}^{-1}$) in the 1.0 µm range. Fig. 6 shows the filtering efficiency of these three types of filters for PSL particles of size 1.0 µm with and without sterilisation and for the two flow rate conditions. It is observed from Fig. 6 that filtering efficiency for N95 mask shows greater than 96.25±0.67% even after sterilization for both the flow rate conditions. The filtering efficiency of surgical mask is found to be in the range of 71.12±2.09 [83.95±1.04% before sterilisation and it reduced to 43.2±5.65 [56.58±1.69% after gamma sterilisation. The measured filtering efficiency of cloth mask in the range of 55.82±4.56 [63.89±4.44% before sterilisation and 45.07±6.69 [59.68±0.79% after sterilisation. The cotton mask showed not much variation after sterilisation. The lower efficiency is attributed to density of fibres in the non-woven type masks while the density of wrap and weft per unit area in the case of cloth mask. However, these masks are effective for the particles in the size range of 1.0 µm and above (about 50% efficiency). It is also to be noted that the filtration efficiency of all three types of mask is more for 90 L min$^{-1}$ flow rate for 1.0 µm aerosol when compared to the 20 L min$^{-1}$. This is due to higher filtration capability for micron sized aerosols by impaction at large flow rate condition.

Filtering efficiency evaluation of facemask with 102.7 nm aerosol

The $FE$ of N95 facemask has been evaluated for nano-sized laboratory generated PSL aerosols. This gives added information and performance of masks in terms of $FE$ for nano-sized aerosols. This is also relevant in the present pandemic situation too, because transmission vector of Covid-19 infection takes place in ultrafine aerosol size and corona virus itself is in the range of 60 ± 140 nm (Kim et al., 2020; Cascella et al., 2020). The N95, cloth and surgical facemasks are exclusively tested for 102.7 nm aerosols with concentration in the order of $10^4 \text{ cm}^{-3}$. Fig. 7 shows an average $FE$ of N95 mask for both un-irradiated, gamma sterilized and for two flow rate conditions. It can be seen from the figure that, the filtering efficiency is more than 98.02±0.15% for un-irradiated condition and for both flow rates. The
efficiency found to be reduced from 99.83±0.09% to 96.17±0.99% for the flow rate of 20 L min⁻¹ and 98.02±0.15% to 80.29±1.13% for 90 L min⁻¹ under gamma-sterilized condition. The filtering efficiency for 90 L min⁻¹ is found to be less when compared to 20 L min⁻¹ condition (opposite to 1.0 µm aerosols) where nano-sized particles are carried away due to high flow rate by the flow gas streamlines in the filtering media. Further, FE of the cloth and surgical masks are also evaluated for nanoparticles. The FE of cloth masks is 20.59±3.69% and 17.67±5.01% for 20 L min⁻¹ and 90 L min⁻¹ respectively. The variation in the efficiency is not significant. The FE of surgical masks is 45.12±4.61% and 10.13±3.39% for 20 L min⁻¹ and 90 L min⁻¹ respectively. The variation in the efficiency is significant due to unstructured packing of fibres in the surgical mask which paves way for particles to trace the gas streamlines at higher flow rate. The FE of surgical masks is more than cloth masks for 102.7 nm aerosols for 20 L min⁻¹ while in case of 90 L min⁻¹ flow rate, the FE of cloth masks is more compared to the surgical masks.

### Evaluation of Filtering Efficiency of N95, cloth and surgical masks for aerosols from 10 nm to 5.0 µm

The filtering efficiency of N95, cloth and surgical masks are examined by combining data of OPC and SMPS covering from the range of 10 nm to 5 µm sized aerosols. The evaluation in the lower size range may be useful for the users, who are working or interested in filtration of nanoparticles in the facility like microelectronics fabrication environment. Further, as per ASTM standard, 2018, it is required to study the performance evaluation with respect to filtering efficiency less than 100 nm (ASTM standard, 2018). The FE of N95 mask under all conditions (un-irradiated, gamma sterilised and for two flow rates) is shown in Fig. 8. The filtering efficiency of N95 mask shows a typical conventional U shaped curve for aerosols ranging from 10 nm to 5.0 µm with minimum efficiency of control mask is 99.68±0.05% for 20 L min⁻¹ and 94.98±1.98% for 90 L min⁻¹ for 300 nm aerosols. The minimum efficiency of sterilized N95 mask is 69.78±1.07% for 20 L min⁻¹ at 300 nm sized aerosols while 64.25±2.05% for 90 L min⁻¹ in the range of 200 - 300 nm sized aerosols. The filtering efficiency is more for 20 L min⁻¹ than 90 L min⁻¹ in all the three respective conditions i.e. for the control, 15kGy and 25kGy. It is known that, the aerosol filtration takes place by five basic mechanisms viz. gravitational settling, inertial impaction, interception, diffusion and electrostatic interaction (Hinds, 1999 and Vincent, 2007). The gravitational and impaction settling play a major role in filtering the aerosols larger than 1.0 µm. As aerosol size decreases in the range of 0.1 to 1.0 µm, the Brownian diffusion and mechanical interception are the predominant mechanisms and for aerosols size less than 0.1 µm, which can easily slip from filtering media, are captured predominately by electrostatic attraction in addition to the mechanical processes. The N95 mask consists of electrostatic filtration media which encompass a broad class of materials that are capable of capturing and retaining fine air borne particulates through electrostatic interaction (Coulomb and dielectrophoretic forces) in addition to mechanical processes (Impaction, settling, Interception and Diffusion) (Myers and Arnold, 2003). It is known that, least efficiency is associated with particles in the range of 0.1 µm.
0.3 µm that is bigger for diffusion and smaller for interception; hence, the 99% efficiency is achieved for this range by electrostatic interaction. When the media loses its charges, the particles are captured only by mechanical processes where the efficiency is reduced from 99% to 65% (Fig. 8 and table 3). In the case of 1.0 µm particles, the efficiency is not found reduced even after gamma irradiation (Fig. 8 and table 3). Further, the N95 masks are designed for filtering efficiency more than 95% of aerosols size greater than Most Penetration Particle Sizes (MPPS), and therefore, their underperformance below MPPS is not surprising results (Balazy et al., 2005 and 2006). The FE of mechanical filters has least efficiency at MPPS and increases with increase or decrease of aerosol size from MPPS.

The FE of cloth and surgical masks has been investigated for two flow rates and is shown in Fig. 9. The FE of both cloth and surgical masks shows a typical conventional filtering curve for aerosols ranging from 10 nm to 10 µm. The FE is less for 90 L min<sup>-1</sup> flow rate when compared to the 20 L min<sup>-1</sup> for both cloth and surgical masks. The minimum FE of cloth masks is 14.27±2.85% for 90 L min<sup>-1</sup> and 4.32±1.35% for 20 L min<sup>-1</sup> for the aerosols in the range of 50–150 nm and 60–80 nm respectively. Similarly, the minimum FE of surgical masks is 22.59±3.05% for 90 L min<sup>-1</sup> and 12.54±1.51% for 20 L min<sup>-1</sup> for 300 nm and 200 nm aerosols respectively. The FE of cloth and surgical masks increases with increase of optical diameter and decrease of mobility diameter from least efficient MPPS and the value of MPPS is lower for high flow rate compared to the low flow rate.

**Comparison of N95, cloth and surgical mask filtering efficiency for total test aerosols concentration of sizes < 300 and > 300 nm**

The filtering characteristics of any mask depends much on aerosol characteristics like diameter, charge and density of aerosols, concentration of aerosols and airflow velocity (flow rate) apart from filter characteristics. Here, we have compared the FE of N95 mask for total test aerosols concentration in sizes less than 300 nm and greater than 300 nm. The total measured aerosols number concentration is in the order of 10<sup>3</sup> cm<sup>-3</sup> and 10<sup>4</sup> cm<sup>-3</sup> for aerosol sizes >300 nm (0.3 – 5.0 µm) and <300 (10 – 300 nm) nm respectively. Table 4 gives FE of N95 masks for two-flow rate conditions for the masks including control and after sterilization. The FE is found to be ≥ 99% for particles sized >300 nm and <300 for both the flow rates. The FE reduces after sterilisation from 99.98±0.01 to 84.28±1.68% and 99.89±0.03 to 99.04±0.11% for particles >300 nm and <300 nm respectively for fixed 20 L min<sup>-1</sup> flow rate. In the case of 90 L min<sup>-1</sup> flow rate, the FE of mask is reduced after sterilisation from 99.31±0.05 to 89.07±1.15% and 98.92±0.12 to 95.49±0.89% for particles >300 nm and <300 nm respectively. The reduction is found to be more for particles>300 nm aerosols when compared to that of <300 nm aerosol for both flow rates. The N95 mask performed most efficiently for low flow rate and nano-sized aerosols even after gamma sterilization. The electrostatic filters are efficient for nano-sized aerosols at low airflow velocity (flow rate) rather than high airflow velocity (Colbeck and Lazaridis, 2014).
The FE of cloth mask is $46.76\pm2.58\%$ and $36.58\pm2.87\%$ for 20 and 90 L min$^{-1}$ respectively for particles <300 nm. Similarly, the FE of surgical masks is $63.82\pm1.78\%$ and $28.75\pm1.52\%$ for 20 and 90 L min$^{-1}$ respectively for particles <300 nm. The FE of surgical masks is more compared to the cloth mask for <300 nm aerosol size and 20 L min$^{-1}$ flow rate while for 90 L min$^{-1}$ FE of cloth mask is more. The FE of cloth and surgical masks is more for <300 nm aerosol size compared to the >300 nm for both flow rates.

**Observation of morphological change by optical microscope**

The fiber structure of N95 and surgical masks are examined in the optical microscope (Make and Model: Axioplan 2 Imaging, Metasystems, Germany) under 100X magnification. The image taken by optical microscope for N95 and surgical mask is shown in Fig. 10 and 11 respectively. The dimension of each image is 65 µm x 65 µm and the filter fibre diameter is in sub-micrometre range for N95 mask while micrometre range for surgical mask. It is observed from Fig. 10 (a), (b) and (c) that, no observable and significant change in morphology of filter fibre is found with gamma sterilization upto 25 kGy dose. Similar observations were reported by Scanning Electron Microscopy (SEM) up to 61 kGy dose (IAEA technical report). The surgical mask consists of three layer viz. repellant the outer colored layer, the filter medium in the middle and absorbent at the innermost layer. Fig. 11 (a), (b), (c) are the microscopic image of repellant, filter media and absorber of the control mask respectively and Fig. 11 (d) and (e) belong to the filter medium exposed to 15 kGy and 25 kGy. It is observed from Fig. 11 (a), (b) and (c) that, the structure of the filter fibre media is bonded together by using chemical adhesive and appeared entangled structure. It is observed from Fig. 10 (d) and (e) that, there is no observable change in the structure of the filter fibre after gamma sterilisation.

**Comparison of N95 mask filtering efficiency from literature after gamma sterilisation**

A comparison of filtering efficiency of N95 respiratory mask with various works from the literature under gamma-sterilized condition is summarized in table 5 (Cramer et al., 2020; Man et al., 2020; Lin et al., 2020). It can be seen from the table that, the irradiation dose for mask sterilization is varied from 1.0 to 50 kGy and mask efficiency has been tested for aerosols ranging from 0.1 to 1.0 µm. The reduction in efficiency is found to be more for most penetrating particle size (0.3 µm) in all the cases. Among all the works carried out, the work of Cramer et al. (2020) showed the highest reduction in efficiency under gamma-sterilized condition. This may be due to their filtering media and relatively large face velocity (0.4 m s$^{-1}$), as the control mask itself is showing 5-15% less efficiency from others works. The filtering efficiency of present work and by Man et al.(2020) is found to have similarity for particles > 0.3 µ m, but here also, at what flow rate that masks have been tested is not mentioned. It is noted that in all the works, the testing flow rate has mentioned in few works. However, it is important to test the masks under
breathing rate condition towards fit for the purpose and that condition and that is followed in our work. The Lin et al. (2020), has presented his work for aerosol size distribution ranging from 7 to 882 nm with CMD around 75 nm and FE of N95 mask was found to be 44 to 77 % after gamma sterilization, which is much less than that of present work.

**Summary And Conclusion**

Three types of facemask viz. N95, surgical mask and self-made double layer cloth mask have been tested for particulate filtering efficiency for two-flow rate condition viz. 20 and 90 L min⁻¹ before and after gamma sterilization using atmospheric aerosols in the size range of 0.3 to 5 µm and laboratory generated aerosols of size 1.0 µm and 102.7 nm (PSL). The sterilization was carried out for two-dose condition viz. 15 kGy and 25 kGy. The measured pressure drop during filter testing were found to be much less than the inhalation and exhalation resistance limit viz. 343 and 245 pascal respectively. All three types of masks showed no significant changes in fit or measurable structural changes when exposed to the 25 kGy dose. The filtering efficiency of surgical and cloth masks are found to be in the range of 15.76±0.22 to 22.48±3.92%, 49.20±8.44 to 60±7.59% and 73.15±3.73 to 90.36±4.69% for aerosol sizes 0.3 to 5.0, 1.0±5.0 and 3.0±5.0 µm atmospheric aerosols respectively and found to be in the same range when tested with 1.0 µm laboratory generated aerosols for two flow rate, control and irradiated conditions. The FE of surgical masks is more than cloth masks for 102.7 nm aerosols for 20 L min⁻¹ while in case of 90 L min⁻¹ flow rate, the FE of cloth masks is more compared to the surgical masks. The FE of cloth and surgical masks increases with increase of optical diameter and decrease of mobility diameter from least efficiency and MPPS is smaller for high flow rate compared to the low flow rate.

In the case of N95 mask, the filtering efficiency is found to be more than 95% for control masks, for both flow rates and atmospheric aerosols (0.3 to 5µm). The filtering efficiency reduces to about 70% for most penetrating aerosols (0.3 µm) after gamma sterilisation for 20 L min⁻¹ flow rate and still lesser with higher flow rate (90 L min⁻¹) for ambient aerosols. Further, the filtering efficiency of N95 mask is more than 96% for laboratory generated aerosols of 1.0µm and 102.7 nm sizes for both flow rates under unsterilized condition. However, the minimum FE, after gamma sterilisation is found to be 84.28±1.68% for the flow rate of 20 L min⁻¹ and for the total tested aerosols of size > 300 nm while, the minimum FE is 89.07±1.15% for the tested particles< 300nm for 90 L min⁻¹ flow rate. The comparison of filtering efficiency of N95 mask for present work and literature shows that, after gamma sterilisation, the mask remain fit but FE found to be reduced for most penetrating particle size i.e 0.1 to 0.3 µm aerosols.

The breathability test (pressure drop) and filtering efficiency conveys that, more than double layer (or sometimes triple layer) cotton masks could be potential substitute for medical or surgical masks (not for N95 masks) for respiratory infected persons in sterile environments. The healthy or common population may use daily double layered cotton masks in the social community since it is washable and reusable. Since, the particle generated from coughing/sneezing is ranging from 0.1 to 100 µm (Yang et al., 2007; Gralton et al., 2011; Lindsley et al., 2012), the surgical and cotton masks significantly reduce (more than
50%) the microorganism expelled during coughing/sneezing. Further, even with reduced filtering efficiency, the N95 masks after gamma sterilisation is found to be a better option than the surgical and cloth masks and can be recommended for volunteers, security personnel and health workers. Instead of throwing or disposing of N95 masks after single use, they still could be reused as N70 masks during these pandemic crises after sterilisation using gamma

**Recommendations**

We highlight few recommendations from the present studies:

- Cotton cloth masks of double layer (sometimes three layer) with tight weaves, low porosity and high thread count are preferred for the public. Further, cotton mask is a potential substitute for the public instead of a surgical mask due to its cost effectiveness and it could be reused even after gamma irradiation for decontamination.

- The N95 masks, which are made of electret filtering media are not recommended for sterilisation or decontamination by ionising radiation, it will compromise the filtering efficiency.

- However, N95 masks after gamma sterilisation is found to be a better option than the surgical and cloth masks and can be recommended for volunteers, security personnel and health workers in case of

- In the cases of N95, the filtration efficiency is >84% for aerosols >0.3µm and > 95% for aerosols < 3µm for both flow rate and after gamma sterilisation and it is far better from any other type of masks, so it can be reused for few times. It is not recommended for handling Covid-19 patients after sterilisation using gamma radiation.

**Declarations**

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**Tables**

Due to technical limitations, Tables 1-5 are provided in the Supplementary Files section.

**Figures**
Figure 1

Schematic of the experimental setup.
Figure 2

Image of (a) nonwoven fabric, (b) double layer cotton cloth and (c) N95 facemask.
Figure 3

(a) Upstream aerosols concentration as a function of mobility particle size measured by SMPS. (b) Downstream aerosols concentration as a function of mobility particle size measured by SMPS.
Fig. 4 (a).

Fig. 4 (b).

Figure 4

(a) Upstream aerosols concentration as a function of optical particle size measured by OPC. (b) Downstream aerosols concentration as a function of optical particle size measured by OPC.
Figure 5

Filtering efficiency of cloth mask as a function optical particle size with and without gamma sterilization and two flow rate measured by OPC.
Figure 6

Filtering Efficiency of three type of masks with irradiation and two-flow rate for 1.0 µm PSL aerosols.
Figure 7

N95 facemask filtering efficiency for 102.7 nm PSL aerosols.
Figure 8

Filtering Efficiency of N95 mask for the aerosols of size ranging from 10 nm to 5 µm, for 15 kGy and 25 kGy dose exposure and for the two flow rates 20 and 90 L min⁻¹.
Figure 9

Filtering Efficiency of cloth and surgical mask for the aerosols of size ranging from 10 nm to 10 µm, for the two flow rates 20 and 90 L min⁻¹.

Figure 10

Optical microscope image of inner layer fibre of N95 mask (a) control, (b) 15 kGy and (c) 25 kGy.
Figure 11

Optical microscope image of three layers control surgical mask (a) repellent, (b) filter medium, (c) absorbent and filtering media of sterilised mask (d) 15 kGy and (c) 25 kGy.

Supplementary Files

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- Tables.docx