

Quick laboratory methodology for determining the effectiveness of face mask respirators in the wake of COVID-19 pandemic

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Abstract

Recent crisis in the form of COVID-19 has rendered wearing a face mask mandatory for patients, health care workers and even members of public worldwide. This has caused a sudden shift of focus on availability, effectiveness, re-use and development of face masks. It is imperative that commercialization of face masks is subjected to certification, following standard procedures, from authorized agencies. However, at times, there is a need to conduct a quick investigation on their performance, specially, when new materials are being used for making the masks. In the current pandemic situation, the shortage of masks has also led to a rethinking on strategies of reuse of masks after due sterilization. For such situations, a quick laboratory methodology to test/determine the effectiveness of face mask respirators has been developed. The testing parameters include the particle capture efficiency of the mask material, pressure drop and the fit factor. Two different, simple, make-shift set-ups have been adopted for the present context. The first is used to measure the intrinsic particle capture efficiency and pressure drop of the filter material and the second is employed as a 'full mask sampler' to assess the leakages through seams and joints. For particle filtration efficiency, measurements in optical particle diameter range (0.3-20 μm) are most important as they cover the most penetrating particle size (MPPS) range; nevertheless, we also measured aerosol number concentration in sub-micrometer and ultrafine size ranges. Experiments conducted with atomized NaCl test aerosols, using these setups on three types of face masks viz. commercial N-95, surgical mask and cloth mask have been used for the validation and interpretation of results. This paper hopes to provide a crucial laboratory link between the face mask developers and the final certification agencies in the times of urgency.

Introduction

The world is facing an unprecedented crisis in the form of COVID-19 (coronavirus, SARS-CoV-2 disease) pandemic, a highly infectious disease. As of 30th May, 2020, more than 6 million cases and 365k deaths¹ indicate the severity of the current situation. The modes of transmission for SARS-CoV-2 in populations include droplets, aerosols and physical contact, very similar to some recent pandemics (Severe acute respiratory syndrome (SARS)-1, Middle east respiratory syndrome (MERS), Influenza)²⁻⁴. Wearing of face mask (or filtering facepiece respirator: FFR) is one of the key public recommendation made by the scientists⁵, designated authorities and governments. This is posed as a last defense to control the transmission from the infected to healthy individuals, implying better public health. Although the research studies on face masks have been consistent, resurgence is seen during the pandemic period⁶, periodically bringing the focus on aspects related to the effectiveness of face masks in controlling the airborne transmissions.

A face mask is a combination of aerosol filters and/or fabrics designed to reduce the concentration of inhaled particulates to which the wearer is exposed. Other factors crucial to its design are pressure drop, moisture absorption, reliability, reusability and comfort fit^{7,8}. There are different nomenclatures to specify

face mask designs as per their characteristics and targeted users. Non-powered air purifying particulate respirators are segregated as N-series (for workplace free of oil aerosols) and R- & P- series (exposure includes oil-based liquid particulates) respirators⁹. N-series respirators are classified as per their capture efficiency for the most penetrating particle size (MPPS) of 0.3 μm . Thus N-95 class refers to 95 % capture efficiency for the MPPS at the testing conditions specified as per the documented protocols given by certifying agencies. FFRs (or filtering face piece: FFPs) are also classified as FFR1 (80 %), FFR2 (94%) and FFR3 (99%) designs.

Respirators remove particles from the inhalable stream via aerosol filtration processes i.e. interception, diffusion, gravitational settling, impaction and electrostatic deposition. The efficiency of removal depends on aerosol characteristics viz. concentration, particle size, charge and flow rate of the air stream. In terms of particle capture considerations, decrease in fiber diameter and increase in respirator thickness is sought from face mask designs¹⁰. A balance between the quality factor¹¹ and other issues such as compromising breathability, availability of the raw material etc. finally determines the choice amongst the options of traditional facemasks, surgical masks and nanofiber FFRs¹². Several scientific bodies recommend guidelines to be followed for the use and certification of the face masks. For example, in United States of America, Occupational Safety and Health Administration (OSHA) recommends a compliance program where the use of National Institute for Occupational Safety and Health (NIOSH)-approved respirator is mandated. Similarly, standard testing procedures in terms of documents and protocols are in place worldwide (American Society for Testing and Materials standards, Bureau of Indian standards, European Union protocols, Korean Food and Drug Administration protocols etc.). The various filtration test methods differ in terms of aerosol type, flow rate/face velocity and sample type and extensive studies have been carried out on optimizing effectiveness of different types of face masks under these guidelines. The effectiveness of N-95 FFRs and surgical mask in health care setting has been extensively reviewed^{13,14}. As per the convenience and due to the concept of MPPS (generally in the range of 0.2 to 0.5 μm) for aerosol filtration, optical based detection (> 0.2 μm particle size) has been preferred in these test methods. As infected individuals release considerable numbers of submicron particles in the exhaled breath^{15,16}, detailed measurements in this size range have also been reported^{17,18}. These mostly include electrical mobility measurements for interpretation and methodology development¹⁹⁻²¹.

Contamination during manufacturing, transportation and storage of face masks calls for availability of appropriate decontamination strategies²². Decontaminated face masks (including for re-use applications) may get degraded in terms of performance criteria. Prevention of leakages in face masks, including edge seal leakages is another crucial aspect which decides the performance of the full mask^{23,24}. Moreover, it is important to ascertain the fit of the mask normally as well as following any decontamination treatment^{25,26}. In the past epidemics as well as in the present COVID-19 situation, there has been a dearth of supply of N-95 masks for health care workers²⁷ and for other essential services workers. Hence, urgent efforts are undertaken to develop new designs or to explore alternative arrangements. In past, different materials as the component of face mask have been explored w.r.t. their

performance²⁸⁻³³. New designs need testing in a set-up which either is accessible at ease or can be made in a laboratory or industrial setting. A simple methodology to determine whether the risk of the use of designed face mask is acceptable is the utmost desirable deliverable of such a set-up.

The objective of this work is to evolve a quick methodology, which can be adopted very easily by a standard aerosol laboratory, for testing the quality of a face mask in terms of its particle (intrinsic and full mask) capture efficiency, pressure drop and the fit factor. The test conditions may not conform to a particular standard, but are more tuned towards getting first level impressions. Nevertheless, the setup can be tuned for stricter test conditions depending on the requirement. The study discusses experiments with 3 different types of face masks and enumerates the results with a view to evolve an appropriate methodology for the present context.

Materials And Methods

For the assessment of the 'material particle capture efficiency (to be called as intrinsic efficiency hereafter), a laboratory set up was made with a glass pipe having provisions to hold the filter material, connect optical particle counter and a manometer, upstream and downstream across the test specimen. This was also capable of measuring the pressure drop across the specimen. For the full mask testing, a glass jig acting as a mannequin, was connected to a cylindrical aerosol sampling station at one end while the other end was used for air suction without and through the test mask. After validating the set-up and the methodology, 3 types of face masks were employed as 'test specimens' in the current work. The details are presented as under:

Aerosol instrumentation:

We used optical particle counter (OPC), condensation particle counter (CPC) and scanning mobility particle sizer (SMPS) for the measurement of aerosol characteristics. Grimm OPC (model 1.108) was used for measuring the size distribution of test particles in the size range of 0.3-20 μm (particle optical diameter). It works on the principle of light scattering by the particles and follows Mie scattering patterns for the deconvolution of size distribution from the light intensity profile. Results from OPC measurements have been used for studying and interpreting the variation of filtration (capture) efficiency as a function of particle size. In addition, SMPS was used in these experiments to cover size range down to nucleation mode particles. SMPS measures mobility size distribution of test particles by size classifying particles on the basis of their electrical mobility. Grimm SMPS (model no. 5403) was used in this work covering the size distribution measurements in the size range of 0.01-0.9 μm (particle mobility diameter). OPC and SMPS sampled the particle-laden air with the flow rates of 1.2 Lmin^{-1} and 0.3 Lmin^{-1} from the aerosol sampling station. We also used our setup for the estimation of 'fit factor' utilizing the measurements of total number of particles (of all sizes) carried out with a CPC. Grimm CPC (model no. 5416), sampling at the flow rate of 0.3 Lmin^{-1} and measuring total number concentration of particles (>4 nm particle diameter) was employed for this purpose. Other relevant details about these instruments and sampling

protocols have been provided elsewhere^{34,35}. TSI Portacount respirator fit tester (model no. 8038) was used for validating the results for fit factor (FF) obtained from our set-up. It is a modified condensation nuclei counter designed to measure respirator fits. It samples aerosol particles at the flow rate of 0.35 Lmin^{-1} and measures the FF by comparing number concentration of test particles sampled from ambient environment and mask. Aerosol atomizer (TOPAS ATM226) was used for the generation of 'NaCl test particles' during these measurements. These test particles were passed through an 'aerosol neutralizer' and 'dryer' before passing through the mixing chamber and the test section. We also conducted few tests under ambient atmospheric conditions and the interpretations are discussed in a later section.

Test set-up:

Fig. 1 (a) shows the set-up used for the evaluation of intrinsic efficiency and pressure drop of the filter media. It comprises of a cylindrical glass pipe (to be named as 'intrinsic sampler' hereafter) of volume 2.2 liters (length: 140 cm, diameter: 4.5 cm) having provisions to connect aerosol particle stream, aerosol instrumentation (OPC, in this case) and a manometer. The 'test filter media' (cut piece of diameter 4.5 cm) was placed in the line of air stream using a clamping arrangement. A 'full mask sampler' has been utilized for the evaluation of full face masks. The block diagram of this sampler and the associated setup has been shown in fig. 1 (b). The core part of this set-up is a leak proof face mannequin (a modified 2 liters round glass flask) which had 3 circular openings on its round bottom; 2 openings of diameter 1.5 cm and one larger opening of diameter 2.5 cm, representing the facial nostrils and mouth. The face mask to be tested can be attached over these openings in 'face fix position' (i.e., attached by means of elastic bands symbolic of as on a human face) or 'sealed position' (wherein the mask edges were completely sealed onto the openings on the mannequin to give the most conservative results). The sampling arrangement has been designed so as to sample the aerosol particles from the 'exposed environment' (NaCl or ambient particles, outside the mask) and 'inhaled stream' (inside the mask) alternatively and continuously by a controlled switching arrangement. This sampler can be connected to an aerosol sampling station or any other measurement network depending on the requirements of the test protocols. Fig. 1 also shows the aerosol instrumentation used in the present work.

Test specimen:

Three types of face masks were selected for the present study. The first one was a commercial 'N-95 face mask' (NIOSH approved) which served as a reference specimen. A commercially available 'Surgical mask' was taken as the second candidate for these tests. This was picked in order to demarcate the expected differences in terms of aerosol capture efficiency and pressure drop in comparison to a standard N-95 mask. For the third specimen, we preferred a 'Cloth face mask' representing the public choice in the current circumstances.

It is to be noted that these specimens were not checked for their characteristics as per any particular standard certifying procedures but merely used for interpretations on the basis of their expected characteristics for the developed in-house methodology. As mentioned earlier, we focused more on validating our setup by comparing the results for a certified commercial face mask.

Experimental methodology and statistical analyses:

Standard testing procedures mostly focus on testing the face masks or the material at the worst case scenario or the most conservative test conditions. Attaining and maintaining these conditions in a simultaneous aerosol sampling manifold is not simple and requires a considerable amount of efforts in terms of engineering design, flow matching, isokinetic sampling and/or instrumentation. For a quick preliminary estimate, test conditions can be tuned in accordance with the capabilities of the set-up. For our case, we used number concentration of test particles as the quantitative parameter for efficiency estimates. The statistical parameters of the size distribution of steady state atomized NaCl particles varied slightly between different experiments (Count median diameter: 70-100 nm, Geometric standard deviation: 1.8-2.2, Total number concentration: 50,000-60,000 cm⁻³). We also carried out few representative measurements with atmospheric aerosol particles. Flow rate for aerosol capture efficiency (intrinsic as well as full mask) was fixed at 28.3 Lmin⁻¹. This is above the normal breathing rate of 7.5 Lmin⁻¹ and light activity breathing rate of 13-25 Lmin⁻¹ for an average adult³⁶. The corresponding face velocities work out to be 29.67 cm/sec for intrinsic measurements and 1.88-2.36 cm/sec for full mask, respectively. Flow rate and face velocities in this range have been used by several researchers for different contexts in the past^{30,37}. Pressure drop measurements have also been carried out at 8 Lmin⁻¹, as per standards^{38,39}. Sampling flow rate for the 'fit test' on the mask sampler was taken as 0.3 Lmin⁻¹, corresponding to the sampling flow rate of the CPC as it was close to that of commercial fir tester. Each specimen was tested 5 times and the mean values and standard deviation (1 σ) were estimated in accordance with error propagation rules.

Results And Discussion

Aerosol capture efficiency for the filter media/material can be defined as the ratio of captured (filtered) to the inlet aerosol concentration. It can be estimated using the upstream (inlet) and downstream (outlet) aerosol concentration for the case of 'intrinsic sampler'. For the case of full mask, it can be estimated from exposed (outside the mask) and inhaled (inside the mask) concentration. The formulation used in the present work for the intrinsic particle capture efficiency (η_i) and the full mask particle capture efficiency (η_{FM}) in % are as below.

$$\eta_i = \frac{C_{upstream} - C_{downstream}}{C_{upstream}}$$
$$\eta_{FM} = \frac{C_{exposed} - C_{inhaled}}{C_{exposed}}$$

Intrinsic efficiency and pressure drop:

The first step in our measurements pertains to the testing of the filter media material in terms of aerosol capture efficiency and pressure drop. The material, as such, is expected to qualify against the set specifications during the development phase. It is also applicable for the case of sterilization where the process should not degrade the material in terms of the initial specifications. These tests were performed in intrinsic sampler with atomized NaCl aerosols as the test particles and OPC as the measurement system. The average capture efficiency for 0.3 μm particles was measured as 96.19, 40.08 and 14.22 % for N-95, surgical mask and cloth mask, respectively. This is listed in Table 1 along with the capture efficiencies for a few other sizes as well. As seen, all three test specimens gave expected capture efficiency in this test.

For the pressure drop measurements, ΔP (in mm H₂O) at 28.3 Lmin⁻¹ was measured as 21, 14, 18 mm H₂O for N-95, surgical mask and cloth mask, respectively. At the flow rate of 8 Lmin⁻¹, ΔP was measured at 6, 3, 4 mm H₂O for N-95, surgical mask and cloth mask, respectively. For N-95 mask (NIOSH approved), this corresponds to breathability resistance of 0.03 mm H₂O/cm² which is well below the prescribed upper limit (4-5 mm H₂O/cm²)³⁹.

Full mask sampler-Measurements with optical particle counter:

As the capture efficiency tests are specified at MPPS (0.2-0.5 μm) range or sometimes at other stated higher particle sizes such as 1 μm , measurements with OPC covering these size ranges are sufficient for first level interpretations. In an aerosol laboratory as well as filtration related industrial set-ups, optical sizers are generally available. In recent times, low cost sensors⁴⁰ are also being used for aerosol measurements but issues are also reported for high accuracy applications⁴¹. It should be noted that proper aerosol measurements require an appropriate understanding of the instruments, set-up, sampling and data interpretation. Any new set-up requires a validation check in terms of leakages, representative and true sampling and engineering aspects e.g. flow and pressure matching. After validation, the developed set-up and a calibrated OPC is sufficient to infer the parametric estimations required for filter/full mask testing. Table 1 summarizes measurements performed in full mask sampler with OPC for all three specimens.

Table 1: Aerosol capture efficiency measurements for the three test specimen

Sr no.	Mask type	Efficiency test method (n=5)	Aerosol capture Efficiency (%) for particle size			
			0.3 μm	0.5 μm	1.0 μm	Total ($>0.3 \mu\text{m}$)
1.	N-95	Intrinsic	96.19 \pm 2.55	96.67 \pm 2.18	100.00 \pm 0.00	96.64 \pm 2.21
		Mask on jig (Face fix)	95.08 \pm 3.18	95.24 \pm 2.93	96.44 \pm 3.27	95.24 \pm 3.11
		Mask on jig (Sealed)	95.60 \pm 3.09	96.51 \pm 2.54	97.78 \pm 2.10	95.83 \pm 2.53
2.	Surgical mask	Intrinsic	40.08 \pm 3.85	56.35 \pm 4.41	84.12 \pm 6.76	42.44 \pm 3.91
		Mask on jig (Face fix)	19.94 \pm 6.67	41.17 \pm 12.38	62.70 \pm 20.55	24.83 \pm 10.32
		Mask on jig (Sealed)	41.65 \pm 2.98	50.74 \pm 5.81	82.73 \pm 5.11	44.11 \pm 2.60
3.	Cloth mask	Intrinsic	14.22 \pm 5.05	26.49 \pm 11.18	39.05 \pm 20.29	14.48 \pm 4.86
		Mask on jig (Face fix)	11.67 \pm 5.15	23.89 \pm 13.62	33.85 \pm 17.13	12.42 \pm 6.02
		Mask on jig (Sealed)	13.79 \pm 4.73	29.16 \pm 9.42	38.24 \pm 15.82	13.94 \pm 4.87

Table 1 gives the comparison of the capture efficiencies with the mask fitted in full mask sampler in both face fix and sealed position. These numbers are also compared with the intrinsic efficiencies obtained for the same specimens when measured in intrinsic sampler. As is observed, sealing slightly improved the efficiency for N-95 mask moving it closer to the intrinsic efficiency of the filter material. Any significant difference in the efficiency values between the intrinsic efficiency and the sealed mask indicate the leakage through stitches, joints etc. For the case of surgical mask, difference observed between face fix and sealed position is indicative of an inappropriate fit on the mannequin jig. This kind of difference is expected to arise due to leakages through face-mask sealing owing to the flat fit as compared to the cup-shaped fit of the N-95 mask. For cloth mask, significant standard deviation (relative to N-95 and surgical mask) probably indicates the difference in the texture/material quality within the selected 5 specimens. For all the masks, efficiencies for the full masks in sealed fit came closer to the intrinsic efficiencies within the error estimates.

Fit factor estimations:

The Fit tests for face masks are reported in terms of fit factor (FF) which is ratio of ambient to the inhaled concentration. In terms of the full mask particle capture efficiency (η_{FM} in %), the minimum value of FF can be represented as

$$FF = \frac{100}{100 - \eta_{FM}}$$

For comparison of FF obtained from 'Portacount' and our setup ('full mask sampler'), we used the CPC as the measurement system in our setup. This ensured that both instruments gave the results based on concentration of particles in almost similar size ranges. The estimations of FF were made for both 'face fix position' and 'sealed position' for first test specimen i.e. N-95 mask. As can be seen in Table 2, FF estimated from both instruments used with the set-up matched closely.

Table 2: Fit factor on the mask sampler estimated by CPC and Portacount

Mask type	Fitting Method on the Mask Sampler	Fit factor determined using	
		Portacount	CPC
N95	Face fix	28.86±5.37	30.43±7.43
	Sealed	61.43±17.46	58.95±13.89

The average FFs obtained from Portacount corresponds to 96.54 % and 98.37 % intrinsic capture efficiency for face fix and sealed fit, respectively. These values when obtained via mask sampler correspond to 96.71 % and 98.30 % for face fix and sealed fit, respectively. The setup can also be used for determining the FFs on human subjects as is specified for the 'Portacount system'. FFs for different nominal breathing rates (following OSHA protocols or any other user defined protocols) can be obtained by modifying the face mask sampling arrangement. However, this is beyond the scope of this work. In the present context, measurement of FFs from our setup and standard commercial instrument used for this purpose were performed for validating the set-up only.

Efficiency evaluations in sub-micron and nano size ranges:

In addition to OPC measurements, we generated data from SMPS and CPC when the test specimens were investigated in full mask sampler. This kind of added information may be useful for some specific contexts and applications. For example, a user may be more interested in filtering out nanoparticles in a specialized place e.g. microelectronics fabrication area. Also, some standards notify the performance in terms of particle capture efficiency at $0.1 \mu\text{m}^{39}$. This is relevant in the present pandemic situation too because although the transmission of vectors of COVID-19 infection takes place in particle size ranges well above ultrafine size range, the virus itself (unattached) is in the range of $0.06\text{-}0.14 \mu\text{m}^{42}$. Fig. 2 compares the capture efficiencies obtained for all test specimens at $0.02 \mu\text{m}$, $0.05 \mu\text{m}$, average of $0.06\text{-}0.14 \mu\text{m}$, $0.3 \mu\text{m}$, $0.5 \mu\text{m}$ and $1.0 \mu\text{m}$ particle sizes. These values are taken for sealed position of the masks on the jig of full mask sampler. The first three values are obtained from SMPS measurements while the last 3 are the same which were given in Table 1.

It can be inferred from the above figure that capture efficiency for $0.06\text{-}0.14 \mu\text{m}$ was measured at 96.94 %, 52.44 % and 8.27 % for N-95, surgical mask and cloth mask, respectively. It is to be noted that these values could be quite different for different designs of the categories of the face masks selected for this work. This section just explores the possibility of measurements below the OPC size ranges with any developed setup depending on the interest and the application domain. We also compared the capture efficiency for all particles (cumulative of the particle size range of the instrument) measured by the instruments (OPC, SMPS and CPC) for all three specimens. Fig. 3 shows these values measured for sealed fit position in full mask sampler.

Whereas the efficiency of N-95 and cloth mask changed marginally in particle size ranges below 0.3 μm , it became significantly higher for the case of surgical mask. This hints at better filtration efficacy of the material of surgical mask for the particles lesser than 0.3 μm which was also seen in fig. 2.

Efficiency evaluations using atmospheric aerosols:

Filtration efficiencies cannot be performed using ambient atmospheric aerosols for OPC size (0.3-20 μm) ranges in case of very stringent applications. The reason being, the number concentration of ambient aerosol particles in these size ranges is low (compared to the concentration in sizes $<0.3 \mu\text{m}$) and may increase statistical errors. Further the dynamic behavior of the atmospheric aerosol spectrum affects the consistency of the results. However, if the measurements are targeted in ultrafine size ranges, atmospheric measurements may be used for a first-estimate or guiding purposes. Such an exercise can be adopted during initial stages of the development phase of an in-house filter media material/face mask. We demonstrate one example where we measured the effect of sealing on an in-house full face mask. Fig. 4 shows the efficiency evaluated by the combined SMPS-OPC measured particle size spectrum using full mask sampler.

The above figure shows the conventional U-shaped capture efficiency curve for an aerosol filter. While the minimum efficiency was measured at 89-90 % for 0.2-0.4 μm particle sizes for face fix position, it improved to 94-95 % for sealed position. This significant difference could be rectified by slight modifications in the design of the mask. This demonstrated the capability of such a laboratory set up during the R&D stages.

Guidelines for face mask testing:

Based on the studies carried out, we evolved a set of guidelines for carrying out the performance evaluations of the face masks in the laboratory, before approaching a certifying agency. These are presented below.

1. Check the specified characteristics of the filter media/face mask material at an appropriate test condition. A set-up similar to 'intrinsic sampler' can be used for this purpose. We measured the intrinsic capture efficiency and the pressure drop of the filter material in our setup as first step. The material should pass the 'set specifications test' or the 'standard reference test' during this step.
2. Perform the leakage test of set-up intended to test full face masks at the test conditions. We developed 'full mask sampler' for this purpose and tested the employability by following standard aerosol sampling protocols and utilizing a comparison of fit factor with a commercial instrument. In absence of the latter, full mask sampler should be thoroughly tested for any leakage paths (zero testing), representative sampling etc. by in-house methodology.
3. For a design of face mask, perform a 'jig fit test' using ambient atmospheric aerosols as test particles. This should give the first hint of inefficacy of the mask design.

4. Perform test experiments with the set-up made for the full mask testing. In this step, test conditions should be taken as per any standard testing reference document or an in-house testing methodology. We used 3 test specimens viz. N-95 mask, surgical mask and cloth mask for conducting experiments in full mask sampler.

Conclusions

We have presented a quick laboratory methodology for testing the effectiveness of face masks in terms of their particle capture efficiency. The set ups developed for the same are simple and can be put together quickly in a standard aerosol laboratory. An 'intrinsic sampler' was developed and employed for testing the material of the face masks. A glass mannequin was fabricated and used as a 'full mask sampler' for testing of full masks. A provision to place the mask on the mannequin in 'face fix' and 'sealed' position was made with the full mask sampler. Three test specimens viz. commercial N-95 mask, surgical mask and a cloth mask was used for demonstration and validation experiments. The primary parameter of investigation in these experiments was aerosol capture efficiency of filter media/face mask. Experiments were performed at a carrier flow of 28.3 Lmin^{-1} while adopting an atomizer for the generation of test particles. Optical particle counter was used to measure the number concentration of test particles in the size range $> 0.3 \mu\text{m}$. Scanning mobility particle sizer and condensation particle counter was also used during the experiments for specific purposes. In the first level, testing experiments with intrinsic sampler, average capture efficiency for $0.3 \mu\text{m}$ particles was measured as 96.19, 40.08 and 14.22 % for N-95, surgical mask and cloth mask, respectively. Fit factor estimated with full mask sampler was validated with a commercial instrument in the second step. The work compares the capture efficiency obtained for both face fix and sealed position with intrinsic efficiency of the material.

Interpretation of the observations lead to the improvements of the face masks in the design and development phase itself. For example, a significant difference in efficiency values for 'intrinsic media' and 'sealed position' indicate a leakage through the joints, seams etc. The paper also attempts to provide guidelines which can be followed for testing in laboratory conditions. This paper is written in a view to help face mask developers before they approach final certification agencies. This will be helpful to reduce the time gap between the development and the finally certified product ready for commercialization. This is utmost important in times of urgency as is due to COVID-19 pandemic.

Declarations

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Competing interests:

The authors declare no competing interests.

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Figures

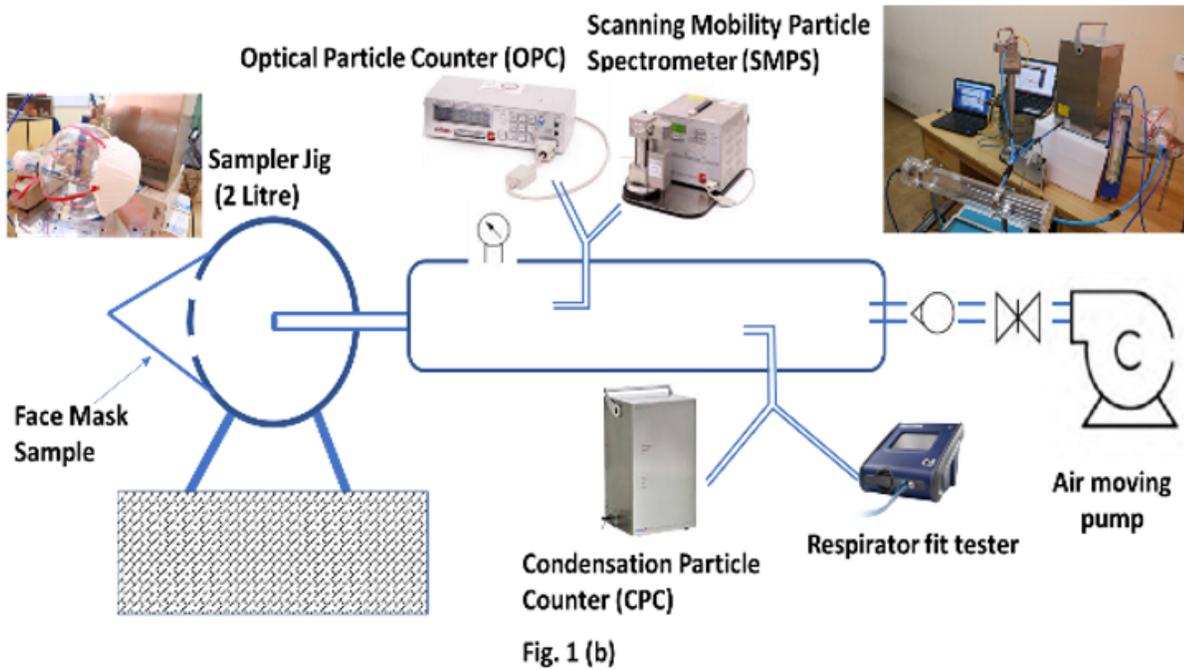
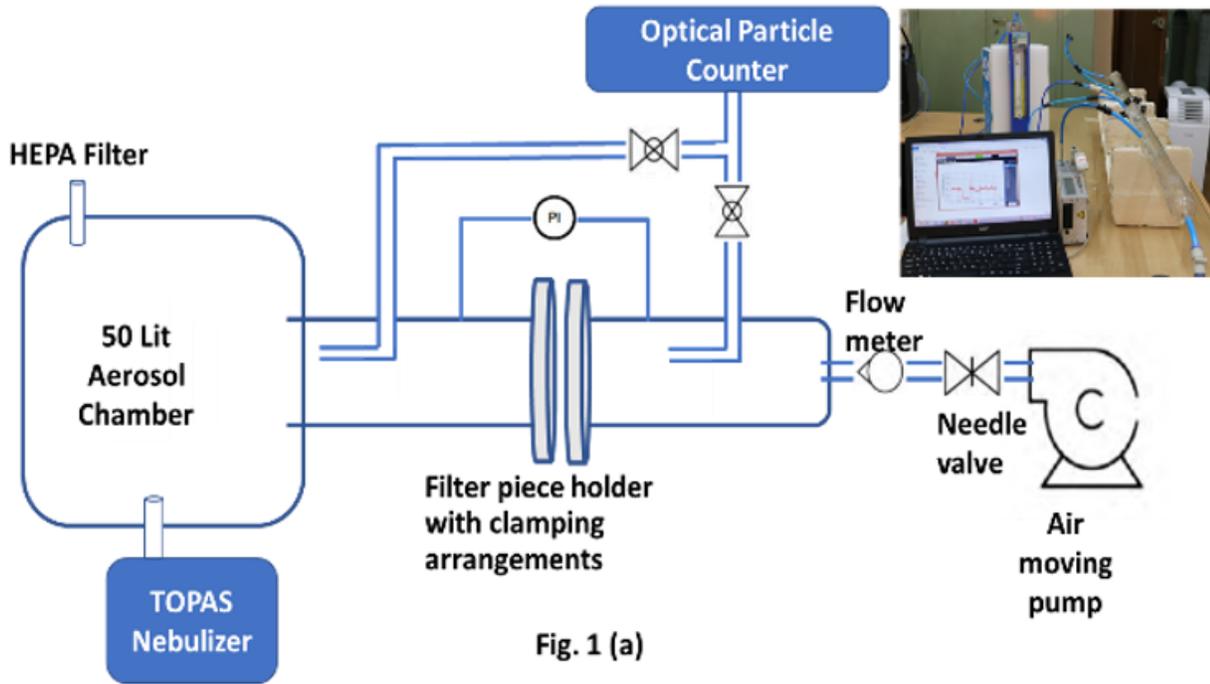


Figure 1

Block diagram of the setup used in experiments for a) intrinsic particle capture efficiency and pressure drop measurements and b) full mask performance assessment (Inset shows the photograph of the setup)

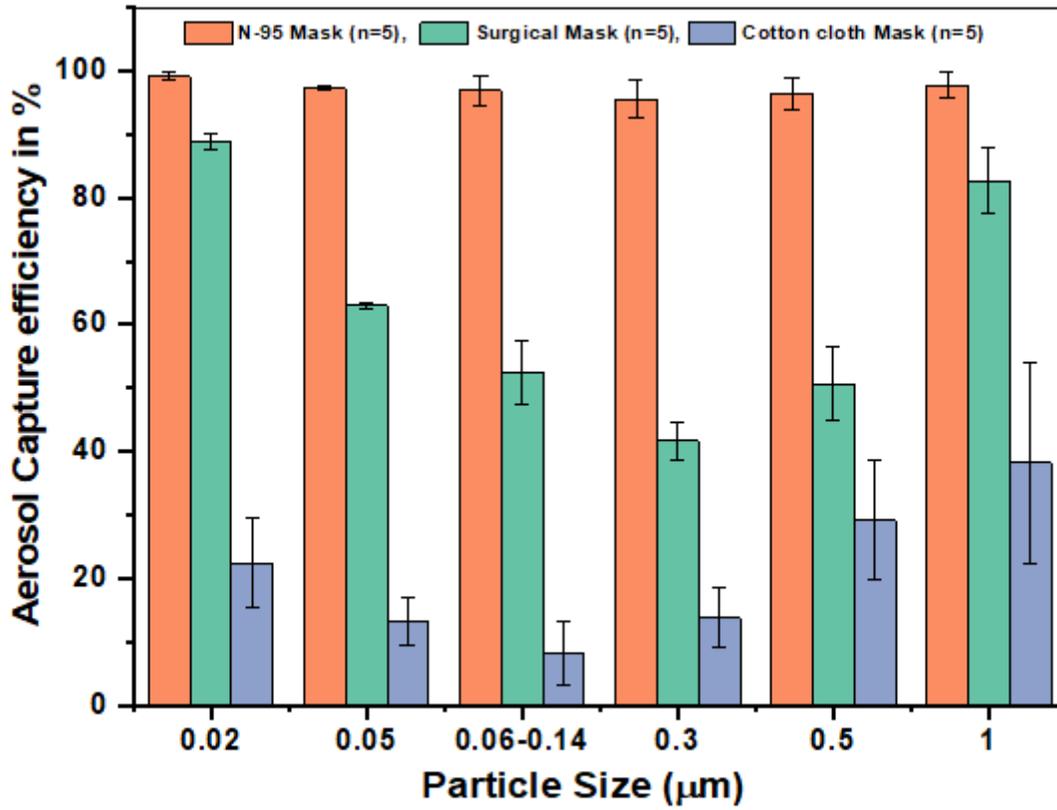


Figure 2

Aerosol capture efficiencies of the test specimen for nano and sub-micron sizes estimated under sealed fit condition on the full mask sampler

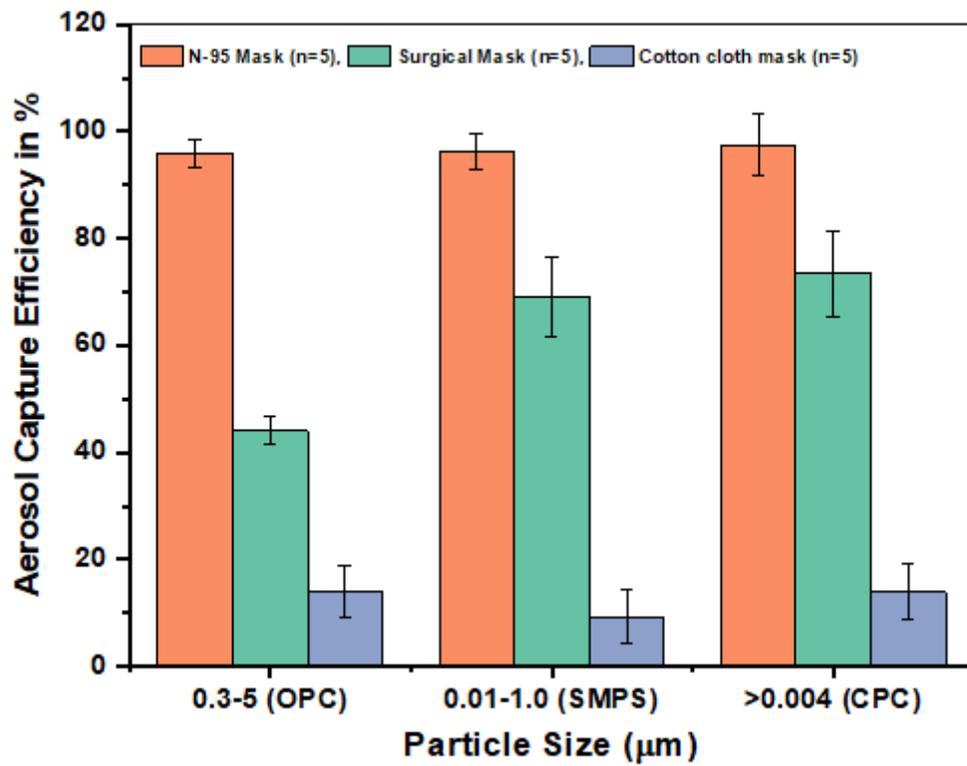


Figure 3

Aerosol capture efficiency for all particle sizes (cumulative of all particles sizes in the measurement range) as measured by OPC, SMPS and CPC

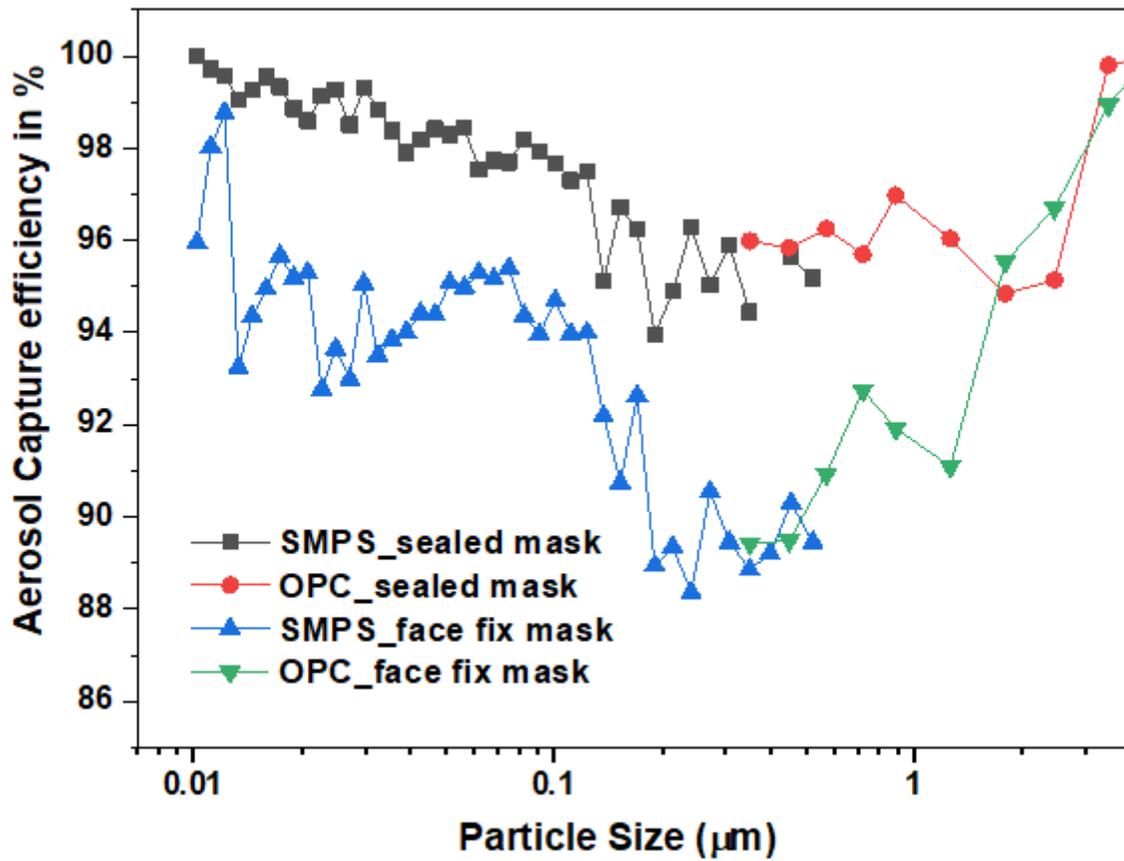


Figure 4

Demonstration of the effect of mask sealing on the jig on the capture efficiency for an in-house developed N-95 face mask in the entire particle size range (0.01 – 3 µm)