Recharging improves efficiency of decontaminated N95 masks

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N95 masks form a critical part of the personal protective equipment used by frontline health-care workers, and are typically meant for one-time usage. However, the recent COVID pandemic has resulted in a serious shortage of these masks leading to a worldwide effort to develop decontamination and re-use procedures. A major factor contributing to the filtration efficiency of N95 masks is the presence of an intermediate layer of charged polypropylene electret fibers that trap particles through electrostatic or electrophoretic effects. This charge degrades quickly when the mask is used. Moreover, simple decontamination procedures (e.g. use of alcohol) immediately degrade any remaining charge from the polypropylene, thus severely impacting the filtration efficiency post decontamination. In this brief report, we summarize preliminary results on the development of a simple laboratory setup allowing measurement of charge and filtration efficiency in N95 masks. We show how the charge on the mask changes due to decontamination treatments, and correlate with reduced filtration efficiency. Additionally, we propose and show that it is possible to recharge the masks post-decontamination treatment and recover filtration efficiency. Importantly, recharging can be performed using readily available equipment and materials, and so can be employed both in urban and rural settings.

We emphasize that because of the current worldwide lockdown, the measurements reported in this report are preliminary, performed with hastily constructed home-built equipment on a small variety of masks available to us. Although we are confident in our results, we encourage groups with special-purpose equipment to redo and verify our experiments.

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I. INTRODUCTION AND BACKGROUND

N95 masks form a critical part of the personal protective equipment used by frontline health-care workers [1, 2]. The name designation N95 indicates that these masks can filter 0.3µm sized particles with 95% efficiency [1]. At the present time, various brands of masks available commercially are meant for one-time usage due to potential contamination, as well as the rapid degradation of their filtration efficiency with use. However, the recent COVID pandemic has resulted in a serious shortage of these masks which has started an intensive search for various decontamination procedures. A summary of various procedures is available at N95decon.org. Several processes are possible, including dry and wet heat, hydrogen peroxide vapor, ozone, UV radiation etc.,[2, 3] but it seems to be general knowledge that most decontamination procedures baring the one that uses hydrogen peroxide vapor [4] adversely impacts the filtration efficiency of the masks.

As with other filtering processes, N95 masks also filter by intercepting the foreign particles in different layers of the mask material. A particle can be captured either if it finds a mask material fiber directly in its way or if the mask material can attract the particles and trap them [5]. Flow through the mask is usually thought to be laminar, such that the flow would usually bend smoothly around an obstacle (fiber). If this is the case, mechanical capture of the particle on the surface of the fiber happens either when the inertia of the particle is large enough such that it can deviate from its streamline path and make an impact with the mask material, or the particle is small enough such that its Brownian diffusion is strong and it deviates from the streamline which allows it to make an impact with material.

In addition to the above two possibilities, an electrostatic capture mechanism of the particles (charged or uncharged) that is possible when the fibers are charged is also extremely important [6]. These charged fibers can attract both inherently charged particles by Coulombic forces as well as neutral polar particles (such as tiny aqueous droplets) by dielectrophoretic forces that come from the interaction of polarized objects and electric field gradients. Most N95 masks depend on both mechanical and electrostatic effects to achieve filtration. The electrostatic filtration of N95 masks is performed by a mesh of charged polypropylene melt-woven charged fibers (electrets). Most of the pores in the mesh have a characteristic length scale of about 15µm and about 90% of its space is void.

Pure polypropylene is a non-polar polymer with a band gap of 8eV. However, the presence of molecular level defects both chemical and physical in nature allow the formation of localized energy states that can trap charge [7]. Moreover, its electrical polarization properties are often enhanced by introducing various charge enhancer additives like magnesium stearate [8] or BaTiO$_3$ [9] which are added to the polymer melt to increase the electret performance. Nevertheless, the charge on the polypropylene undergoes significant degradation when open to the surroundings, which is exacerbated by the warm humid environment created by respiration during use. Additionally, simple decontamination methods such as sanitizing with alcohol completely removes all the charges.

Thus, a key aspect of the performance of an electret-based mask is its ability to maintain its charge

![FIG. 1. (left) The compact, low-cost mask tester developed in the lab. The mask was attached to a hard plastic ball simulating a human head, and air flow through the mask was effected by a small diaphragm pump. Particle counts were performed using an Air Quality Indicator system from Respirer Living Sciences that uses the Plantower PMS7003 sensor chip. (right) Filtration tests on a pristine Venus V4400 N95 mask.](image)
TABLE I. Filtration efficiency and charge of masks tested.

| Mask Type         | Filtration Efficiency of 0.3 \(\mu m\) Particles | Free Charge (nC) |
|-------------------|--------------------------------------------------|------------------|
| Halyard           | 98 %                                             | ±9               |
| Primeware Magnum  | 95%                                              | 1                |
| Venus-V4420       | 96 %                                             | 1                |
| Venus-V4400       | 95 %                                             | 1                |

in a hot and humid atmosphere. Failing this, extended usage can only be obtained through a cycle of decontamination and recharging, if this is possible. Thus, a simple procedure for electrically recharging a decontaminated mask without disassembling it would be very useful, especially if it does not rely on special-purpose equipment which would not be readily available.

The standard methods for charging polymer fibers are

- corona discharge \[10\]
- Photoionisation induced by particle beams (gamma rays, x-rays, electron beams) \[11, 12\]
- tribo-electrification \[13\]
- liquid contact charging \[14\]

The first three methods are not easily deployable in hospital conditions on preassembled masks. In the following, we propose a simple recharging method based on high electric fields, and provide evidence of its effectiveness. Crucially, our method can be performed using readily available equipment and materials, and so can be employed both in urban and rural settings.

II. MASK FILTRATION TESTING

Since we did not have access to special-purpose mask filtration equipment, we constructed a rough apparatus to measure the efficiency of filtration of particulate matter, using an air-quality monitor (ATMOS AQI sensor from Respirer Living Sciences Pvt. Ltd) as a particle counter. The setup is shown in Fig. 1 along with data from a pristine N95 mask. While the air-quality monitors are optimized for 2.5 \(\mu m\) particle measurements, the Plantower PMS7003 sensor also has a 0.3\(\mu m\) channel, and we use the residual sub-micron room air particles as a source for particles to be filtered through a mask. The filtration efficiency, \(\eta_{\text{mask}}\), can be determined from the ratio of particles per unit time detected with, \(N_{\text{mask}}\), and without the mask attached, \(N_{\text{ambient}}\).

\[
\eta_{\text{mask}} = 1 - \frac{N_{\text{mask}}}{N_{\text{ambient}}}
\]

We emphasize that these are preliminary results, taken using a small diaphragm pump to suck air through a mask attached to a plastic ball at flow rates (\(\sim 19 L/min\)), considerably higher than human resting breathing rates (\(\sim 6 L/min\)). The hard plastic ball does not always guarantee a perfect fit to the mask, allowing air leakage from the sides. To obtain reproducible values, the masks edges were taped to the ball using paper masking tape. The filtration data is presented only to show the ability of a quickly constructed, low-cost, home-made setup to test mask filtration. More precise measurements using dedicated special-purpose mask-testers would be welcome.

III. CHARGE MEASUREMENT

We used three brands of commercial masks for our experiments, Venus V4420 and V4400 masks, a Primewear Magnum mask, and an O&M Halyard 46727 mask. All masks were obtained in pristine condition from the Tata Memorial Hospital in Mumbai.

We used a Keithley 2410 source meter to apply voltage, and a Keithley 6514 electrometer to measure the charge. Our experimental set-up measures the free charge on a mask, but may not account for the total bound charge. Moreover, the field in the mask fiber electrets could be dipolar, and as such, our results should be regarded as giving a relative indication, but not as precise measurements of the total charge on the masks. The experimental protocol was as follows:
1. A pristine mask was first placed on a flat metal piece connected to the electrometer to measure its charge. The filtration efficiency of this mask at 0.3 µm was measured using the mask tester. There is an apparent correlation between the amount of charge in the pristine mask and its filtration efficiency, \( \eta \), as shown in Table 1. An interesting observation is that the O&M Halyard mask, which has two different (orange and white) surfaces has two halves, having positive and negative charges respectively on these surfaces (see Fig. 3 (left panel)). This mask has almost an order of magnitude more charge on each surface than the other masks studied.

2. The mask was then discharged.
   - The Venus V4420 mask was discharged by steaming it for 10 minutes.
   - The Primewear Magnum mask was discharged by dipping it in ethanol and then drying it.
   - The charge on the O&M Halyard mask was allowed to discharge by keeping it in open for 10 days (RH 67%).

3. The masks were recharged by sandwiching them between two metal plates. The two electrodes were connected to the high and the low output terminal of the Keithley 2410 source meter. In the experiments, the low terminal was grounded and a suitable voltage of positive or negative polarity was applied from the high output terminal of the source meter.

4. After charging, the masks were placed on an isolated metal plate. This metal plate was connected to the charge sensing terminal of the Keithley 6514 electrometer. The input of the electrometer is a three-lug triax connector. The innermost wire (input high) is the charge sensing terminal. In our experiments we used the guard off condition, i.e., the common (input low) and the chassis are grounded.

Recharging

The data presented in Figs. 3 (right panel), 4, 5 show the results of recharging for the three types of mask. **Data is shown for masks which have already undergone more than 10 charging and discharging cycles.** As seen in Fig. 3 (right panel), the Halyard mask charges to roughly 25% of its pristine value after charging at 1000 V for 8 minutes. The two sides charge to different levels, similar to the pristine case shown in Fig. 3 (left panel). Fig. 4 shows that the ethanol sterilized Magnum mask can be recharged to a value comparable to its pristine charge by charging at 1000V for 8 minutes. To test an alternative charging procedure, we treated the Venus N95 mask with argon plasma for 10 minutes. As seen in Fig. 5, however, we found that argon plasma treatment discharged the mask to a level of 0.06 nC.

We find that the total charge deposited on the masks depends strongly on the charging time, as seen in Fig. 6. The left panel shows the result of different charging times on the Halyard mask, with the pristine value almost reattained after a 60 minute charge. The right panel of Fig. 6 compares the original charge on the masks to the values obtained when they are recharged for 8 minutes at 1000V.

We note that although we do not have definitive quantitative evidence, preliminary observations suggest that the presence of light and controlled humidity can substantially affect the charging efficiency. This would mean that using a metal mesh as electrodes and perhaps shining UV light on to the masks might markedly improve charging (and thus filtration) efficiency. We are currently developing experiments along these lines.

FIG. 2. Schematic of (left ) mask charging and (right) charge measurement setup.
FIG. 3. (Left panel) Charge on a pristine O&M Halyard mask. Note that the two surfaces of this mask are very different! The mask was put in contact with the electrometer at time $t \approx 3.5$ s. (Right panel) Recharge of an O&M Halyard mask: The discharged mask was recharged at 1000V for 8 minutes. Longer charging times result in increased charging.

**Charge retention after recharging**

To measure how long the masks can hold the charge, we performed the following experiments:

- The mask was charged (1000 V, 10µA) for 30 minutes.
- The mask was then placed on the charge measurement plate for 10s and then removed. After a lapse of 10s the mask was placed again on the charge measurement plate and after 10s it was removed. This measurement / removal procedure was performed for many cycles; representative portions of the data are shown in Fig. 7. No care was taken in handling the masks, mimicking the likely scenario in actual use. We noted that at some points in the process of mask placement or removal, the zero value of the electrometer changed abruptly, which we believe was due to unintended contact of the plate with a hand. The rate of charge decay is small; we typically found that the masks hold 65% of their charge for about 5 hours.

FIG. 4. Charging measurements for Magnum brand masks. The top panel shows the data for new masks. The bottom panel shows data for masks that were initially discharged by dipping in ethanol and then re-charged at 1000V for 8 minutes. In the discharged condition, the charge was too small to be measured.
In the previous section we demonstrated that the application of relatively high voltage recharges the masks. Of course, the important test is whether this recharging translates into improved efficiency in the filtration of fine particles. To assess this, we first obtained a baseline measurement for the filtration efficiency of brand-new pristine masks. We then performed typical sanitization protocols, during which the masks effectively lost all their charge and measured the filtration efficiency of the discharged masks. We then recharged the masks and measured their filtration efficiency. We note that in this protocol (as opposed to the in situ protocol to be discussed later), the mask was removed and reattached at each point. This clearly is a source of error in precision. Because we only had three masks at our disposal, we employed a different sanitization protocol for each mask.

FIG. 5. (a) Charge measurements for a Venus mask which was charged at 1000V for 8 minutes. (b) Charge measurements for the same mask, following a plasma treatment. This indicates that plasma recharging does not work.

IV. FILTRATION EFFICIENCY OF RECHARGED MASKS

We emphasize again that we are measuring primarily the free charge.

FIG. 6. (Left panel) Charge accumulated as a function of charging time for Halyard mask. Only the positive charge is shown. (Right panel) Comparison of charging data for different masks, which were charged for 8 minutes at 1000V.

1 We emphasize again that we are measuring primarily the free charge.
FIG. 7. Charge retention test - cycles of measurement (placement) and removal of the charged Halyard mask on the charge measuring plate. The mask was charged at 1000 V, 10 µA) for approximately one hour. Only the positive charge is shown.

Protocol for testing the recharged Venus 4420 mask

The Venus 4420 mask underwent sterilization via exposure to steam, after which its charge and filtration efficiency were measured. The mask was then recharged, and the filtration efficiency was measured again. This data is presented in Fig. 8, which also has a filtration comparison to a unused new mask of the same type. Note that the pristine mask used for comparison at the end of the run shown in Fig. 8 was a different mask of the same type, so that the comparison should be considered illustrative rather than precise.

Specifically, the protocol for this run was:

1. The mask was exposed to steam for 5 minutes on each side, following which we measured the charge to be $\sim 0.03nC$, indicating that the mask has lost effectively all its charge.

2. The mask was attached to the filtration tester, with the edges of the mask taped to prevent leakage from the sides. We obtained a filtration efficiency, $\eta$, of about 77% for 0.3µm particles.

3. The mask was then checked after recharging at 1000V for 5 minutes. Without taping the efficiency, $\eta$, was measured at 79%, on taping the mask to the mask holder the efficiency, $\eta$, improved to 86%. Though this number is lower than the pristine mask, we believe that this number can be improved by prolonged charging.

FIG. 8. Filtration efficiency of Venus 4420 mask after steam treatment and recharge, and comparison with a new mask. The first dip corresponds to a steamed Venus mask. The filtering efficiency, $\eta$, drops to 77%. The edges of the mask were taped to prevent leakage from sides. The second dip corresponds to the filtering of the same steamed mask after being recharged (1000 kV ) for 5 minutes. Without taping the efficiency, $\eta$, was measured at 79%, on taping the mask to the mask holder the efficiency, $\eta$, improved to 86%. See Fig. 1 for the experimental set-up.
4. Baseline: We measured the filtering efficiency, $\eta$, of a pristine Venus 4420 mask for 0.3$\mu$m particles to be $\sim 95\%$. This mask was taped to the mask holder. The measured charge was $\sim 1$ nC.

**Protocol for testing the recharged Magnum mask**

The Magnum mask was sanitized by dipping it in ethanol. After recharging the mask to $\sim 1$ nC the efficiency recovers to $\sim 86\%$. This recharged mask was discharged in situ by dropping ethanol on the mask (see Fig. 9(a)).

Specifically, the protocol for this run was:

1. Baseline: We measured the filtering efficiency, $\eta$, of a brand-new N95 Magnum mask with the edges taped for 0.3$\mu$m particles to be $\sim 95\%$. The measured charge was $\sim 1$ nC.

2. The mask was sanitized by dipping it in ethanol and drying overnight, after which the charge was measured to be $\sim 0.03$ nC, indicating that the mask had lost effectively all its charge.

3. The mask was then recharged for at 1000 V for 60 minutes.

4. The charged mask was put on the mask tester (see Fig. 9(a) at 2200 s). The edges of the mask were taped to prevent leakage from sides. We obtain efficiency of about 86%.

5. At about 3125 s (see Fig. 9(a)) about 1 ml of ethanol was spread on the mask. The filtration efficiency, $\eta$, was reduced to 70%. This is due to the loss of charge in the mask.

6. At about 4500 s (see Fig. 9(a)) this mask was taken off. It was then dried by blowing hot air (50$^\circ$C).

7. The dried mask was then put back on the mask tester. The efficiency, $\eta$, of this mask is about 50%. This indicates that residual alcohol was responsible for blocking pores of the mask, resulting in apparent increased filtration efficiency.

**In situ recharging measurements**

The previous experiments involved extensive handling of the masks in attaching and detaching them from the filtration tester. In order to reduce errors due to changes in mask fitting on the apparatus, as well as those due to handling, we undertook an in situ experiment. In this experiment, a mask was
affixed to the filtration tester, and charging was effected by two small metallic meshes (mesh size about 0.5 mm) which were taped to the mask. These meshes are big enough that they do not influence the filtration at 0.3 µm. The Magnum mask was sanitized (and thus discharged) by dipping it in ethanol, as above. It was then attached to the filtration tester and its efficiency measured. An electric field was then applied by charging the metallic screens, and the filtration efficiency, $\eta$ measured, This is shown in Fig. 9(b).

Specifically, the protocol for this run was:

1. Fine wire meshes were taped to both sides of the discharged Magnum mask.

2. The mask was put on the mask tester (see Fig 9(b) at 6500 s). The edges of the mask were taped to prevent leakage from sides. We obtain efficiency, $\eta$, of about 80%. Note that we had to use masking tape to hold the metallic screens, which reduced the effective filtration area of the mask; this explains why the filtration efficiency is higher than other ethanol treated masks.

3. At about 9000s (see Fig. 9(b) ) 1kV was applied across the meshes. The efficiency, $\eta$ increased to 90%.

This clearly shows that electric field can be used to recover filtration efficiency in a sanitized mask which has been discharged.

V. Conclusions

Since the loss of electrical charge from the polypropylene filter layer in N95 masks is known to impact the filtration efficiency, we investigated the possibility of mask recharging in a few commercially available N95 masks using a simple laboratory setup. Our preliminary results suggest that it is possible to recharge the masks post sterilization and recover filtration efficiency. We emphasize that these are initial results that need to be cross-checked and verified, however, this is a promising development that merits further research as it may allow simple decontamination processes to be effectively used for practical applications. In particular, this method may allow for N95 masks to be used for a considerably longer period of time than is the current norm, which can have a significant effect in hospitals where mask supply is insufficient.

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