

Recharging N95 masks by van de Graaff generator for safe recycling

K. Sugihara*

Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba Meguro-Ku, Tokyo
153-8505, Japan

Correspondence: kaori-s@iis.u-tokyo.ac.jp

ABSTRACT

N95 respirators, used in the current COVID-19 pandemic, filter virus-containing aerosols by the static electricity of melt-blown polypropylene sheets. Their shortage at hospitals demanded their recycling, whereas the standard sterilization methods, including alcohol spraying, washing, autoclaving, heating in hot water, cannot be easily implemented because they compromise the electrostatic charges and thus their filtering effect. We report that van de Graaff generator, commonly used for the demonstration of static electricity, can be used as a safe, cheap and quick method to recover the polypropylene electric charges that are lost during sterilization processes. We will show that this recharge also restores the masks' filtering function.

N95 respirator is a mask that health caretakers use at hospitals for taking care of COVID-19 patients. The classification “N95” shows that it filters out at least 95% of airborne particles, certified by the U.S. National Institute for Occupational Safety and Health (equivalent to FFP2 by European Union and DS2 from Japan) despite the fact that its pore size ($\sim 10\text{ }\mu\text{m}$) is larger than small aerosols ($< 1\text{ }\mu\text{m}$). This is thanks to the static electricity of melt-blown polypropylene fabric used in the mask,¹⁻⁵ which captures small aerosols by electrostatic forces as most aerosols are electrically charged. Any contact with water such as prolonged exposure to exhaling breaths and storage in humid places could potentially remove the static electricity and lower its filtering efficiency. This is why these masks are, in a normal situation, for one time use for limited durations. However, during the pandemic, the pressure for recycling surged at hospitals due to their shortage in supply,⁶ whereas the standard sterilization methods, including alcohol spraying, washing, autoclaving, heating in hot water, cannot be easily implemented because they could affect the electrostatic charges and thus their filtering effect. In response to this challenge, scientific communities have proposed different methods to safely reuse masks.⁷⁻⁹ Ultraviolet radiation, was employed at the University of Nebraska Medical Center in Lincoln.^{10, 11} Fumigation, where masks are exposed to vaporized hydrogen peroxide, was used at Duke University Hospitals.¹² Baking was examined at Stanford University.^{13, 14} Steeping in hot water (typically $60 - 80\text{ }^{\circ}\text{C}$) or autoclaving, followed by drying with a hair dryer to restore the electrostatic charges, was tested at Beijing University of Chemical Technology.^{15, 16} Although they have provided an important guidance to tackle the issue, to fulfill all the criteria (easy, safe, perfect sterilization efficiency, restored static electricity and filtering function, reproducibility *etc.*) remains a challenge. Recently, a method to “recharge” static electricity of masks by applying 1 kV potential via a DC voltage generator was demonstrated.¹⁷ Their direct approach to restore the charge is probably more reproducible and reliable than drying with a hair dryer, however, the necessity of the high-voltage generator

limits the use outside of labs because of its high cost, safety issues, and the relatively long operation time (60 min) for the recharge.

In this work, we report a safe, easy and cheap method to recharge N95 masks at ~ 100 kV for 3 min via van de Graaff generator. This recharge is quick thanks to the used two-orders-of-magnitude higher voltage. Van de Graaff generator is an electrostatic generator commonly used for the demonstration of static electricity at science museums or in science classes that can produce over 100 kV. Such a high voltage, if generated by a standard DC voltage generator, requires a specialized safety measure to handle, whereas van de Graaff generator can be even touched due to the extremely low current as the metal electrode is electrically floating. In addition, the price range of van de Graaff generator ($\sim 1,000$ USD) is an order of magnitude cheaper than the standard DC voltage generator that can generate above 1 kV. By combining autoclaving or heating in hot water, we will show that N95 masks can be sterilized without losing their filtering effect.

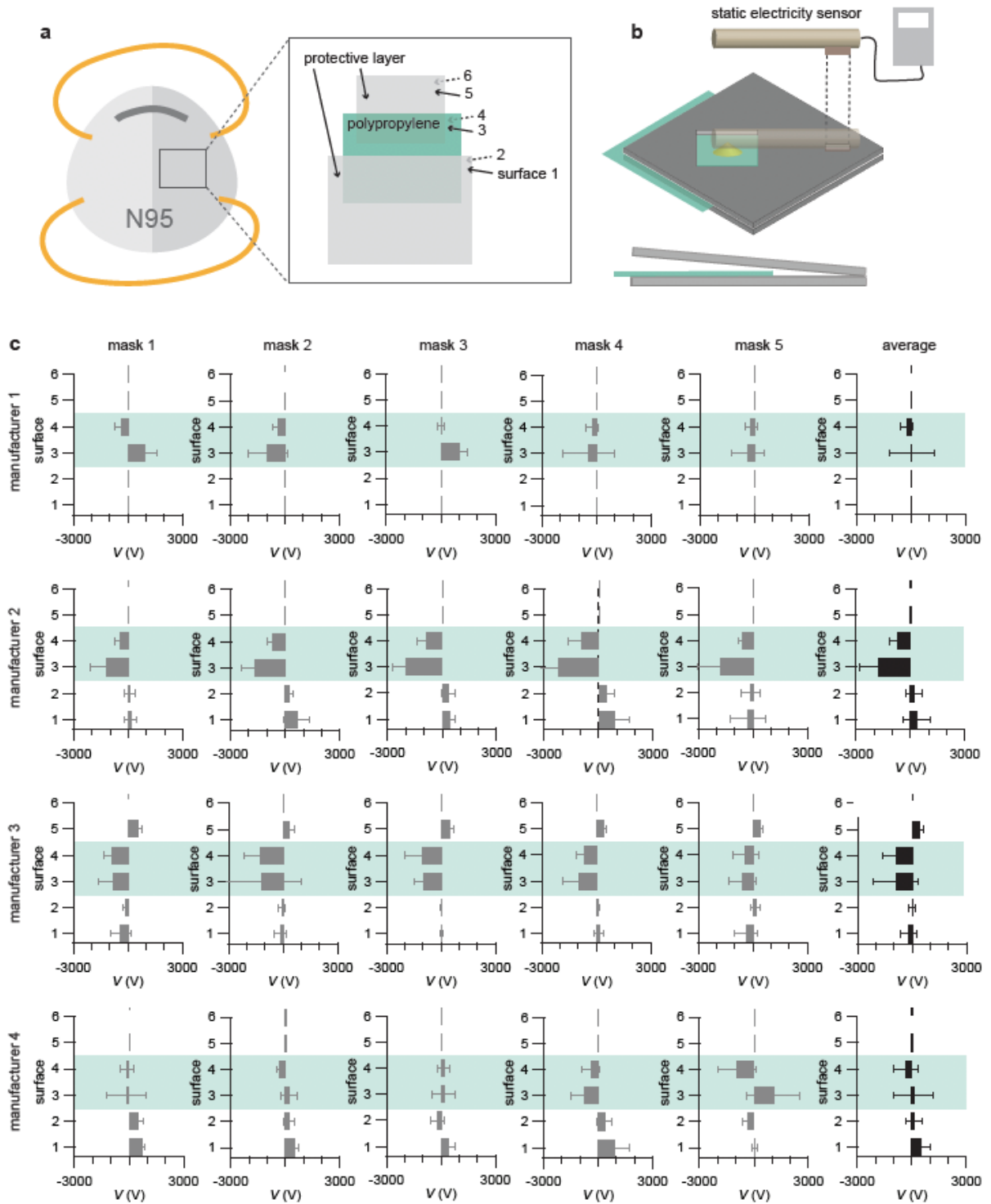


Figure 1: a, A scheme of an N95 grade mask. b, The setup of the voltage measurement. c, Voltages measured at 6 surfaces indicated in (a). For each mask 10 locations were measured per surface and the averages and the standard deviations are shown. 5 masks were measured from 4 manufacturers. The “average” on the right side is the average of all of the 5 masks.

The amplitude, polarity, reproducibility of polypropylene static electricity depended on the manufacturer. First, we measured the static electricity of N95 or DS2 grade masks from

four manufacturers by a voltage static meter. All of the masks consisted of three layers, where polypropylene is sandwiched with two protective layers (Figure 1a). Since the used non-contact voltmeter is sensitive to the distance between the sample surface and the sensor, a home-made wooden clamp was used to fix this distance at 1 cm for the reproducible measurements (Figure 1b). Static electricity was measured on six surfaces indicated in Figure 1a for five masks per manufacturer. The polypropylene layers in manufacturer 1 had electrostatic charges, yet their amplitude and polarity were almost random (Figure 1c, manufacturer 1). The polypropylene layers in manufacturer 2 and 3 had reproducible negative electrostatic charges (Figure 1c, manufacturer 2, 3). The polypropylene layer in manufacturer 4 had weak and non-reproducible charges (Figure 1c, manufacturer 4). These data suggested that the amount of the electrostatic charges vary among manufacturer and individual masks. This may be partially because of the ways these masks were stored, since the charge distribution was different even from the same manufacturer. Since the static electricity on the polypropylene from manufacturer 2 was the most reproducible, we will perform the rest of the experiments mainly with these masks.

one time reduced the static electricity by 54% for the layer 4 and 51% for the layer 3, respectively (Figure 2a, autoclaved). These numbers are smaller than the ones, where only the polypropylene sheets (without the protective layers) were autoclaved once (60% for the layer 3 and 74% for the layer 4. Figure 2a, autoclaved, “pp”), implying that the protective layers partially prevented the polypropylene from losing their charges. Additional autoclaving twice and three times further reduced the charges for the layer 4 (Figure 2a, autoclaved, “2, 3”). Washing with detergent and color bleach in a washing machine diminished the charges nearly 100% for both layers (Figure 2a, washed with detergent). Heating in boiling water for 10 min also reduced the charges by 53% for the layer 4 and 99% for the layer 3 (Figure 2a, heated in boiling water). Similar results were obtained with the masks from manufacturer 3 (Figure S1).

Van de Graaff generator recovers the static electricity in 3 min. To restore the static electricity that are reduced or lost during the sterilization procedures, these masks were recharged by a van de Graaff generator and the voltages were measured. Van de Graaff generator is an electrostatic generator, invented by Robert J. Van de Graaff around 1930s.¹⁸ Positive and negative electrostatics formed by the triboelectric effect of the moving belt are stored in a large and a small metallic spherical shell (Figure 2b). It is a cheap and safe way to generate up to 100 kV even with a table-top version, whereas a larger setup can create several MV. Application of high voltages to polymers are known to inject electric charges, well-studied in the field of insulation materials for *e.g.* cable shielding.^{19, 20} Although its exact mechanism is still under debate, trapping electrons or holes at defect sites or impurities causes these charges.²¹⁻²³ A mask was attached to the larger metallic sphere of the van de Graaff generator and the smaller metallic sphere was hovered overed the mask with a distance of several centimeter for 3 min, where corona discharge was occasionally observed. First as a control, only the polypropylene sheets without the protective layers were recharged via this

method. The polypropylene after washing with detergent and color bleach recovered the charge back to 26% of the original charge (refer to Figure 2a°, Figure 2a* and Figure 2c*). The polypropylene after steeping in hot water recovered the charge back to 255% (refer to Figure 2a°, Figure 2a** and Figure 2c**). Note that the range of the x axis is different in Figure 2c**). This suggests that the process before recharge affects the extent of the charge recovery. The polypropylene washed by detergent and color bleach recovered the charge less probably because house-hold detergents contain anti-static materials that remove charges and prevent them from reoccurring. In both cases, the layer 4 did not recover charges significantly despite the fact that it was in the proximity to the larger metal sphere with positive charges, because polypropylene has a tendency to acquire negative charges by nature. Next, the entire masks were heated in hot water and recharged. The layer 3 regained the negative charge back to 153% of the original value, whereas the layer 4 presented a slight positive voltage (refer to Figure 2a°, Figure 2a** and Figure 2c***). This shows that the reduced charge by sterilizing procedures could be restored via the van de Graaff generator.

Recharged masks after washing restored the filtering efficiency. Finally, as a first step to study the masks' function after recharge, the filtering efficiency was measured by a mask fitting tester. Mask fitting tester measures the number of particles in and outside of masks by aspirating air for calculating the particle filtering efficiency by the following equation.

$$\eta = \left(1 - \frac{N_{in}}{N_{out}}\right) \times 100.$$

Masks were folded into two with one of the tubes inside, sealed with a duct tape for eliminating leakages, and placed in a box with the other tube that measures the particles outside the mask. These masks were challenged by aerosols created by a humidifier that contains water with NaCl, which is also placed in the box. Particles in the range of 0.3 – 0.5 μm were counted for 20 second and the filtering efficiency was calculated. Note that the accuracy of this instrument

is lower than the filter tester used in industries²⁴ (e.g. Automated Filter Tester Model 8130A, TSI) and detects no particle below 0.3 μm . Therefore, the results presented here should be regarded as rather qualitative data. Brand new masks presented the filtering efficiency of $96\% \pm 1\%$, whereas three-time autoclaved, detergent-and-color-bleach washed, and hot-water steeped masks were $94\% \pm 3\%$, $72\% \pm 17\%$, $93\% \pm 5\%$ respectively (Figure 2d). Considering the error bars, the reduction in the filtering efficiency was detected only with the washed masks probably because the used instrument was not sensitive enough especially for smaller particles. Next, these masks were recharged by the van de Graaff generator and the filtering efficiency was studied again (Figure 2d). The efficiency became back to $94\% \pm 4\%$ for the washed masks. This result supports that the recharge by van de Graaff recovers the masks' filtering efficiency.

In conclusion, we report that N95 grade masks can be sterilized and recharged by a van de Graaff generator. The filtering efficiency recovered after recharge, supporting the importance of the static electricity in their functions. Nevertheless, use of new masks will always be preferable as we noticed the deformation of the masks during the sterilization procedures, which could hinder the proper fitting of the masks to the face, thus induces leakages. The demonstrated cheap, safe and quick method to recharge polypropylene sheets may be also applied for other filtering applications such as industrial and house-hold air purifiers.

MATERIALS AND METHODS

Masks

8210 (3M, USA), 8210J (3M Japan, JP), High-Luck (KOKEN, JP), and X-1702 (Vilene, JP) were purchased and used as delivered.

Static electricity measurement

Digital low voltage static meter KSD-3000 (Kasuga, JP) was combined with a home-made mask clamp. The clamp was made of wood, which holds little electrostatics by nature, to avoid any influence of the electrostatics of the clamp on the measurement. To measure different surfaces, masks were cut open and each layer was placed in the clamp to keep the distance to the sensor at 1 cm. The measurement was performed at room temperature (25 °C) at relative humidity of around 50% - 60%. 10 locations were measured per surface and their average and the standard deviation are shown in figures.

Sterilizing procedures

Autoclaving was performed at 120 °C under 0.12 MPa for 10 min, while including the temperature ramp the total program was around 1 h. Washing was performed by house-hold detergent and color bleach in a washing machine with the standard program that takes around 1 h. Heating in hot water was performed by steeping masks in boiling water for 10 min. All of the masks were naturally dried and used for the experiments.

Recharging with a van de Graaff generator

The used van de Graaff generator (Gakurinsha co. ltd., JP) is equipped with a motor for moving the belt to cause the triboelectric effect. Masks were fixed to the larger metal shell with the bands of the masks, so that the face-side (layer 6) is in contact with the metal. The motor was

run for 3 min, while the smaller metallic sphere was hovered over the mask with a distance of several cm. Corona discharge was occasionally observed.

Filtering efficiency measurement

Mask fitting tester MT-03 (Sibata, JP) is equipped with two tubes connected to an aspirator, where they count particles in and outside of masks for estimating the filtering efficiency. Masks were folded into two with a tube placed inside and sealed with a duct tape, whereas the other tube was fixed nearby outside of the masks. These masks with tubes were placed in a box with a humidifier with salt water (150 mM) for simulating aerosols. The particle count was performed for 20 s with the particle size mode of 0.3 μm – 0.5 μm . The first 3 measurements were abandoned as they could be influenced by the left-over particles inside the masks, and following 3 measurements were averaged and presented in Figure 2 with standard deviations.

CONFLICTS OF INTEREST

There are no conflicts to declare.

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SUPPLEMENTAL INFORMATION

Figure S1 is available in the supplemental information.

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