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Microorganism-ionizing respirator with reduced breathing resistance suitable for removing airborne bacteria

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ABSTRACT

In this paper, we have demonstrated the feasibility of using microorganism-ionizing respirators with reduced breathing resistance to remove airborne bacteria. Using a miniaturized corona ionizer and two pairs of separator electrodes, airborne bacteria were ionized and removed from the airflow. Two microorganism-ionizing respirator designs were experimentally evaluated with flow rates ranging from ∼10 to 20 L/min and yielded airborne bacterial removal efficiencies of ∼75%–100%. Further, they were in close agreement with the analytical airborne particle removal efficiencies, at a similar range of flow rates. These flow rates also correspond to the breathing rates of standing and walking adults. More importantly, the breathing resistance could be reduced by more than 50% for flow rates of ∼200 L/min. Using manganese (IV) oxide coated mesh, the ozone concentration in the air outflow was reduced to less than 0.1 ppm, at a flow rate of ∼20 L/min, thus enabling safe use. The power consumption was less than 1 W.

1. Introduction

Airborne pathogenic outbreaks are a recurring theme in apocalyptic movie scenarios, where a deadly bacterium or virus rapidly transmits from human to human through the air. Exactly 100 years ago, the 1918 flu pandemic took its toll with at least 50 million dead and 500 million infected [1]. Recent airborne pathogenic viral outbreaks such as severe acute respiratory syndrome in 2003 and middle east respiratory syndrome in 2015, managed to spread across tens of countries causing multiple deaths [2–5]. In addition to viruses, there arehighly contagious airborne bacteria that can be transmitted person-to-person, causing diseases such as whooping cough (*Bordetella pertussis*), diphtheria (*Corynebacterium diphtheriae*), and tuberculosis (*Mycobacterium tuberculosis*) [6–8]. In the 1990 s, there were over 20 million cases of whooping cough worldwide, resulting in over 200,000 deaths [9]. In 2009, worldwide deaths due to tuberculosis were estimated at ∼150,000 [10]; in 2013 alone, there were almost half a million tuberculosis cases [11]. Airborne transmission between humans occurs via respiratory droplets, with sizes ranging from 0.58 to ∼5 μm [12,13].

In the event of an outbreak, the health advisories and precautions issued by the Health Protection Agency of the United Kingdom (HPA UK) and the United States Centers for Disease Control and Prevention (US CDC) was often limited to the use of N95 or higher-grade respirators to minimize further exposure and transmission [12,14,15]. Existing N95-based respirators employ woven fibers for mechanical filtration via inertia impaction, interception and diffusion to remove airborne particles and microorganisms from the air stream [16,17].

Unfortunately, the use of mechanical filtration is also accompanied by an increase in breathing resistance. Breathing resistance could increase by more than 100%, with a ∼40% reduction in air exchange volume [18]. Further, with the gradual loading of particles on the mechanical filter, the pressure drop could also increase, by as much as a factor of 10 [19]. Therefore, associated discomfort and impaired breathing are not uncommon [20]. When used long-term, these problems can result in either the wearer loosening the respirator, causing improper fitting, or a complete avoidance. Mechanical filtration can also be augmented electrostatically (electret filtration) so that the fibers are electrically pre-charged. But it is equally susceptible to particle loading and the fibers lose their electrical charge over time. Although powered air-purifying respirators can circumvent the breathing resistance caused by mechanical and electret filters by using a large motorized air blower, they are exceedingly bulky and noisy. At this juncture, it is important to highlight the fact that non-usage of a respirator (due to discomfort) could result in increased patient-to-patient transmission in a crowded environment, such as an emergency room

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[21].

Inspired by industrial electrostatic precipitators, and borrowing from our prior work on their miniaturization, we investigated the feasibility of a microorganism-ionizing respirator (MIRI) [22–33]. This would be intended as a low breathing resistance alternative to existing mechanical filtration based personal respirators. Electrostatic precipitators are well known for their use in removing airborne particles, with efficiencies exceeding 90% [22–28]. Even in their miniaturized form, they have been shown to effectively capture airborne particles and microorganisms [29–33]. In particular, a miniaturized corona ionizer with pin cathode and liquid anode was used as a bio-precipitator to charge, capture, and lyse airborne bacteria prior to detection [33]. However the use of liquid anode only allows it to operate for a short duration (~1 min). In this work, MIRI employs a miniaturized corona ionizer with pin cathode and metallic anode to electrically charge the incoming airborne microorganisms, which are then captured downstream by a pair of separator electrodes. In addition, it uses manganese (IV) oxide coated mesh to remove excess ozone generated by the miniaturized corona ionizer. Since the airflow would be relatively unimpeded, compared to using mechanical filtration, the differential pressure (hence breathing resistance) would also be reduced.

In this study, we present two MIRI designs: MIRI-1 is designed for fitting over commercial facepieces, and MIRI-2 is designed with a custom facepiece. First, we will present the design and principle of operation. This is followed by an estimation of analytical airborne particle removal efficiency. Experimental measurements of the corona current versus applied voltage were performed for the miniaturized corona ionizer. The differential pressure across MIRI-1 was experimentally measured and compared with a commercial N95 respirator (Model 9322 K, 3 M, Paul, MN, USA), and a control (unobstructed flow). The ozone removal efficiency of the manganese (IV) oxide coated mesh (subsequently referred to as MnO mesh), was also experimentally characterized and compared against US-EPA's safety standard for ozone inhalation. Finally, the airborne bacterial removal efficiency was demonstrated for varying airflow rates. This was performed by using plate counting to monitor the amount of airborne bacteria removed by MIRI-1 and MIRI-2.

2. Materials and methods

2.1. Design and principle of operation

As shown in Fig. 1a and b, MIRI-1 consists of a miniaturized corona ionizer (pin-to-plane configuration), two pairs of separator electrodes, and two sets of manganese (IV) oxide coated mesh. The miniaturized corona ionizer further consists of a pin cathode (stainless steel, diameter ~50 μm) and a plane anode (aluminum shim, 8 mm × 3 mm), with an electrode gap of ~2 mm. The separator electrodes consist of two parallel planes (aluminum shim ~25 mm × 25 mm × 0.5 mm) with a gap of ~3 mm. The MnO mesh in the ozone removal stage consists of a folded steel mesh (thickness ~0.45 mm, mesh pore size ~1.6 mm × 1.3 mm) coated with manganese (IV) oxide powder (70%, Atom Scientific, Manchester, UK). There were two MnO mesh designs: Design A with 4 orthogonal folds, and Design B with 7 orthogonal folds (Fig. S1). The body of MIRI-1 was 3D printed with polylactic acid (Model CubePro, 3D Systems, Rock Hill, CA, USA) and the components were fastened with screws. A high voltage DC-DC converter (Model Q20N-5, EMCO, Chico, CA, USA) was positioned below the miniaturized corona ionizer in a separate compartment. An air inlet cover was used to prevent the user accidentally making contact with the corona ionizer.

The design of MIRI-2 was similar to MIRI-1. Its miniaturized corona ionizer used a pin-to-curve instead of a pin-to-plane configuration (Fig. S1). It also had a different MnO mesh design (Design C with 2 transverse folds). MIRI-2 also had a built-in fan to facilitate airflow (Model MF15B-05, SEPA Europe GmbH, Eschbach, Germany). The key dimensions of MIRI-1 and MIRI-2 are summarized in Table 1.

As shown in Fig. 2a–c, MIRI-1 was attached externally to a modified commercial facepiece. Note that the modified commercial facepiece was essentially an N95 respirator (Model 9322 K, 3 M) with the valve flap and valve cover removed to expose the valve opening. MIRI-1 was then fitted over the valve opening. In this way, most of the air entered via MIRI-1. On the other hand, MIRI-2 was attached internally to its own custom facepiece. Fig. 2d shows the interior of MIRI-2 with the back cover and MnO mesh removed. The characteristic glow of the miniaturized corona ionizer can be observed from the rear, via the air outlet (Fig. 2d and e). Fig. 2f shows the photo of the miniaturized corona ionizer used in MIRI-2. It has the similar footprint to a 8 pin integrated circuit dual inline package and can be plugged in or removed easily. Fig. 2g and h shows the photo and electron micrographs (SNE-3000MS, SEC, Suwon, Korea) of the MnO mesh (Design A).

During operation, air laden with microorganisms entered via the air inlet and flowed past the miniaturized corona ionizer. The electron and gas ion cloud, generated by the corona ionizer, electrically charged the airborne microorganisms. As the charged airborne microorganisms entered the electric field of the separator electrodes, they acquire a drift velocity that was orthogonal to the airflow. The charged microorganisms were captured as they drifted toward, then made contact with, the separator electrodes. As the miniaturized corona ionizer also generated ozone, the excess ozone in the airflow was removed by the MnO mesh (by the following decomposition equations) prior to exiting through the air outlet [34].

$$O_3 + * \rightarrow O_2 + O^* \tag{1a}$$

$$O_3 + O^* \rightarrow O_2 + O_2^* \tag{1b}$$

$$O_2^* \rightarrow O_2 + * \tag{1c}$$

2.2. Analytical airborne particle removal efficiency

Assuming the airborne particles acquired saturation charge via combined charging, the particle saturation charge is given by [35,36]

$$Q_p^\infty = \left\{(1 + K_n)^2 + \left(\frac{2}{1 + K_n}\right)\left(\frac{\varepsilon_r - 1}{\varepsilon_r + 2}\right)\right\}\pi\varepsilon_o d_p^2 E_I \tag{2}$$

where $Q_p{}^\infty$ is the particle saturation charge, K_n is the Knudsen number given by $2\lambda/d_p$, $\lambda = 65$ nm is the air mean free path at 298 K and 1 atm, d_p is the particle diameter, $\varepsilon_r = 2$ is the electrical permittivity of the particle (conservative estimate), $\varepsilon_o = 8.85 \times 10^{-12}$ F/m is the electrical permittivity of free space, and E_I is the electric field between the cathode and anode of the corona ionizer.

Given the particle's charge from Eq. (2), the particle's drift velocity is calculated as follows [36,37]:

$$V_{drift} = \frac{Q_p{}^\infty C_c E_s}{3\pi\mu d_p} \tag{3}$$

where $\mu = 1.8 \times 10^{-5}$ kg/m/s is the dynamic viscosity of air at 298 K and 1 atm, E_s is the electric field of the separator electrodes, and C_c is the Cunningham slip coefficient that in turn is given by $C_c = 1 + 1.647 K_n$ [38].

The analytical airborne particle removal efficiency $R_{eff\text{-}analytical}$ is calculated using a similar scheme to Chua et al., and is given by [32]

$$R_{eff-analytical} = \frac{V_{drift}\tau}{X_{SE}} \tag{4a}$$

$$\tau = \frac{U_{air}}{Y_{SE}} \tag{4b}$$

where X_{SE} is the electrode spacing of the separator electrodes, Y_{SE} is the length of the separator electrodes, τ is the airborne particle residence time between the separator electrodes, and U_{air} is the airflow velocity