Design and Development of a Novel Nanofiber Nasal Filter (NNF) to Improve Respiratory Health

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ABSTRACT

Currently available nasal filters are not well-suited for protecting humans against the fine and ultrafine airborne particles. In this research, we designed and evaluated a novel nanofiber nasal filter (NNF) capable of reducing personal exposure not only to large allergenic particles but also to ultrafine particles, thus reducing respiratory health risks. A new hybrid filter (HF) medium for the NNF was fabricated by overlaying a carbon filter substrate with nylon nanofibers produced by electrospinning. After optimizing the filter’s production parameters, the HF was produced using the Nylon-6 polymer solution with a concentration of 15 wt%, a substrate based on a MERV 5 carbon filter with a density of 61 kg m−3, and a nanofiber surface coating density of 0.72 g m−2 (or 0.54 g m−2 as a second choice). The new HF was tested with fluorescent polystyrene latex beads sized 0.026–3.1 µm and at operating flow rates of 7.5–30 L min−1. The newly developed NNF showed more than a 90% collection efficiency for particles > 1 µm, representing bacteria and molds, and more than a 50% efficiency for particles < 0.5 µm, including ultrafine particles—about a 2.3-fold improvement compared to commercially available nasal filters. Thus, this NNF may serve as a useful tool to minimize our exposure to airborne pollutants.

Keywords: Personal exposure; Electrospinning; Hybrid filter; Carbon filter; Ultrafine particles.

INTRODUCTION

Outdoor air pollution is a major contributor to the global environmental burden of disease, including the risk of cancer (Reding et al., 2015). It is estimated that 100 out of 156 countries have PM2.5 (particulate matter smaller than 2.5 µm) concentrations exceeding World Health Organization (WHO) air quality standards which results in approximately 1.4 billion people worldwide breathing air with pollutant levels exceeding those standards (Johansson and Hahtela, 2004; Laumbach et al., 2015; Jiang et al., 2016). In addition, inhalation of airborne allergens such as mold, pollen, dust mites, and allergens from dogs or cats (Peden and Reed, 2010) can create a miserable combination of nasal congestion, itching, drainage and sneezing (Gershwin and Klingelhofer, 1998). As a result of exposure to various airborne allergens, one in six Americans is affected by allergic rhinitis (Seidman et al., 2015). One can avoid exposures to airborne pollutants and limit the resulting health effects by minimizing the time spent outdoors, especially of high-pollution days, and/or by using air purifiers indoors, where we spend more than 90% of our time (Evans and McCoy, 1998; Nelson et al., 1988; Höppe, 2002; Laumbach et al., 2015). However, that would deny us the benefits associated with outdoor activities; cleaning the indoor air is not always effective due to the ubiquitous and varying nature of allergens stemming from a variety of sources and considerable energy expenditure needed to run air purifiers (Fisk et al., 2002).

On the other hand, personal protective equipment such as face masks and respirators could be used (Rengasamy et al., 2004; Lin et al., 2017; Wang et al., 2017). However, despite the apparent practicality of respirators and face masks, they often fall short of efficiently protecting against airborne allergens due to improper fit or facial leakage (Loeb et al., 2009); they also impose strain to our breathing (Höppe, 2002). Thus, they are used only by 1% of allergy sufferers (Storms et al., 1997; O’Meara et al., 2005). For comparison, 74% of hay fever and asthma sufferers have used medications (Storms et al., 1997; Ziment and Tashkin, 2000). While medication is widely used to alleviate allergy symptoms, it often is inadequate, and many people avoid medications due to their side-effects such as nausea, drowsy, or dizziness (Boulet, 1998).

Another option to avoid exposure to airborne allergenic
particles is to use personal nasal filters (O’Meara et al., 2005; Renström et al., 2006) which have been available since the 1990s (Graham et al., 2000; Poulos et al., 1999; Renström et al., 2002; Sercombe et al., 1998). However, they have not been widely used due to multiple physical and technical issues, e.g., air leakage, discomfort, air flow resistance, and a lack of consensus regarding their performance (Sigsgaard and Tovey, 2014). Such filters are placed within the nasal passages and are supposed to prevent airborne pollutants from entering the respiratory system. They typically contain a certain quantity of filter material (e.g., woven nontoxic mesh, non-woven type, or porous filters) and work like miniature air filters. It is reported that some nasal filters could reduce daily sneezing and runny nose by an average 45% and 12%, respectively (Kenney et al., 2014). Most commercially available nasal filters show good collection efficiency for large airborne particles (e.g., pollens, household dust, dust mites, and pet hair and dander) (O’Meara et al., 2005; D’Amato et al., 2012). However, according to our preliminary experiments presented below in the section “Performance of existing nasal filters,” their efficiency drops substantially for fine particles (less than 2.5 micrometers in diameter), and such particles are even more injurious to the lungs than large particles (Kim et al., 2015a; Li et al., 2017). In addition, there are growing concerns about the health effects of ultrafine particles (UFP) which are <100 nm in diameter and can be easily inhaled and travel deep into the human lung (Hoet et al., 2006; Kim et al., 2015a). Previous studies have indicated an association between UFP exposure and health effects ranging from heightened allergic inflammation (Chalupa et al., 2004; Falcon-Rodriguez et al., 2017) to adverse respiratory and cardiovascular effects (Morawska et al., 2006), including death from respiratory and cardiovascular illnesses (Delfino et al., 2005). UFPs are encountered during our daily activities such as operating consumer appliances or while being outdoors due to the UFP production by combustion sources (Chang et al., 2004; Schripp et al., 2011). Exposure to airborne engineered nanosized particles is also a potential health concern (Oberdörster et al., 2005; Buzea et al., 2007; Weichenthal et al., 2007; Nazarenko et al., 2011). Therefore, it is imperative to investigate and develop an easy-to-use, yet efficient means which would be capable of preventing personal exposures to a wide range of airborne particles, including UFPs (Sambudi et al., 2017).

Thus, the main goal of this study was to design and develop a more efficient and convenient-to-use nasal filter by applying nanofibers onto a conventional filter base (Choi et al., 2017). Such a filter would serve as a means for reducing personal exposures to various common allergens and ultrafine particles and the resulting health risks. The first step of this study was to develop and optimize a new hybrid filter, where layers of electrospin nanofibers were deposited on a commercially available conventional filter. Each step of the process (e.g., electrospinning conditions and substrate selection) had to be optimized to yield the best performance of the new hybrid filter. In the second step, the performance of the new hybrid filter (i.e., a filter which has overlapping layers of nanofibers and microfibers) was compared with three commercially available nasal filters when tested with a wide range of polystyrene latex (PSL) particles (i.e., 26 nm–3.1 µm) at three filtration periods (i.e., 10, 60, and 240 min). For the new nasal filter, two different filter frame prototypes were fabricated by 3D printing technology and are presented here in the supplementary material. The text below presents the development and testing of this novel nanofiber nasal filter.

**PERFORMANCE OF EXISTING NASAL FILTERS**

Among the many different types of commercially available nasal filters (e.g., a disk type and a container type), seven filters were purchased from Amazon (www.amazon.com). These filters are reusable and were made in China, Japan, Korea, Taiwan, and the United States. We investigated their collection efficiency with 1.0 and 3.1 µm PSL particles (these sizes represent typical bacteria and mold spores) at a sampling flow rate (\( Q_s \)) of 10 L min\(^{-1} \) per one piece, i.e., equivalent to 20 L min\(^{-1} \) breathing rate to simulate inhalation rate during moderate physical activity (Önerci, 2013). The details of the test system are presented below in Materials and Methods. The results presented in Fig. 1 show that all but one tested nasal filter were not efficient at collecting 1.0 and 3.1 µm PSL. Thus, these filters are not well-suited for effective protection against airborne contaminants, especially particles of smaller size (i.e., fine particles with a diameter of less than 2.5 µm). In addition, since the health concerns regarding ultrafine particles (i.e., particles smaller than 0.1 µm) have been growing, there is a need to develop easy-to-use and comfortable nasal filters that could be used to protect against a wide range of environmental pollutants, from nanosized particles to pollen.

**MATERIALS AND METHODS**

**Electrospinning Setup for Producing Nanofibers**

The electrospinning system designed and built for this study is presented in Fig. 2(a). It consisted of three main components: 1) a syringe feeder system (i.e., pump, syringe, and needle), 2) a collector, and 3) a high voltage power supply. The syringe feeder system had a syringe pump (Genie Plus, Kent Scientific, Torrington, CT), a 10 mL syringe (McMaster-Carr Co., Elmhurst, IL), and a stainless steel needle 0.7 mm in inner diameter (19 SS, McMaster-Carr Co.) (Ahn et al., 2006). The collector was a stationary circular stainless steel plate with a diameter of 50.8 mm (2 inches) affixed to a stand of static dissipative material (e.g., Delrin) at a certain distance from the needle. A DC high-voltage source (Bertan Associates Inc., Valhalla, NY, USA) was connected to the needle and the collector plate and provided a +25 kV voltage. The system was housed inside a custom-made clear acrylic safety cabinet (width: 38.1 cm × length: 60.1 cm × height: 27.9 cm), which was equipped with a protective front door and a controllable exhaust fan. The exhaust pipe was connected to a fume hood system (Purair 5-36, Air Science LLC, Fort Myers, FL).
Fig. 1. Collection efficiencies of seven commercially available nasal filters at 10 L min⁻¹ flow rates. Collection efficiencies were determined by measuring particle number concentrations upstream and downstream of each filter. Each data point is an average of at least three repeats, and the error bars represent one standard deviation.

Fig. 2. (a) Photograph of the newly fabricated electrospinning apparatus and (b) DSLR camera snapshots of electrospinning of polymer solution: 1/400 s at ISO 400. The inner diameter of the needle was 0.7 mm.

Electrospinning Materials, Parameters, and Process Control
Nylon-6 pellets (Sigma-Aldrich Corp., St. Louis, MO) were used as material to produce nanofibers. The polymer solution was prepared by dissolving polymer pellets in 88–91% formic acid (Sigma-Aldrich Corp.) at room temperature.
by gently stirring the solution for 8 hours. Three different concentrations (15, 20, and 25 wt%) of Nylon-6 solution were prepared, and the conductivity (mS cm$^{-1}$) of each polymer solution was measured by a conductivity meter (VWR International LLC, Radnor, PA). The values were 4.2 ± 0.02, 3.8 ± 0.01, and 3.4 ± 0.02 mS cm$^{-1}$ for 15, 20, and 25 wt%, respectively (Table 1).

The diameter of the electrospun fibers can be affected by some parameters: solution concentration, electric field strength, feed rate, and the distance between the needle and collector (Huang et al., 2003); the structure and mechanical characteristic of the electrospun fibers (e.g., Nylon-6.6) can be affected by the processing conditions (Zussman et al., 2006). In our setup, the solution feed rate was 2 µL min$^{-1}$, and the stainless steel collector was located 5 cm away from the tip of the needle resulting in the electrostatic field 5 kV cm$^{-1}$. These parameters were optimized by other investigators (Ahn et al., 2006; Li et al., 2006).

In order to get the desired surface coating density (e.g., 0.54 or 0.72 g m$^{-2}$) of the coverage area (i.e., a 25.4 mm diameter substrate attached to the 50.8 mm diameter collector), we controlled the operating time of the syringe pump from 4 seconds to 5 minutes and then estimated the coating density by using the following parameters: the spent volume (V) of Nylon-6 solution, the coverage area (CA), the solution concentration (C), and density (D = 1.2 g mL$^{-1}$) of Nylon-6 polymer solution. The desired coating density was calculated by the following equation (Li et al., 2006):

$$CD = \frac{V \times C \times D}{CA}$$

(1)

In order to produce a hybrid filter (HF), we affixed a non-conductive substrate to the collector and operated the system. Here, the voltage of +25 kV between the needle and the collector drew the charged threads of polymer solution through the needle toward the stainless steel collector, and, in the process, deposited them onto the substrate, i.e., the base of the HF. Fig. 2(b) shows the electrosprinning images taken with a DSLR camera (NEX 6, Sony Corp.): a polymer solution droplet at the tip of the needle when the power is off (left) and nanofiber threads in the air when the power is on (right). As potential substrates of the HF, we tested conventional membrane filters (Nuclepore Track-Etched Polycarbonate Membrane, VWR International, Radnor, PA) and carbon filters (McMaster-Carr Co., Elmhurst, IL) as candidate materials for the base of HF.

**Experimental Setup to Test the Hybrid Filter**

The test system was comprised of a flow control system, a particle generation system, an air-particle mixing system, and a particle monitoring system (Fig. 3). The system was housed in a Class II Biosafety Cabinet (NuAire, Inc., Plymouth, MN). The same system was used to test the performance of commercially available nasal filters (Fig. 1).

A six jet Collison nebulizer (Mesa Laboratories Inc., Butler, NJ) was used to aerosolize test particles from a liquid suspension at a flow rate ($Q_a$) of 5 L min$^{-1}$ (pressure of 12 psi), and the aerosolized particles were combined with a dry air flow, $Q_d$ (5 L min$^{-1}$). The dry air and aerosolized particle streams were combined ($Q_d + Q_a = 10$ L min$^{-1}$) and passed through a 2-mCi Po-210 charge neutralizer (Amstat Industries, Inc., Glenview, IL) to reduce aerosolization-induced electrostatic particle charges to Boltzmann charge equilibrium. A HEPA-filtered dilution air flow, $Q_d$ (60 L min$^{-1}$), provided by an in-house compressor was used to further dry and dilute the particle stream; it was controlled by a pressure regulator and monitored by a mass flowmeter.

### Table 1. Parameters of the investigated Nylon-6 polymer solutions: concentrations, electrical conductivity, and the resulting fiber diameter.

<table>
<thead>
<tr>
<th>Polymer solution concentration, wt%</th>
<th>Conductivity, mS cm$^{-1}$</th>
<th>Fiber diameter, nanometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>4.2 ± 0.02</td>
<td>51 ± 19</td>
</tr>
<tr>
<td>20</td>
<td>3.8 ± 0.01</td>
<td>135 ± 23</td>
</tr>
<tr>
<td>25</td>
<td>3.4 ± 0.02</td>
<td>190 ± 65</td>
</tr>
</tbody>
</table>

**Fig. 3.** Schematic diagram of the experimental setup to test hybrid filters. The test system was comprised of a flow control system, a particle generation system, an air-particle mixing system, and a particle monitoring system.
The entire air stream with electrically-neutralized particles then passed through the first mixing box (Han et al., 2005) which improved the uniformity of particle distribution across the flow cross-section. A second mixing box was connected by a U-type duct to enhance turbulence further and improve particle mixing. A well-mixed flow stream then entered a raised test section. A second mixing box was connected by a U-type transport tube after a 90-degree elbow. Mixing. A well-mixed flow stream then entered a raised test section. A second mixing box was connected by a U-type transport tube after a 90-degree elbow. Each hybrid filter 25 mm in diameter was produced as described above. Its collection efficiency was tested with green fluorescent polystyrene latex particles (Duke Scientific Corp., Palo Alto, CA) of six aerodynamic diameters (0.026, 0.1, 0.2, 0.5, 1.0, and 3.1 µm) which represent typical size range of single viruses to bacteria to mold spores (Reponen et al., 1996; Lee et al., 2008). During each test, the airborne concentration of fluorescent PSL particles upstream of the filter was approximately $1.3 \times 10^3$ to $4.4 \times 10^4$ L$^{-1}$, as measured by an optical particle counter (model 1.108, Grimm Technologies, Inc., Douglasville, GA). The air was pulsed through the hybrid filter at flow rates ($Q_s$) of 7.5, 15, and 30 L min$^{-1}$ provided by a vacuum pump, and the $Q_s$ was monitored using a mass flowmeter (TSI Inc., Shoreview, MN).

The average inspiratory flow of an adult is considered 15 L min$^{-1}$. Given that an average cross-sectional area of a single nostril at the entrance of the nose is about 1.5 cm$^2$ (Sigsgaard and Tovey, 2014), the average inhaled air velocity for a single nostril is approximately 0.8 m s$^{-1}$ and Reynolds number of 800 (laminar flow). Our selected test flow rates, therefore, resulted in air velocities across HF ranging from 0.25 to 1 m s$^{-1}$ and Reynolds numbers ranging from 450 to 1800 (laminar flows). The test time varied from 2 to 240 minutes.

**Protocol to Produce a New Hybrid Filter**

Hybrid filters were fabricated by overlaying nanofibers onto the substrates using the electrospinning process, and several commercially available filters were tested as substrates. The final hybrid filter was produced through the following iterative steps.

**Step 1: Finding an Optimal Concentration (wt%) of the Nylon-6 Polymer Solution and Electrospinning Time**

Nine hybrid filters were fabricated from 3 polymer concentrations (e.g., 15, 20, and 25 wt%) × 3 electrospinning times (e.g., 4, 8, and 40 seconds). The layers of electrosprun nanofibers were coated on a conventional membrane filter (Nuclepore Track-Etched Polycarbonate Membrane, 25 mm, Pall Inc., East Hills, NY), and the resulting coating densities ranged from 0.012 to 0.2 g m$^{-2}$. The optimal polymer concentration was selected by comparing the collection efficiency and pressure drop of the resulting hybrid filters. In addition, the morphology of electrosprun nanofibers was analyzed by using a scanning electron microscope (Genesis-1000, EMCRAFTS Co., Ltd., Korea) and image analyzer (EmCrafts Virtuoso v1.1, EMCRAFTS Co., Ltd., Korea). The diameter of the produced nanofibers was determined by using a field emission scanning electron microscope (ZEISS 982, Carl Zeiss, LLC, NY) and image analyzer (SmartSEM, Carl Zeiss, LLC, NY).

**Step 2: Finding Optimal Substrate (i.e., Basis of the Hybrid Filter)**

Once the optimal coating density was determined, a substrate for the HF was selected from five commercially available activated carbon filters (Table 2) by comparing their collection efficiency and pressure drop without any nanofiber coating. We chose the activated carbon filters as the basis for our HF because they have been widely used as pre-filters in air conditioners or air purifiers and are generally classified by a Minimum Efficiency Reporting Value (MERV) rating (ASHRAE Standard, 2007). Table 2 shows the MERV rating, carbon density (g m$^{-2}$), thickness (mm), and filter density (kg m$^{-3}$) of each tested filter. This experiment was performed with 0.026, 0.5, and 3.1 µm PSL particles at a flow rate of 7.5 L min$^{-1}$ (i.e., 0.25 m s$^{-1}$ face velocity). The conventional membrane filter was not used as a basis beyond Step 1 because of its high-pressure drop.

**Step 3: Finding Optimal Coating Density**

Once the polymer concentration and substrate were selected, we determined the optimal nanofiber coating density by testing the following coating densities: 0.54, 0.72, 0.81, and 0.9 g m$^{-2}$. The range of these coating densities was obtained by coating the base via electrosprning for 3, 4, 4.5, and 5 minutes. The collection efficiency tests were

**Table 2.** Characteristics of commercially available carbon filters (CF) that were tested as bases for the new hybrid filter.

<table>
<thead>
<tr>
<th>Carbon filter (CF)</th>
<th>MERV*</th>
<th>Carbon density, g m$^{-2}$</th>
<th>Thickness, mm</th>
<th>Filter density, kg m$^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>44</td>
<td>12.7</td>
<td>36</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>6</td>
<td>4.8</td>
<td>61</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>50</td>
<td>9.7</td>
<td>67</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>14</td>
<td>4.8</td>
<td>91</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>25</td>
<td>4.8</td>
<td>134</td>
</tr>
</tbody>
</table>

* MERV: Minimum Efficiency Reporting Value. Filter properties were provided by the manufacturer (McMaster-Carr Co., Elmhurst, IL).
carried out as a function of coating density with 0.026 µm PSL particles at three different face velocities (e.g., 0.25, 0.51, and 1.0 m s⁻¹).

**Determination of the Hybrid Filter’s Performance**

The collection efficiency of each produced HF, \( \eta_{HF} \), was determined using the experimental setup shown in Fig. 3, calculated as follows:

\[
\eta_{HF} = 1 - \frac{C_{DN}}{C_{UP}}
\]

where \( C_{UP} \) and \( C_{DN} \) are airborne particle number concentrations upstream and downstream of the HF, respectively. The concentrations were determined by an OPC for 0.5, 1.0, and 3.1 µm PSL particles and a P-Trak ultrafine particle counter (UPC 8525, TSI Inc., Shoreview, MN) for 0.026, 0.1, and 0.2 µm PSL particles. The measurement duration was two minutes. The pressure drop across the filter was measured by a pressure gauge (Dwyer Instruments Inc., Michigan City, IN); the sampling flow rate was provided by a vacuum pump (VAC-U-GO, SKC Inc., Eighty Four, PA) and monitored by a mass flowmeter (TSI Inc., Shoreview, MN). The measurements for each parameter were repeated three times.

**RESULTS AND DISCUSSIONS**

**Iterations for Fabricating an Optimized Hybrid Filter**

The results in this section correspond to the optimization Steps 1–3 described above.

Step 1. Fig. 4 shows SEM images of Nylon-6 nanofibers produced from different polymer solution concentrations (15, 20, and 25 wt%) and deposited on the membrane filter via electrospinning for 4–40 sec. The average diameters of Nylon-6 fibers were 51 ± 19 nm (15 wt%), 135 ± 23 nm (20 wt%), and 190 ± 65 nm (25 wt%) (Table 1). The average diameters of electrospun Nylon-6 fibers decreased with decreasing solution concentration since high electrical conductivity favors thinner electrospun fibers (Li et al., 2006). Fig. 5 presents the collection efficiency and pressure drop of electrospun nanofibers deposited onto the polycarbonate membrane filter as a function of the concentration of the polymer solution (0, 15, 20, and 25 wt%) when sampling 26 nm PSL particles at 7.5 L min⁻¹ flow rate (corresponding to 0.25 m s⁻¹ face velocity). The concentration of 26 nm airborne PSL particles was approximately 10⁴ L⁻¹. Depending on the electrospinning time (e.g., 4, 8, and 40 sec), each concentration of polymer solution resulted in a range of coating densities: 0.012–0.12 g m⁻² (15 wt% polymer), 0.016–0.16 g m⁻² (20 wt% polymer), and 0.01–0.2 g m⁻² (25 wt% polymer). For each polymer solution concentration, the collection efficiency of the HF increased when electrospinning time increased from 4 to 40 sec: from 43.3 ± 0.9% to 70.4 ± 0.3%, from 34.5 ± 0.9% to 59.7 ± 0.4%, and from 35.2 ± 1.0% to 53.8 ± 1.3%, respectively, while the collection efficiency of the pristine substrate (e.g., membrane filter without coating) was 30.7 ± 1.1%. One could also observe that for each electrospinning time, the collection efficiency decreased with increasing polymer solution concentration. At the lowest polymer solution concentration of 15 wt%, the average collection efficiency of the produced hybrid filter was approximately 1.3–2.3× higher compared to the collection efficiencies at polymer concentrations of 20 and 25 wt% at the same electrospinning times, and 1.4–2.3× higher compared to the pristine substrate. However, the lowest polymer solution concentration, which produced filters with the highest collection efficiency, resulted in the highest pressure drop. The use of lower polymer solution concentration results in thinner fibers as shown in Fig. 4 and Table 1, and, as a result, for the same coating density

![Fig. 4. Scanning electron microscope (SEM) images of the polycarbonate membrane filter surface coated by nanofibers at different concentration of the tested Nylon-6 polymer solution ((a) 15 wt%, (b) 20 wt%, and (c) 25 wt%).](image-url)
more nanosized particles travel near the fiber, resulting in higher diffusion and interception efficiencies (Graham et al., 2002). A two-way ANOVA with Holm-Šidák post hoc method indicated the statistically significant effect of both variables (i.e., the concentration of polymer solution and electrospinning time); pairwise comparisons showed that the collection efficiency was statistically different (P < 0.05) except the following pairs: concentrations of 20 wt% vs. 25 wt% at every electrospinning time.

Fig. 5 also shows pressure drop across the HF as a function of the polymer solution concentration and electrospinning time. The pressure drop for the pristine filter was 3.4 ± 0.2 kPa. When the polymer solution concentration increased from 15 to 20 and then to 25 wt%, the pressure drop for each electrospinning time (4, 8, and 40 s) decreased: from 4.2 ± 0.2 kPa to 3.1 ± 0.1, from 5.6 ± 0.4 kPa to 3.1 ± 0.2 kPa, and from 5.8 ± 0.4 kPa to 3.7 ± 0.2 kPa, respectively. According to the pairwise comparison, the pressure drop was not statistically significant for all concentration pairs except the concentrations of 15 wt% vs. 25 wt% (p = 0.012); the effect of electrospinning time was not statistically significant (p > 0.05) except 4 s vs. 40 s at every polymer concentration. For fibers with less than 0.5 micrometers in diameter, a slip flow phenomenon, where the continuum velocity at the nanofiber surface is not zero, needs to be considered (Graham et al., 2002). This phenomenon occurs for fibers with a diameter less than 400 nanometers at standard conditions, and pressure drop in slip flow regions is inversely proportional to the fiber diameter (Pich, 1971; Cheng et al., 1988; Jaroszczyk et al., 2009). Thus, the best collection efficiency was observed for the 15 wt% polymer solution concentration, but it showed the highest pressure drop. The pressure drop was deemed acceptable at this stage of the HF development, and the 15 wt% polymer solution concentration was chosen for the next steps.

In Step 2, a substrate for HF was selected. Five carbon filter substrates with MERV 5 and MERV 6 ratings were explored, and their manufacturer-provided properties are shown in Table 2. The collection efficiencies of these non-coated substrates were tested using 0.026, 0.5, and 3.1 µm PSL particles at 1.0 m s⁻¹ face velocity, and the results are presented in Fig. 6. When 26 nm particles were used, the average collection efficiency across all filters was approximately 6.7 ± 2.5%. Similarly, for 0.5 and 3.1 µm particles, the average collection efficiency was 13.1 ± 1.6% and 44.9 ± 8.9%, respectively. Based on the one-way ANOVA with Holm-Šidák post hoc method, the collection
efficiency of CF-2 filter (61 kg m\(^{-3}\) filter density) was significantly lower than that of other filters; the collection efficiency among other filters was not statistically different. For 0.5 \(\mu\)m particles, the collection efficiency was not statistically different \((p > 0.05)\). With 3.1 \(\mu\)m particles, the CF-5 \((134 \text{ kg m}^{-3}\) filter density\) had a statistically significantly higher collection efficiency compared to other filters.

As far as pressure drop, the CF-2’s pressure drop was significantly lower than that of others \((p < 0.05)\). Since the CF-2 \(\text{(MERV 5: 6 g m}^{-3}\) carbon density and 4.8 mm thickness\) had a similar collection efficiency as other filters and the lowest pressure drop \(< 0.05 \text{ kPa}\), which is important for nasal filters, it was selected as a substrate for the HF.

In Step 3, the collection efficiency of the HF produced by overlaying nanofibers at different densities on the selected substrate \(\text{(CF-2)}\) was investigated, and the results are shown in Fig. 7. The nanofiber coating density was varied from 0.54 to 0.90 g m\(^{-2}\). The experiments were performed with 26 nm PSL particles at 0.25, 0.51, and 1.0 m s\(^{-1}\) filter face velocities. At 0.25 m s\(^{-1}\) face velocity, the collection efficiency was 50–66% and the pressure drop was 0.14–0.24 kPa; when the face velocity was increased to 0.5 m s\(^{-1}\), the collection efficiency was 45–59% and the pressure drop was 0.28–0.47 kPa; at the highest investigated face velocity \(1.0 \text{ m s}^{-1}\), the collection efficiency was 43–55% and the pressure drop was 0.40–0.62 kPa. In general, the collection efficiency increased with increasing coating density and decreased with increasing face velocity; the effect of both variables was statistically significant \((p < 0.001)\). However, at the highest face velocity \(V_f = 1.0 \text{ m s}^{-1}\), the collection efficiency was not different for coating densities 0.72–0.9 g m\(^{-2}\). Also, for the 0.5 and 1.0 m s\(^{-1}\) face velocities, the collection efficiency was not different at the three lower coating densities \((0.54, 0.72, 0.81 \text{ g m}^{-2})\). The collection efficiency decreased with increasing face velocity because of decreasing time to capture particles by diffusion (Fig. 7(a)). The pressure drop, however, increased linearly with the increasing face velocity and coating density (Fig. 7(b)) and the effect was statistically significant \((p < 0.001)\), except the following pairs: 0.72 g m\(^{-2}\) vs. 0.81 g m\(^{-2}\) and 0.81 g m\(^{-2}\) vs. 0.9 g m\(^{-2}\) at each face velocity.

In general, it is preferable to have a filter that provides the highest collection efficiency with the lowest pressure drop. A useful criterion for comparing the performance of fibrous filters is their quality factor \((QF)\), i.e., the ratio of penetration factor \(1-\eta_{HF}\) to the pressure drop across the filter. The greater the value of \(QF\), the better the filter. Based on the results presented in Fig. 7 and the resulting \(QF\), a filter with 0.54 g m\(^{-2}\) coating density \((QF = 2.82)\) and a filter with 0.72 g m\(^{-2}\) coating density \((QF = 2.65)\) were selected for further investigation. The \(QF\) values of the other two filters were lower: \(QF = 2.61 \text{ at 0.81 g m}^{-2}\) coating density and \(QF = 2.57 \text{ at 0.9 g m}^{-2}\) coating density. The two selected filters had the following characteristics: (1) the 15 wt% polymer solution concentration used to produce nanofibers, (2) the MERV 5 carbon filter basis with 61 kg m\(^{-3}\) density and (3) 0.54 (or 0.72) g m\(^{-2}\) nanofiber coating densities.
Investigation of the Hybrid Filter’s Performance When Challenged with a Wide Range of Particle Sizes over Several Collection Times

Collection efficiencies of the two selected hybrid filters (25 mm in diameter) with different coating densities, when tested with PSL particles of 0.026, 0.1, 0.2, 0.5, 1, and 3.1 µm in aerodynamic diameter at 1.0 m s\(^{-1}\) face velocity, are shown in Fig. 8. Their performance was also compared against three commercially available nasal filters (i.e., Type-B, Type-G, and Type-H); the Type-B and G were the same filters used in the preliminary experiment (Fig. 1), and the Type-H was a newly added filter (made in the United States) for this experiment. These three commercially available filters were selected to represent three different types of exterior design: B, disk type; G, container type; and H, self-adhesive tape type. When collecting particles < 1 µm, both HF filters had higher efficiencies compared to the three other filters: 38 ± 2% (HF with 0.54 g m\(^{-2}\) coating density) and 53 ± 2% (HF with 0.72 g m\(^{-2}\) coating density) compared to 21 ± 2% (Type-B), 16 ± 3% (Type-G), and 18 ± 5% (Type-H). The average collection efficiencies sharply increased when particles ≥ 1 µm in aerodynamic diameter were collected, and the HF filters again exhibited the best performance: 92% (HF with 0.54 g m\(^{-2}\) coating density) and 94% (HF with 0.72 g m\(^{-2}\) coating density) compared to 68% (Type-B), 45% (Type-G), and 25% (Type-H). In summary, the collection efficiency of HF with 0.72 g m\(^{-2}\) coating density was the highest across the tested particle range, and about 1.9× higher compared to the commercially available nasal filters when challenged with 1 and 3.1 µm particles, sizes that represent typical bacteria and mold spores (Fig. 8). This result also indicates that exposure to PM\(_{2.5}\) particle mass concentration would be reduced by 80–90% when wearing the HF nasal filter. When the filter performance was analyzed using ANOVA with Holm-Šidák post hoc test, all pairwise filter comparisons for each particle size were statistically different, except the following pairs: Type-B vs. Type-H for 0.1 µm PSL particles; HF-0.54 g m\(^{-2}\) vs. HF-0.72 g m\(^{-2}\) and Type-G vs. Type-H for 1 µm PSL particles; and HF-0.54 g m\(^{-2}\) vs. HF-0.72 g m\(^{-2}\) for 3.1 µm PSL particles.

It is obvious that the two HFs had higher collection efficiencies than the other filters. Therefore, we selected the HF with 0.72 g m\(^{-2}\) coating density to test its collection efficiency and pressure drop when collecting 26 nm and 3.1 µm PSL particles for 10, 60, and 240 min at the 1.0 m s\(^{-1}\) face velocity (Fig. 9). When the sampling time was increased from 10 to 240 min, the average collection efficiency decreased slightly from 54.4 ± 0.7% to 51.9 ± 0.9% with 26 nm PSL particles and from 98.5 ± 0.6% to 93.3 ± 1.0% with 3.1 µm PSL particles; yet, the decrease was statistically significant (p < 0.001). As could be expected, when the operating time increased from 10 to 60 and then to 240 min, the pressure drop increased linearly from 0.002 to 0.018 and then to 0.065 kPa (with 26 nm PSL particles) and from 0.01 to 0.051 and to 0.182 kPa (with 3.1 µm PSL particles), due to more material deposited on the filter (Fig. 9).

Overall, the new hybrid filter material that will be used to produce nasal filter has higher collection efficiency compared to commercially available nasal filters when removing not only fine and coarse particles but also ultrafine particles (Fig. 8). Thus, the nanofiber nasal filter (NNF) could improve the quality of life by preventing various allergens from reaching the respiratory tract, including efficient removal of the PM\(_{2.5}\) mass fraction and substantial removal of nanosized, or ultrafine, particles, such as those resulting from diesel exhaust or other combustion emissions.

The next phase of this research will address the relationship between total mass deposited on the nasal filter and pressure drop for the real-world filter use. Usually, filters are replaced when particle loading becomes high leading to discomfort when breathing. For this reason, an N95 respirator, which is the most used respiratory protection device in the occupational environments in the...
U.S. (Rengasamy et al., 2008), has air flow resistance limits of 0.34 kPa (inhalation resistance to airflow) and 0.25 kPa (exhalation resistance to airflow) (Kim et al., 2015b). At the same time, there are no guidelines for respiratory

![Fig. 8. Collection efficiencies of the developed hybrid filters with surface coating densities of 0.54 g/m² and 0.72 g/m² versus commercially available nasal filters (Type-B, Type-G, and Type-H) as a function of challenge particle size (0.026, 0.1, 0.2, 0.5, 1, and 3.1 µm). The experiments were performed at 1.0 m s⁻¹ face velocity. Each data point is an average of at least three repeats, and the error bars represent one standard deviation.](image)

![Fig. 9. Collection efficiencies and increase in pressure drop (y-axis on the right side) of the hybrid filter with surface coating density of 0.72 g m⁻² as a function of filtration time (10, 60, and 240 min) when tested with PSL particles of 0.026 and 3.1 µm at 1.0 m s⁻¹ face velocity. Each data point is an average of at least three repeats, and the error bars represent one standard deviation.](image)
A distinctive feature of the NNF is that it effectively protects with 26 nm and 3.1 µm PSL particles for up to 4 hours. This was achieved without a significant pressure drop when tested against not only fine but also ultrafine particles—a feature that is not present in the commercially available nasal filters. The high collection efficiency was approximately 2.3× higher than that of three commercially available nasal filters. The NNF showed a filtration efficiency of aggregate aerosols.

CONCLUSIONS

A new nanofiber nasal filter (NNF) has been successfully developed and fabricated by using a conventional activated carbon filter (the MERV 5 filter with a density of 61 kg m⁻³) as the base, which is then overlaid with electrospun Nylon-6 polymer nanofibers (with a diameter of 51 ± 19 nm on average). The NNF showed a filtration efficiency of approximately 2.3× higher than that of three commercially available nasal filters. The high collection efficiency was achieved without a significant pressure drop when tested with 26 nm and 3.1 µm PSL particles for up to 4 hours. A distinctive feature of the NNF is that it effectively protects against not only fine but also ultrafine particles—a feature that is not present in the commercially available nasal filters. Thus, the NNF may serve as a personal protective device against exposure to various airborne pollutants, including allergens and ultrafine particles. Further development of the NNF will include the development of advanced materials and changes in the design to improve its collection performance against ultrafine particles further while reducing the airflow resistance. Future studies will also include extensive use and evaluation of the NNF by human subjects.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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