Effects of Electric Field Strength on an Antimicrobial Air Filter

Gi Byoung Hwang¹, Hyun-Seol Park², Gwi-Nam Bae¹*, Jae Hee Jung¹3†

¹ Center for Environment, Health, and Welfare Research, Korea Institute of Science and Technology (KIST), Hwarangno 14-gil 5, Seongbuk-gu, Seoul 136-791, Korea
² High Efficiency and Clean Energy Research Division, Korea Institute of Energy Research, 152 Gajeong-ro, Yuseong-gu, Daejeon 305-343, Korea
³ Department of Electrical Engineering, California Institute of Technology, 1200 E. California Blvd., Pasadena, CA, 91125, USA

ABSTRACT

We investigated the effects of a surrounding electric field (EF) on the performance of antimicrobial air filters coated with natural-product nanoparticles. The filtration efficiency of the control filter increased with increasing EF strength, whereas the filtration efficiency of the antimicrobial filter did not, probably because its original efficiency was already high (> 99%) and non- or relatively weakly charged bacterial aerosols were hardly affected by EF strength. The bacterial deposition profiles through the depth of the antimicrobial filters were evaluated. The bacterial concentration at depths of 0–68 µm was increased by about 30% at an EF of 7.7 kV/cm compared with the concentration at 0 kV/cm. Scanning electron microscopy revealed that at 7.7 kV/cm, but not at 0 kV/cm, the bacteria formed dendrites on the fibers of the filter, and the concentration of bacteria deposited on the fibers at 7.7 kV/cm was two to three times that at 0 kV/cm. In antimicrobial tests, the performance of the antimicrobial filters increased with increasing concentration of antimicrobial nanoparticles, but the effectiveness differed between 0 and 7.7 kV/cm. At an identical nanoparticle concentration, the inactivation efficiency of the antimicrobial filter at 7.7 kV/cm was at most 23% lower than that at 0 kV/cm, because the relative increase in bacterial concentration and dendrite formation in the first layer of the antimicrobial filter at 7.7 kV/cm reduced the surface contact area between the bacteria and the antimicrobial nanoparticles. This study provides valuable information for developing a hybrid air purification system that serves various functions and can be used in an indoor environment.

Keywords: Electric field (EF); Bacteria aerosol; Antimicrobial filter; Deposition profile in filter.

INTRODUCTION

Indoor air quality (IAQ) has become more important with the increase in human indoor activities. An investigation of time budgets for U.S. residents reported that individuals spend, on average, 88% of their day inside buildings; 7% in vehicles; and 5% outdoors (Robinson et al., 1995). During the last several decades, building designs have implemented advanced construction technologies to improve energy efficiency, leading to a much greater use of synthetic building materials (D'Amato et al., 1994). These changes have created indoor environments in which air pollutants are easily produced and can accumulate at higher concentrations than those in the outside environment. Indoor air pollutants include combustion products from heating and cooking, tobacco smoke, volatile organic compounds (VOCs), bioaerosols, asbestos, nitrogen dioxide (NO₂), and carbon dioxide (CO₂). Exposure to high concentrations of these airborne pollutants can have harmful effects on human health (Selikoff et al., 1964; Koenig et al., 1987; Burger, 1990; Koren et al., 1992; Morawska et al., 2002; Larsson et al., 2004; Pöyhönen et al., 2004).

Over the last several decades, significant effort has been devoted to developing efficient air quality control devices. Air filtration technology has been used as a means to control IAQ (Liu, 2007). Although air filters can efficiently remove pollutants from the air stream, their overall performance depends on the type of filter. Using high-efficiency filters requires too much energy and is prohibitively expensive because of excessive airflow resistance (Fisk et al., 2002). To improve filtration efficiency without increasing airstream resistance, electrostatic air filtration technologies have been widely used in residential and industrial air

* Corresponding author.
Tel.: 82-2-958-5676; Fax: 82-2-958-5805
E-mail address: gnbae@kist.re.kr
† Corresponding author.
Tel.: 82-2-958-5718; Fax: 82-2-958-5805
E-mail address: jaehee@kist.re.kr
conditioning systems (Boelter et al., 1997; Grass et al., 2004). Common electrostatic technologies include electrostatic precipitation and electret filters.

Electrostatic precipitators (ESP) use electrostatic force to collect charged particles. They contain two components: electrostatic or discharge electrodes, and collecting electrodes. The two basic steps of electrostatic precipitation are charging the particles and then subjecting them to an electric field. The electrostatic migration velocity of the particles, which results from dielectrophoresis, causes them to deposit on a collection plate (Masuda et al., 1984; Navarrete et al., 1997; Chang et al., 2000; Jaworek et al., 2007). Although ESPs have a particle collection efficiency of >99% with low cost and pressure drop, they are less efficient at removing fine particles, and the back corona and insufficient particle charging at the inlet field result in poor ESP performance. Thus, ESP/fabric filter hybrids, high-voltage (HV) and/or low-voltage (LV) power sources, and HV sources with automatic voltage controllers have been proposed as alternatives (Grass et al., 2004; Gutierrez et al., 2007; Parker et al., 2009).

Electret filters are fiber filters consisting of dielectric materials with a quasi-permanent electrical charge (Gu and Schill, 1997). The filtration efficiency of electret filters is higher than that of conventional filters, especially for submicron-sized particles. Electret filters are manufactured by several methods, including electrostatic spinning, corona charging, triboelectric charging, and induction charging (Nifuku et al., 2001; Tsai et al., 2002). The particle capture mechanism of electret filters relies on a combination of conventional (impaction, interception, and diffusion) and electrostatic mechanisms (Coulombic and dielectrophoresis) (Emi et al., 1987). The filtration efficiency of electret filters is strongly affected by the charge state and size of the particles. According to research conducted by Romay et al. (1998), single-charged particles with diameters of 0.1–0.3 μm are filtered by a simultaneous combination of Coulombic attraction and dielectrophoresis. The Coulombic effect is dominant for particles with diameters <0.1 μm, and dielectrophoresis is dominant for particles with diameters >0.3 μm. In the case of neutral particles with diameters >0.1 μm, both mechanical filtering and dielectrophoresis were dominant. Polarized electrostatic air filters (PEAFs) and ion emissions on filters have also been studied as alternative filtration technologies (Hendricks et al., 1973; Nelson et al., 1978; Kim et al., 2000; Lee et al., 2004).

With regard to the filtration mechanism in PEAFs, research has revealed that when particles enter the electric field (EF), they experience a net force toward the region of highest EF intensity, which occurs at the fiber surface, and the attractive force increases with the EF. However, in conditions of >70% relative humidity, excessive current flow can lead to sparking. With regard to ion emissions on filters, research has revealed that air ions with high mobility are captured by the fibers. Thus, the creation of a macroscopic electric field affects the motion of incoming particles that are also charged by air ions, and unipolarly charged particles approaching the fiber surface are influenced by two forces that act in opposite directions (drag and Coulombic repelling forces). The difference between these forces causes some particle deceleration at the inlet stream of the filter, and this phenomenon leads to a reduction in particle penetration efficiency (Agranovski et al., 2006; Huang et al., 2008).

In recent years, outbreaks of epidemic diseases such as severe acute respiratory syndrome and a novel swine-origin influenza A (H1N1), along with the possibility of airborne pathogen transmission, have emphasized the importance of controlling airborne microorganisms (Lee et al., 2003; Smith et al., 2009; Tellier, 2009). A variety of control methods have been suggested, including thermal energy, ultraviolet irradiation, antimicrobial filters, and titanium dioxide catalysis (Ireland et al., 1993; Lin et al., 2002; Lee et al., 2006; Huang et al., 2010; Jung et al., 2011). Among these, antimicrobial filtration technology is considered a promising method because it can be readily applied to conventional air conditioning systems. Previous studies have shown that during the aerosol filtration process, silver or copper nanoparticles effectively inactivate bacterial aerosols, and that antimicrobial effectiveness is related to exposure time, relative humidity, and the concentration and size of the particles (Ji et al., 2007; Lee et al., 2010). With regard to improving antimicrobial effectiveness against nanoparticles, research conducted by Rangari et al. (2010) revealed that Ag/CNTs and Nylon-6/Ag/CNTs hybrid particles exhibited relatively significant antimicrobial activities compared with pure Ag particles. Also, Jung et al. (2011) demonstrated the applicability of antimicrobial hybrid nanoparticles after developing a simple method to fabricate Ag/CNTs hybrid nanoparticles and antimicrobial filters. However, given the harm caused by exposure to airborne nanoparticles, antimicrobial filters using natural products that are less harmful are being investigated. In some studies, essential oils extracted from natural products produced satisfactory inhibition in bacterial inactivation tests when used in indoor environments and ventilation systems (Pibiri et al., 2006), and antimicrobial filters coated with tea tree oil or natural nanoparticles inactivated over 90% of the bacteria on a filter surface within 5 to 30 min (Pyankov et al., 2008; Jung et al., 2011).

As mentioned above, with the increasing importance of IAQ, a variety of technologies such as antimicrobial filters, electrostatic precipitators, electret filters, and catalysis filters have been developed to remove harmful airborne pollutants. Some of these technologies have been used simultaneously in hybrid indoor air cleaners and ventilation systems. Although the combination of multiple technologies used simultaneously in a single system may be effective, it is unknown whether their hybrid use improves or reduces the performance of the individual technologies.

Therefore, the purpose of this study was to investigate changes in antimicrobial performance when antimicrobial filters and EFs are used simultaneously in one system. We designed an EF system and used it to investigate the effect of EF strength on natural product nanoparticle-deposited filters that were fabricated through a nebulization-thermal drying process. The filtration efficiency and antimicrobial effectiveness of the filters were determined when using various electric field strengths. The deposition structures
and profiles of bacteria aerosols in the filters were also investigated.

MATERIALS AND METHODS

Preparation of Antimicrobial Filters

In this study, we used an antimicrobial filter coated with *Sophora flavescent* natural-product nanoparticles. The perennial herb *S. flavescent*, which is a source of traditional herbal medicine, is widely distributed in northeast Asia and is known to potently inhibit pathogens (Kim et al., 2003; Kim et al., 2006; Young et al., 2008; Jung et al., 2011c). Freeze-dried *S. flavescent* plant ethanolic extract was provided by the Functional Food Center at the Korea Institute of Science and Technology, Gangneung Institute. To prepare antimicrobial filters with natural-product nanoparticles, 0.25 g of *S. flavescent* ethanolic extract powder was mixed with 40 mL of 99% ethanol (111,727; Merck KGaA, Darmstadt, Germany) and sonicated for 10 min. The liquid was filtered through a cellulose acetate membrane filter with a 0.45-µm pore size (National Scientific Co., Rockwood, TN) to remove insoluble residues. Fig. 1(a) shows the production scheme for the natural product nanoparticle-deposited filters. The filtered *S. flavescent* extract (20 mL) was loaded into a one-jet Collison nebulizer (BGI Inc., Waltham, MA, USA), which sprayed the liquid suspension as droplets. The *S. flavescent* nanoparticles were produced as the droplets passed through an active carbon absorber and a thermal glass quartz tube furnace (inside temperature, 75°C) to remove ethanol vapor. The size, number, concentration, and morphology of generated nanoparticles were measured using a scanning mobility particle sizer system that included a differential mobility analyzer (DMA 3081; TSI Inc., Shoreview, MN), a condensation particle counter (CPC 3776; TSI Inc.), and a Nova NanoSEM (NanoSEM 200; FEI Co., Hillsboro, OR, USA). The diameters of the natural product nanoparticles had a log-normal distribution, with a peak diameter of 118 nm, a geometric mean diameter of 122 nm, and a geometric standard deviation of 1.61 nm (Figs. 1(b) and 1(c)). Their morphology was mostly non-coalesced and spherical. The nanoparticles were deposited continuously onto a polyurethane fiber filter (fiber diameter, 2 µm; thickness, 0.6 mm). Three particle deposition times between 60 and 360 s were used.

Test Bacteria

*Staphylococcus epidermidis* (Korean Collection for Type Cultures KCTC 1917, Biological Resource Center, Korea) was selected as a test bacterium. *Staphylococcus epidermidis*, a gram positive bacterium, is found on the skin and mucous membranes of humans and animals. Although *S. epidermidis* is not usually pathogenic, patients with compromised immune systems are often at risk for developing an infection. In this study, *S. epidermidis* was incubated in a nutrient broth medium (Becton Dickinson, Franklin Lakes, NJ, USA) at 37°C. When the optical density of the bacterial solution reached 0.8 at 600 nm, the bacteria were harvested by centrifugation and washed three times with distilled water. The concentration of the bacterial suspension was approximately $10^8$ colony forming units (CFU)/mL. A 30-mL aliquot was loaded into a six-jet Collison nebulizer (BGI Inc.).

Configuration of the EF system

Fig. 2 presents the design of the system used to apply an EF to the antimicrobial filter. The system consisted of a high-voltage power supply, an EF exposure area, and polytetrafluoroethylene tubes. The EF exposure area was assembled using two 0.1-cm-thick metal meshes with diameters of 2.5 cm. Nonconductive plastic supports maintained a distance of 0.3 cm between the inner sides of the two meshes, and the filter was loaded between the plastic supports. The metal mesh at the front side of the filter was connected to the power supply, which could provide up to 10 kV of positive voltage (DC +15kV; Korea Switching, Korea), and the mesh at the back side was grounded. The EF strength (E) was controlled by adjusting the power supply and was calculated using the following equation:

$$E = \frac{U}{d},$$

where $U$ is the applied voltage and $d$ is the distance between the electrodes.

![Fig. 1](image_url). (a) Experimental setup to fabricate antimicrobial filters. (b) Size distribution of natural-product nanoparticles. (c) SEM image of natural-product nanoparticles on a filter.
where \( U \) is the voltage applied between the two meshes and \( d \) is the distance between the inside sides of the two meshes. Four different electric field strengths were used, ranging from 0–7.7 kV/cm.

### Filtration Efficiency

The experimental setup for testing the effect of an EF on the antimicrobial filter consisted of a clean air tank, a nebulizer, a diffusion dryer, a mass flow controller (MFC), a HEPA filter, and an electric field system (Fig. 3). Droplets containing bacteria were aerosolized by a six-jet Collison nebulizer (BGI Inc.), moisture was removed while the droplets passed through a diffusion dryer, and the bacterial aerosols were deposited on the filter, which was located in an EF system. To determine the filtration efficiency of the antimicrobial filter, the size distribution and concentration of bacterial aerosols were measured at the inlet and outlet of the filter using an aerodynamic particle sizer (APS 3321; TSI Inc.). Filtration efficiency was calculated using the following equation:

\[
\eta = 1 - \frac{C_{\text{outlet}}}{C_{\text{inlet}}},
\]

where \( C_{\text{inlet}} \) and \( C_{\text{outlet}} \) represent particle concentrations (particles/cm\(^3\) air) of the bacteria aerosols measured at the filter inlet and outlet, respectively.

The net charge of \( S. \) epidermidis aerosols was measured using an aerosol electrometer (3086; TSI Inc.) and the average elementary charge of the bacteria was calculated using the following equation:

\[
n_p = \frac{I}{e \times N \times q_s},
\]

where \( I \) represents the electrical current (pA), \( e \) represents the elementary unit of charge (1.602 \times 10^{-19} \text{ Coulombs}), \( N \) represents the particle number concentration (particles/cm\(^3\)), and \( q_s \) represents the sampling flow rate (cm\(^3\)/sec).

There are fundamental limits on the amount of charge that can be acquired by an aerosol particle of a given size, and this amount increases with particle size. Because the bacterial aerosols used in this study had a polydisperse size distribution, we calculated the amount of charge per bacterial aerosol as the average elementary charge.

### Test of Antimicrobial Filter

When determining the effect of an EF on the antimicrobial filter, bacteria aerosols were generated with an air flow of 5 L/min, and to ensure that each filter had identical deposition concentrations, bacteria deposition time on the filter was adjusted depending on the concentration of the aerosol and filtration efficiency. An EF was applied to the filter while the bacteria aerosols were being deposited on the antimicrobial filter. After deposition, the bacteria had a residence time of 10 min on the filter without exposure to an EF. Then each filter was placed in 5 mL of phosphate-buffered saline (PBS; pH 7.4) with 0.01% Tween 80 and sonicated in a sonic bath for 10 min to ensure that the bacteria were transferred from the filter to the PBS. The bacteria were separated from the remaining natural-product nanoparticle by centrifugation, and a 1-mL sample of the bacterial suspension was used to calculate the physical extraction efficiency of the filter for bacteria, using a fluorescence microscopic method and the ImageJ program (ImageJ; http://imagej.nih.gov/ij/). The remainder of the bacterial suspension was serially diluted, plated onto nutrient agar (Becton Dickinson), and incubated at 37°C for 24 h. The colonies that grew on the plates were counted.

Relative microbial survival (RMS) was calculated as
Fig. 3. Experimental setup to test the effect of an electric field (EF) on the antimicrobial filter.

follows (Jung et al., 2011b):

$$\text{MSCF} = \frac{\text{CFU}_{\text{control}}}{N_{\text{control}}},$$  \hspace{1cm} (4)

$$\text{MSAF} = \frac{\text{CFU}_{\text{antimicrobial}}}{N_{\text{antimicrobial}}},$$  \hspace{1cm} (5)

$$N_{\text{control}} \text{ or } N_{\text{antimicrobial}} = \frac{C_{\text{inlet}} \times Q_{\text{sampling}} \times \eta \times \xi_{\text{extraction}}}{V_{\text{extraction}}},$$  \hspace{1cm} (6)

$$\text{RMS} = \frac{\text{MSAF}}{\text{MSCF}},$$  \hspace{1cm} (7)

where MSCF is microbial survival from the control filter and MSAF is microbial survival from the antimicrobial filter; CFU\textsubscript{control} and CFU\textsubscript{antimicrobial} are the concentrations (CFU/mL of suspension) of colonies cultured from the control and antimicrobial filters, respectively; $N$ is the number of bacteria particles/mL of extraction suspension that were plated on the agar culture medium; $Q_{\text{sampling}}$ is the total airflow sampling volume; and $\xi_{\text{extraction}}$ is the physical extraction efficiency of the filter for bacteria, which is defined as the ratio between the number of particles transferred from the filter to the extraction liquid and the number of particles removed from the airflow by the filter. Finally, as shown in Eq. (6), the microbial survival from each antimicrobial filter was normalized to the microbial survival from the control filter to calculate the RMS.

**Deposition Profile of Bacteria Inside a Filter**

To investigate the deposition profile of bacteria inside filters exposed to an EF of 0 or 7.7 kV/cm, filters were constructed by overlapping nine layers of polyester fiber filter (fiber diameter, 17 µm; thickness, 0.068–0.07 mm). Using a microbalance (Micro MYA 5/F; Radwag, Radom, Poland), each filter layer was weighed before and after being coated with natural product nanoparticles, and again after the deposition of bacteria.

The deposition profile throughout the whole depth of the filter was calculated as follows:

$$R = \frac{m_{\text{after}} - m_{\text{before}}}{m_{\text{after}} - m_{\text{before}}},$$  \hspace{1cm} (8)

where $R$ is the ratio between the mass of bacteria deposited on a specific layer and the bacterial mass summed over all of the layers; $m_{\text{before}}$ and $m_{\text{after}}$ are the masses of a layer before and after particle deposition, respectively.

**RESULTS AND DISCUSSION**

The filtration efficiency of filters under various EF conditions was tested using S. epidermidis aerosols that had a log-normal aerodynamic size distribution, a peak diameter of 0.898 µm, a geometric mean diameter of 0.914 µm, and a geometric standard deviation of 1.17. The total concentration of bacteria in the aerosols ranged from approximately $16.4 \times 10^3$ to $16.8 \times 10^3$ particles/cm$^3$.

In the EF system both without a fiber filter and with a control fiber filter inserted between the two metal meshes, the filtration efficiency increased with an increase in EF strength (Table 1). Compared with the efficiency at 0 kV/cm, the efficiency at 7.7 kV/cm increased by 13.6% for the EF system without a filter and by 3.7% for the system containing a control filter. Previous studies have indicated that microorganisms carry high electrical charges in a waterborne or airborne state and that the electrical charge on the surface of a bacterial cell is largely attributable to the kinds of ionizable groups on the cell surface and their spatial distribution (Sherbet et al., 1973; Mainelis et al., 2002). The magnitude of the electrical charge carried by airborne bacteria depends on the dispersion method (Mainelis et al., 2001) and can reach a maximum of 13,000 elementary charges. In the present study, the aerosolized bacteria carried their natural charges plus electrical charges induced by the spray process (Hendricks, 1973). The average elementary charge of the S. epidermidis bacteria aerosols was 570 (negative). Thus, bacterial aerosols were attracted by the electric force while they passed through the EF system, and the amount of bacteria removed increased with an increase in EF strength.
Table 1. Filtration efficiency of the electric field (EF) system with and without antimicrobial filters under different EF strengths (n = 3).

<table>
<thead>
<tr>
<th>EF Strength (kV/cm)</th>
<th>Inlet ($\times 10^3$ particles/cm$^3$)</th>
<th>Electric field (EF) system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without filters</td>
<td>With control filter</td>
</tr>
<tr>
<td></td>
<td>Outlet ($\times 10^3$ particles/cm$^3$)</td>
<td>$\eta$ (%)</td>
</tr>
<tr>
<td>0</td>
<td>16.70 ± 0.10$^b$</td>
<td>15.76 ± 0.15 5.62</td>
</tr>
<tr>
<td>4</td>
<td>16.50 ± 0.17</td>
<td>14.86 ± 0.25 9.93</td>
</tr>
<tr>
<td>6</td>
<td>16.53 ± 0.25</td>
<td>14.10 ± 0.01 14.7</td>
</tr>
<tr>
<td>7.7</td>
<td>16.53 ± 0.05</td>
<td>13.36 ± 0.15 19.2</td>
</tr>
</tbody>
</table>

$^a$ 3-min nanoparticle-deposited filter.
$^b$ Filtration efficiency.
$^c$ Average ± standard deviation $\times 10^3$ particles/cm$^3$.

When the EF system contained an antimicrobial filter, a relationship between EF strength and filtration efficiency could not be identified. This was likely because the original filtration efficiency of the antimicrobial filter for bacterial aerosols was so high (> 99%) and non- or relatively weakly charged bacterial aerosols were hardly affected by EF strength. Fig. 4 shows the deposition profiles of bacteria and naturally produced nanoparticles inside a layered filter made by overlapping nine layers of polyester fiber filter. Approximately 37% of the total natural-product nanoparticles were deposited at depths of 0 to 68 µm (first layer), and the concentration of deposited particles declined exponentially with increasing filter depth. These results are in agreement with the experimental results of Thomas et al. (2001) with monodispersed particles with diameters of 0.18 and 0.31 µm. With an EF of 0 kV/cm, about 91% of the total bacteria were deposited at depths of 0–200 µm (first to third layers), with the highest concentration in the first layer (depth, 0–68 µm). The deposition profile of bacteria at 7.7 kV/cm differed from that at 0 kV/cm. In an EF of 7.7 kV/cm, approximately 68% of the total bacteria were deposited at depths of 0–68 µm, and the concentration decreased significantly with increasing depth. Approximately 10% of the total bacteria were deposited between 200 and 610 µm (third to ninth layers).

It is well known that an EF applied across a fibrous filter improves the particle collection efficiency of the filter (Zebel, 1965; Wu et al., 1999; Wang, 2001). Thus, it can be concluded that the increased concentration of bacteria deposited on the first layer of the filter is attributable mainly to the electric force between the bacterial aerosols and the first layer of filter fibers. As a result of the change in the deposition profile, the physical extraction efficiency for bacteria ($\xi_{\text{extraction}}$) increased by 25%.

Based on previous research (Payatakes et al., 1976; Bhutra et al., 1979; Payatakes et al., 1980), the process of bacterial deposition in a fibrous filter can be classified into four consecutive stages depending on deposition time or concentration: 1) deposition on a clean fiber, 2) virtually unhindered growth of dendrites, 3) further growth and intermeshing of neighboring dendrites, and 4) internal cake formation. In this study, the surfaces of the control and antimicrobial filters were observed using SEM (NanoSEM200; FEI Co.) to confirm the bacterial deposition structure. The particle deposition patterns were clearly distinguishable between 7.7 and 0 kV/cm (Fig. 5). Contrary to the results at 0 kV/cm (Figs. 5(b) and 5(e)), particles formed dendrites on filter fibers exposed to 7.7 kV/cm (Figs. 5(c) and 5(f)), which matched the stage of virtually

![Deposition profile of natural product in antimicrobial filter](image1)
![Deposition profile of bacteria in antimicrobial filter at 0 kV/cm](image2)
![Deposition profile of bacteria in antimicrobial filter at 7.7 kV/cm](image3)

Fig. 4. Deposition profiles of natural-product nanoparticles and bacteria in control and antimicrobial filters. Error bars indicate standard deviations (n = 2).
Fig. 5. SEM images of control and antimicrobial filters with *S. epidermidis* bacteria with EF strengths of 0 and 7.7 kV/cm. a: Control filter; b: Antimicrobial filter.
unhindered dendrite growth. Previous studies (Nielsen and Hill, 1976; Auzerais et al., 1983; Park and Park, 2005) have demonstrated that particle dendrites form on fibers in a pattern that is parallel to the direction of the EF applied across the filter. Particle deposition at 0 kV/cm corresponded to the process of deposition on a clean fiber. Moreover, the concentration of particles deposited on the first fiber layer of the filters was higher at 7.7 kV/cm than at 0 kV/cm. The concentrations in the control filters were approximately 1.47 and 2.62 particles/µm² fiber at 0 and 7.7 kV/cm, respectively, and the respective concentrations in the antimicrobial filters were about 1.36 and 3.03 particles/µm² fiber. Therefore, the change in bacteria deposition structure and the increased bacterial concentration in the first filter layer were due to the EF applied across the filter.

Under each of the two EF strengths, the inactivation efficiency of the antimicrobial filter increased with an increase in the antimicrobial particle concentration (Fig. 6). However, the intensity of the antimicrobial reaction differed among filters depending on the nanoparticle deposition time. At 0 kV/cm, approximately 97.4% of *S. epidermidis* bacteria were inactivated on a filter with a nanoparticle deposition time of 1 min, and 99.9% were inactivated on a filter with a nanoparticle deposition time of 6 min. At 7.7 kV/cm, 74.4% and 89.9% of the bacteria were inactivated on 1-min and 6-min nanoparticle-deposited filters, respectively. In accordance with the findings of Ji et al. (2007) and Pal et al. (2007), the contact surface area between bacteria and antimicrobial particles was a significant factor for the inhibitory effect, and inhibition was influenced by factors that affected the contact surface area, including the size, concentration, and shape of particles. At an EF of 7.7 kV/cm, the relative increase in bacterial concentration and dendrite formation in the first layer of the antimicrobial filter would have reduced the surface contact area between the bacteria and natural-product nanoparticles, which could account for the reduction in the antimicrobial effect.

Additionally, it is likely that the EF itself did not affect the inactivation of *S. epidermidis* bacteria. Although a previous study reported that the culturability of *P. fluorescens* was reduced upon exposure to an EF > 5 kV/cm for 15 min (Yao et al., 2005), the bacteria used in the present study had more resistance to environmental stresses than *P. fluorescens*, and the EF exposure time for *S. epidermidis* was less than 4 min.

**CONCLUSIONS**

This study demonstrated that the filtration efficiency of the EF system for *S. epidermidis* bacterial aerosols increased with an increase in EF strength. However, an increase in EF strength reduced the antimicrobial performance of filters because it increased the concentration of bacteria deposited on the first layer of the filter, thereby reducing the surface contact area between the bacteria and natural-product nanoparticles. The airborne bacteria used in this study were strongly charged during the aerosolization process. In a natural environment, it is likely that the electrical charges on airborne microorganisms will be affected by free atmospheric ions or natural radiation. In the normal atmosphere, cosmic rays and radioactive elements produce bipolar ions. Thus, airborne bacteria in a natural environment may have a smaller charge than the aerosolized bacteria in our study. Therefore, compared with the results of the present study, the EF strength may have a weaker effect on the performance of antimicrobial filters under real-world conditions. This study provides valuable information for the development of a hybrid air purification system that serves various functions and can be used in indoor environments.

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