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Polymersomes as virus-surrogate particles for evaluating the performance of air filter materials

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The development of antivirus air filter materials has attracted considerable interests due to the pandemic of coronavirus disease 2019 (COVID-19). Filtration efficiency (FE) of these materials against virus is critical in the assessment of their use in disease prevention. Due to the high cost and biosafety laboratory required for conducting research using actual virus samples, surrogates for virus are commonly used in the filtration test. Here, we explore the employment of polymersomes (polymeric vesicles) as a new type of surrogate. The polymersomes are hollow shell nanoparticles with amphiphilic bilayer membranes, which can be fabricated in nanosized, and possess similar size and structural features to virus. The performance of commercial KN95 mask and surgical mask with micro-sized fibers, and electrospun polyvinylidene fluoride (PVDF) and polyacrylonitrile (PAN) nanofibers were chosen to be evaluated. The filtration tests against fluorescent-labeled virus-surrogate particles (VSPs), i.e. polymersomes, allowed the determination of the FE of the multilayerel filter materials in a layer-specific manner. The results suggested the importance of hydrophobicity in designing the nanofibrous filter materials. The employment of VSPs in filtration performance evaluation allows a cost-effective way to estimate the FE against virus, providing guidance on future development of air filter materials.

Introduction

Since the end of 2019, the coronavirus disease 2019 (COVID-19) has posed severe threats on the global health, resulting in more than 452 million confirmed cases and 6 million deaths worldwide, as of March 12, 2022 [1]. The disease is caused by a new form of coronavirus named Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2) [2,3]. Same as other respiratory viruses, the SARS-CoV-2 viruses transmit via contact or airborne pathways [4]. In the latter pathway, an infected person expels respiratory virus-containing droplets, and if these droplets were inhaled by other persons within short distance, it would cause infection. Commonly, the droplets smaller larger than 5 μm also refer to as aerosols. The aerosols can transport with the airflow for longer distance, while the viruses in the aerosols will sustain and remain viable for hours, leading to long-range transmission if they were inhaled by others [5,6]. Recently, increasing evidence suggests that the airborne pathways appear to be the primary pathway for the transmission of SARS-CoV-2 [7–10].

In order to prevent the virus transmission via airborne pathways, extensive efforts have been made to develop air filter
materials for applications such as face masks as well as heating, ventilation, and air-conditioning (HVAC) systems [11–13]. One of the key properties of these filter materials is their filtration efficiency (FE) against virus, which refers to the percentage of viruses that would be captured by the filter in a filtration test. However, the data of FE against actual viruses is still limited, as filtration test using actual virus samples requires higher expenditure and certified biosafety laboratory [14]. A common strategy to address this issue is to conduct filtration test against surrogates such as sodium chloride (NaCl) particles, polystyrene latex spheres, and oil aerosols [15,16]. These surrogates could be fabricated into various sizes ranging from tens of nanometers to several micrometers in order to mimic virus or virus-containing aerosols [17,18]. While the test results could be used to understand the dependence of filtration performance on the particle size, however, it remains unknown to what extent the differences in composition, morphology, and other properties between the currently available surrogates and the virus would affect the test results. Alternative surrogate possesses properties closer to virus is worth to be explored.

In last three decades, polymersomes, or polymeric vesicles [19], which are based on the self-assembly of amphiphilic block-copolymers in water, have attracted lots of attention due to promising applications in nanomedicine field, e.g. new generation (targeted) drug delivery vehicles [20–23]. Polymersomes are hollow shell structure that assembled from amphiphilic block copolymers [24–28]. As their sizes can be controllably fabricated into nanoscale (e.g. ~100 nm) and they are composed of polymeric bilayer membranes similar to the enveloped viruses that are surrounded by bilayer phospholipid membranes, polymersomes have been considered as promising models for virus mimicry [29–31]. Moreover, with the improvement of the fabrication techniques in recent years, polymersomes of various shapes, surfaces, and other structural features can be produced [32,33], expanding their potential to mimic virus of diverse structures [34]. In fact, there have already been studies using virus-minicking polymersomes in biomedical applications such as controlled drug delivery [35,36].

In this study, we employed polymersomes as virus-surrogate particles (VSPs) for filtration performance evaluation of air filter materials. Nile red (NR)-encapsulated VSPs made of methoxy-poly(ethylene glycol)-block-poly(D,L-lactic acid) (mPEG-b-PLA) diblock copolymer were fabricated. The VSP solution was sprayed by either a sprayer or an ultrasonic nebulizer to mimic the respiratory droplets freshly emitted from patients or the virus-laden aerosols suspended in the air, respectively. The droplets or aerosols were introduced into a custom-made system for filtration, after which the NR dyes were eluted from the filter materials and the FE was determined based on relative fluorescence intensities. KN95 mask, surgical mask, polivinylidene fluoride (PVDF) nanofiber and polyacrylonitrile (PAN) nanofiber were chosen as representative filter materials to be tested. The study on the filtration performance was conducted mainly in three steps. First, the filtration performances of PVDF and PAN nanofibers were preliminarily tested against VSP-laden droplets for the selection of a collector layer implemented in the filtration system. Second, the FE of all filter materials were systematically determined VSP-laden droplets and aerosols. Third, to understand if the low FE of PAN nanofiber is related to its higher wettability, the VSP solution was further adapted to contain Amino G acid (AGA) fluorescent dye for water tracing [37]. To our knowledge, the employed VSP model is the first reported model used in the filtration experiments that resemble the size and structure of the virus. The employment of VSP in filtration performance evaluation enables not only a rapid and efficient estimation on the FE against virus but also a way to get insights into the factors affecting the FE.

**Experimental section**

**Materials**

mPEG_{5000}-b-PLA_{12000} was purchased from Jinan Daigang Biomaterial Co., Ltd. PVDF polymer (Mn ~ 600 kDa), PAN polymer (Mn ~ 150 kDa), tetrahydrofuran (THF, HPLC grade), methanol (MeOH, General-Reagent), N,N-dimethyformamide (DMF, General-Reagent), and acetone (Acc, General-Reagent) were purchased from Aladdin. NR and AGA dyes were obtained from Tansool. PVDF and PAN polymers were dried at 50°C under vacuum for 48 hours before use. All other chemicals were used as received unless otherwise stated.

KN95 mask (Kingfa Sci.&Tech. Co., Ltd.), disposable surgical mask (Kingfa Sci.&Tech. Co., Ltd.), and handheld ultrasonic nebulizer (Yuwell-Jiangsu Yuyue medical equipment & supply Co., Ltd.) were purchased from Jingdong Mall (an online shopping platform) (https://www.jd.com/). Each mask was conditioned for a minimum of 4 hours at a temperature of 25 ± 2°C and relative humidity of 75% ± 10% prior to testing.

**Preparation and characterization of VSPs**

NR-encapsulated VSPs were prepared by using a solvent switch method. First, NR solution (1 mg/mL) was prepared by dissolving in THF solution. Second, mPEG-b-PLA copolymer (20.0 mg) was dissolved in 200 μL 3:1 (v/v) THF:MeOH, and 20 μL Nile red solution (1 mg/mL) was added into the polymer solution. Then, the mixed solution was added dropwise to phosphate buffered saline (PBS, pH 7.4, 10 mL) under vigorous mechanical stirring. Finally, the solution was dialyzed against PBS (5 times, 1.0 L) for 48 hours using a dialysis bag with a molecular weight cut-off of 3000 Da. For visualization of the water content of the VSP solutions in the confocal microscopy, additional 1 mg/mL AGA fluorescent dye would be introduced into the VSP solution before spraying. The above experiments were carried out under dark conditions.

The morphology of the VSPs was characterized using transmission electron microscopy (TEM). Briefly, 5 μL of VSP sample was placed on copper grid for 1 minute. Then, the sample was blotted with a filter paper and dried for 1 minute. The grid was then immersed into a 20 μL drop of 2% phosphotungstic acid (PTA) for 15 seconds. The excess PTA solution was blotted with filter paper, and the grid was dried in the air. Images were acquired on a JEOL JEM1400 microscope (Japan) at an accelerating voltage of 120 kV.

Hydrodynamic diameter and polydispersity (PDI) of the VSP were determined by dynamic light scattering (DLS) using a NanoBrook Omni Particle Size Analyzer (Brookhaven Instruments) in a backscattering angle (173°). The concentration
of the VSP was prepared to be ~0.2 mg/mL. The data was analyzed using the built-in Particle Solutions Software (v2.6).

Fabrication and characterization of nanofibers
The nanofibers were fabricated by electrospinning methods using homemade apparatus [38,39]. The polymer solutions were prepared by dissolving 12% w.t. PVDF powder in 6:4 (v/v) DMF:Ace solution and 10% w.t. PAN powder in DME, respectively. The as-prepared solutions were added into 10-mL syringes capped with 20-G metal needles and pumped out by using a micro syringe pump. The feeding rate of the solution and the direct voltage applied to the tip of needles was at 1 mL h⁻¹ and 20 kV, respectively. The resulting nanofibers were deposited on an aluminum foil covered roller at a distance of 25 cm and rotating at a speed of 30 rpm. The fabrication process was conducted under fixed conditions with temperature of 25 ± 2°C and humidity of 35% ± 5%. The deposition time was carefully adjusted to control the base weight of the nanofibers.

The morphology of the filter materials was characterized using transmission electron microscopy (SEM) on a JEOL JSM-7900F microscope (Japan). To enhance the signal quality, samples were firstly sputtered with a layer of platinum before examination. The diameter distribution of fibers was analyzed by ImageJ software.

The water contact angle (WCA) were measured in air by using an OCA 20 contact-angle system (Dataphysics, Germany). The fiber samples to be tested were amount on glass slides. The average WCA measurements were conducted by dropping 5 μL droplets on five different positions of the same sample respectively.

The basis weight of the filter materials was measured using an electronic balance (M204E, Mettler-Toledo Group, Switzerland). Fibers were cut into rectangular specimens with dimensions of 4 × 4 cm. Basis weight (g·m⁻²) is calculated by dividing the weight of a filter material by its area.

The gas adsorption measurements were carried out using 3H-2000PM Specific Surface & Micropore Analyzer from BeiShiDe Instrument (China). The Brunauer-Emmet-Teller (BET) analysis was performed at relative vapor pressures of 0.01 to 1 (P/P₀). The pore-size distribution was analyzed using Barret-Joyner-Halenda (BJH) method.

Design of the filtration performance investigation system
The schematic representation of the experimental setup is shown in Fig. 1. A sprayer was used to spray the VSP solution into droplets of various sizes ranging from micrometers to millimeters, mimicking the virus-laden droplets freshly produced from an infected person. For simplicity, this type of the sprayed VSP solution will be termed as VSP-laden droplets. Alternatively, the VSP solution was sprayed by an ultrasonic nebulizer to generate aerosols to mimic the virus-laden aerosols, and this type of the sprayed VSP solution will be termed as VSP-laden aerosols. The morphology of the VSPs upon sprayed by ultrasonic nebulizer will also be examined. The VSP-laden droplets or aerosols will be introduced into a custom-made test chamber. The filter materials...
(6 cm²) to be tested and a collector layer were placed in the middle of the test chamber by a sample holder. Note that material of the collector layer would be selected based on the results in this study. The distance between the sprayer and the filter materials was kept at 15 cm, and ∼ 200 μL of VSP solution was sprayed in a single filtration experiment. A continuous inlet air flow of 5 cm/s flow rate controlled by a glass rotameter (LZB-3WB, Shuanghuan, China) and last for 1-hour duration was introduced in the chamber for each experiment. A differential pressure gauge (Meokon, China) was connected to the downstream of the sample chamber for measurement of the pressure drop (Δp). All tests are conducted under dark conditions at temperature of 25 ± 2°C and relative humidity of 75% ± 10%.

**Determination of the FE and the quality factor (QF)**

The FE refers to the ratio of VSPs captured by the filter materials. To determine of the FE, the filter materials and the collector layer were collected from the test chamber after the filtration experiments, and each piece of the material was eluted by soaking in 2 mL 3:7 (v/v) THF:H₂O for overnight. The fluorescence intensities of the eluents were measured by using a fluorometer (FL-320, Gangdong, China). The excitation wavelength and emission wavelength were set to 520 nm and 635 nm, respectively.

The FE was determined using the following equation:

\[
FE = \frac{I_f}{I_f + I_c} \times 100\%
\]

where \(I_f\) and \(I_c\) were the fluorescence intensities of eluents for filter fibers and collector, respectively. Each experiment was repeated for three times, and an average value was taken.

The QF of the filter materials is another indicator of their performance, which can be calculated using the following equation [40]:

\[
QF = -\frac{\ln (1 - FE)}{\Delta p}
\]

where \(\Delta p\) is the pressure drop of the filter material.

**Confocal microscopy imaging**

Confocal microscopy imaging was carried out on a Zeiss CLSM 880 confocal microscope (Germany). To visualize the VSPs and optionally trace the liquid water content on the fibers, the fiber sample was amount on a glass slide and sealed with a coverslip. To estimate the size of the aerosols, the solution was sprayed on a Petri dish with hydrophobic surface and imaged by a confocal microscopy immediately. The AGA and NR dyes were excited with the laser wavelengths of 405 nm and 488 nm, respectively.

**Results and discussion**

The VSPs and the sprayed VSP solution

The central aim of this study has been to demonstrate the feasibility of employing VSPs in the filtration test. Fig. 2a showed the representative TEM image of the fabricated VSP, which appeared to be of spherical shape. The DLS measurement showed an average size of ∼114 nm (Fig. 2b). The shape and size of the VSP are similar to those of the SARS-CoV-2, which are also spherical and sized from 60 to 140 nm [3].

The VSPs solution was sprayed by the sprayer and ultrasonic nebulizer to mimic the virus-laden droplets and virus-laden aerosols, respectively. Upon spraying, the VSPs were found to remain stable with no apparent changes in morphology and size (Fig. S1a, b). The sprayed solution from the sprayer was expected to have random size ranging from millimeter to nanometer scale. To estimate the size of aerosols generated from the nebulizer, the liquids were collected on Petri dish and visualized by confocal microscopy immediately (Fig. S1c). As expected, VSP-containing liquids with an average size of 4 μm ± 1 μm were observed, confirming that the sprayed VSP solution from the nebulizer was suitable to mimic the virus-laden aerosols.

The filter materials

Masks are typical examples of filter materials which are used for personal protection. N95 mask and surgical mask are two common multilayered masks. The masks certified as N95 grade are tested according to the 42 CFR 84 standard of National Institute of Occupational Safety and Health (NIOSH), which requires a minimum FE of 95% for 0.3 μm NaCl particles. One of the tested masks certified as KN95 grade is tested according to Chinese standard GB2626 with the same FE requirement of 95% for 0.3 μm NaCl particles [41]. The disposable surgical masks in China are
Representative SEM images of (a₁-a₄) the outer NW layer, the cotton layer, the meltblown layer, and the inner NW layer of the KN95 mask, (b₁-b₄) the outer NW layer, the meltblown layer, and the inner NW layer of surgical mask, (c) PVDF nanofiber, and (d) PAN nanofiber. On the NW layers of the masks, the thermal bonding sites produced during the manufacturing process were indicated by yellow arrows.

(a) Representative confocal images of the two layers of PVDF nanofibers in the filtration test. (b) Fluorescence measurement of the eluents from the two layers of PVDF nanofibers. (c) Representative confocal images of the two layers of PAN nanofibers in the filtration test. (d) Fluorescence measurement of the eluents from the two layers of PAN nanofibers.
tested according to Chinese standard YY/T0969, which requires FE against bacteria > 95% [42]. The optical images of the purchased masks were shown in Fig. S2. The morphology of the fibers in the masks was examined by SEM (Fig. 3a, b). The KN95 mask is composed of four layers, including an outer non-woven (NW) polypropylene (PP) layer, a poly(ethylene terephthalate) (PET) cotton layer, a meltblown PP layer, and an inner NW PP layer. The surgical mask is composed of three layers, including an outer non-woven layer, a meltblown layer, and an inner NW layer, which are all made up of PP. The diameters of the fibers in KN95 and surgical masks were all in micrometer scale ranging from 2-26 μm (Table S1), which were in the same magnitude to the reported values [43]. These micrometer-sized fibers provide the air purification function through two major mechanisms including mechanical mechanisms (interception, physical sieving, inertial separation, and diffusion) and electrostatic mechanism [44]. However, with the attenuation of static electricity during wearing or cleaning, the meltblown fibers gradually lost the capability of capturing small particles due to the relatively larger pore sizes. In this regards, nanofibers are considered as promising alternative filter materials for long-term use [45]. The PVDF and PAN nanofibers are two most commonly used nanofiber scaffolds for air filtration due to their good chemical and mechanical properties. The as-spun PVDF and PAN nanofibers were shown in Fig. S2 and characterized by SEM (Fig. 3c, d) and their diameters were found to be ranged from ~200-300 nm (Table S1). All the fiber inside the masks and the nanofibers exhibit randomly oriented alignment. The other parameters of the fibers including the base weight, WCA, and the pressure drop were measured and summarized in Table S1. Generally, the nanofibers have much lower base weight than a layer of the multilayered masks, while their pressure drops were comparable with the masks. Besides, it was found that the PVDF nanofiber is hydrophobic with a WCA of 138°, while PAN nanofiber is hydrophilic with a WCA of 41° as shown in Fig. S3. To understand the pore features of the nanofibers, the average pore diameter and BET surface area of PVDF and PAN nanofibers were given in Table S1, and the pore diameter distributions were shown in Fig. S4.

Selection of the collector layer
As mentioned in the Materials and methods Section, for determination of the FE, it is required to install a collector layer in the filtration system to capture the VSPs passed through the filter materials (Fig. 1). The nanofibers were expected to have higher FEs
than the fibers in the masks, therefore they were tested first for the selection of collector layer. Two layers of PVDF nanofibers or PAN nanofibers were tested against VSP-laden droplets. Confocal microscope was used to visualize the captured VSPs. As shown in the Fig. 4a, the NR-encapsulated VSPs were present on the first PVDF nanofiber layer, while no fluorescence signal was observed on the second PVDF nanofiber layer, suggesting that almost all the VSP were captured by the first layer. Meanwhile, the fluorescence intensities of eluted VSPs from the PVDP nanofibers were measured (Fig. 4b), which showed that the NR dyes were only present on the first PVDF layer, consistent with the observations by confocal microscope.

The testing was also carried out for two layers of PAN nanofiber. Unexpectedly, the VSPs were present on both PAN nanofiber layers (Fig. 4c). The eluents from both layers also showed characteristics peaks of NR dye (Fig. 4d). Taken these observations together, the VSPs had penetrated the first layer of PAN nanofiber during the filtrations. Therefore, PVDF nanofibers was chosen as the collector layer to be installed in the filtration test.

**Determination of the FE**

The FEs of all filter materials against VSP-laden droplets and aerosols were determined (Fig. 5a, b). The KN95 mask had an average FE ≥ 99% against either VSP-laden droplets or aerosols, while the surgical mask showed an average FE of 99% against VSP-laden droplets, and slightly lower average FE of 97% against VSP-laden aerosols. For the nanofibers, the PVDF nanofiber showed high FE ≥ 99% against VSP-laden droplets and aerosols, while the PAN nanofiber showed FE of 65% against VSP-laden droplets and 75% against VSP-laden aerosols, respectively.

The high FEs of the KN95 mask and the surgical mask (≥ 97%) were reasonable as these masks were certified based on the filtration test against NaCl particles or bacteria. Their calculated quality factors were also provided in Table S1, which were of the same magnitude as previously reported values [40]. The relative fluorescence intensities of each layer were extracted to understand their contributions on the overall FEs. As shown in Fig. 5c, when tested against the VSP-laden droplets, average around 99% VSP were captured by the first two layers of KN95 mask, i.e. the outer NW layer and the cotton layer. The average capture ratio of these two layers dropped to around 90% while tested against the VSP-laden aerosols due to the smaller liquid size. Nevertheless, most of the penetrated VSPs were captured by the third meltblown layer and the fourth inner NW layer, giving an overall FE ≥ 99%. For the surgical mask, the average ratio of the penetrated VSP through the outer NW layer is ~27% against VSP-laden droplets and ~48% against VSP-laden aerosols (Fig. 5d), respectively. Although more VSP reached the meltblown layer in surgical mask when compared with the KN95 mask, the meltblown layer was still capable of capturing most of them, which probably due to the electrostatic
interactions, and gave rise to an overall FE of approximate 97%. To the best of our knowledge, this work for the first time unraveled the relative contributions of each layer from the multilayered mask during a single test.

**Underlying reasons for the filtration performances**

A schematic diagram of the filtration phenomenon of the filter materials against VSP-laden droplets or aerosols based on the above results was presented in Fig. 6. Conventionally, the intended functions of the layers in a mask were that the outermost NW layer was for repelling water or large droplets, the middle meltblown layers was for filtering aerosols or particles, and the innermost NM layer was for absorbing moisture [46]. An extra cotton layers might be added at the middle of N95 or KN95 mask to improve moisture absorption [47]. In this study, the results showed that KN95 and surgical masks could bring about minimum FEs of 97% against VSP suspended in either droplets or aerosols. In all cases, more than half of the VSPs were captured by the first layer, while the VSP suspended in aerosols penetrated more into the deeper layers (Fig. 6a, b). As the size of the VSP-laden aerosols was ~4 μm, some of them would pass through the first layer of fibers along with the air flow, and others were stopped likely due to inertial impaction, which accounted for filtering particles of ~1-5 μm [48]. Although the VSP-laden aerosols passed through the first layer could be efficiently captured by the deeper layers as these layers could capture ~80-95% VSPs individually (Fig. S5), more attention should be paid when incorporating antivirus materials such as silver or copper nanoparticles to the first layer of the masks [49] as virus might accumulate on the materials.

For nanofibers, the PVDF nanofiber and PAN nanofiber showed distinct FEs. The PVDF nanofiber captured almost all VSPs while PAN nanofiber could only achieve FEs around 60-70%. The QF of PVDF nanofiber (∼0.14 Pa⁻¹) was similar to those multilayered masks while the QF of PAN nanofiber (∼0.04 Pa⁻¹) was much lower (Table S1). This was indeed out of our expectation as these two types of nanofibers had been widely used as the scaffolds for the development of air filtration materials. The gas adsorption measurements showed that the average pore sizes of as-spun PVDF and PAN nanofibers were about 10 nm. For both nanofibers, due to their small pore sizes, droplets or aerosols were expected to impact the fibers instead of direct passing through. To provide hints for how droplets and aerosols interact with the nanofibers, we adapted the VSP solution to contain AGA dye for water tracing, and sprayed tiny volumes of adapted VSP solution on the nanofibers, which were dried without air flow. Before impacting on the nanofiber, the droplets and aerosols were expected to be of spherical shape. After impacting on the nanofiber and being dried, the fluorescence on the PAN nanofiber showed circular patterns (Fig. 7a), suggesting that the droplets or the aerosols penetrated quickly into the deeper layer and resulted in the 2D projection of the liquid spheres. However, in the case of the PVDF nanofiber,
the fluorescence pattern appeared to be of irregular shape (Fig. 7a), suggesting the VSPs and the surrounding liquids remained on the surface of PVDF nanofiber and move horizontally along the nanofibers during drying. Such as difference in penetration was in accordance with the WCA analysis of the nanofibers where PAN nanofiber showed much higher wettability (Fig. S3). We then further conducted filtration experiments with the adapted VSP solution. For PVDF nanofiber, only a little AGA fluorescence was observed on the collector (Fig. 7b), indicating that VSP and most liquid water content remained on the PVDF filter layer. The situation is distinct for the PAN nanofiber, where NR and AGA fluorescence were both observed on the collector (Fig. 7c). Therefore, the lower FE of the PAN nanofiber was attributed to the higher wettability of the fibers. Although most droplets or aerosols will impact on the hydrophilic nanofibers, liquids could still move deeper through capillary effect in the nanofiber due to intrinsic wettability and air flow pressure [50]. Such a penetration might be a complex process which could involve the capture of VSP from the liquid and resuspension of VSP in newly arrived liquid. We believed that a comparison between VSP, actual virus, and liquid droplets/aerosols in a filtration test would bring about more insights about the filtration mechanisms. Nonetheless, the results in this study suggested that hydrophobic nanofibers were more suitable than hydrophilic nanofibers to serve as air filter materials for virus or other microorganisms suspended in droplets or aerosols. Besides, while the current developed VSPs are focused on estimating the FE against virus in this work, how the VSP could be utilized as an additional model to understand the virus-killing effect is worth to be explored in the future.

Conclusions
In this work, the employment of the polymersome as surrogate for virus to evaluate the filtration performance of antiviral air filter materials was demonstrated. Compared with using conventional surrogates, the method allows the determining the filtration performance of each layer of multilayered filter materials. The similarities between the VSP and virus may also give rise to more accurate estimation of the FE against the virus. The results showed that the electrospun PVDF nanofiber showed similar FE of 99% as KN95 mask, whereas the surgical mask showed slightly lower FE of 97%. This confirmed the potential of using PVDF nanofiber as the scaffold for further development of antiviral filter materials. The electrospun PAN nanofiber showed a low FE of 65% against droplets and 75% against aerosols due to the high wettability, revealing the importance of hydrophobicity of the filter materials. We believed the VSP and its corresponding filtration testing system demonstrated in this study can serve as a promising strategy for FE testing of antivirus air filter materials.

Appendix A. Supplementary data
Supplementary data: Fig. S1-S5, Table S1

Declaration of Competing Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials
Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.j.giant.2022.100104.

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