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An efficient virus aerosol sampler enabled by adiabatic expansion

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ABSTRACT

Protection of public health against pathogenic viruses transmitted through the airborne route requires effective sampling of airborne viruses for determination of their concentration and distribution. However, sampling viable airborne viruses is challenging as conventional bioaerosol sampling devices operate on inertia-based mechanisms that inherently have low sampling efficiency for virus aerosols in the ultrafine size range (< 100 nm). Herein, a Batch Adiabatic-expansion for Size Intensification by Condensation (BASIC) approach was developed for efficient sampling of virus aerosols. The BASIC utilizes adiabatic expansion in a supersaturated container to activate condensation of water vapor onto virus aerosol particles, thus amplifying the size of the particles by orders of magnitude. Using aerosolized MS2 bacteriophage, the BASIC's performance was evaluated and optimized both from the perspectives of physical size amplification as well as preservation of the viability of the MS2 bacteriophage. Experimental results show that one compression/expansion (C/E) cycle under a compression pressure of 103.5 kPa and water temperature of 25 °C was sufficient to increase the particle diameter from < 100 nm to > 1 μm; further increases in the number of C/E cycles neither increased particle number concentration nor diameter. An increase in compression pressure was associated with physical size amplification and a higher concentration of collected viable MS2. Water temperature of 40 °C was found to be the optimal for size amplification as well as viability preservation. No significant effect on particle size enlargement was observed by changing the dwell time after expansion. The results illustrate the BASIC's capability as a simple, quick and inexpensive tool for rapid sampling of viable airborne viruses.

1. Introduction

Airborne transmission of certain viruses can lead to widespread outbreaks of severe illnesses. Due to their potential to cause pandemics and sometimes fatal diseases, it is very important to understand and control the dynamics of airborne virus transmission. This pathway has been recognized as the most effective route for transmitting episodic respiratory viruses (e.g., Severe Acute Respiratory Syndrome (SARS) Coronavirus, Middle East Respiratory Syndrome (MERS) Coronavirus and H7N9 Influenza virus) and

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those more frequent respiratory infectious diseases such as seasonal flu and common colds that can lead to pneumonia (Brankston, Gitterman, Hirji, Lemieux, & Gardam, 2007; Goldmann, 2000; Lapinsky, 2010; Otter et al., 2016; Wang, 2013; Yu et al., 2004). Many virus aerosols are classified by their size under the category of ultrafine particles (UFPs, with aerodynamic diameter smaller than 100 nm) as the size of viruses ranges from 20 to 300 nm, and typically less than 100 nm (Pease, 2012). This magnifies the concern regarding airborne transmission of the pathogenic viruses since the UFPs can travel long distances (Alonso, Raynor, Davies, & Torremorell, 2015) and penetrate deep into the alveoli region of the human respiratory system (Milton, Fabian, Cowling, Grantham, & McDevitt, 2013). To gain a better understanding of the presence of virus aerosols and better ascertain the inhalation risks they pose, efficient collection of viable virus aerosol is needed.

A variety of samplers for collecting bioaerosol have been developed, but they mostly utilize inertial impaction for particle collection. A significant fraction (42%) of the influenza viruses dispersing into the air after a human cough were detected in airborne particles smaller than 1 μm (Lindsley, Blachere, & Thewlis, 2010). Therefore, the mentioned samplers are inherently ineffective for these ultrafine virus particles. For example, the BioSampler® (SKC Inc., Eighty Four, PA, USA) has been widely used for bacterial and fungal collection, but its collection efficiency is less than 10% for particles smaller than 100 nm (Hogan et al., 2005). In addition to efficient physical collection, preserving viability of the virus aerosol is the other critical factor in assessing the health risk associated with airborne transmission of pathogenic virus.

To address the abovementioned drawbacks, several studies proposed the use of water vapor condensation to amplify the size of virus aerosol particles before collection by inertial impaction (Oh et al., 2010; Pan et al., 2016). When the partial pressure of water vapor exceeds its saturation vapor pressure, supersaturation condition is established and subsequently condensation of water on colder surfaces occurs (Kousaka, Niida, Okuyama, & Tanaka, 1982). There are three common approaches for establishing the supersaturation condition to enlarge airborne particles: 1) mixing a hot saturated vapor with the flow of incoming particles, 2) convectively cooling the airstream of the target particles, and 3) creating an adiabatic-expansion condition in the air volume surrounding the targeted particles (Vanhanen et al., 2011). The first two mechanisms have been implemented for virus aerosol sampling. For instance, Oh et al. (2010) compared a mixing type of bioaerosol amplification unit (mBAU) with a cooling type of bioaerosol amplification unit (cBAU), and observed that the mBAU performed better than the cBAU in collecting viable virus aerosol. The cooling type did not work well when using water vapor as condensation fluid because water's mass diffusivity is greater than air's thermal diffusivity (Hering & Stolzenburg, 2005). Thus, condensation mainly occurred on the cold wall surface rather than on aerosol particles. Hering, Spielman, and Lewis (2014) utilized a water-wetted hot wall instead of a cooling tube for the particle growth, and they demonstrated its capability to efficiently amplify nanosized aerosol (down to 6 nm) to sizes larger than 1 μm. High efficiency in collection of viable virus aerosol was further attempted on MS2 and H1N1 influenza virus using the same technique (Jiang et al., 2016; Lednicky et al., 2016; Pan et al., 2016, 2017).

The third approach, i.e., adiabatic expansion, includes an instant volume expansion whereby there is no heat transfer between the contained volume and its surroundings (Bailyn, 1994). For a system with a certain volume, the temperature, volume and pressure of the system before and after the adiabatic-expansion are related as follows:

$$P_0 V_0^{\gamma} = P_f V_f^{\gamma} \tag{1}$$

$$T_0 V_0^{\gamma-1} = T_f V_f^{\gamma-1} \tag{2}$$

where *P, V, T* are pressure, volume and temperature, respectively, subscripts 0 and f refer to before and after adiabatic expansion, respectively, and γ is heat capacity ratio (i.e., the ratio of specific heat of relevant gas at a constant pressure over that at a constant volume, $\gamma = \frac{c_p}{c_v}$; Strey, Schmeling, & Wagner, 1986). Aitken (1888) implemented this principle to create supersaturation by lowering temperature of the surrounding air of target dust aerosol. Pollak and O'connor (1955) applied this principle in their photoelectric condensation nucleus counter (CNC), wherein a photoelectric sensor was used to count the number of enlarged mist particles. Pollak and Metnieks (1960) investigated the performance of the CNC under different volume expansion ratios (i.e., $\frac{p_f}{p_0}$) and achieved a high saturation ratio of 3.50 under a compression ratio of 1.21, which exceeded the required Kelvin ratio for ultrafine particles (Miller & Bodhaine, 1982b). In their research, the CNC successfully amplified particles as small as 20 nm (Miller & Bodhaine, 1982a). Compared to the mixing and cooling approaches, the adiabatic expansion approach can result in an extremely high supersaturation ratio instantly, which activates the growth of particles in a very short time. This high supersaturation ratio played a key role in activating amplification of ultrafine particles as small as 13 nm (Liu et al., 1984). While there have been a handful of studies on size enlargement of particles using adiabatic expansion as discussed (e.g., the one by Okuyama et al., 1984), there is no study regarding size enlargement of viable virus aerosol by this approach yet.

This study was embarked on to apply the adiabatic expansion principle to engineer a simple but highly efficient size amplification device to address limitations associated with previously mentioned methods. On this ground, a prototype of Batch Adiabatic-expansion for Size Intensification by Condensation (BASIC) sampler was designed and fabricated. Performance of the BASIC apparatus in regards to size amplification was evaluated. Since collection of viable virus aerosols was the main purpose for the new device, experiments were conducted to evaluate its ability in collecting viable viruses. To optimize the BASIC's operation, sensitivity analyses of key parameters were conducted, including compression pressure, number of compression/expansion cycles (C/E cycles), temperature of the condensing water and dwell time after the expansion.