



## Transport and Mitigation of Exhaled Electronic Cigarette Aerosols in a Multizone Indoor Environment

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### ABSTRACT

Using an electronic cigarette (e-cig) has been shown to emit a substantial amount of particles and degrade indoor air quality. Here, we tested the effectiveness of different mitigation strategies to reduce indoor particulate pollution due to e-cigs. We simultaneously measured concentrations of particle number (PNC) and fine particle (PM<sub>2.5</sub>) mass in a vaping room and an adjacent non-vaping room, both of which were well controlled, during e-cig use under six different experimental conditions: (1) the baseline scenario, in which the connecting door between the two rooms was open, the ventilation in both rooms was low, and no air purifier was operated; (2) the connecting door between the two rooms was closed; (3) the ventilation was enhanced in the vaping room; (4) the ventilation was enhanced in the non-vaping room; (5) an air purifier was operated in the vaping room; and (6) an air purifier was operated in the non-vaping room. We found that the particle concentrations significantly decreased in both of the rooms when either the ventilation was enhanced or the air purifier was operated. Closing the connecting door between the two rooms produced the largest reduction (42%) of PNC in the non-vaping room; however, it also led to a 26% increase of PNC in the vaping room. Previous studies have demonstrated that vape shops contain high concentrations of particles when no mitigation strategies are implemented. Our results provide a basis for assessing and reducing exposure to e-cig aerosols and its associated health effects in future studies.

**Keywords:** Electronic cigarette; Ultrafine particles; PM<sub>2.5</sub>; Transport; Mitigation.

### INTRODUCTION

An electronic cigarette (“e-cig”) is a popular nicotine delivery alternative to traditional tobacco cigarette (“t-cig”). Compared with t-cig, e-cig does not have the tobacco combustion process or side stream, and therefore may be perceived as less harmful to human health. E-cigs generate aerosols by vaporization of e-liquids, which typically consist of propylene glycol (PG), vegetable glycerin (VG), nicotine, flavor additives and water (Etter *et al.*, 2013; Kim and Shin, 2013; Geiss *et al.*, 2015). The U.S. e-cig market has proliferated in recent years and is expected to reach \$6.59 billion by 2024 (Mordor Intelligence, 2018). The advertised moderate cost and appealing flavors (Morean *et al.*, 2018) have attracted many users, including adolescents and non-smokers to e-cigs. In the United States, the current e-cig users in middle schools and high schools have increased from 0.6% and 1.5% in 2011 to 4.9% and 20.8% in 2018, respectively (Cullen *et al.*, 2018).

Although labeled as “a safer t-cig alternative,” studies have shown that the use of e-cigs can worsen indoor air quality and may adversely affect human health (Li *et al.*, 2020b). In mainstream e-cig aerosols, mean particle number concentrations (PNCs) on the order of 10<sup>7</sup> to 10<sup>9</sup> particles cm<sup>-3</sup> have been reported in chamber studies (Ingebrethsen *et al.*, 2012; Fuoco *et al.*, 2014; Mikheev *et al.*, 2016; Zhao *et al.*, 2016) and mean PM<sub>2.5</sub> concentrations of 184 µg m<sup>-3</sup> have been reported (Lee *et al.*, 2017). Toxic compounds have also been reported, including volatile organic compounds (VOCs); heavy metals (including aluminum, tin, nickel, chromium, and copper); carbonyl compounds, which are possibly byproducts formed during the thermal degradation of glycols and glycerin; and tobacco-specific nitrosamines (TSNA) (McAuley *et al.*, 2012; Williams *et al.*, 2013; Goniewicz *et al.*, 2014; Jensen *et al.*, 2015; Lerner *et al.*, 2015; Mikheev *et al.*, 2016; Sleiman *et al.*, 2016). Recently, public concern has been raised by the outbreak of *e-cig, or vaping, product use-associated lung injury* (EVALI) and recent data show Vitamin E acetate and tetrahydrocannabinol (THC) are associated with EVALI, which is still under investigation by the federal agencies, state and local health departments, and other clinical and public health professionals (Blount *et al.*, 2020; CDC, 2020).

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With the rapid increase in e-cig users, secondhand involuntary exposure to exhaled e-cig aerosols has become a serious public health concern (Li *et al.*, 2020b). Indoor PNC of  $10^4$  to  $10^5$  particles  $\text{cm}^{-3}$  and  $\text{PM}_{2.5}$  concentrations of  $152\text{--}375\ \mu\text{g m}^{-3}$  were reported in real-world studies (Czogala *et al.*, 2014; Schober *et al.*, 2014; Zhao *et al.*, 2017). Besides, VOCs, aldehydes and ketones, polycyclic aromatic hydrocarbons (PAHs), and metals were also found in exhaled e-cig aerosols (Schober *et al.*, 2014). These findings suggest secondhand exposures to exhaled e-cig aerosols may affect the health of bystanders.

Because of the potential health effects of e-cig use, policies have been made to regulate e-cigs (U.S. Food and Drug Administration, 2019) and many states and cities have published laws restricting e-cig use in smoke-free venues (American Nonsmokers' Rights Foundation, 2019). Nevertheless, in certain public indoor spaces, such as vape shops, unlimited e-cig use is still permitted. In our previous study, high concentrations of particles were found during business hours in vape shops (Nguyen *et al.*, 2019). Besides, a study conducted at an e-cig vaping convention found the 24-h average  $\text{PM}_{10}$  was 12-fold higher than the EPA regulation (Chen *et al.*, 2018). Vape shops were adjacent to at least one business in southern California (Nguyen *et al.*, 2019); the exhaled e-cig aerosols from the vape shop may infiltrate to nearby businesses and cause involuntary exposures. Currently, strategies including increasing room ventilation, air purification, and door segregation were found to be efficient in removing environmental tobacco smoke (Miller and Nazaroff, 2001; Wang *et al.*, 2012; Ciuza, 2016) and applied to mitigate the transport of secondhand smoke (SHS) successfully (Miller and Nazaroff, 2001). However, no study has investigated the transport of exhaled e-cig aerosols in a multizone indoor environment and it is unclear whether strategies could be extended to exhaled e-cig

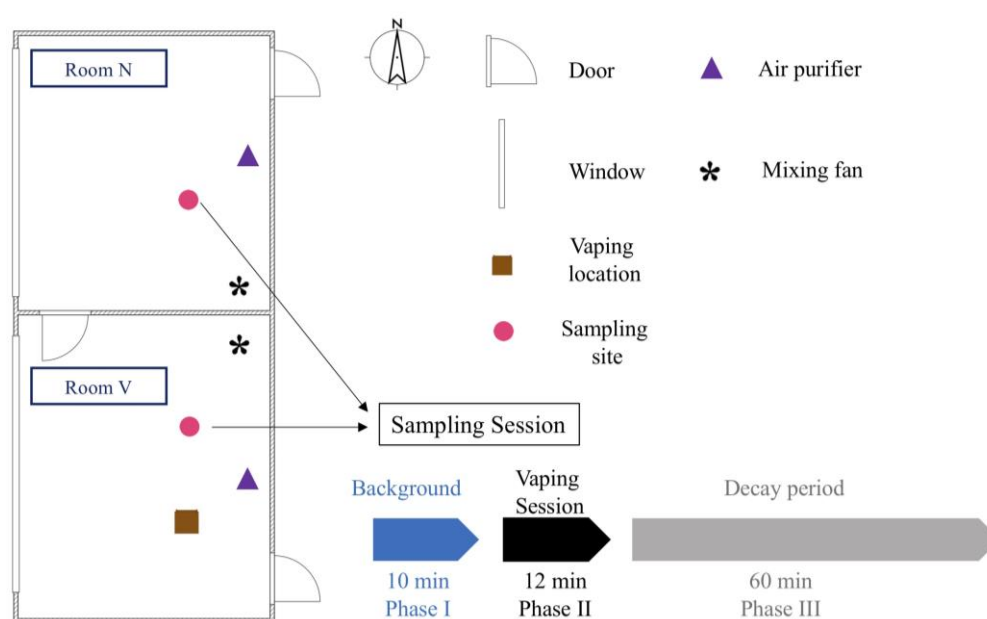
aerosols which have different physiochemical characteristics than SHS (Li *et al.*, 2020b).

To address these knowledge gaps, in this study, we aim to investigate the transport of exhaled e-cig aerosols and evaluate the effectiveness of mitigation strategies in a multizone indoor environment. Real-time measurements of PNC and  $\text{PM}_{2.5}$  were conducted in a vaping room (Room V) and an adjacent non-vaping room (Room N) before, during, and after a 12-min well-controlled e-cig vaping session under six experimental conditions with different mitigation strategies. This is the first study to report the transport and mitigation of exhaled e-cig aerosols in a multizone environment.

## MATERIALS AND METHODS

### Experimental Setting

As shown in Fig. 1, the study was conducted in two adjacent laboratory rooms. Room V, the designated vaping room, with a volume of  $89\ \text{m}^3$  ( $6.2\ \text{m} \times 5.3\ \text{m} \times 2.7\ \text{m}$ ), has a French window, a door exited to the outside corridor, and four air ventilation outlets across the room on the ceiling. Similarly, Room N, the non-vaping room, with a slightly smaller volume of  $80\ \text{m}^3$  ( $5.6\ \text{m} \times 5.3\ \text{m} \times 2.7\ \text{m}$ ), also has a French window, a door exited to the outside corridor, and four air ventilation outlets on the ceiling. To minimize air leakage, doors that exited to the outside corridor in both rooms were sealed during the experiments. A fan was operated at the corner of each room to blow air towards the opposite corner to enhance air mixing. Central ventilation air outlets were either fully open or completely sealed depending on experimental conditions. Similarly, a door ( $0.9\ \text{m} \times 2.1\ \text{m}$ ) that connects the two rooms was either completely open or closed. This experimental setting is similar to a typical vape shop and a nearby business in terms of room size and ventilation (Nguyen *et al.*, 2019).



**Fig. 1.** The schematic diagram of the two-zone testing environment and the three phases of each sampling session. Room V, the vaping room; Room N, the non-vaping room.

E-cig aerosols were generated through active vaping by a volunteer who is an experienced e-cig user. The volunteer sat on a chair near the center of Room V and exhaled e-cig aerosols at a height of roughly 1.3 m above the floor. In each room, the sampling site was located 2 m away from the middle wall between the two rooms and a portable air purifier (LV-PUR131 True HEPA Air Purifier; Levoit Corp., Anaheim, CA) was located on the floor, near the wall to the outside corridor.

### Experiment Protocol

As shown in Fig. 1, each experiment lasted for 82 min which included three sampling phases: a 10-min background measurement (Phase I), a 12-min vaping session (Phase II), and a 60-min decay period (Phase III). During the vaping session, the volunteer used an e-cig continuously and followed a protocol of 3-s puffing, 3-s holding, and 24-s pause until the next puff (Zhao *et al.*, 2017). This vaping protocol is equivalent to a total vaping frequency (TVF) of 120 puffs  $\text{h}^{-1}$ , which is within the range of reported TVF in vape shops (Nguyen *et al.*, 2019). The e-cig used in this study was a rechargeable device of box mod style from Smoktech (Smok Mag TC Vape Starter Kit; Smoktech, Shenzhen, China). The e-liquid had a nicotine level of 0.3 mg  $\text{mL}^{-1}$  (0.3%) and PG/VG ratio of 70/30 with a popular berry flavoring which was a common e-liquid choice for vapers.

A total of six experimental conditions were designed to evaluate the effectiveness of various mitigation strategies in reducing exposures and the transport of exhaled e-cig aerosols. Mitigation strategies were designed around three concepts, including door segregation, ventilation modification, and air filtration (Miller and Nazaroff, 2001). The summary of the six experimental conditions is shown in Table 1, including experimental conditions, the status of the connecting door, air ventilation, air purifier, and measured room air exchange rate (AER). The room filtration was provided by operating a portable air purifier with a clean air delivery rate (CADR) of 230  $\text{m}^3 \text{h}^{-1}$ . Under each condition, four repeat experiments were conducted by the same volunteer to minimize the uncertainties of emissions.

### Measurements and Instrumentation

#### Particle Number and $\text{PM}_{2.5}$ Mass Concentrations

Two identical sets of instruments were used in Room V and Room N to collect PNC and  $\text{PM}_{2.5}$  data concurrently. In each room, at the sampling location, a Diffusion Size Classifier (DiSCmini; Testo SE & Co. KGaA, Germany) and a Water-based Condensation Particle Counter (Nano-

WCPC 3787; TSI Inc., Shoreview, MN, USA) were used to measure PNC and a DustTrak II Aerosol Monitor (DustTrak 8532; TSI Inc., Shoreview, MN, USA) was used to measure  $\text{PM}_{2.5}$  concentrations. A Scanning Mobility Particle Sizer (sampling flow rate = 0.6  $\text{L min}^{-1}$ , up scan = 100 s, down scan = 20 s; SMPS 3080; TSI Inc.) and an Aerodynamic Particle Sizer (APS 3321; TSI Inc.) were used to measure particle size distribution in the particle size range of 7–289 nm and 0.5–19.8  $\mu\text{m}$ , respectively. Besides,  $\text{CO}_2$  concentrations were measured by an indoor air quality monitor (Q-Trak 7575; TSI Inc.). All particle and  $\text{CO}_2$  concentrations were collected at 1 s and then averaged to 1 min for data reduction and analysis. The AER in both rooms was calculated based on the  $\text{CO}_2$  tracer gas method (ASTM, 1995) as described in detail in Section S1 in the Supporting Information (SI).

#### Quality Control/Quality Assurance for Data Collection and Analysis

To ensure that data from different units of the instrument were comparable, 60-min collocation tests were conducted. The inlets of two instrument units were placed side by side to collect samples at a 1-s interval and also averaged to 1 min for data analysis. Collocation tests between DiSCmini and WCPC were conducted for PNC measurements. Figs. S1 and S2 in the SI present the regression results for the collocation tests. The ratio of data from DiSCmini A to WCPC (as the standard) was  $0.66 \pm 0.005$  ( $R^2 = 0.99$ ) and the ratio of data from DiSCmini B to WCPC (as the standard) was  $0.68 \pm 0.006$  ( $R^2 = 0.99$ ). PNCs from DiSCminis were lower than those from WCPC measurements, likely due to a narrower particle size range of DiSCmini (10–700 nm) as compared with that of WCPC (2.5–3000 nm). The ratio of data from DustTrak II A to DustTrak II B was  $0.98 \pm 0.004$  ( $R^2 = 0.99$ ). Gravimetric calibration of DustTrak II data was conducted as described previously (Nguyen *et al.*, 2019), and the calibration factor of 0.25 ( $R^2 = 0.95$ ) was applied to correct all DustTrak II data. In addition, before each sampling session, all instruments were zero-checked for 3 min for data quality assurance. Regression results from the above collocation and calibration tests were used to correct all particle data in this study.

#### Statistical Data Analysis

Under each condition, the particle concentrations measured in the first 10 min (Phase I) were treated as the background concentration and subtracted from the subsequent measurements including the vaping session (Phase II) and

**Table 1.** Summary of the six experimental conditions.

Experimental Condition	Connecting Door	Ventilation		Air Purifier		AER ( $\text{h}^{-1}$ )	
		Room V	Room N	Room V	Room N	Room V	Room N
#1 Baseline	Open	Low	Low	Off	Off	2.3	2.2
#2 Segregation	Closed	Low	Low	Off	Off	2.0	2.1
#3 Enhanced Ventilation in Room V	Open	High	Low	Off	Off	4.9	3.3
#4 Enhanced Ventilation in Room N	Open	Low	High	Off	Off	4.2	8.2
#5 Increased Filtration in Room V	Open	Low	Low	On	Off	2.4	2.3
#6 Increased Filtration in Room N	Open	Low	Low	Off	On	2.3	2.5

the decay period (Phase III). Mean particle number/mass concentrations across Phase II and Phase III were calculated, as indicators of exposure to exhaled e-cig aerosols that a bystander might encounter. Mean concentrations were calculated by taking the sum of the 1-min measurements and dividing by the time of Phase II and Phase III (72 min), as:

$$Mean_{measure} = \frac{\int_0^t (C_t - C_b) dt}{t} \quad (1)$$

where  $Mean_{measure}$  (PNC (particles  $cm^{-3}$ ) or  $PM_{2.5}$  ( $\mu g m^{-3}$ )) is the mean concentration due to the use of e-cig,  $C_t$  (particles  $cm^{-3}$  or  $\mu g m^{-3}$ ) is the measured particle concentration (PNC or  $PM_{2.5}$  mass concentrations),  $C_b$  (particles  $cm^{-3}$  or  $\mu g m^{-3}$ ) is the background particle concentration measured in Phase I, and  $t$  (min) is the time period of Phase II or Phase III (72 min total).

Permutation test (also known as *Fisher's two-sample randomization test*) was performed to compare the mean measures (PNC or  $PM_{2.5}$ ) between the baseline condition (#1) and each of the other five conditions in both rooms, separately. The significance level was taken at  $p < 0.05$ . A ratio of the mean measure (PNC or  $PM_{2.5}$ ) in Room N to that in Room V was also calculated and used as an indicator to reflect the magnitude of the transport of exhaled e-cig aerosols. Permutation test was also performed to compare the ratios between the baseline condition (#1) and each of the other five conditions, separately with significance level  $p < 0.05$ .

In addition, the decay rate of exhaled e-cig aerosols in Room V was determined using the following equation:

$$-\ln(C_t/C_0) = k \times t \quad (2)$$

where  $C_t$  (particles  $cm^{-3}$ ) is the measured particle concentration,  $C_0$  (particles  $cm^{-3}$ ) is the particle concentration measured at the start of each decay, and  $k$  ( $h^{-1}$ ) is the averaged particle decay rate. When determining the particle decay rate, a high  $C_0$  is needed; thus we only calculated  $k$  in Room V.

R 3.4.0 and Microsoft Excel 2016 (Microsoft, Seattle, WA, USA) were used to summarize the statistical results of PNC and  $PM_{2.5}$  concentrations and perform the significance test. SigmaPlot 12.5 (Systat Software Inc., San Jose, CA, USA) was used to generate the figures.

## RESULTS AND DISCUSSION

### Concentrations and Dynamics of PNC and $PM_{2.5}$ Due to e-cig Use

The temporal trends of PNC under different experimental conditions are shown in Fig. 2. The baseline condition (#1) represents a typical exposure scenario in a multizone indoor environment without any mitigation strategy. In Room V, the PNC started to increase right after vaping began, peaked at the end of the vaping session, up to  $2.7 \times 10^4$  ( $1.5 \times 10^4$ ) particles  $cm^{-3}$  (arithmetic mean and standard deviation in

parenthesis, same as below), and returned to the background concentration within 40–50 min. Mean PNCs were measured at  $2.0 \times 10^4$  ( $1.0 \times 10^4$ ) particles  $cm^{-3}$  in Phase II and  $5.8 \times 10^3$  ( $2.6 \times 10^3$ ) particles  $cm^{-3}$  in Phase III, respectively.

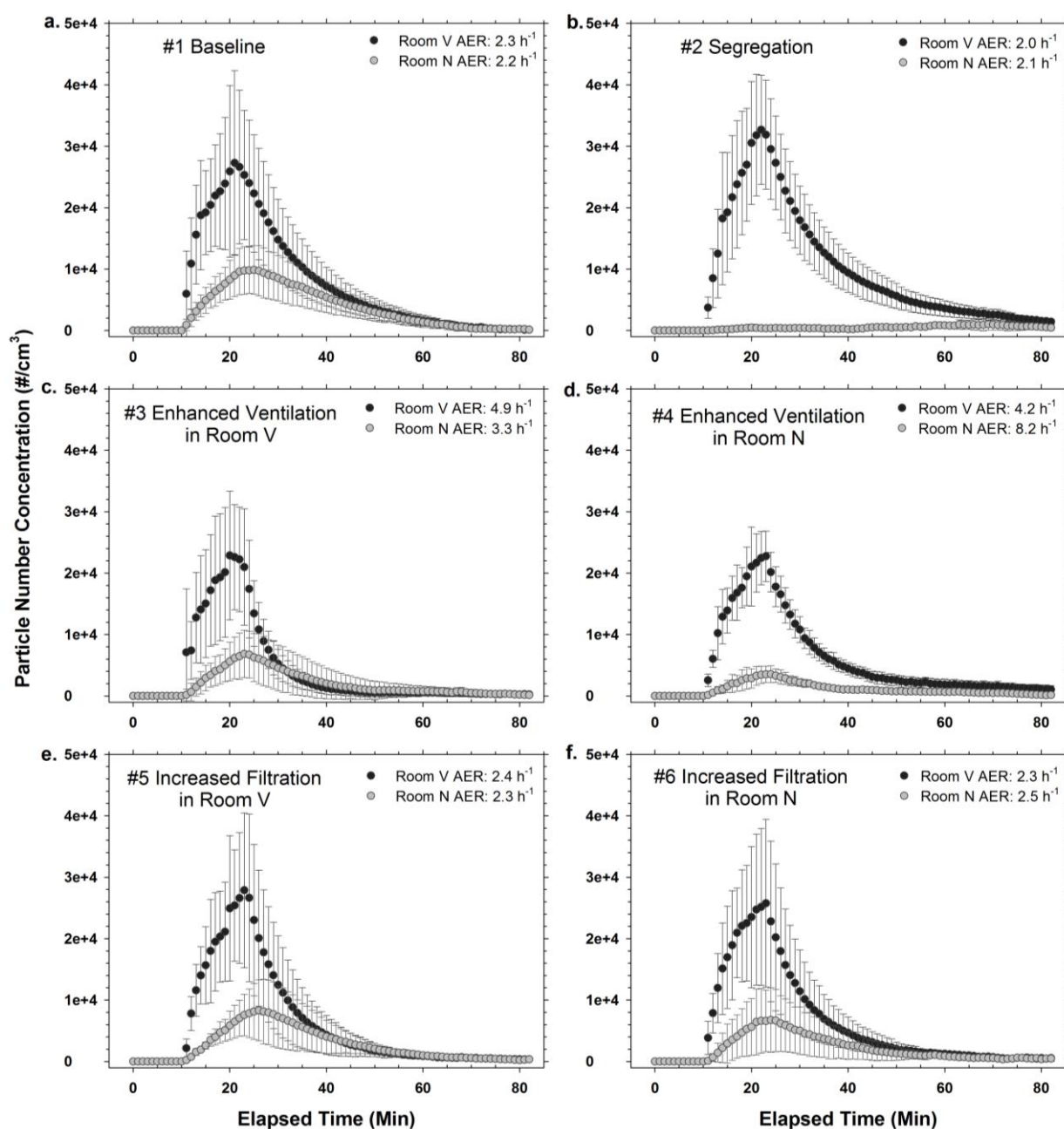
In Room N, PNC started to increase 1 min after vaping began and increased up to  $9.9 \times 10^3$  ( $4.0 \times 10^3$ ) particles  $cm^{-3}$  about 3 min after vaping ended, suggesting a rapid transport of ultrafine particles from Room V to Room N. The PNC returned to the background concentration about 40 min after vaping ended. Overall, mean PNCs were  $5.7 \times 10^3$  ( $2.6 \times 10^3$ ) particles  $cm^{-3}$  in Phase II and  $3.6 \times 10^3$  ( $1.7 \times 10^3$ ) particles  $cm^{-3}$  in Phase III.

As shown in Fig. 2, the overall temporal trends of PNC under the mitigation conditions (#2–6) were similar to that under the baseline condition (#1). The difference is that in Room V, less time was taken for PNC to decay to near background concentration when ventilation was enhanced (#3) or air filtration was increased (#5). Likewise, in Room N, it took 20 min less for PNC to return to near background concentration when ventilation was enhanced (#4).

Many factors could affect the measured particle concentrations including source strength (i.e., TVF), air exchange rate, and measurement location (Schripp et al., 2013; Zhao et al., 2017). In this study, measurements were taken at 2.4 m away from the e-cig user under TVF of 120 puffs  $h^{-1}$ . In a previous study, when the measurements were taken at 2 m away from the e-cig user under TVF of 60 puffs  $h^{-1}$ , Ruprecht et al. (2017) reported mean PNC value of  $8.7 \times 10^3$  particles  $cm^{-3}$  during the vaping session after subtracting the background concentration. In comparison, Schober et al. (2014) reported median PNC varied from  $4.4 \times 10^4$  to  $8.4 \times 10^4$  particles  $cm^{-3}$  at 1 m away from the e-cig user under TVF of 66 puffs  $h^{-1}$ . Melstrom et al. (2017) reported a mean PNC of  $2.8 \times 10^4$  particles  $cm^{-3}$  where measurements were taken in the middle of the table with three e-cig users sitting around. These studies indicate that the proximity effect played an important role in particle concentration measurements, where concentrations of exhaled e-cig particles were much higher in close proximity to the source than farther away (Zhao et al., 2017).

Besides measurement location, the relatively high AER used in this study likely lowered particle concentrations. In Ruprecht et al.'s study (2017), the slightly higher PNC ( $8.7 \times 10^3$  particles  $cm^{-3}$  compared with  $5.8 \times 10^3$  particles  $cm^{-3}$  in this study) is observed under a lower AER of  $1.5 h^{-1}$  (compared with  $2.3 h^{-1}$  in this study). When room AER was  $0.56 h^{-1}$  in Schober et al.'s study (2014), the PNC increased to high median values ranging from  $4.8 \times 10^4$  to  $8.8 \times 10^4$  particles  $cm^{-3}$ . In our previous study, the ranges of AER were  $0.1$ – $0.2 h^{-1}$ ,  $1.0$ – $3.0 h^{-1}$ , and  $4.0$ – $5.0 h^{-1}$  for vape shops with no ventilation or A/C, natural ventilation, and central ventilation systems, respectively (Nguyen et al., 2019). In the current study performed in a building with central ventilation system (Lin et al., 2019), the AERs were comparable with those in real vape shops with central ventilation systems. It is likely that in vape shops with lower AERs due to limited ventilation, vaping could lead to higher indoor particle concentrations as compared with our study.

As shown in Fig. 3, the temporal trends of real-time  $PM_{2.5}$



**Fig. 2.** The temporal trends of PNC (mean and standard deviation of four repeated measurements) in Room V and Room N under Conditions #1–6. Background concentration was subtracted.

mass concentrations are somewhat different from those of PNC. A smaller increase of  $PM_{2.5}$  concentration was observed in Room N and less time was needed for it to return to the background concentration. Under the baseline condition (#1), in Room V,  $PM_{2.5}$  started to increase 1 min after vaping began, peaked coinciding with the end of the vaping session, up to 64 ( $45 \mu g m^{-3}$ ), and then fell to near background concentration in 6 min. In Room N, after subtracting the background, the maximum  $PM_{2.5}$  concentration only reached 4 (3)  $\mu g m^{-3}$ . The temporal trends of  $PM_{2.5}$  under Conditions #2–6 were similar to that under the baseline scenario (#1).

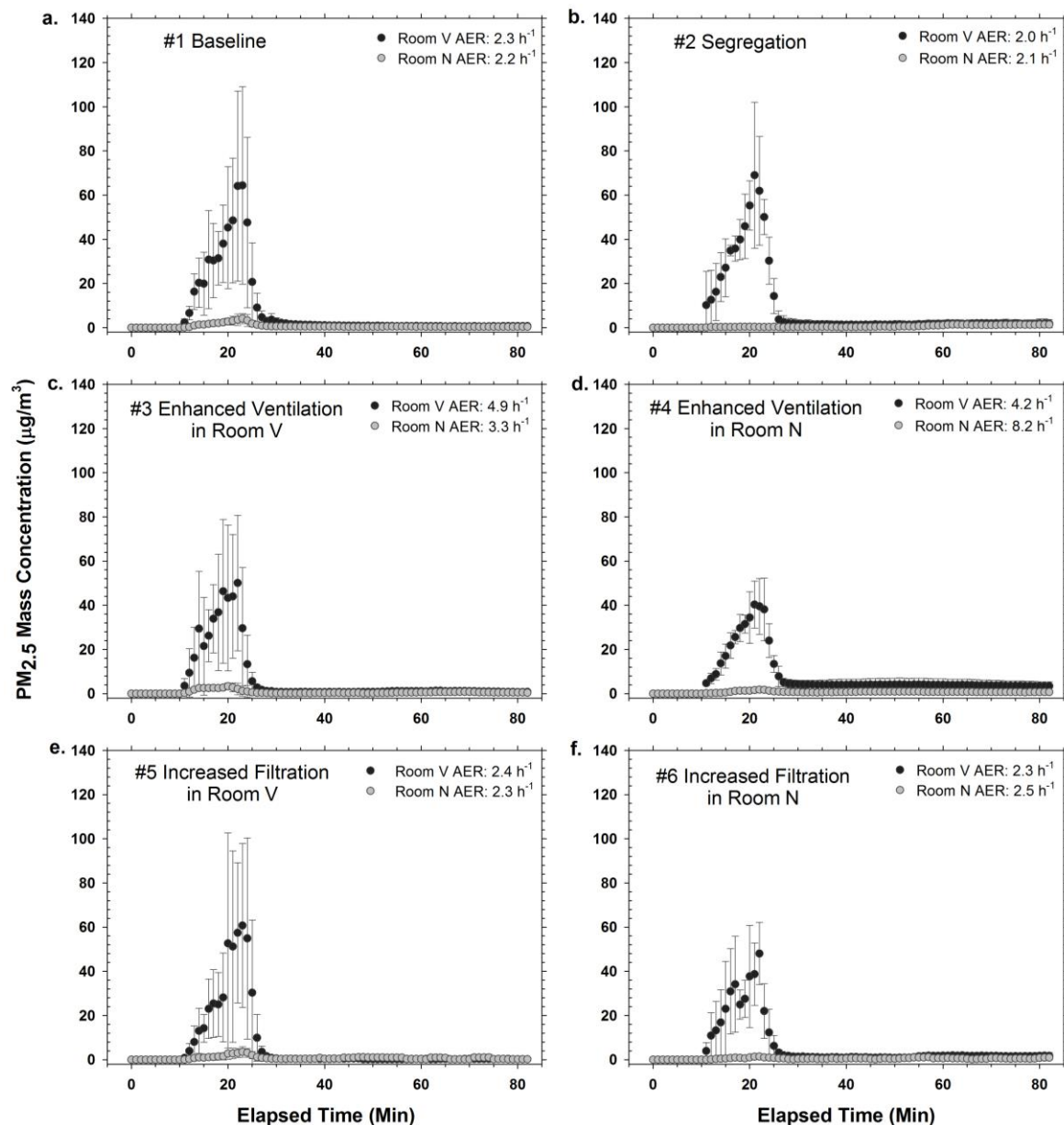
Zhao *et al.* (2017) reported similar  $PM_{2.5}$  concentrations under the same TVF and found more than 90% of  $PM_{2.5}$

reduction occurred between two measurement locations of 0.8 m and 2.5 m from the vaping source. In Schober *et al.*'s study (2014), the measurements were taken at 1 m away from the source under a TVF of 66 puffs  $h^{-1}$  and the observed  $PM_{2.5}$  values ( $191 \mu g m^{-3}$ ) were much higher than those observed in this study, where  $PM_{2.5}$  measurements were taken at 2.4 m away from the e-cig user. These results highlight the importance of proximity effects on understanding e-cig aerosol secondhand exposures.

#### *Transport of Exhaled e-cig Aerosols*

Real-time measurements of PNC and  $PM_{2.5}$  presented in Figs. 2(a) and 3(a) indicate that exhaled e-cig aerosols could



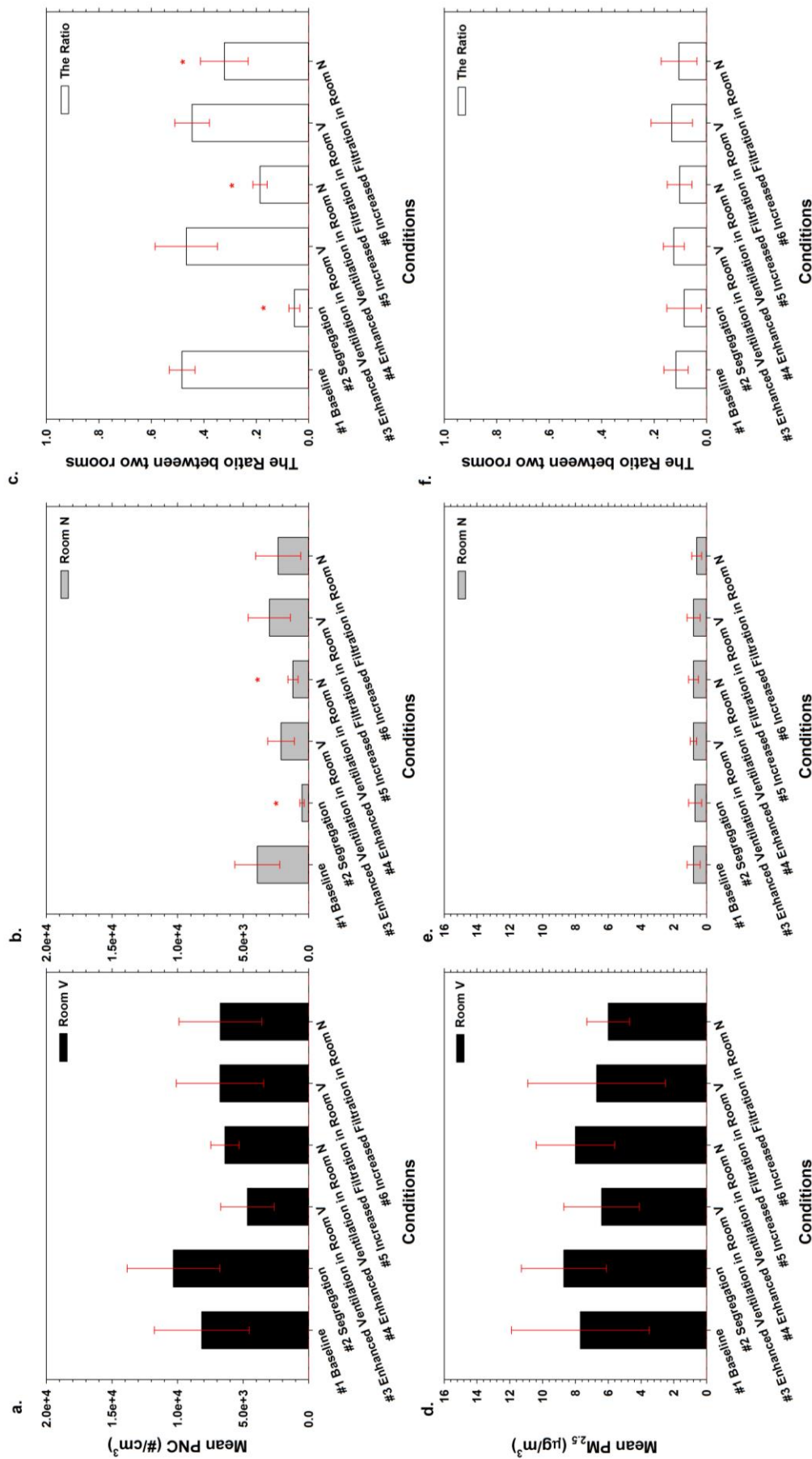


**Fig. 3.** The temporal trends of PM<sub>2.5</sub> mass concentration (mean and standard deviation of four repeated measurements) in Room V and Room N under Conditions #1–6. Background concentration was subtracted.

transport in a multizone indoor environment and lead to secondhand exposures. Based on Eq. (1) in Section 2.4, the mean measures of PNC and PM<sub>2.5</sub> in both rooms under all six experimental conditions are presented in Fig. 4. In addition, the ratio for mean PNC and PM<sub>2.5</sub> between the two rooms was also presented, as an indicator of the magnitude of the transport of exhaled e-cig aerosols from Room V to Room N.

Figs. 4(a) and 4(b) present the mean PNC due to e-cig use across Phase II and III in Room V and Room N, respectively. Under the baseline condition (#1), mean PNC in Room V was  $8.1 \times 10^3$  ( $3.8 \times 10^3$ ) particles cm<sup>-3</sup> across Phase II and Phase III, meaning that a bystander might encounter a mean exposure concentration of  $8.1 \times 10^3$  particles cm<sup>-3</sup> across Phase II and Phase III. The corresponding PNC level was  $3.9 \times 10^3$  ( $1.8 \times 10^3$ ) particles cm<sup>-3</sup> in Room N.

Figs. 4(d) and 4(e) present the mean PM<sub>2.5</sub> due to e-cig use across Phase II and III in Room V and Room N. Under the baseline condition (#1), mean PM<sub>2.5</sub> was 8 (5) µg m<sup>-3</sup> in Room V. In comparison, the mean PM<sub>2.5</sub> in Room N (1 µg m<sup>-3</sup>) was much lower. In addition, ratios for the mean PNC was 0.48 between Room V and Room N, indicating that 48% of the exhaled e-cig particles transported from Room V to Room N. In comparison, the ratio for mean PM<sub>2.5</sub> was only 0.12, suggesting fine particles transport much less than ultrafine particles. This is likely due to particle evaporation since our previous chamber study has shown higher loss rates of PM<sub>2.5</sub> (i.e., 4.4–7.0 h<sup>-1</sup>) compared to ultrafine particles (i.e., 0.6–1.2 h<sup>-1</sup>) (Li *et al.*, 2020a). Particle evaporation led to a quicker decrease in particle mass compared with particle number.



**Fig. 4.** Mean PNC due to e-cig use across Phase II and III in (a) Room V and (b) Room N and (c) the ratio between two rooms; mean PM<sub>2.5</sub> due to e-cig use in (d) Room V and (e) Room N and (f) the ratio between two rooms; \* indicates statistically significant ( $p < 0.05$ ) based on the permutation test of the ratio between each condition and the baseline (#1).

The above findings suggest that e-cig use from a single user could contribute to high PNC in a typical indoor environment. Despite the rapid decay rate of exhaled e-cig aerosols (Zhao *et al.*, 2017), a higher percentage (48%) of particle number could still be detected in the adjacent Room N. This indicates that some of the exhaled e-cig particles could remain airborne long enough to translocate in a multizone indoor environment when no mitigation was applied. To protect bystanders from secondhand exposures, we investigated various mitigation strategies that could reduce the exposure and decrease the transport of exhaled e-cig aerosols, as detailed in the following section.

### **Effects of Mitigation on Particle Concentrations**

We tested five mitigation strategies aiming to reduce particle concentrations in Room V and Room N. PNCs in both rooms were largely affected by mitigation strategies. Briefly, as shown in Fig. 4, when the door connecting Rooms V and N was closed (#2), mean PNC in Room N was significantly reduced by 87% to less than  $1.0 \times 10^3$  particles  $\text{cm}^{-3}$  across Phase II and Phase III. It should be noted that mean PNC (#2,  $1.0 \times 10^4$  ( $3.5 \times 10^3$ ) particles  $\text{cm}^{-3}$ ) in Room V was slightly higher relative to the baseline scenario (#1,  $8.1 \times 10^3$  ( $3.8 \times 10^3$ ) particles  $\text{cm}^{-3}$ ) across both phases, likely because the dilution in Room N was inhibited. When ventilation was enhanced in Room V (#3), mean PNC decreased by 42% in Room V and decreased by 46% in Room N across Phase II and Phase III. Similarly, when ventilation was enhanced in Room N (#4), mean PNC reduced from  $8.1 \times 10^3$  ( $3.8 \times 10^3$ ) to  $6.4 \times 10^3$  ( $1.6 \times 10^3$ ) particles  $\text{cm}^{-3}$  in Room V and significantly reduced from  $3.9 \times 10^3$  ( $1.8 \times 10^3$ ) to  $1.2 \times 10^3$  ( $5.2 \times 10^2$ ) particles  $\text{cm}^{-3}$  in Room N, respectively. When air filtration was increased in Room V (#5), mean PNC slightly reduced by 17% in Room V and reduced by 23% in Room N across Phase II and Phase III. Similarly, when air filtration was increased in Room N (#6), mean PNCs were reduced by 17% in Room V and by 40% in Room N across Phase II and Phase III.

As to the  $\text{PM}_{2.5}$  concentrations, similar results were found under Conditions #2–6 relative to the baseline scenario (#1). In Room V, mean  $\text{PM}_{2.5}$  concentrations were measured at  $6\text{--}9 \mu\text{g m}^{-3}$  across Phase II and Phase III. When the door connecting Room V and Room N was closed (#2), peak  $\text{PM}_{2.5}$  concentrations increased from 64 (45) (#1) to 69 (33)  $\mu\text{g m}^{-3}$  (#2) in Room V. Peak value reduced by 38% to 40 (14)  $\mu\text{g m}^{-3}$  when ventilation was enhanced in Room N (#4). In Room N, under Conditions #2–6, mean  $\text{PM}_{2.5}$  concentrations were about  $1 \mu\text{g m}^{-3}$  and peak concentrations were less than  $5 \mu\text{g m}^{-3}$  across Phase II and Phase III.

Miller and Nazaroff (2001) have investigated the transport of SHS with a similar experimental design. The PNC in their study decayed much slower in the smoking room (120–240 min) than exhaled e-cig particles in our study (25–50 min), presumably due to e-cig particle evaporation (Czogala *et al.*, 2014). Similar to what we observed under Condition #2, when door segregation was used, the transport of SHS was effectively reduced.

To better understand the effects of tested mitigation strategies on the transport of exhaled e-cig aerosols, the

ratios for mean PNC and  $\text{PM}_{2.5}$  were also presented in Figs. 4(c) and 4(f). Segregation was the most effective method to reduce the transport of ultrafine particles, in which the ratio was significantly reduced from 0.48 under the baseline condition to 0.06 ( $p < 0.05$ ). Mitigation strategies applied in Room N, including enhancing ventilation (#4) and filtration (#6), significantly reduced the ratio to 0.19 and 0.32, respectively. However, when mitigations were applied in Room V, no significant differences were found. As to  $\text{PM}_{2.5}$ , the ratios were about 0.11 (0.09–0.13) with mitigations and no significant difference was found compared with the baseline (#1, 0.12). Overall, the transport of exhaled e-cig aerosols could be effectively mitigated, especially by segregation. Other mitigations, including enhanced air ventilation and air filtration, could also increase particle removal. It should be noted that although the vaping activities were conducted by the same person with a consistent protocol, marked variations in particle emissions were observed even with the same mitigation conditions. Therefore, the experiment was repeated four times under each condition to capture these uncertainties, which is accounted for in statistical tests. Nevertheless, it is important to note that our results based on statistical tests are conservative, and the lack of statistical significance did not imply no risks since marked adverse effects might be occasionally caused by high emissions.

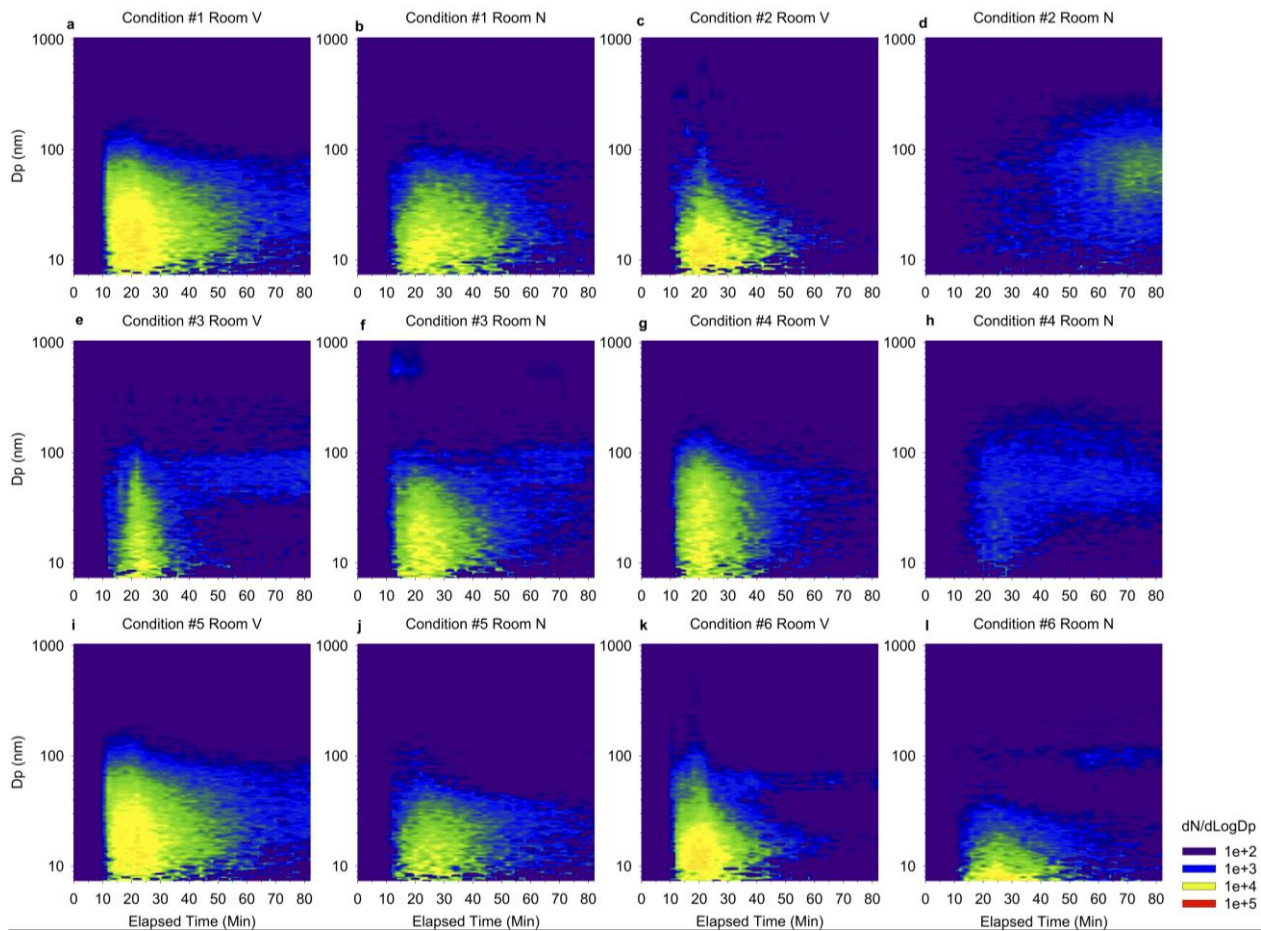
The infiltration of outdoor PM might also impact the observation in our study, but is expected to be minimal. In our previous study in the same building, we have observed a low infiltration rate for  $\text{PM}_{2.5}$  (0.02–0.13), due to the use of Minimum Efficiency Reporting Value (MERV) 14 filters in the central ventilation system (Lin *et al.*, 2019). In addition, even when marked outdoor emission (e.g., diesel exhaust) exists, the corresponding indoor  $\text{PM}_{2.5}$  increase was around  $3 \mu\text{g m}^{-3}$ , which was much lower than the  $\text{PM}_{2.5}$  increase observed in Phase II and III. Thus, we do not expect the infiltration of outdoor PM affects the conclusion of the current study.

### **Effects of Mitigation on Particle Size Distribution and Decay Rate**

Several factors determine the concentration of exhaled e-cig particles in an indoor environment, including particle generation, AER, and particle removal due to aerosol dynamics. In this study, to minimize the effect of particle generation, vaping was conducted by the same e-cig user using the same e-cig device and e-liquid with a prescribed vaping protocol. The background concentration was also subtracted to minimize the impact of infiltrated outdoor aerosols, leaving AER and particle removal due to aerosol dynamics the most important factors in determining indoor particle concentrations.

Fig. 5 presents the contour plots of the time-resolved particle size distributions measured in Room V and Room N under six conditions. The color in Fig. 5 shows the particle number concentration (dN/dLogDp) for a given time and a given size. Overall, during the vaping session (Phase II; elapsed time = 11–22 min), the particle size distribution in Room V was unimodal with a mode diameter at appropriately 15 nm. During the 60-min decay (Phase III; elapsed time = 23–82 min), PNC decreased for 40 min before returning to





**Fig. 5.** The time-resolved particle size distributions ( $dN/d\log D_p$ ) measured in Room V and Room N under Conditions #1–6. The vertical axes represent particle size on a logarithmic scale, the horizontal axes represent elapsed time from the start of sampling, and the color scale represents particle number concentration at a certain time and diameter.

the background concentration. AER was also found to be an important variable related to particle size distribution. A clear pattern was observed showing that the e-cig aerosols decayed faster and the peak concentration decreased (Fig. 5(e)) when ventilation was enhanced in Room V (#3). The transport of exhaled e-cig aerosols was largely reduced when door segregation was applied (#2, Fig. 5(d)) or ventilation was enhanced in Room N (#4, Fig. 5(h)), suggesting the effect of mitigations on the transport of exhaled e-cig aerosols.

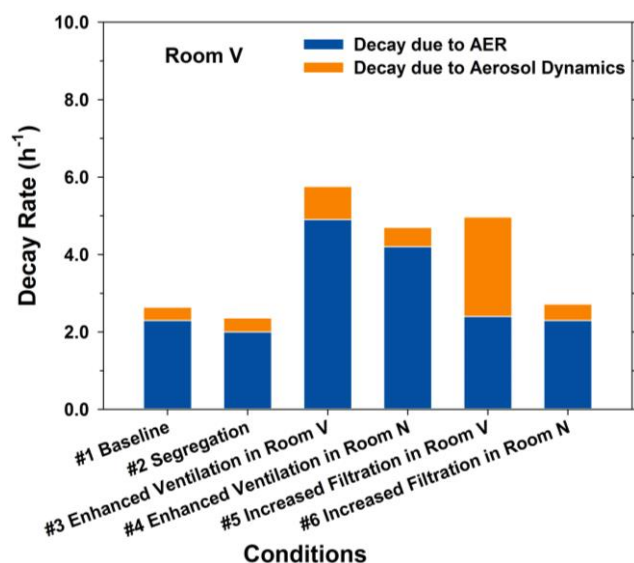
Besides particle size distribution, the effect of mitigations on particle decay rate was also investigated. Averaged particle number decay rate ( $k$ ;  $\text{h}^{-1}$ ) in Room V is affected by two factors: aerosol dynamics ( $\alpha$ ;  $\text{h}^{-1}$ ) and the AER ( $\lambda$ ;  $\text{h}^{-1}$ ). Thus, Eq. (2) can be expressed as:

$$-\ln(C_t/C_0) = k \times t = (\alpha + \lambda) \times t \quad (3)$$

The decay due to aerosol dynamics  $\alpha$  includes processes of particle gravitational setting, filtration, evaporation, surface deposition, coagulation, etc., which can be determined from the differences in the averaged decay rate  $k$  and AER. The results are presented in Fig. 6.

The relative contribution between AER  $\lambda$  ( $\text{h}^{-1}$ ) and aerosol dynamics  $\alpha$  ( $\text{h}^{-1}$ ) to the overall particle decay in Room V are

different across the five tested mitigation strategies. The averaged particle decay rates were measured at  $2.4\text{--}5.8 \text{ h}^{-1}$  ( $R^2 = 0.82\text{--}0.97$ ) across six conditions. Compared with the value under the baseline condition ( $2.6 \text{ h}^{-1}$ ), the decay rate decreased to  $2.4 \text{ h}^{-1}$  when door segregation was applied (#2). The decay rate increased to  $5.8 \text{ h}^{-1}$  when ventilation was enhanced in Room V (#3) and to  $5.0 \text{ h}^{-1}$  when filtration was applied in Room V (#5). When ventilation was enhanced in Room N (#4), the decay rate also increased to  $4.7 \text{ h}^{-1}$  in Room V, which supports our finding reported in Section 3.2, where the mean PNC in Room V under this condition reduced by 22% across Phase II and Phase III. Without filtration, decay due to AER contributed to about 85% of the decay rate. When the air purifier was on in Room V (#5), particle decay due to AER decreased to about 50%. These results suggest that AER is the primary contributor to the decay rate of exhaled e-cig particles. However, it should be noted that in real vape shops, the exhaled e-cig aerosols remained persistent and mixed due to factors including puffing activities by multiple e-cig users, the people's movement and more random exhalation behaviors. Unlike this experimental setting, the previous study found a relatively low decay rate and high mixing potential of exhaled e-cig aerosols in vape shops (Nguyen *et al.*, 2019).



**Fig. 6.** The decay rate of particle number concentration in exhaled e-cig aerosols in Room V. The decay due to aerosol dynamics includes processes of particle gravitational settling, filtration, evaporation, surface deposition, coagulation, etc.

Similar findings were reported in previous studies for SHS where greater particle decay rates were observed at a higher AER. For example, Liu and Zhu (2010) reported that decay rates of SHS particles were at 11.6–19.7 h<sup>-1</sup> inside a moving vehicle, of which the AER were 5.3–7.8 h<sup>-1</sup>. In an office room with a volume of 30 m<sup>3</sup>, AER and SHS decay rates were reported at 1.3 h<sup>-1</sup> and 1.3–3.5 h<sup>-1</sup>, respectively (Ning *et al.*, 2006). These results suggest that the AER is closely related to particle removal in an indoor environment and enhanced air ventilation increases particle removal efficiency.

Although our results suggest marked benefit of increasing AERs by reducing indoor PM levels originated from vaping, precautions must be made before extrapolating our findings to other indoor settings with natural or no ventilation. The building in the current study was centrally ventilated and MERV 14 filters are used to reduce the infiltration of outdoor PM. However, in other cases, increasing AERs may result in increased infiltration of outdoor PM, which should be taken into consideration when choosing mitigation strategies in the real world.

## CONCLUSIONS

This study focuses on the transport of exhaled e-cig aerosols and the effectiveness of mitigation strategies in a multizone indoor environment. The PNCs and PM<sub>2.5</sub> mass concentrations were measured continuously in two well-controlled adjacent rooms, a vaping room (Room V) and a non-vaping room (Room N), before, during, and after a 12-min vaping session under six different conditions. Although e-cigs, which do not use the tobacco combustion process or release a side stream, are perceived to be less harmful than traditional cigarettes to human health, high concentrations of particles—peaking at  $2.7 \times 10^4$  and  $9.9 \times 10^3$  particles cm<sup>-3</sup> in

Room V and Room N, respectively—were still detected in both of the rooms when no mitigation strategy was applied, with approximately 48% of PNCs and 12% of PM<sub>2.5</sub> being transported from Room V to Room N. Closing the connecting door between the two rooms reduced the particle transport from Room V to Room N by 94%, and enhancing the air ventilation or applying air filtration decreased the particle concentrations in Room V. These conclusions were also supported by the time-resolved particle size distribution measurements. The exhaled e-cig particles in our study decayed more quickly (25–50 min) than the SHS particles (120–240 min) reported by Miller and Nazaroff (2001). In the absence of the air purifier, the particle decay rate was primarily determined by the AER, which contributed about 85%; when the air purifier was operated in Room V, this contribution decreased to about 50%.

Our results offer insight into potential mitigation strategies in real-world settings, including vape shops and their adjacent businesses, which are potentially affected by the high particle concentrations emitted inside the former during business hours, and can be applied to minimize involuntary exposure and protect human health in a multizone environment.

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## DISCLAIMER

The authors declare that there is no conflict of financial interests or personal relationships in the outcome of this study.

## SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <https://doi.org/10.4209/aaqr.2020.03.0088>

## REFERENCES

- American Nonsmokers' Rights Foundation (2019). States and Municipalities with Laws Regulating Use of Electronic Cigarettes. <https://no-smoke.org/#1555694220625-13093c40-f073>
- American Society for Testing and Materials (ASTM) (1995). Standard test method for determining air change in a single zone by means of a tracer gas dilution. ASTM International, West Conshohocken, PA.
- Blount, B.C., Karwowski, M.P., Shields, P.G., Morel-Espinosa, M., Valentin-Blasini, L., Gardner, M., Braselton, M., Brosius, C.R., Caron, K.T., Chambers, D., Corstvet, J., Cowan, E., Jesús, V.R.D., Espinosa, P., Fernandez, C.,

- Holder, C., Kuklenyik, Z., Kusovschi, J.D., Newman, C., ... Pirkle, J.L. (2000). Vitamin E acetate in bronchoalveolar lavage fluid associated with EVALI. *N. Engl. J. Med.* 382: 697–705. <https://doi.org/10.1056/nejmoa1916433>
- Centers for Disease Control and Prevention (CDC) (2020). Outbreak of lung injury associated with the use of e-cigarette, or vaping, products. [https://www.cdc.gov/tobacco/basic\\_information/e-cigarettes/severe-lung-disease.html](https://www.cdc.gov/tobacco/basic_information/e-cigarettes/severe-lung-disease.html)
- Chen, R., Aherrera, A., Isichei, C., Olmedo, P., Jarmul, S., Cohen, J.E., Navas-Acien, A. and Rule, A.M. (2018). Assessment of indoor air quality at an electronic cigarette (Vaping) convention. *J. Exposure Sci. Environ. Epidemiol.* 28: 522–529. <https://doi.org/10.1038/s41370-017-0005-x>
- Ciuzas, D. (2016). Indoor air quality management by combined ventilation and air cleaning: An experimental study. *Aerosol Air Qual. Res.* 16: 2550–2559. <https://doi.org/10.4209/aaqr.2015.10.0577>
- Cullen, K.A., Ambrose, B.K., Gentzke, A.S., Apelberg, B.J., Jamal, A. and King, B.A. (2018). Notes from the field: Use of electronic cigarettes and any tobacco product among middle and high school students—United States, 2011–2018. *MMWR Morb. Mortal. Wkly. Rep.* 67: 1276–1277. <https://doi.org/10.15585/mmwr.mm6745a5>
- Czogala, J., Goniewicz, M.L., Fidelus, B., Zielinska-Danch, W., Travers, M.J. and Sobczak, A. (2014). Secondhand exposure to vapors from electronic cigarettes. *Nicotine Tob. Res.* 16: 655–662. <https://doi.org/10.1093/ntr/ntt203>
- Etter, J.F., Zäther, E. and Svensson, S. (2013). Analysis of refill liquids for electronic cigarettes. *Addiction* 108: 1671–1679. <https://doi.org/10.1111/add.12235>
- Fuoco, F.C., Buonanno, G., Stabile, L. and Vigo, P. (2014). Influential parameters on particle concentration and size distribution in the mainstream of e-cigarettes. *Environ. Pollut.* 184: 523–529. <https://doi.org/10.1016/j.envpol.2013.10.010>
- Geiss, O., Bianchi, I., Barahona, F. and Barrero-Moreno, J. (2015). Characterisation of mainstream and passive vapours emitted by selected electronic cigarettes. *Int. J. Hyg. Environ. Health* 218: 169–180. <https://doi.org/10.1016/j.ijheh.2014.10.001>
- Goniewicz, M.L., Knysak, J., Gawron, M., Kosmider, L., Sobczak, A., Kurek, J., Prokopowicz, A., Jablonska-Czapla, M., Rosik-Dulewska, C., Havel, C., Jacob, P. and Benowitz, N. (2014). Levels of selected carcinogens and toxicants in vapour from electronic cigarettes. *Tob. Control* 23: 133–139. <https://doi.org/10.1136/tobaccocontrol-2012-050859>
- Ingebrethsen, B.J., Cole, S.K. and Alderman, S.L. (2012). Electronic cigarette aerosol particle size distribution measurements. *Inhalation Toxicol.* 24: 976–984. <https://doi.org/10.3109/08958378.2012.744781>
- Jensen, R.P., Luo, W., Pankow, J.F., Strongin, R.M. and Peyton, D.H. (2015). Hidden formaldehyde in e-cigarette aerosols. *N. Engl. J. Med.* 372: 392–394. <https://doi.org/10.1056/NEJMc1413069>
- Kim, H.J. and Shin, H.S. (2013). Determination of tobacco-specific nitrosamines in replacement liquids of electronic cigarettes by liquid chromatography–tandem mass spectrometry. *J. Chromatogr. A* 1291: 48–55. <https://doi.org/10.1016/J.CHROMA.2013.03.035>
- Lee, M.S., LeBouf, R.F., Son, Y.S., Koutrakis, P. and Christiani, D.C. (2017). Nicotine, aerosol particles, carbonyls and volatile organic compounds in tobacco- and menthol-flavored e-cigarettes. *Environ. Health* 16: 42. <https://doi.org/10.1186/s12940-017-0249-x>
- Lerner, C.A., Sundar, I.K., Watson, R.M., Elder, A., Jones, R., Done, D., Kurtzman, R., Ossip, D.J., Robinson, R., McIntosh, S. and Rahman, I. (2015). Environmental health hazards of e-cigarettes and their components: Oxidants and copper in e-cigarette aerosols. *Environ. Pollut.* 198: 100–107. <https://doi.org/10.1016/j.envpol.2014.12.033>
- Li, L., Lee, E.S., Nguyen, C. and Zhu, Y. (2020a). Effects of propylene glycol, vegetable glycerin, and nicotine on emissions and dynamics of electronic cigarette aerosols. *Aerosol Sci. Technol.* <https://doi.org/10.1080/02786826.2020.1771270>
- Li, L., Lin, Y., Xia, T. and Zhu, Y. (2020b). Effects of electronic cigarettes on indoor air quality and health. *Annu. Rev. Public Health* 41: 363–380. <https://doi.org/10.1146/annurev-publhealth-040119-094043>
- Lin, Y., Hu, D., Fung, C.C., Marino, E. and Zhu, Y. (2019). Infiltration of diesel exhaust from a loading dock into a nearby building. *Atmos. Environ.* 216: 116949. <https://doi.org/10.1016/j.atmosenv.2019.116949>
- Liu, S. and Zhu, Y. (2010). A case study of exposure to ultrafine particles from secondhand tobacco smoke in an automobile. *Indoor Air* 20: 412–423. <https://doi.org/10.1111/j.1600-0668.2010.00665.x>
- McAuley, T.R., Hopke, P.K., Zhao, J. and Babaian, S. (2012). Comparison of the effects of e-cigarette vapor and cigarette smoke on indoor air quality. *Inhalation Toxicol.* 24: 850–857. <https://doi.org/10.3109/08958378.2012.724728>
- Melstrom, P., Koszowski, B., Thanner, M.H., Hoh, E., King, B., Bunnell, R. and McAfee, T. (2017). Measuring PM<sub>2.5</sub>, ultrafine particles, nicotine air and wipe samples following the use of electronic cigarettes. *Nicotine Tob. Res.* 19: 1055–1061. <https://doi.org/10.1093/ntr/ntx058>
- Mikheev, V.B., Brinkman, M.C., Granville, C.A., Gordon, S.M. and Clark, P.I. (2016). Real-time measurement of electronic cigarette aerosol size distribution and metals content analysis. *Nicotine Tob. Res.* 18: 1895–1902. <https://doi.org/10.1093/ntr/ntw128>
- Miller, S.L. and Nazaroff, W.W. (2001). Environmental tobacco smoke particles in multizone indoor environments. *Atmos. Environ.* 35: 2053–2067. [https://doi.org/10.1016/S1352-2310\(00\)00506-9](https://doi.org/10.1016/S1352-2310(00)00506-9)
- Mordor Intelligence (2018). E-cigarette market - growth, trends and forecast (2019 - 2024). <https://www.mordorintelligence.com/industry-reports/global-e-cigarettes-market-industry>
- Morean, M.E., Butler, E.R., Bold, K.W., Kong, G., Camenga, D.R., Cavallo, D.A., Simon, P., O'Malley, S.S. AND Krishnan-Sarin, S. (2018). Preferring more e-cigarette flavors is associated with e-cigarette use frequency among adolescents but not adults. *PLoS One* 13: e0189015. <https://doi.org/10.1371/journal.pone.0189015>
- Nguyen, C., Li, L., Sen, C.A., Ronquillo, E. and Zhu, Y. (2019). Fine and ultrafine particles concentrations in vape

- shops. *Atmos. Environ.* 211: 159–169. <https://doi.org/10.1016/J.ATMOENV.2019.05.015>
- Ning, Z., Cheung, C.S., Fu, J., Liu, M.A. and Schnell, M.A., (2006). Experimental study of environmental tobacco smoke particles under actual indoor environment. *Sci. Total Environ.* 367: 822–830. <https://doi.org/10.1016/j.scitotenv.2006.02.017>
- Ruprecht, A.A., De Marco, C., Saffari, A., Pozzi, P., Mazza, R., Veronese, C., Angellotti, G., Munarini, E., Ogliari, A.C., Westerdahl, D., Hasheminassab, S., Shafer, M.M., Schauer, J.J., Repace, J., Sioutas, C. and Boffi, R. (2017). Environmental pollution and emission factors of electronic cigarettes, heat-not-burn tobacco products, and conventional cigarettes. *Aerosol Sci. Technol.* 51: 674–684. <https://doi.org/10.1080/02786826.2017.1300231>
- Schober, W., Szendrei, K., Matzen, W., Osiander-Fuchs, H., Heitmann, D., Schettgen, T., Jörres, R.A. and Fromme, H. (2014). Use of electronic cigarettes (e-cigarettes) impairs indoor air quality and increases FeNO levels of e-cigarette consumers. *Int. J. Hyg. Environ. Health* 217: 628–637. <https://doi.org/10.1016/J.IJHEH.2013.11.003>
- Schripp, T., Markewitz, D., Uhde, E. and Salthammer, T. (2013). Does e-cigarette consumption cause passive vaping? *Indoor Air* 23: 25–31. <https://doi.org/10.1111/j.1600-0668.2012.00792.x>
- Sleiman, M., Logue, J.M., Montesinos, V.N., Russell, M.L., Litter, M.I., Gundel, L.A. and Destailats, H. (2016). Emissions from electronic cigarettes: Key parameters affecting the release of harmful chemicals. *Environ. Sci. Technol.* 50: 9644–9651. <https://doi.org/10.1021/acs.est.6b01741>
- U.S. Food and Drug Administration (2019). Vaporizers, e-cigarettes, and other electronic nicotine delivery systems (ENDS). <https://www.fda.gov/tobacco-products/products-ingredients-components/vaporizers-e-cigarettes-and-other-electronic-nicotine-delivery-systems-ends#regulation>
- Wang, B., Ho, S.S.H., Ho, K.F., Huang, Y., Chan, C.S., Feng, N.S.Y. and Ip, S.H.S. (2012). An environmental chamber study of the characteristics of air pollutants released from environmental tobacco smoke. *Aerosol Air Qual. Res.* 12: 1269–1281. <https://doi.org/10.4209/aaqr.2011.11.0221>
- Williams, M., Villarreal, A., Bozhilov, K., Lin, S. and Talbot, P. (2013). Metal and silicate particles including nanoparticles are present in electronic cigarette cartomizer fluid and aerosol. *PLoS One* 8: e57987. <https://doi.org/10.1371/journal.pone.0057987>
- Zhao, T., Shu, S., Guo, Q. and Zhu, Y. (2016). Effects of design parameters and puff topography on heating coil temperature and mainstream aerosols in electronic cigarettes. *Atmos. Environ.* 134: 61–69. <https://doi.org/10.1016/j.atmosenv.2016.03.027>
- Zhao, T., Nguyen, C., Lin, C.H., Middlekauff, H.R., Peters, K., Moheimani, R., Guo, Q. and Zhu, Y. (2017). Characteristics of secondhand electronic cigarette aerosols from active human use. *Aerosol Sci. Technol.* 51: 1368–1376. <https://doi.org/10.1080/02786826.2017.1355548>

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