

Highlights

The effect of air purifiers on aerosol dispersion and removal in multi-patient hospital rooms

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- Stand alone air purifiers evaluated as a method of preventing disease transmission.
- Novel transient aerosol release experiments used to determine cross-room transport times and effective air cleaning rates.
- Effective cleaning rates are close to those predicted by the purifier air flow.
- Concentrations mix within the room in less than the air exchange time, and only floor length curtains around the beds result in substantial reductions in aerosol transport.

The effect of air purifiers on aerosol dispersion and removal in multi-patient hospital rooms

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Abstract

Abstract Airborne particles cause indoor transmission of COVID-19. Here, aerosol dispersion and removal in an unoccupied 4-bed hospital room was characterized using a novel aerosol tracer experiment. NaCl particle concentrations were measured around the room following a tracer aerosol release for 27 configurations of air purifiers and curtains. Tests without portable air purifiers produced an air exchange rate of 3.8-7.4. The transportation time between the start of aerosol injection and detection at other sensors was 1.3 - 3.6 minutes indicating that even smaller droplets would be well-dispersed in the room before being removed by the ventilation system or settling. Short curtains surrounding the beds had little effect on aerosol distribution while long curtains helped in increasing both the Air Changes per Hour (ACH) and transportation time. The best configuration was 4 purifiers (effective ACH: 11.6) in the corners of the room (with curtains) and exhausting towards the ceiling. Conversely, using two purifiers located between beds, with the exhaust directed to the center of the room produced a high level of mixing and

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could spread large droplets through the room.

Keywords: Air purifiers, portable filter units, aerosol dispersion, hospital rooms, ventilation, COVID-19 transmission, aerosols, droplets

1. Introduction

Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-COV-2), the virus responsible for the COVID-19 pandemic, has killed over 2.5 million people by March 2021 (WHO, 2021). Disease transmission largely results from virus-containing particles produced via coughing, sneezing, vocalizations and even normal breathing (Jayaweera et al., 2020). The virus-laden particles can transmit the disease directly as another person inhales the particles (airborne transmission) (Zhang et al., 2020) or after being deposited on surfaces which are then touched by susceptible people (fomite mechanism) (Jayaweera et al., 2020). In the early days of the pandemic, different scientific communities had very different opinions on the critical transmission mechanisms. Public health agencies initially implemented inconsistent policies on wearing masks (Feng et al., 2020), but have now generally acknowledged that airborne transmission is the major mechanism, as suggested initially by some researchers (Morawska and Cao, 2020; Bazant and Bush, 2021).

There has been debate about the particle size which is of higher importance in the context of COVID-19 outbreak (Morawska et al., 2020; Tang et al., 2021). According to World Health Organization, respiratory infections can be transmitted through droplets of different sizes: when the droplet particles are $> 5\mu\text{m}$ in diameter they are referred to as respiratory droplets, and when they are $< 5\mu\text{m}$ in diameter, they are interchangeably referred to as

aerosols, droplet nuclei and airborne particles(WHO, 2014). Airborne particles are easily filtered by almost any building air handling unit but will be distributed by the gentle air currents found in most indoor settings. Larger droplets (roughly, $> 30\mu\text{m}$) will tend to settle to the ground within a few meters of a coughing or speaking person, whether they are indoors or outdoors.

The specific motivation for this research was an outbreak in October 2020 in a multi-patient hospital room in British Columbia, which resulted in several patients and workers testing positive for COVID-19(Fraser-Health, 2020). The main causes of the outbreak are still under investigation, but airborne particle transmission remains a likely candidate. The main room under investigation was supplied by an older Heating Ventilation and Air Conditioning (HVAC) system. Air Changes per Hour (ACH) is a key metric in determining ventilation rates and is defined as the volume of air added to or removed from a space in one hour, divided by the volume of the space. The HVAC system in the room (baseline) in question provided an ACH of 3.8-7.4 (slightly lower than other rooms in the hospital). Furthermore, the air supply and exhaust points were distributed so that some parts of the room had much lower ACH while there was cross-room transport in other areas.

Masks reduce airborne transmission(Macintyre and Ahmad, 2020), and both patients and workers in hospitals are expected to wear them. However, the pleated over-the-ear surgical masks often fit very poorly, allowing up to 30-40% of the particles to be transmitted via leakage. Even fitted N95 masks could have up to 10% leakage(Rogak et al., 2020; Darby et al., 2021).

Furthermore, patients in a hospital room cannot be expected to always wear their masks correctly. In this article, we focus on hospitals, but these issues are present in public spaces such as bars and restaurants, where mask wearing is counter to the purpose of the space. Thus, there is a need for a layer of protection on top of mask wearing, in many types of indoor spaces (Morawska et al., 2020).

Particles generated by occupants of a room will be dispersed before settling to the floor or leaving via the room's air exhaust ducts. The residence time of air in a room would range from about 5 minutes (12 ACH) to 30 minutes (2 ACH). Room ventilation flows will control the concentrations of particles with settling times much larger than the room residence time (small particles), while concentrations of particles with shorter settling times (larger particles) will be controlled by gravity. For reference, a 10 μm particle will settle out of a room in about 10 minutes (Hinds, 1999). Typical outdoor removal rates would be orders of magnitude higher, and it is impractical to increase building ventilation rates to match outdoor conditions. Furthermore, increasing the airflow in a room could have unintended consequences of transporting particles more effectively from one person to another, or in lofting particles that would otherwise settle quickly to the ground. The importance of long-range droplet transmission has been highlighted in a recent analysis of infection cases in a Korean restaurant, which were shown to occur due to brief exposures in a strong air current (about 1 m/s) from the index patient to a line of people who were infected (Kwon et al., 2021).

The possibility of using portable air filtration systems to reduce airborne concentrations of pollutants has been discussed by several scientists in dif-

ferent environments (Novoselac and Siegel, 2009; Ward et al., 2005). Few studies are concerned with the efficacy of air purifiers in reducing transmission of SARS-COV-2. One study focused on aerosol removal efficiency of air purifiers with different filters: fine filters (F6) and high-efficiency particulate absorbing (HEPA) filters and recommended the use of air purifiers in dental clinics (Zhao et al., 2020) but did not make recommendations about location/placement of such filters inside rooms. Another study focused on effectiveness of air purifiers in a single patient hospital room (Lee et al., 2021) but did not consider other interventions such as curtains and diffusers. Another study focused on using plastic curtains in hospital rooms to create multiple rooms, with portable HEPA units to reduce particle concentrations in one space and control room-room flow. A key result was that migration of aerosols from the patient space to the neighboring corridor could be reduced by 98% (Mousavi et al., 2020). However, the main transmission route is likely to be short range transport of particles from one patient to a neighboring patient or health-care worker in the same room. Simply placing an air purifier in that room will decrease average concentrations but will also create cross-room currents that could increase viral transmission. Another group used an extraction system with a small enclosure around the patient, but did not consider how the filtered air exhaust would affect cross-bed airflows (Mead and Johnson, 2004). Another group conducted experiments in a 6-bed hospital ward with a single HEPA filter (rated 4.7 ACH for the room) and found that the effective cleaning produced by the cleaner was within 30% of this theoretical value, and that the exhaust, aimed to the room center, produced a global circulation that dominated the overall air flow pattern (Qian

et al., 2010). However, the experiment was not set up to quantify particle transport from one bed to another. Very local extraction was developed by many groups for Aerosol Generating Medical Procedures (AGMP) such as intubation (Mick and Murphy, 2020; Sommer et al., 2020; François et al., 2020; Cottrell et al., 2020). Although this would be the most efficient source control possible, it is not suitable for patients that need to move around, or in the case that healthcare workers need good access to the patient.

Two very recent studies address the effectiveness of air purifiers in minimizing COVID19 transmission, and will be considered later in detail in the Discussion. Firstly, computer simulations were used to evaluate different configurations of purifiers added to a classroom (He et al., 2021). Secondly, an experimental study of an occupied classroom determined the effective ACH of air purifiers and the degree of concentration uniformity in a large room without any ventilation (Curtius et al., 2021).

In this article, our two main objectives were to: a) test several configurations of air purifiers placed in a real (but unoccupied) hospital room, and b) determine which configurations can reduce aerosol concentrations without increasing the spread of larger droplets.

2. Methods

These experiments supported the purchase of air purifiers by the local health authority, and it was decided to carry out the experiment in realistic conditions in a hospital room. Naturally, it was impossible to conduct the tracer experiments in an occupied room. Many variables were considered, using commercially available air purifiers. Because we could not carry out

a full factorial test plan, it was difficult to isolate controlling factors in the experiments. On the other hand, working within the natural variability of the setting, we were able identify some robust patterns – that is, results likely applicable to a range of room types.

2.1. Particle Measurements

This study relied mainly on the Remote Affordable Multi-Pollutant Sensor (RAMP, SENSIT Technologies). The RAMP includes low-cost sensor modules for measuring Particulate Matter (PM₁, PM_{2.5}, PM₁₀), NO, NO₂, CO, Ozone(O₃) and CO₂ within a weather-proof shell (Zimmerman et al., 2018). The RAMP uses laser scattering to measure PM and electrochemical sensors to measure CO, NO, NO₂ and O₃. CO₂ is measured using a Non-dispersive Infrared sensor. Data from the RAMP sensors are uploaded via cellular networks to an online server enabling remote monitoring. The RAMP records data every 15 seconds. A smoothing function (smoothdata) in MATLAB was used with a ‘movmedian’ setting to smooth the RAMP data by taking the median over a three-element sliding window. The accuracy of low-cost optical PM sensors signal is affected by (i) the omission of particles smaller than minimum detectable size ($< 300nm$); (ii) influence of temperature and (iii) Relative Humidity (RH) (Malings et al., 2019). Calibration or collocation alongside scientific grade instruments is needed for the PM sensors and gas-phase sensors (Zimmerman et al., 2018; Malings et al., 2019, 2020). We conducted a side-by-side collocation of all RAMPs and Pearson’s correlation coefficient was above 0.97 (Figures S1, S2, S3 and S4 in SI). The sensor IDs referred to in the SI are located as shown in Figure 1. RH and temperature were approximately constant (Figure S2 and S3 in SI)

with variation observed in 2 sensors at different time periods. Using the correction factors previously published (Malings et al., 2020) and using sample RH (50%) and T (22°C), it is estimated that raw PM_{2.5} measurements of 10 $\mu\text{g m}^{-3}$ and 100 $\mu\text{g m}^{-3}$ correspond to a corrected PM_{2.5} of 9.63 $\mu\text{g m}^{-3}$ and 71.17 $\mu\text{g m}^{-3}$. A different RH (30%) and same T(22°C) would result in similar values: 10 $\mu\text{g m}^{-3}$ (8.57 $\mu\text{g m}^{-3}$) and 100 $\mu\text{g m}^{-3}$ (65.88 $\mu\text{g m}^{-3}$) where values in parenthesis indicate corrected PM_{2.5} concentrations. However, in this study, we are concerned with the relative change in concentrations and not absolute values. Hence, raw measurements as reported by RAMPs have been used directly without applying any correction factors.

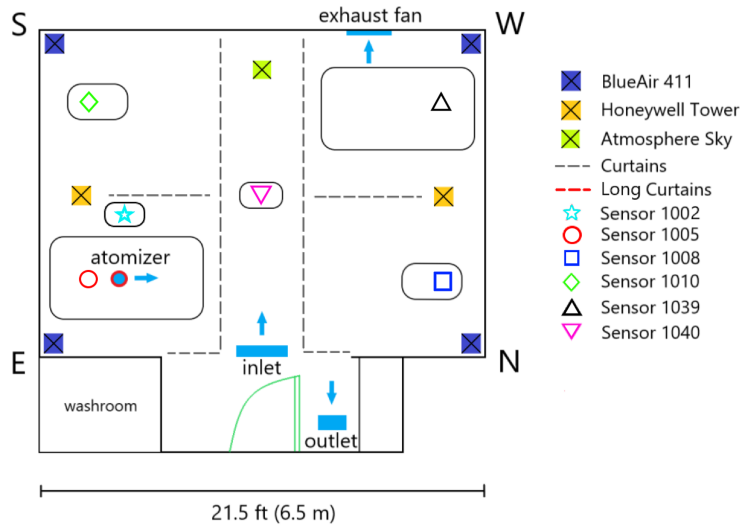


Figure 1: Plan of test room. Air purifier locations (X) are shown in relation to the RAMP positions. Supply (inlet) grill is mounted on the edge of the alcove drop ceiling and directs air to the SW. Return (outlet) grill is mounted on the drop ceiling.

Particle size distributions were also measured using an Optical Particle Sizer (OPS, TSI Model 3330). The OPS measures particles from 0.3 to 10

μm in 16 user adjustable size channels.

2.2. Aerosol Source and Test Sequence

A sodium chloride (NaCl) solution was dispersed using a Sonair MedPro ultrasonic nebulizer, without charge neutralization. The concentration of the solution was set to produce dried aerosol particles with a mass median diameter of approximately $3 \mu\text{m}$. For this particle size, gravitational settling reduces concentrations at a rate equivalent to 0.5 ACH, on top of the true air exchange or cleaning rate. Also note that for this particle size, particle removal efficiency would be nearly 100% for all purifiers tested. The nebulizer was placed near the middle of one bed to simulate the cloud of particles produced by an infected patient. The nebulizer produced a jet of particles with a “throw” of 30-50 cm directed towards the foot of the bed, away from the sensor in that space. The nebulizer automatically operates for 10 minutes and 15 seconds after it is turned on. All experiments were conducted using this same period of aerosol generation, followed by 15 minutes in the specified configuration, followed by 10 minutes of clearing with all purifiers on. By the end of the 35-minute sequence, PM_{10} concentrations were consistently reduced to less than $1 \mu\text{g m}^{-3}$ – about 1% of the peak values recorded during the experiment. The pulse tracer technique (Persily and Axley, 1990) has been used for gaseous tracers, but we are not aware of it having been used to assess aerosol transport time.

2.3. Air Purifier Configurations

We tested configurations with 0, 1, 2 or 4 purifiers in the room, in locations that would cause minimal disruption to the activities of patients and

health care workers.

2.3.1. Corner upflow

In this configuration, a vertical exhaust purifier was placed in the room corner near the head of the bed. The intake was located 4 feet above the floor. For the corner upflow configuration we used the Blue Air 411 purifiers (except for experiments 3 and 4 which used 2 Honeywell towers on their sides, in addition to 2 Blue Air units). These units use cylindrical “HEPA type” filters with a nominal efficiency of 99% for $\text{PM}_{2.5}$. Our tests of the filter material suggest that the actual performance is approximately 99% filtration at $1\ \mu\text{m}$. These units use a radial inflow and with a vertical exhaust. Each is rated for 5 ACH in a 161 sf ($15\ \text{m}^2$) room, equivalent of 103 cfm ($175\ \text{m}^3\text{h}^{-1}$). Thus, 4 of these units should clean 7.1 room volumes per hour.

2.3.2. Between-beds horizontal flow

In this configuration, two horizontal axis towers were placed between pairs of beds. For this configuration, we used a Honeywell HFD 310C (Air Genius 4) for the west wall. It uses a true HEPA filter and is rated for a 250 square feet room with 161 cfm ($274\ \text{m}^3\text{h}^{-1}$). A unit of this type would clean the equivalent of 2.7 ACH. For the east wall (near the aerosol source in most tests), we used a Honeywell HFD 122qc. The filter has a nominal efficiency of 99% at $0.3\ \mu\text{m}$. The unit is rated for 170 sf ($16\ \text{m}^2$) with 109 cfm ($185\ \text{m}^3\text{h}^{-1}$). There are two important variants of the between-beds configuration: exhaust towards the foot of the beds, or exhaust towards the head of the beds (or walls).

2.3.3. Single purifier directed at exterior wall

In this configuration, a single large purifier was positioned on the room center-line with the exhaust directed at the exterior wall. The intention here is to create a symmetrical arrangement opposing the tumble induced by the room's built in ventilation system. The velocity of the exhaust is large but directed at the wall, velocities decay rapidly as air moves up and to each side. For this configuration, we used Atmosphere Sky. This unit has a rectangular HEPA filter and exhaust angled approximately 45 degrees upward. Rated for 465 sf (43 m²), it cleans approximately 300 cfm (510 m³h⁻¹).

2.4. Test Room Layout

The test room (room 213 of Delta Hospital, Figure 1) is intended for 4 patients and has an area of 398 sf (37 m²) including a 48 sf (4.5 m²) entry alcove. The door to the washroom was closed and this small room is not included in the totals above. The room supply air is located on the alcove drop ceiling and directs air along the center-line towards the exterior wall. The return air grill is located directly above the room entry door. Thus, the normal ventilation system creates a tumbling pattern of air moving towards the windows at ceiling height and returning along the floor to the entry door. Flow rates are likely variable, but measurements before the present test program suggests that it provides 3.5 ACH with 206 cfm (350 m³/h). This particular room had been retrofitted with exhaust fans in a window panel of the south wall. Although these fans were not operated during our tests (except for 2 cases as noted below), infiltration/exfiltration through the fan opening could have been very substantial on the second test day, which was windy.

Each bed space was fitted with sliding curtains. These curtains did not run floor to ceiling (unless otherwise stated in Table 1), but instead had gaps of approximately 20 inches (0.5 m) at the top and bottom. On Day 1, measurements were made for curtains open and closed, but on Days 2 and 3, all tests were done with the curtains closed – assuming that this would be the configuration used if there was concern over COVID-19 transmission within the room.

Because tests were conducted in a working hospital applying COVID-19 protocols, the researchers conducting the tests stayed in the room during all tests, wearing masks and remaining in the SE or NW sections of the room. Undoubtedly this had some small effect on air flows, but the level of activity was probably less than the normal activity in an occupied hospital room.

3. Data Analysis

Evaluation of the air purifier configurations was based mainly on measurements from the 5 RAMPs (on Days 1 and 2) and 6 RAMPs (on Day 3). The average concentrations provided some information on purifier effectiveness, but because the tests did not model continuous particle emissions, we focus on extracted features such as decay time (t_{decay}) and transport time (t_{trans}).

We observed that after the aerosol source is turned off, concentrations at all sensors decay at a similar rate. By fitting an exponential for 15 minutes after the aerosol is turned off, we obtained the first order decay time, and from this the “effective air changes per hour”, the ventilation rate for the idealized case of a well-mixed room where the only particle removal mechanism is air

exchange. This parameter controls the steady-state particle concentrations for steady aerosol generation.

We were also concerned about the potential for air purifiers to create drafts that could rapidly transport large droplets from an infected person to other people in the room. As a surrogate for this risk, we extracted the time delay between the start of aerosol generation and the detection of particles at the 4 sensors away from the aerosol source (as a model for 3 other patients and a health care worker in the center of the room). The transport time is indicative of the time available for particles to settle to the ground before the air parcel reaches another person.

4. Results

Table 1 summarizes the main experimental results as well as the experimental conditions. Experiments 1-6 were done on Day 1; experiments 7-19 on Day 2, and 20-27 on Day 3. Figure 2 shows the progress of experiment 5, conducted on Day 2. This experiment was typical of runs without any additional air purifiers. Although the atomizer is directed away from the nearest sensor, circulation in the room brings the particles back to that sensor in approximately 2 minutes. As expected, the concentrations at the 4 sensors away from the atomizer are much lower, and show a delayed response indicating a finite travel time. After the atomizer switches off an exponential fit to the concentrations provides an estimate of the decay rate or effective air changes per hour (ACH). The RAMP in North corner of the room typically showed the lowest concentrations, possibly reflecting the general flow from the East end of the room to South end of the room.

Table 1: Summary of experiments, ordered by configuration rather than the chronological experiment number. BA=Blue Air; HW=Honeywell; Diff=Diffuser.

Expt.	Src. Loc.	Config.	Curtain	Air Changes per Hour				Conc. ($\mu\text{g}/\text{m}^3$)	
				Purifier Nom.	From Decay	Above Base	Delay (min)	Source	Affected Area
1	E	Base	-	-	3.8	-	3.16	163	43
5	E	Base	-	-	4.1	-	2.87	141	42
7	E	Base	yes	-	6.8	-	2.59	75	25
14	E	ex. fan	yes	-	7.1	0.3	2.32	31	25
17	W	Base	yes	-	N/A	-	3.31	143	18
20	E	Base	yes	-	7.4	-	3.32	22	9
27	E	Base	long	-	4.9	-	3.33	61	19
2	E	2 BA	-	3.6	6.9	3.0	3.59	170	36
3	E	2 BA	yes	3.6	6.6	2.7	2.47	175	39
4	E	2 BA 2HW, corners	yes	8.1	15.5	11.5	2.48	224	23
6	E	2 BA 2HW, corners	-	8.1	13.9	10.0	2.64	81	23
8	E	4 BA	yes	7.1	14.4	7.6	1.64	108	25
9	E	4 BA+Diff	yes	7.1	16.8	9.9	2.24	92	21
10	E	4 BA+Diff	yes	7.1	14.4	7.6	2.54	92	20
15	E	4 BA+Diff	yes	7.1	14.7	7.8	2.59	74	16
21	E	4 BA+Diff	yes	7.1	16.9	9.5	3.02	32	7
18	W	4 BA+Diff	yes	7.1	14.2	7.3	2.82	79	15
24	E	4 BA+Diff	long	7.1	14.9	10.0	3.09	81	8
25	E	4 BA	long	7.1	16.5	11.6	2.05	90	19
11	E	2 HW->center	yes	4.6	17.5	10.6	1.61	14	12
22	E	2 HW->center	yes	4.6	19.5	12.1	1.26	10	11
12	E	2 HW->wall	yes	4.6	12.8	5.9	2.45	88	19
13	E	2 HW->wall	yes	4.6	12.8	6.0	2.45	86	21
19	W	2 HW->wall	yes	4.6	14.9	8.0	3.42	104	15
23	E	2 HW->wall	yes	4.6	18.9	11.5	3.63	24	7
26	E	2 HW->wall	long	4.6	13.2	8.3	3.26	15	6
16	E	1 Atm, aisle	yes	5.8	15.1	8.3	2.54	25	11

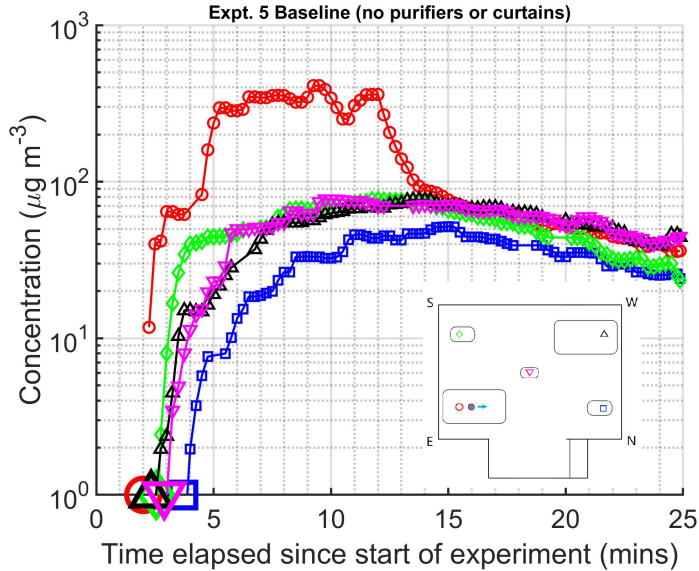


Figure 2: Time series of PM_{10} concentrations as measured by RAMPs placed in different corners of the room during a baseline experiment (Experiment 5; Table 1)). No purifiers or curtains were installed. The enlarged markers on the x-axis denote the transport time (t_{trans}) for each sensor. The trace color and symbol for each sensor on the plot is consistent with the graphical legend provided. Aerosol injection started at $t = 0$ minutes.

Concentrations during Experiment 4 (Figure 3), with four corner-mounted purifiers and curtains installed, behaved similarly to Experiment 1 (Figure S5 in SI), with a few important differences. The transport time for the sensor nearest the atomizer was reduced, and peak concentrations for this sensor were increased. This was due to a circulation induced by the purifiers which drew air from the foot of the bed towards the sensor, up the corner, and away from the corner at ceiling height. Despite the presence of curtains, the 4 sensors away from the atomizer start to register particles at almost the same time as for the no-curtain baseline (Figure 3). The north and west sensors,

separated by two curtains from the atomizer, show the lowest concentrations, but otherwise the curtains have remarkably little effect on the distribution of particles within the room. For example, the signals for all sensors start to rise in 2 to 3 minutes of the atomizer start, for most configurations tested. This is approximately the settling time of a $20 \mu\text{m}$ droplet, implying that droplets and aerosols of smaller size would be well-distributed within the room, regardless of the presence of curtains or purifiers in our experiments.

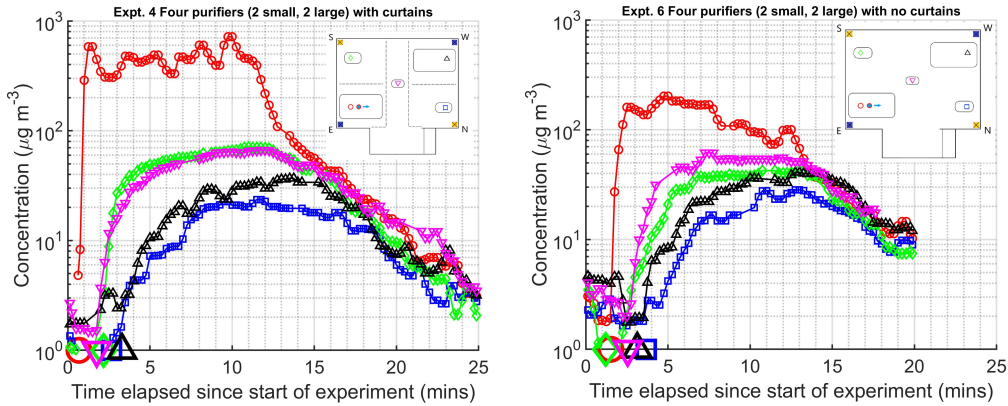


Figure 3: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 4 and Experiment 6. The enlarged markers on the x-axis denote the transport time (t_{trans}) for each sensor. The trace color and symbol for each sensor on the plot is consistent with the graphical legend provided. Aerosol injection started at $t = 0$ minutes. Data logging error prevented collecting the last five minutes of data in the right panel.

The configuration with two purifiers exhausting to the room center (Experiment 11, Figure 4) produced radically different concentration patterns. This configuration induced a flow at bed level from head to foot, directly entraining the atomized particles and carrying them away from nearby sen-

sor. This resulted in the smallest transport time (1.61 minutes), and in fact the sensor nearest the atomizer slightly lagged the other sensors (based on the time to half-maximum). During Experiment 11, it was evident that the exhaust jet of the purifiers produced movement in curtains on the other side of the room, and from the purifier flow rate and exhaust area, one might expect velocities greater than 1 m/s, enough to carry the largest droplets across the room in under 10 seconds. The fact that actual sensor lags were still well over a minute indicates that the high jet velocities are highly localized – they could carry large droplets to an unlucky susceptible person, but the overall mixing in the room is determined by the larger scale motions in the room. The average concentrations for Experiment 11 were considerably lower than in the other cases. This implies that purifiers exhausting to the room center would be the best configuration for smaller aerosol particles, but the decreased transport time and observed drafts increase the risk of large droplet transport.

The Optical Particle Spectrometer provided no spatial information, and poor temporal resolution, but did provide information on particle size. Over the 15 minutes after the atomizer was turned off, the larger particles with reliably high counts (optical size 2.58 to 3.96 microns) decayed faster than the sub-micron particles by a factor of 1.07 to 1.24. This is roughly consistent with the sedimentation losses expected for the larger particles.

The baseline ACH (from concentration decay time) at the start of the Day 1 was 3.81 ACH (Expt. 1), and at the end was 4.06 ACH (Expt. 5). The average of these two was used to estimate the incremental effect of air purifiers or other treatments (such as turning on a supplemental window-mounted

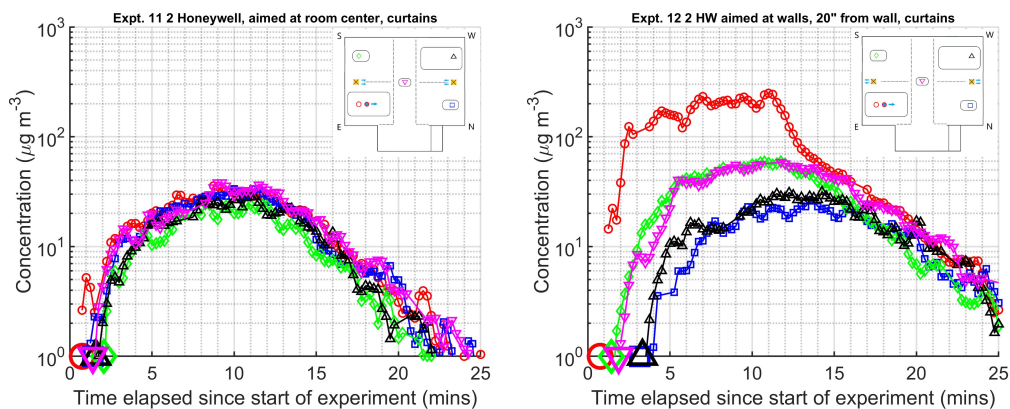


Figure 4: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 11 and Experiment 12. The enlarged markers on the x-axis denote the transport time (t_{trans}) for each sensor. Trace color and sensor symbols are given in the graphical legend. Aerosol injection started at $t = 0$ minutes.

exhaust fan). This “above-baseline” ACH increased with the purifier rated flow (aka “nominal ACH” value) but was often above or below these nominal values. This is physically possible given that the effective ACH depends not only on the purifier flow rate, but on the effective volume being treated. Cases with higher than expected ACH imply that particles are confined to a smaller volume around the purifiers and sensors. The RAMPs provide a signal for PM_1 , and $PM_{2.5}$ in addition to PM_{10} (used for the analysis above). In nearly all cases, the ACH computed from these smaller size cuts was very close to that computed from PM_{10} (Figure S27, S28 and Table S1, S2 for the Supplemental Information). Discrepancies on the order of 30% were observed for 3 experiments with high ACH, and this might have been due to lower signal-to-noise ratio at the end of the experiment.

Days 2 and 3 were windy, and this was reflected in higher ACH for the baseline configurations. Undoubtedly variations in outdoor wind conditions added variability to the experimental results. Average concentrations on Days 2 and 3 were lower than on Day 1, consistent with higher baseline ACH (6.84 for Expt. 7 and 7.38 for Expt. 20). We believe that air was being drawn out of the window-mounted exhaust fan, even when the exhaust fan was turned off. In fact, turning the fan on as the only intervention appeared to have little impact on ventilation (Expt. 14). Experiment 8 exhibits an anomalously low average transport time (1.64 minutes), which we believe to be due to an error in the atomizer start timing. Parameters that would not be affected by a timing error (ACH and average concentrations) in Expt. 8 are similar to the other runs with the 4 corner purifiers.

For experiments 1-16, the atomizer was in the East corner of the room. For experiments 17-19, it was moved to the West corner of the room, which was near the window-mounted fans. Although these experiments showed similar concentration behaviors (Figure S16, S17 and S18 in SI), the average concentrations decreased. This was likely due to the continuous exfiltration of air through the window-mounted fans, even when the fans were turned off.

On Day 3, long curtains were used in experiments 24, 25, 26 and 27 (Figure S23, S24, S25 and S26 in SI). Experiment 9 on Day 2 and Experiment 24 on Day 3 provide a direct comparison between the effect of short and long curtains when 4 air purifiers were used with diffuser cones. The apparent ACH for Experiment 9 was 9.94 and the corresponding number for Experiment 24 was 10.02. The t_{trans} for Experiment 9 was 2.24 minutes and the corresponding value for Experiment 24 was 3.09 minutes. This provides ev-

idence that long curtains increased the transport time of particulate matter from the source to other corners of the Test Room. Long curtains did not have a significant impact on the ACH.

5. Discussion

Here we consider the above results in the context of a simple mass balance model and also in the context of prior studies. Firstly, a model of particle removal can help understand the interactions between particle size, ventilation, and portable air filters. Assuming that particles are well mixed within the room, a steady-state mass balance shows that the concentration of particles of a certain size is a balance between generation rate S per unit volume, fresh air supply Q_s , filtration flow Q_f , and gravitational deposition velocity V_d , which is a strong function of particle size. For a room of volume V and flow area A , the concentration can be calculated as per Equation 1.

$$C = \frac{S}{\frac{(Q_s + Q_f + A * V_d)}{V}} \quad (1)$$

The terms in the denominator are all proportional to air changes per hour (ACH) or the equivalent. Comparing the concentrations with the portable air filtration C_F with the baseline concentrations C_0 , we can formulate Equation 2:

$$f = \frac{C_F}{C_0} = \frac{1}{1 + \frac{ACH_F}{(ACH_S + ACH_d)}} \quad (2)$$

We desire a reduction factor f that is as small as possible, and this is clearly achieved by having a very large flow through the portable filtration unit (high ACH_F) relative to the baseline room ventilation ACH_S and the gravitational settling of particles ACH_d). Gravitational settling becomes the dominant

term for large droplets. Figure 5 shows that for smaller particles (3 μm and below), the reduction in concentration produced by the addition of portable air filtration should be directly proportional to the increase in total air volumes removed or processed $ACH_F/(ACH_F+ACH_S)$. However, for particles substantially larger than 10 μm , air purifiers would have negligible impact on concentrations unless they are very large. For example, the gravitational settling of 30 μm droplets is equivalent to air treatment at a rate of almost 50 ACH. Air distribution for such high ACH is possible but technically challenging. Concentrations of 10 μm particles can be substantially reduced with practical ventilation and portable filtration systems. For most of the experiments reported above, the baseline room ventilation rate was 3-7.5 ACH, and the air purifiers added another 2-12 ACH.

This well-mixed model is neither an upper or lower bound on the reductions that would be achieved in an inhomogeneous environment. If the air filtration system and aerosol source are located in the same partially isolated room sub-volume, then the impact will be larger than expected based on the whole-room air exchanges. However, if the air purifier and source are located in separate volumes with poor communication, then poor performance is expected. The validity of the well-mixed assumption also depends strongly on the particle size. The settling time of 30 μm particles is 1-2 minutes, which is smaller than the transport time for the better configurations tested, but comparable to the transport time in the worst configuration.

Finally, we compare our experimental findings with this model and with two recent papers on air purifiers. The modelling (He et al., 2021) comes closest to our aims but arrives at starkly different results. Firstly, they find

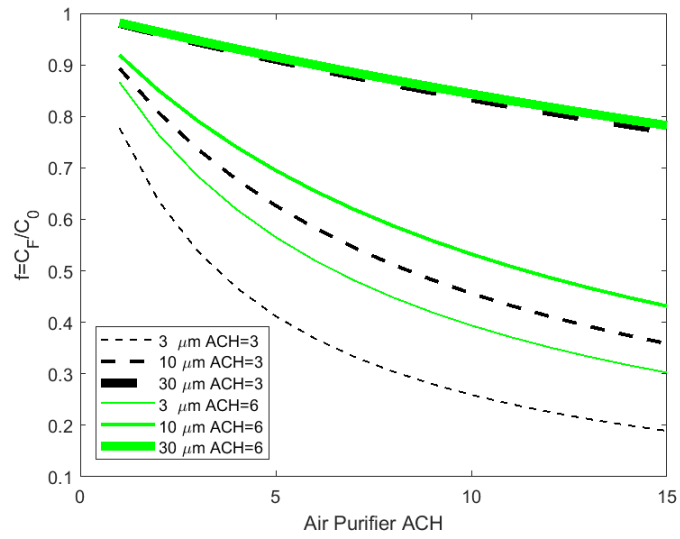


Figure 5: Ratio of concentrations of particles with and without an air purifier, as a function of air purifier treatment rate and the particle size in consideration. Lower values of f indicate greater benefit from adding the air purifier.

highly non-uniform concentrations, with COVID risk (essentially, particle number concentration) falling away by several orders of magnitude within a few meters of an infected person in an open room. This is likely an artifact of using a RANS simulation with a k-epsilon turbulence model. We find that in an open room configuration (ie., no curtains), concentrations become well mixed (to within a factor of 2 or 3) shortly after an aerosol source is turned off. This appears to be consistent with measurements of Curtius et al (Curtius et al., 2021), but the homogeneity there could have been due to having uniform initial concentrations. Curtius et al measured concentrations at only 2 locations, compared to the 5 or 6 locations used in our work.

If the concentrations in the room are approximately well mixed, the impact of an air purifier should be easily predicted known the clean air delivery rate CADR (as assumed in the simple model above). Curtius et al find that the incremental effect of air purifiers is consistently 80% of that expected from the CADR. In those experiments, the two measurement locations were in corners of the room, far from the purifiers, where ventilation might indeed have been lower. In our experiments, the incremental effect of the purifiers was typically higher than expected from the CADR and more variable (see Table 1). This is partly due to the localized cleaning (air purifiers were placed in the zone with the source) and partly due to the difficulting of establishing an accurate baseline ACH (unlike Curtius’s experiments, the building ventilation system was operating and air infiltration could have been substantial). In contrast, He et al find the purifiers to be spectacularly effective if placed by the source, likely due to the underestimated mixing mentioned above. The simulation study also finds that wall losses of 2 micron particles were

equivalent to well over 2 ACH (based on their reported 80% loss over the 50 minute simulation), quite inconsistent with our theoretical expectations and the fact that our measured particle loss rates are consistent with ACH.

Neither of these previous studies consider the effect of purifiers on larger droplets (those with appreciable settling rates). Our experiments also used small aerosols, but the transport delay time at least allows us to make a qualitative assessment of the potential of the different configurations to mix larger droplets across the room.

6. Conclusions and outlook

Transient injections of sodium chloride aerosols were used to assess the ventilation patterns of an unused 4-bed hospital room using various configurations of air purifiers. The baseline ventilation system produced concentration decays equivalent to 3.81 to 7.38 ACH, apparently as a function of outdoor wind conditions. With this ventilation rate, and with curtains around each bed, the particle transport time from one bed to another was only a few minutes, providing ample time for even 10 - 20 μm droplets to disperse widely within the room before settling out. Also, given the low velocities in the room ($\ll 1\text{m/s}$) and large dimensions of the obstacles, inertial impaction of particles is expected to be negligible. Our observations here imply that the plexiglass barriers used in bars, restaurants and stores will be ineffective for these particles which are at the small end of the droplet spectrum, and widely believed to be significant to the transmission of COVID-19.

The best configurations of air purifiers did not decrease the transport time significantly, indicating that they do not introduce much additional risk

of spreading droplets from patient to patient. Most of the systems considered were capable of removing particles twice as fast as the baseline room. This implies that concentrations will be reduced by a factor of 2 for aerosols and the smallest droplets, but by much less for large droplets. As context, these reductions are quite modest compared to the protection provided by masks.

Assuming that large droplet transmission is important, air purifiers should not exhaust horizontally into the main part of a room as this will certainly transport droplets across a typical room. Fortunately, reversing the orientation of the purifier so that the exhaust jet energy is dissipated partly on a wall will help a great deal. The use of small purifiers for each bed should in theory be much better than sharing purifiers between beds. However, the evidence for this is weak so far, perhaps because the curtains surrounding each bed are quite open, and because the baseline room ventilation produces substantial mixing even without purifiers. Further work is needed to determine if addition of better air diffusers or extended curtains could improve the effectiveness of air purifiers placed near hospital beds.

Fundamentally, in selecting the size and location of air purifiers there is a trade-off between wanting a large air cleaning rate (critical for control of aerosols) and avoiding the creation of drafts that would carry large droplets from one person to another. If it turns out that COVID19 is spread mainly through smaller aerosols, then this small risk from exhaust drafts would be eliminated.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgements

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Supporting Information

Supporting Information is available online.

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Supplementary Information - The effect of air purifiers on aerosol dispersion and removal in multi-patient hospital rooms

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A collocation test was conducted prior to Day 3. All 6 RAMP sensors used in this study were placed in a room with uniform mixing. NaCl particles were then introduced diagonally across from the sensors. All sensors picked up the PM₁₀ signal at the same time. The temperature and Relative Humidity (RH) were constant as well. Figure S1 shows the time-series plots for the collocation test. The difference in magnitude of sensor concentrations should not affect the results presented in this study as we focus on the decay rate (to calculate effective ACH) and transport time. RH and Temperature are known to affect the RAMP's PM measurements. Figure S2 and S3 show the time-series of RH and temperature on all three experiment days. The RH remained constant throughout. On Day 2, temperature for Sensor 1039 increased relative to other sensors. Sensor 1039 was located next to the window (West corner) and it is possible that ambient environmental conditions influenced this response. On Day 3, Sensors 1040, 1008 and 1039 exhibited increase in temperature at different times of the day, which are also attributed to ambient environmental

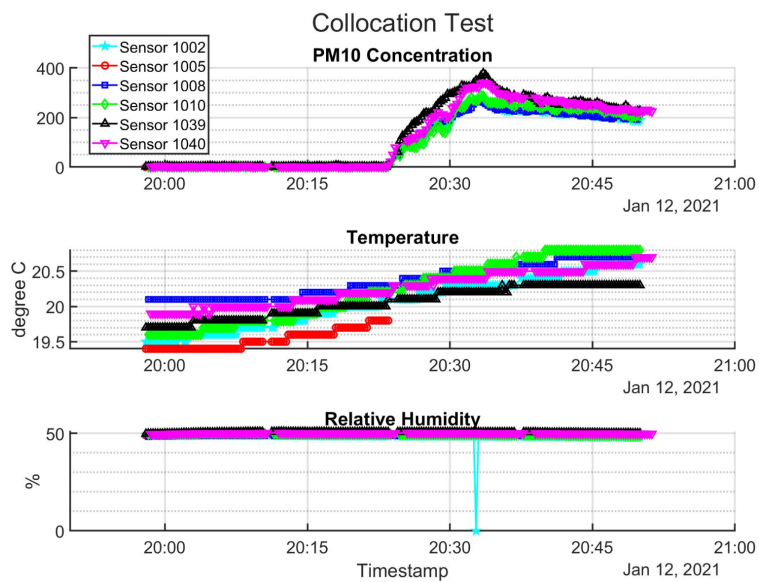


Figure S1: Top-most panel plots PM_{10} concentrations during a collocation test performed prior to “Day 3”. The middle and bottom-most panels show the time-series of Temperature and Relative Humidity during the same time period.

conditions. No temperature and RH corrections were applied to the RAMP data set in this study.

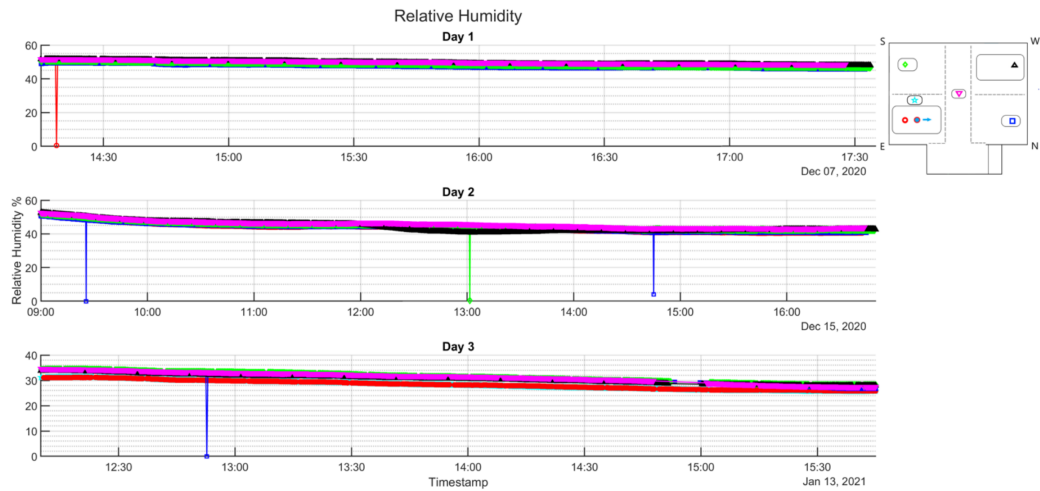


Figure S2: Time series plots of Relative Humidity % on all three experiment days.

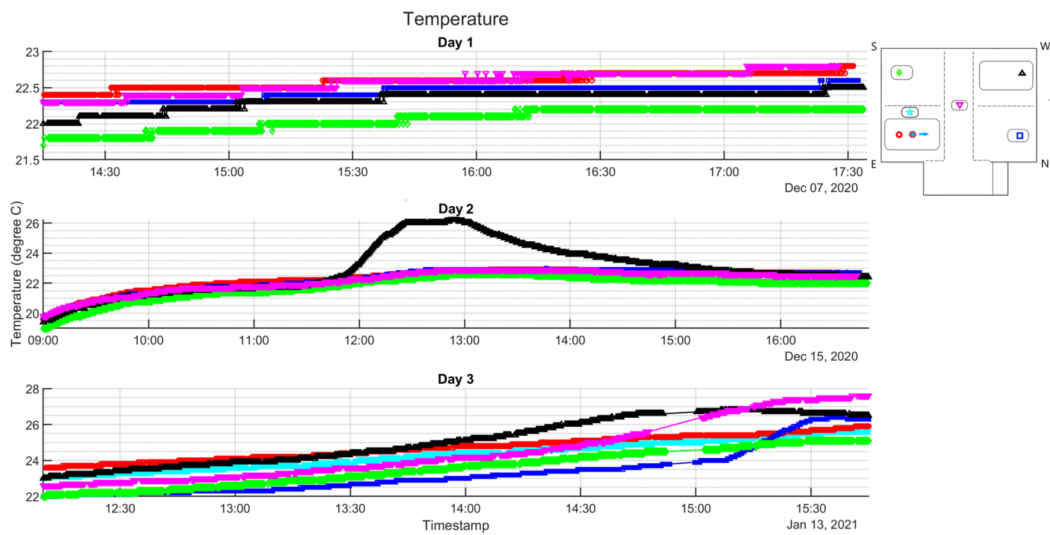


Figure S3: Time series plots of Temperature (deg C) on all three experiment days. Sensor 1039 was an outlier on Day 2 between 12 pm and 3 pm. Sensor 1008 also appears to have elevated temperature between 3.15 pm and 3.45 pm.

	PM_1002	PM_1008	PM_1010	PM_1039	PM_1040
PM_1002	1	1	0.99	0.99	1
PM_1008	1	1	0.99	0.99	1
PM_1010	0.99	0.99	1	0.97	0.99
PM_1039	0.99	0.99	0.97	1	0.99
PM_1040	1	1	0.99	0.99	1

Figure S4: Pearson's correlation coefficient for PM₁₀ as measured by RAMP sensors 1002, 1008, 1010, 1039 and 1040 during collocation test. Data logging error resulted in loss of data for Sensor 1005.

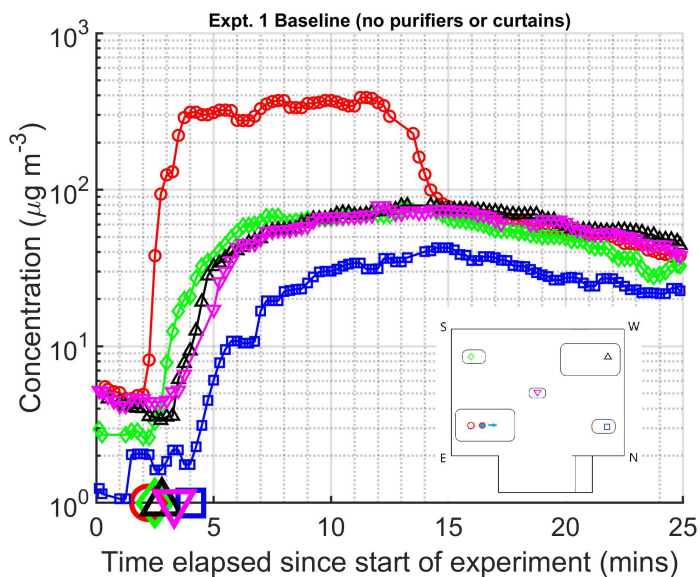


Figure S5: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 1. The y-axis is plotted in log-scale. The enlarged markers on the x-axis denote the transport time (t_{trans}) for each sensor. The trace color and symbol for each sensor on the plot is consistent with the graphical legend provided. Aerosol source was introduced into the test room at $t = 0$ minutes. The response times for each sensor are different depending on their locations.

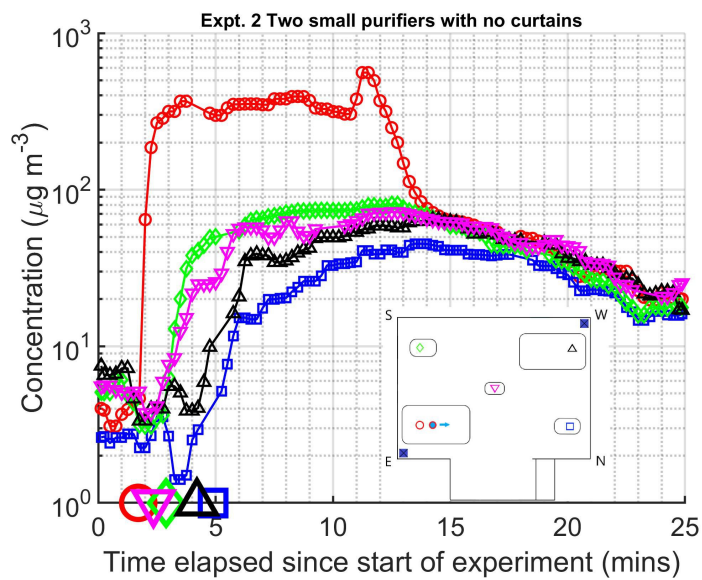


Figure S6: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 2. The y-axis is plotted in log-scale. Two Blueairs air purifiers were deployed at east and west corners.

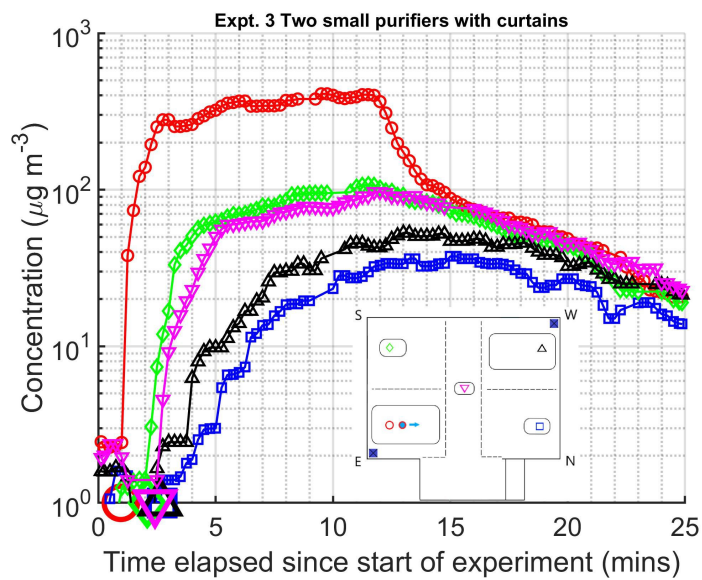


Figure S7: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 3. The y-axis is plotted in log-scale. Curtains are up and two Blueairs air purifiers were deployed at east and west corners.

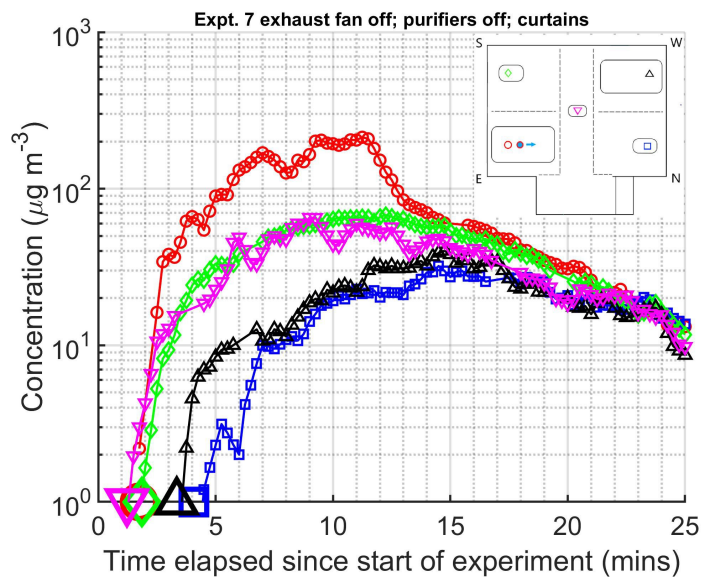


Figure S8: Time series of PM₁₀ concentrations as measured by RAMPs for Experiment 7. The y-axis is plotted in log-scale. Curtains were up.

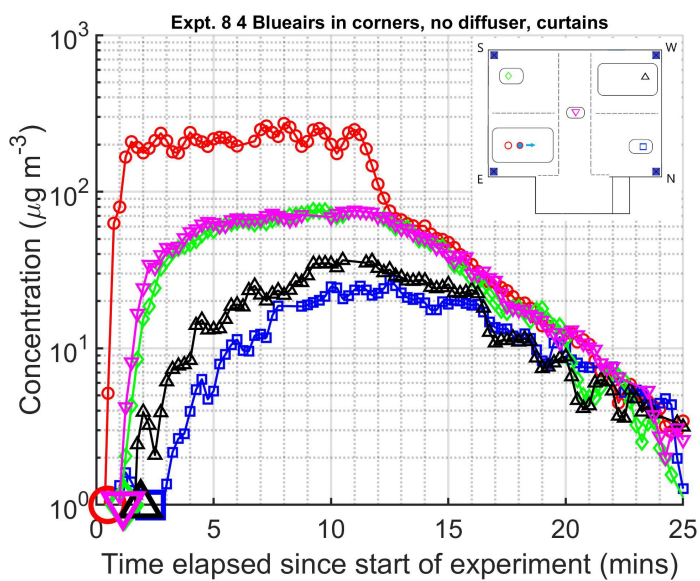


Figure S9: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 8. The y-axis is plotted in log-scale. Curtains are up and four Blueairs air purifiers were deployed at four corners. The effect of purifiers can be observed; the concentration decreases drastically after 10 minutes.

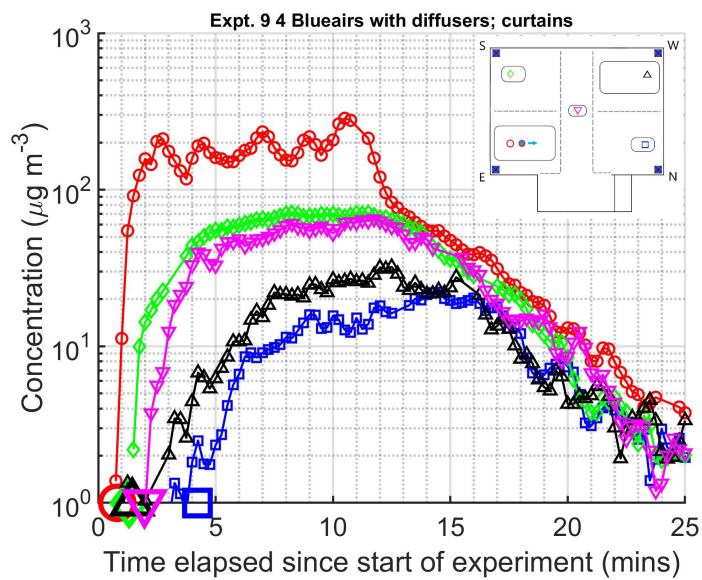


Figure S10: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 9. The y-axis is plotted in log-scale. Curtains were up and four Blueairs air purifiers with diffusers were deployed at four corners.

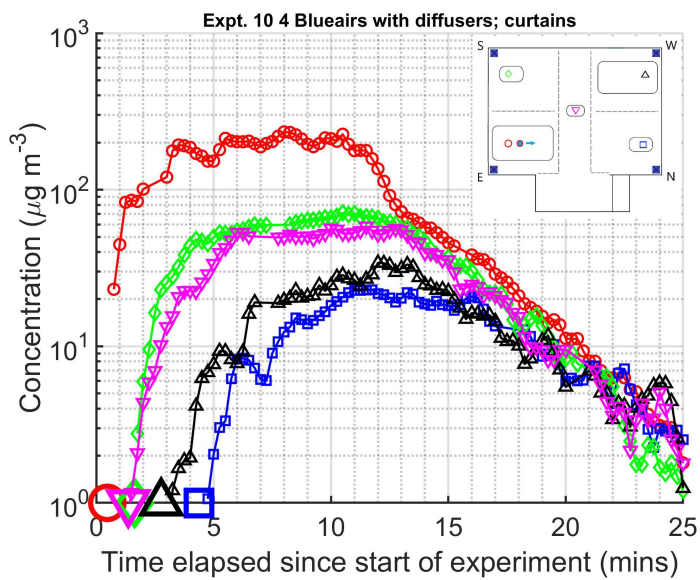


Figure S11: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 10. The y-axis is plotted in log-scale. Curtains were up and four Blueairs air purifiers with diffusers were deployed at four corners.

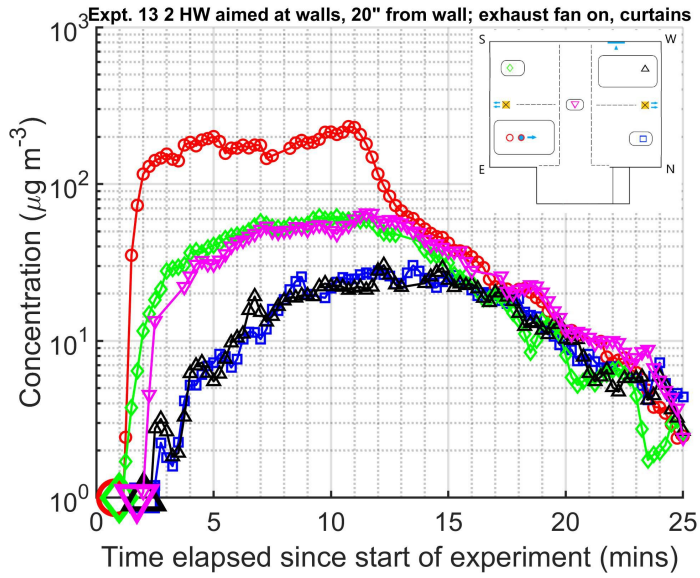


Figure S12: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 13. Curtains were up and two Honeywell air purifiers were deployed.

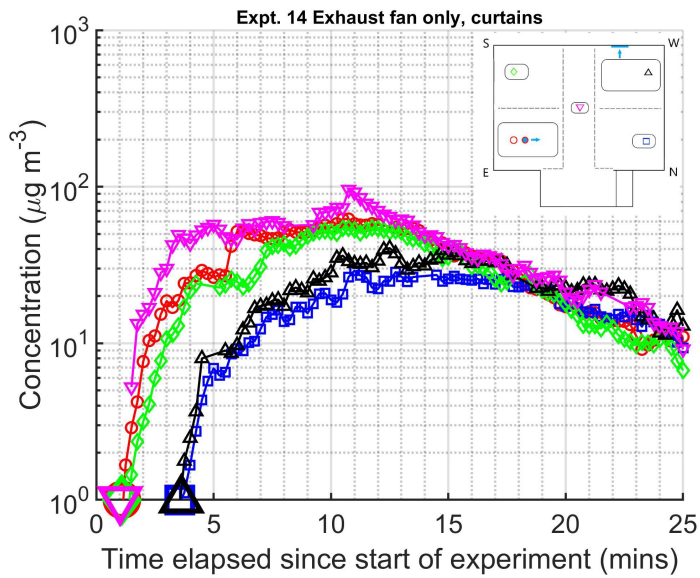


Figure S13: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 14. Only the exhaust fan was on.

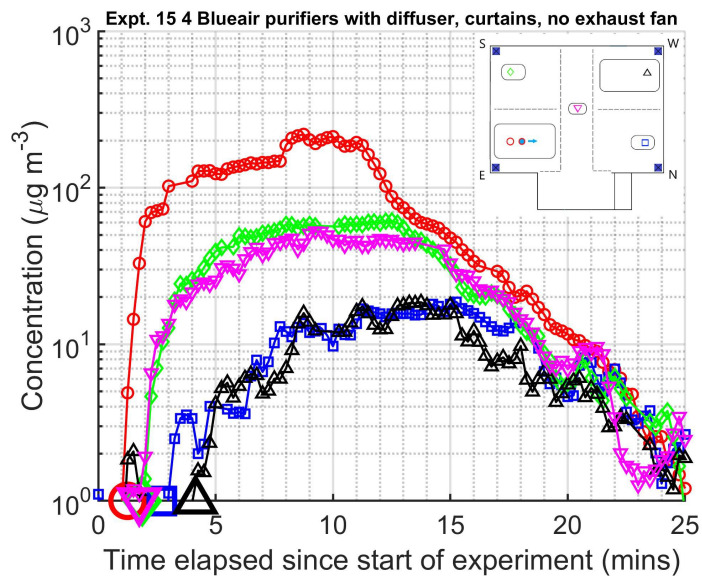


Figure S14: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 15. Curtains were up and four Blueairs air purifiers with diffusers were deployed at four corners.

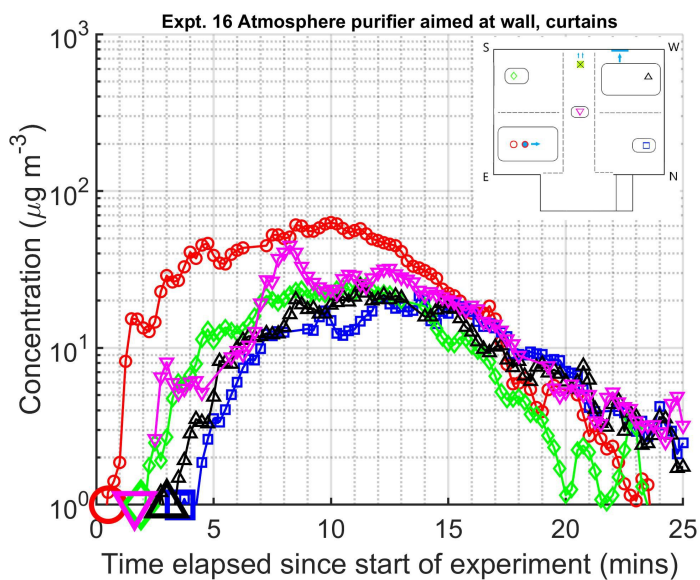


Figure S15: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 16. Curtains were up and one Atmosphere air purifier was deployed.

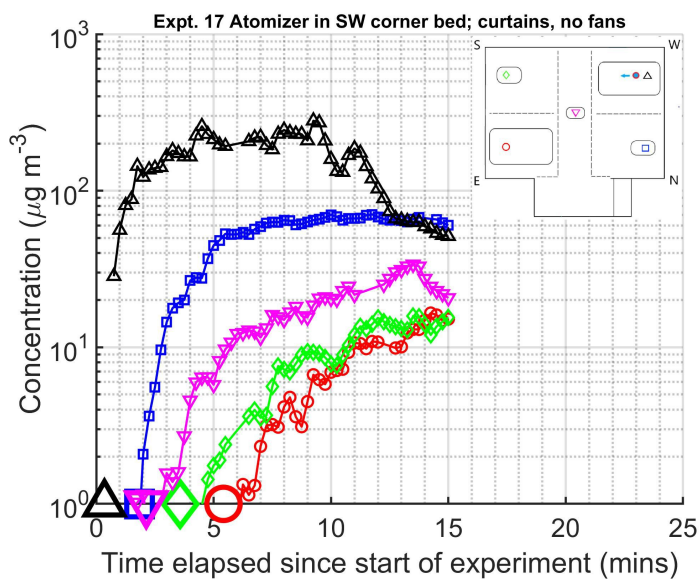


Figure S16: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 17. Curtains were up and the aerosol source was deployed on the west side.

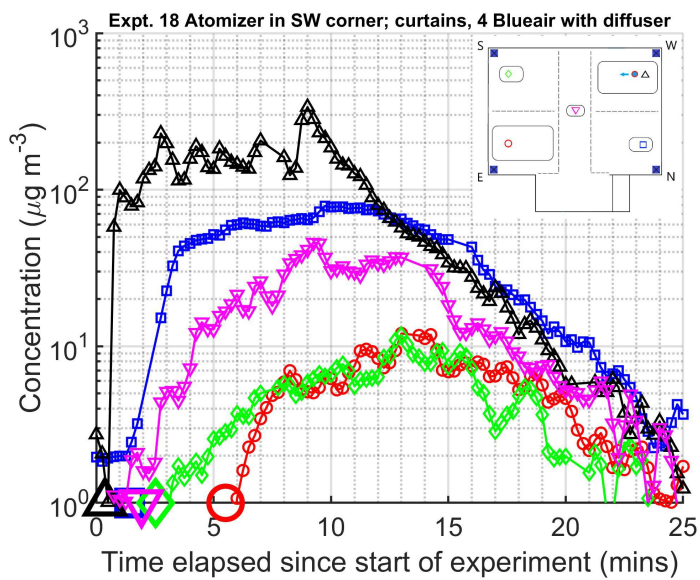


Figure S17: Time series of PM₁₀ concentrations as measured by RAMPs for Experiment 18. Curtains were up and four Blueairs air purifiers with diffusers were deployed at four corners. Aerosol source was placed at west bed.

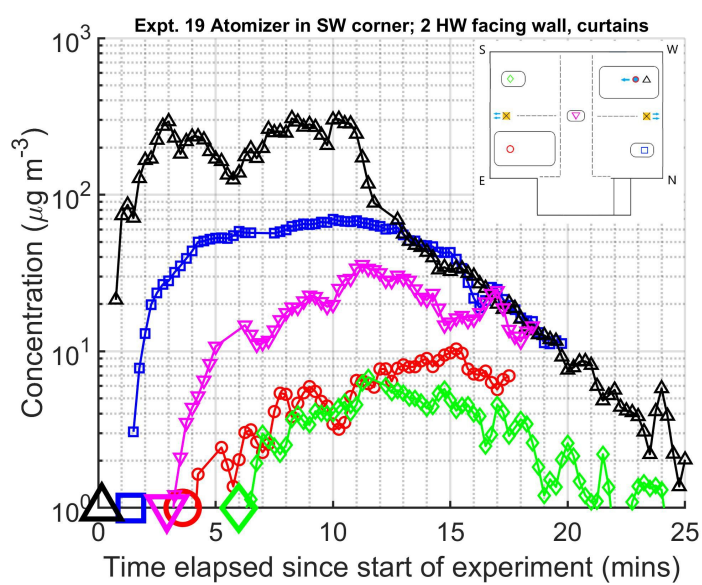


Figure S18: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 19. Curtains were up and two Honeywell air purifiers were deployed. Aerosol source was placed at west bed.

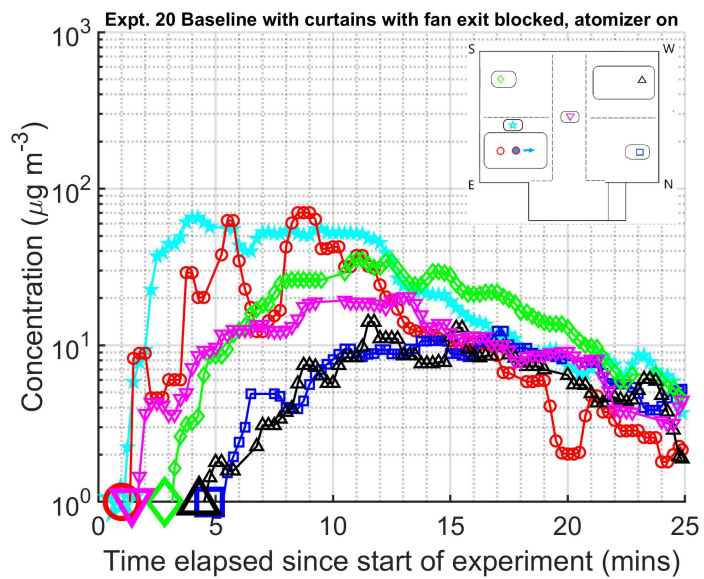


Figure S19: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 20. Curtains were up and another RAMP was added beside the east bed.

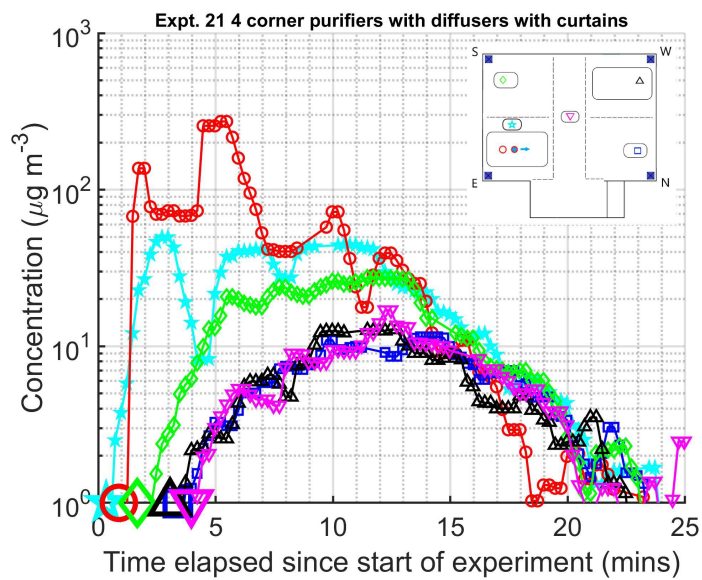


Figure S20: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 21. Curtains were up and four Blueairs air purifiers with diffusers were deployed at four corners.

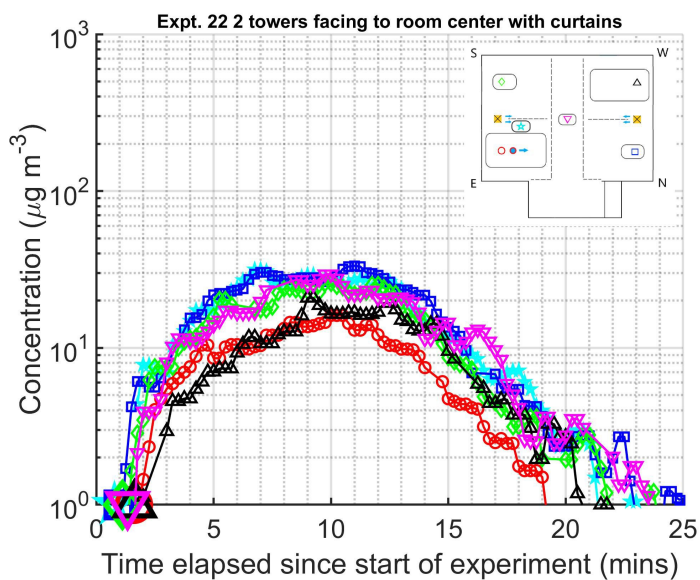


Figure S21: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 22. Curtains were up and two Honeywell air purifiers were deployed.

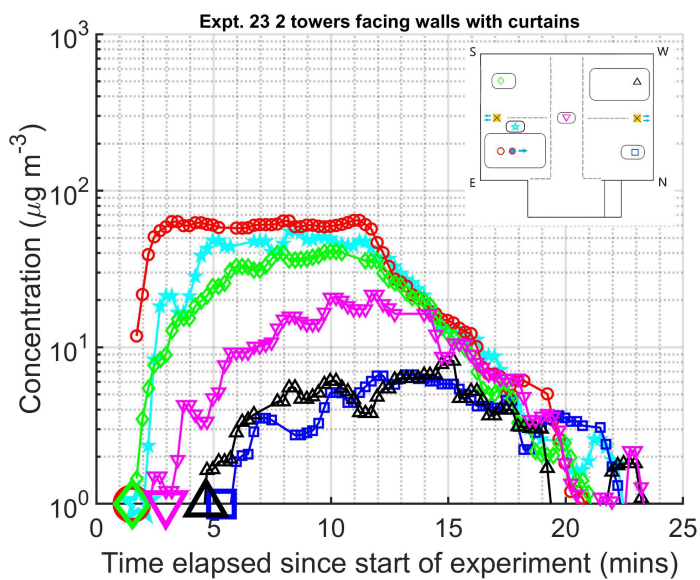


Figure S22: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 23. Curtains were up and two Honeywell air purifiers were deployed.

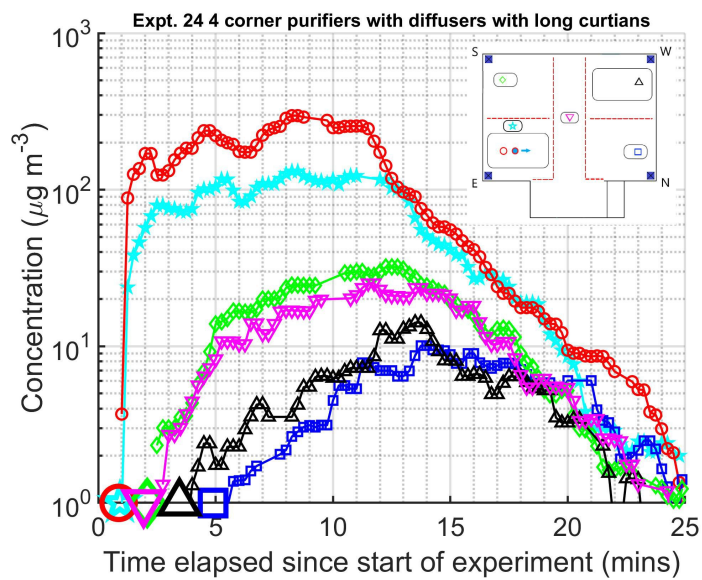


Figure S23: Time series of PM₁₀ concentrations as measured by RAMPs for Experiment 24. Long curtains were up and four Blueairs air purifiers with diffusers were deployed at four corners.

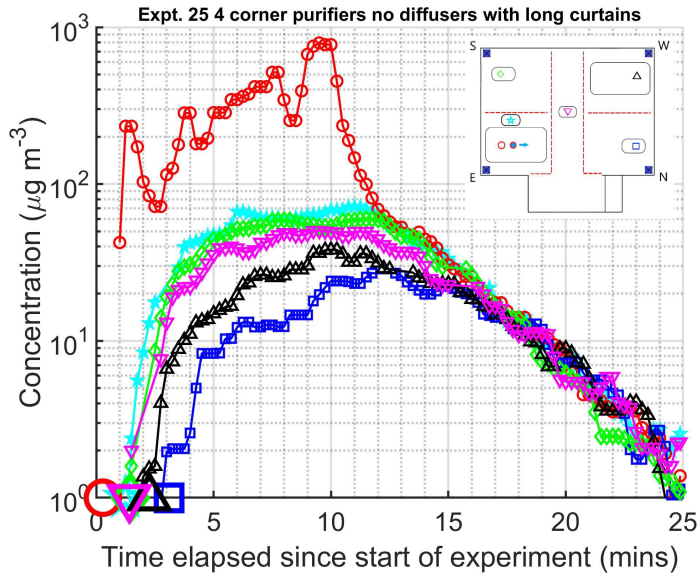


Figure S24: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 25. Long curtains were up and four Blueairs air purifiers deployed at four corners.

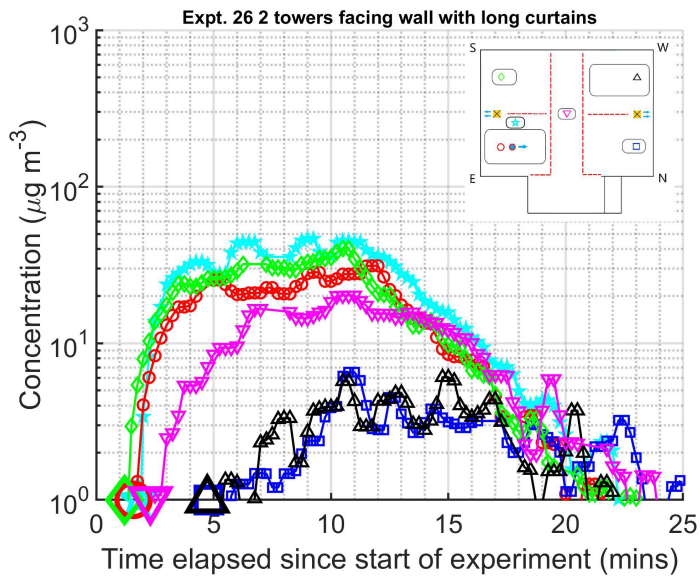


Figure S25: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 26. Long curtains were up and two Honeywell air purifiers were deployed.

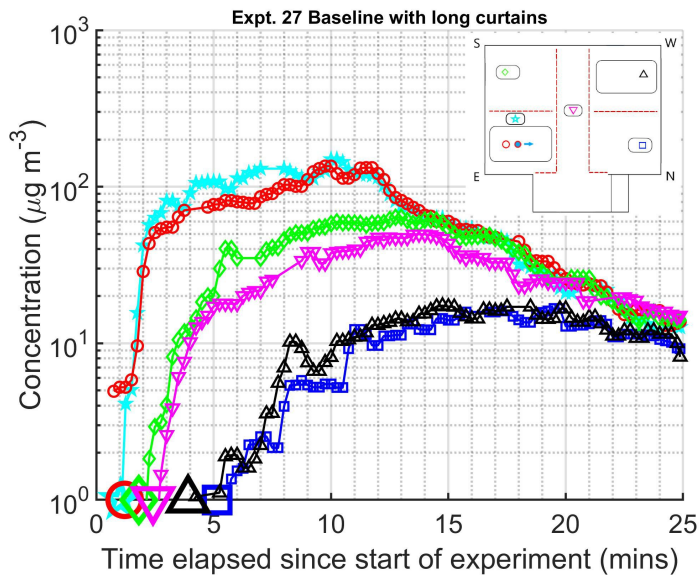


Figure S26: Time series of PM_{10} concentrations as measured by RAMPs for Experiment 27. Long curtains were up.

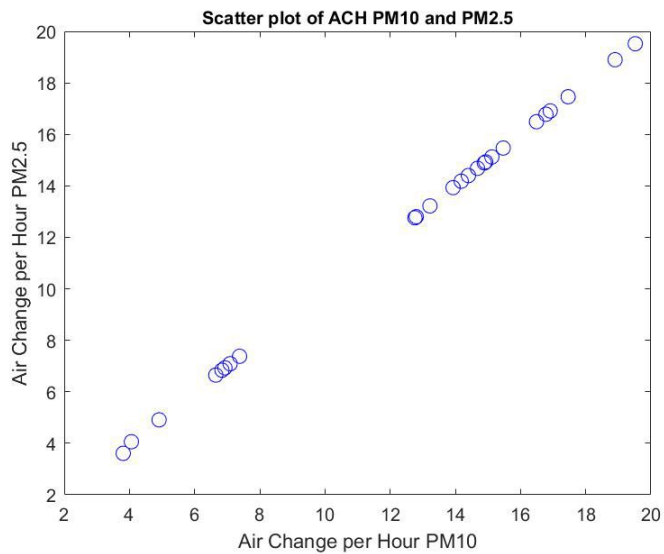


Figure S27: The scatter plot comparing ACH of each experiment for PM_{10} and $\text{PM}_{2.5}$.

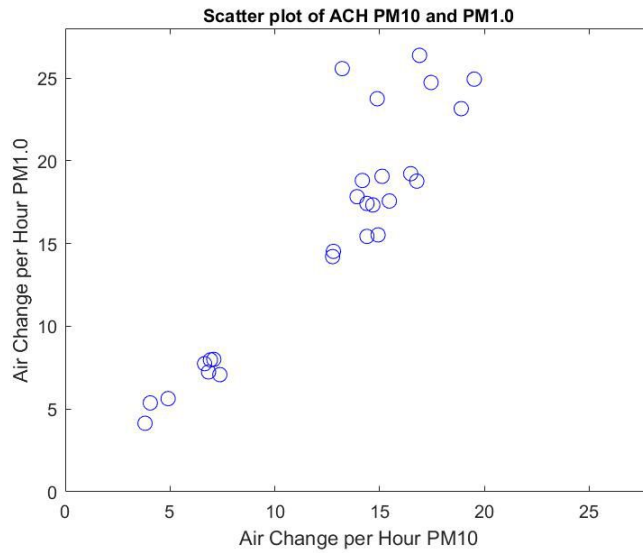


Figure S28: The scatter plot comparing ACH of each experiment for PM₁₀ and PM_{1.0}.

Table S1: The summary table of PM_{2.5}.

PM _{2.5}										
Expt. #	Atom Loc.	# Purifier, Location	Curtains	Air Changes per Hour				Concentration (µg/r)		Additional Notes
				Purifier, Nominal	Above From Decay	Baseline	Delay Times (min)	Source	Affected Area	
1	E	-	-	-	3.6	-	2.93	117	30	
5	E	-	-	-	4.2	-	2.89	100	28	
7	E	-	yes	-	6.8	-	2.62	56	17	
14	E	-	yes	-	7.1	0.3	2.45	23	17	exhaust fan only
17	W	-	yes	-	N/A	-	3.66	92	13	
20	E	-	yes	-	7.8	-	3.41	16	6	
27	E	-	long	-	5.0	-	3.24	47	13	
2	E	2, corner	-	3.6	6.7	2.8	3.62	119	24	2 Blueairs
3	E	2, corner	yes	3.6	6.8	2.9	2.81	126	26	2 Blueairs
4	E	4, corner	yes	8.1	15.4	11.5	2.51	155	15	2 Blueairs, 2 Honeywells
6	E	4, corner	-	8.1	15.4	11.5	3.05	58	15	2 Blueairs, 2 Honeywells
8	E	4, corner	yes	7.1	14.6	7.9	1.56	80	17	4 Blueairs
9	E	4, corner	yes	7.1	17.3	10.5	2.02	68	14	4 Blueairs with diffusers
10	E	4, corner	yes	7.1	15.3	8.6	2.60	69	14	4 Blueairs with diffusers
15	E	4, corner	yes	7.1	15.1	8.3	2.38	55	11	4 Blueairs with diffusers
21	E	4, corner	yes	7.1	20.0	12.2	2.99	17	11	4 Blueairs with diffusers
18	W	4, corner	yes	7.1	15.8	9.0	2.83	51	11	4 Blueairs with diffusers
24	E	4, corner	long	7.1	13.4	8.4	3.26	62	5	4 Blueairs with diffusers
25	E	4, corner	long	7.1	17.0	12.0	1.99	66	14	4 Blueairs
11	E	2, btw beds	yes	4.6	19.6	12.8	1.67	11	8	2 Honeywells exhaust to room center
22	E	2, btw beds	yes	4.6	20.2	12.3	1.26	8	8	2 Honeywells exhaust to room center
12	E	2, btw beds	yes	4.6	13.0	6.2	2.57	65	13	2 Honeywells exhaust to walls
13	E	2, btw beds	yes	4.6	13.5	6.7	1.73	65	14	2 Honeywells exhaust to walls with exhaust fan on
19	W	2, btw beds	yes	4.6	17.8	11.0	3.47	66	11	2 Honeywells exhaust to walls
23	E	2, btw beds	yes	4.6	18.9	11.1	3.55	18	5	2 Honeywells exhaust to walls
26	E	2, btw beds	long	4.6	17.9	12.9	3.27	12	4	2 Honeywells exhaust to walls
16	E	1, aisle	yes	5.8	16.5	9.7	2.42	19	7	1 Atmosphere exhaust to end wall

Table S2: The summary table of PM1.0.

PM1.0											
Expt. #	Atom Loc.	# Purifier,	Location	Curtains	Air Changes per Hour			Concentration ($\mu\text{g}/\text{r}$)		Additional Notes	
					Purifier,	Nominal	From Decay	Above Baseline	Delay Times (min)		Source
1	E	-	-	-	-	4.1	-	2.95	45	15	
5	E	-	-	-	-	5.4	-	3.07	36	13	
7	E	-	yes	-	-	7.2	-	2.89	22	7	
14	E	-	yes	-	-	8.0	0.8	2.51	10	8	exhaust fan only
17	W	-	yes	-	-	N/A	-	3.98	44	6	
20	E	-	yes	-	-	7.1	-	4.43	7	2	
27	E	-	long	-	-	5.6	-	4.46	20	5	
2	E	2, corner	-	-	3.6	8.0	3.2	3.50	43	11	2 Blueairs
3	E	2, corner	yes	-	3.6	7.7	3.0	2.97	46	12	2 Blueairs
4	E	4, corner	yes	-	8.1	17.6	12.8	2.85	51	7	2 Blueairs, 2 Honeywells
6	E	4, corner	-	-	8.1	7.2	13.1	3.16	22	6	2 Blueairs, 2 Honeywells
8	E	4, corner	yes	-	7.1	15.4	8.2	2.02	31	8	4 Blueairs
9	E	4, corner	yes	-	7.1	18.8	11.5	3.32	26	6	4 Blueairs with diffusers
10	E	4, corner	yes	-	7.1	17.4	10.2	2.89	27	6	4 Blueairs with diffusers
15	E	4, corner	yes	-	7.1	17.3	10.1	3.15	21	4	4 Blueairs with diffusers
21	E	4, corner	yes	-	7.1	26.4	19.3	4.09	9	2	4 Blueairs with diffusers
18	W	4, corner	yes	-	7.1	18.8	11.6	3.41	23	5	4 Blueairs with diffusers
24	E	4, corner	long	-	7.1	15.5	9.9	4.64	25	2	4 Blueairs with diffusers
25	E	4, corner	long	-	7.1	19.2	13.6	2.15	24	6	4 Blueairs
11	E	2, btw beds	yes	-	4.6	24.7	17.5	1.81	4	3	2 Honeywells exhaust to room center
22	E	2, btw beds	yes	-	4.6	24.9	17.9	1.38	3	3	2 Honeywells exhaust to room center
12	E	2, btw beds	yes	-	4.6	14.2	7.0	2.80	24	5	2 Honeywells exhaust to walls
13	E	2, btw beds	yes	-	4.6	14.5	7.3	2.32	26	6	2 Honeywells exhaust to walls with exhaust fan on
19	W	2, btw beds	yes	-	4.6	23.8	16.5	4.51	30	5	2 Honeywells exhaust to walls
23	E	2, btw beds	yes	-	4.6	23.2	16.1	4.43	8	2	2 Honeywells exhaust to walls
26	E	2, btw beds	long	-	4.6	25.6	19.9	4.46	5	2	2 Honeywells exhaust to walls
16	E	1, aisle	yes	-	5.8	5.6	11.8	2.73	8	3	1 Atmosphere exhaust to end wall