Evaluation of the Impact of Indoor Air Filtration on Particulate Matter Exposures and Measures of Cardiovascular Health

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Abstract

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Background: The efficacy of the high-efficiency particle arresting (HEPA) air cleaner and its related health benefits have gotten some attention, yet the number of studies on this topic is still modest. Recently, a commercially-available "auto-mode" air cleaner has emerged on the market that adjusts the operating fan speed automatically depending on its built-in particulate matter (PM) sensor, which may improve real-world effectiveness since it doesn't rely on the user to adjust the air cleaner when they perceive the air is polluted.

Objectives: We sought to assess the impact of auto-mode filtration on indoor PM exposure and cardiovascular health among healthy, non-smoking adults in an urban United States location.

Methods: The study approach was a randomized, crossover 3-way air filtration intervention pilot study in the urban Seattle area from February 1 to March 29, 2019. Six non-smoking, healthy young adults were enrolled in the study, provided an air cleaner, and exposed to each of the three following intervention scenarios for 1 week (order of interventions randomized), with each one

separated by a washout period of at least two weeks in duration: (1) a control period consisting of a sham filter installed in the air cleaner, (2) an intervention consisting of the air cleaner set to auto-mode filtration, and (3) an intervention in which participants were allowed to adjust the settings of the air cleaner. In all cases, the air cleaner was used in the participant's living room. Participants were asked to take two blood pressure measurements daily at 8 am and 8 pm. Indoor area $PM_{2.5}$ monitoring was conducted in both the kitchen and the living room of each household using a continuous particle counter.

Results: The indoor mean $PM_{2.5}$ levels measured in the living room and the kitchen were significantly reduced by 5.05 $\mu g/m^3$ (95% CI [-6.19, -3.91]; $p<0.001$) and 6.60 $\mu g/m^3$ (95% CI [-7.86, -5.34]; $p<0.001$) , respectively under the auto-mode filtration compared to the sham-mode filtration; whereas under the adjustable-mode filtration, the indoor $PM_{2.5}$ level was significantly decreased by 3.43 $\mu g/m^3$ (95% CI [-4.57, -2.28]; $p<0.001$) and 5.01 $\mu g/m^3$ (95% CI [-6.27, -3.76]; $p<0.001$) in the living room and kitchen, respectively, compared to sham-mode filtration. Auto-mode filtration significantly reduced the indoor mean $PM_{2.5}$ levels in the living room and the kitchen by 1.63 $\mu g/m^3$ (95% CI [-2.76, -0.48]; $p=0.01$) and 1.59 $\mu g/m^3$ (95% CI [-2.84, -0.34]; $p=0.04$), respectively, compared to adjustable-mode filtration.

12-hour personal exposure, which accounted for time-activity patterns and exposures away from home, was reduced by 5.45 $\mu g/m^3$ (95% CI [-9.51,-1.39]; $p=0.01$) under the auto-mode filtration and 4.26 $\mu g/m^3$ (95% CI [-8.37, -0.14]; $p<0.05$) under the adjustable-mode filtration, compared to sham-mode. Auto-mode reduced the 12-hour personal exposure by 1.19 $\mu g/m^3$ (95% CI [-6.11, 3.73]; $p=0.8$), compared to adjustable-mode filtration. A near statistically significant decrease in

morning systolic blood pressure of 6.1 mm-Hg (95% CI [-12.5, 0.3]; p=0.06) was found under the auto-mode filtration compared to sham-mode.

Conclusions: Results of this study indicated that using HEPA auto-mode filtration resulted in higher reductions in indoor $PM_{2.5}$ level and personal $PM_{2.5}$ exposures. Using an auto-mode air cleaner may lead to real-world effectiveness for reducing indoor $PM_{2.5}$ exposure. The findings on morning blood pressure are suggestive that auto-mode filtration may improve cardiovascular health.

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Chapter 1. INTRODUCTION

1.1 THE GLOBAL BURDEN OF AIR POLLUTION

Air pollution is a major environmental health issue that affects people globally. According to a recent Global Burden of Disease study, exposure to ambient particulate matter with an aerodynamic diameter equal or less than 2.5μm ($PM_{2.5}$) contributed to 4.1 million deaths and 105.7 million disability-adjusted life years (DALYs) in 2016 worldwide, accounting for 7.5% of deaths and 4.4% of DALYs at a global scale (Gakidou et al., 2017). Long-term exposure has been associated with reductions in life-expectancy (Brook et al., 2010; Pope et al., 2009) and increased morbidity and mortality related to cardiovascular disease, whereas short-term exposure to $PM_{2.5}$ can trigger acute cardiovascular events such as myocardial infarction and stroke (Chen et al., 2018), and may be a risk factor for elevated blood pressure (Baumgartner et al., 2011) and increased heart rate (Lin et al., 2009) among healthy adults.

1.2 AIR POLLUTION ISSUES IN THE UNITED STATES

While air pollution remains an important issue in many developing countries, in the United States, where outdoor air pollution levels tend to be lower, high exposures to particles may be elevated in some communities during certain periods, notably during wildfire events that are now a common issue in the summer season for Western and Southeastern regions (Fann et al., 2018). A study has demonstrated even in the United States where the air pollution levels are below the National Ambient Air Quality Standards, exposure to ambient $PM_{2.5}$ still poses a substantial risk to public health (Di et al., 2017). Penetration of these ambient particles into the indoor

environment in addition to other indoor sources from various household activities such as cooking, heating, vacuuming and environmental tobacco smoke may account for a major source of personal exposure (Bhangar et al., 2011; Hammond et al., 2013; Meng et al., 2009; Wallace et al., 2010). For non-smokers, indoor sources have been found to account for 47% of total daily exposure to particles (Wallace et al., 2010).

1.3 Applications of Indoor Air Cleaning in US Households

As the population in the US spends nearly 90% of their daily time indoors (Klepeis et al., 2001), and because of the aforementioned sources of indoor and outdoor particles, the use of air cleaners may be increasing as people have greater awareness and perceive poor indoor air quality. The efficacy of using air cleaners equipped with high-efficiency particulate arresting (HEPA) filters on lowering indoor fine particulate and ultrafine particulate level and its health benefit has been evaluated in numerous studies (Allen et al., 2011; Barn et al., 2007; Brauner et al., 2008; Brugge et al., 2013; Brugge et al., 2017; R. Chen et al., 2015; Chuang et al., 2017; Cui et al., 2018; Day et al., 2018; Kajbafzadeh et al., 2015; Karottki et al., 2013; Li et al., 2017; Morishita et al., 2018; Padró-Martínez et al., 2015; Sultan et al., 2011). However, inconsistent findings of the health benefit in these studies have been reported, which may be due to the variation of study design, including the length of air filtration intervention (Chen et al., 2015; Cui et al., 2018), the demographic characteristic of the study subject (Chen et al., 2015; Cui et al., 2018), the difference in time points within the same subject for conducting the health outcome measurement (Cui et al., 2018) and the influence of subjects' activity patterns on exposure assessment (Brugge et al., 2017; Chuang et al., 2017; Cui et al., 2018; Karottki et al., 2013).

Moreover, few of these air filtration intervention studies have been conducted in the US (Brugge et al., 2017; Morishita et al., 2018; Padró-Martínez et al., 2015).

1.4 Emerging Technologies of Home Blood Pressure Monitoring

Blood pressure monitoring using the auscultatory method with a sphygmomanometer has been regarded as the gold standard of office blood pressure measurement (Pickering et al., 2005). In the past decades, out-of-office blood pressure monitoring has become popular as it provides measurement in non-clinical settings, which may contribute to a more reliable assessment of blood pressure than the conventional office blood pressure monitoring due to the absence of white-coat syndrome (Baguet, 2012). Ambulatory blood pressure monitoring is one of the widely-used out-of-office blood pressure monitoring approaches. However, the monitor required for ambulatory blood pressure monitoring is often expensive, and users are needed to wear the monitor throughout a 24-hour or longer period, which makes it impractical for long-term monitoring for blood pressure (George et al., 2015). Recently, home blood pressure monitoring using automated blood pressure monitors is growing since it does not rely on specialty expertise required for sphygmomanometer use, and can be performed multiple times over a period of time without visiting clinics. A study has also shown that home blood pressure monitoring provides a higher reproducibility and practicability due to the ability to obtain extensive amounts of blood pressure measurement (Imai et al., 2013). Oscillometric blood pressure monitor is one of the most commonly used automated blood pressure monitor for home blood pressure measurement (Forouzanfar et al., 2015), and its precision and accuracy has been evaluated in numerous studies (Deutsch et al., 2014; Kang et al., 2017; Stergiou et al., 2008; Yarows, 2004). In addition, the

oscillometric blood pressure monitor is relatively inexpensive and easy to use, making it a more cost-effective way chosen by people for home blood pressure monitoring (Pickering et al., 2008).

1.5 Study Objectives and Aims

Recently, advances in air cleaner design has introduced models with an "auto-mode" feature, which uses a built-in PM sensor to control the operation of the air cleaner. Compared to the traditional air cleaner which relies on users manually controlling the cleaner, the "auto-mode" feature turns the cleaner on/off, and adjusts the fan speed automatically as triggered by the PM sensor, which may reduce noise, operating energy, increase longevity of the filter, and may result in improved real-world effectiveness since it does not depend on users turning on the cleaner when they perceive the air is polluted. However, we are unaware of any evaluations of the effectiveness of auto-mode air cleaners on reduced PM exposures and improved health effects. To address this need, we conducted a randomized 3-way crossover pilot study using three types of intervention scenario using new HEPA filter air cleaners with auto-mode capability to observe potential impacts on repeated measures of blood pressure:

(1) a control period consisting of a sham filter installed in the air cleaner,

(2) an intervention consisting of the air cleaner set to auto-mode filtration, and

(3) an intervention in which participants were allowed to adjust the settings of the air cleaner.

We refer to these as "sham-mode", "auto-mode", and "adjustable-mode" filtration, respectively. Our long-term goal is to utilize data from this pilot study to inform the design of a larger future public health intervention study which aims to improve indoor air quality and cardiorespiratory health. Furthermore, while household air cleaners are now commonly used in Asia, for this research we are particularly interested in evaluating the effect of air cleaners in an urban US

location (Seattle, Washington), where outdoor air pollution levels are usually lower than in developing countries.

This pilot study will test the hypothesis that an air cleaner set to auto-mode filtration effectively reduces indoor $PM_{2.5}$ concentrations, and improves cardiovascular health, defined as blood pressure improvements among six non-smoking, healthy adult participants. The specific aims are to:

Aim 1: Assess the efficacy of HEPA air cleaners under different air filtration intervention scenarios ("auto-mode" filtration and "adjustable-mode" filtration, relative to "sham-mode" filtration) on reducing indoor $PM_{2.5}$ concentrations and personal exposures to $PM_{2.5}$ over a 1-week period for each intervention scenario.

Aim 2: Assess the effect of the HEPA air cleaner for the different intervention scenarios on repeated measures of morning and evening blood pressure (BP) for each participant recruited for Aim 1.

Aim 3: Examine the feasibility of, and compare the measurements from a new smartwatch blood pressure monitor versus the wrist blood pressure monitor used for Aim 2 of the study.

Chapter 2. METHODS

This study was approved by the University of Washington Human Subjects Division. Participants were provided with a statement of the study procedure through email during the eligibility screening process.

2.1 STUDY POPULATION

A total of 6 healthy participants aged 20 – 40 years old were recruited using a convenience sampling approach by word of mouth within the Graduate School of the University of Washington. All participants were healthy non-smokers, not taking any medication, who lived in a non-smoking household located in the urban Seattle area. Household and demographic characteristics were assessed using a pre-screening questionnaire before the study (Appendix I). The study flow diagram is shown in Appendix II.

2.2 AIR FILTRATION INTERVENTION STUDY DESIGN

The HEPA air cleaner

The HEPA air cleaner (Air Purifier 2000i; Phillips, Andover, MA, approximate cost $300 USD) used in this study is a commercially available air cleaner which contains three layers of filter: a pre-filter, an active carbon filter and a HEPA filter. The clean air delivery rate (CADR) of the HEPA air cleaner for smoke and dust is 179 m^3/hour and 198 m^3/hour, respectively. The recommended working room size for the unit is advertised as 277 square feet. Two operating modes are provided by the air cleaner: the manual mode and the auto-mode. For manual mode,

the user can adjust the fan speed of the air cleaner by choosing “sleep-mode”, speed level 1, level 2, level 3 and Turbo, whereas for the auto-mode, the air cleaner automatically adjusts the fan speed setting according to the built-in PM sensor.

Air filtration intervention scenarios

This study was designed as a randomized, 3-way crossover intervention conducted from February 1st, 2019 through March 29th, 2019. Each participant received the following three different types of 7-day filtration intervention. The ordering of each participants intervention was randomized between the following: “sham-mode” filtration, “auto-mode” filtration and “adjustable-mode” filtration, with each one separated by a washout period which lasted for more than 2 weeks. The HEPA air cleaner was used in participants’ living rooms. Under the sham-mode and adjustable-mode filtration, the participant was allowed to freely adjust the setting of the air cleaner, including the power and the operating fan speed. However, all of the filters in the air cleaner were removed under the sham-mode filtration. For auto-mode filtration, the air cleaner was operating under the auto-mode and the participant was not allowed the adjust the setting of the air cleaner. Each intervention scenario started at 8 pm on Friday for each study week and ended at 8 pm on Friday the following week. All participants were advised to keep windows closed during the filtration intervention.

In order to assess how the air cleaner responded to the $PM_{2.5}$ level in each household under the auto-mode filtration, we monitored the energy consumption of the air cleaner using an energy data logger (HOBO® Plug Load Logger, Model UX120-018, Onset Computer Corp, Bourne, MA). The logger provided real-time logging for the voltage, current, active power and active

energy of alternating current powered plug in loads. The active power reported in unit watts was chosen as a proxy of the operating fan speed of the air cleaner. A measurement was reported every 30 seconds.

2.3 Exposure Assessment

Indoor and outdoor $PM_{2.5}$ level monitoring

The indoor $PM_{2.5}$ level was continuously monitored over the air filtration intervention using two indoor air quality monitors which contain pre-calibrated laser light scattering-based particle counters (PMS-A003; Plantower Co., Ltd, Beijing, China) in the living room and the kitchen of each household. The monitors were placed at a height of 1.2 to 1.7 meters and were at least 1 meter away from the air cleaner and the walls. The monitors measured relative humidity, temperature and the mass concentration of $PM_{2.5}$ every 10 seconds, with data stored on a Secure Digital memory card inside each monitor. The monitoring data was averaged up to one-hour for the analysis.

Participants were asked to complete a time-activity log, which was used to track time spent outdoors, and between indoor (home) vs. other indoor microenvironments. In order to relate indoor to outdoor PM concentrations during the study period, hourly outdoor $PM_{2.5}$ monitoring data was obtained from the Puget Sound Clean Air Agency. The selection of the outdoor monitoring site was based on the location of each microenvironment. An indoor/outdoor ratio of 0.8 was assumed for estimating the $PM_{2.5}$ level in non-home (i.e., non-monitored) indoor

environments, such as at office, school or vehicle (Chen et al., 2011). Any missing values for the outdoor $PM_{2.5}$ monitoring data were imputed using linear interpolation.

Calibration of the PM sensors used for indoor air monitoring

A field calibration was performed for the study's particle counters in a household setting. We co-located all designated monitors with a Grimm Portable Laser Aerosol Spectrometer (Model 1.109; Grimm Aerosol Technik GmbH & CO. KG, Ainring, Germany), which collected reference measurements of PM. This reference instrument provided real-time particle size counts per liter ranging from 1320 nm to 0.540 µm and mass concentration reading of PM_{10}, $PM_{2.5}$ and PM_1 every 10 seconds. For the data analysis, the 1-minute averages were used from both Plantower sensor and the Grimm spectrometer. Any minute with less than 83% data completeness (5 out of 6 readings per minute) was removed. Test particles were generated using an electric stove by performing two similar cooking events, which is considered as an important source of indoor air pollution. A calibrated model was developed for each Plantower sensor to calibrate the raw mass concentrations against the Grimm spectrometer in the following form:

$$Grimm_{PM2.5} = \beta_0 + \beta_1\, Plantower_{PM2.5} + e \quad \text{(Equation 1)}$$

where $Grimm_{PM2.5}$ is the $PM_{2.5}$ mass concentration measured by the Grimm spectrometer, β_0 is the intercept, $Plantower_{PM2.5}$ is the raw $PM_{2.5}$ mass concentration measured by the Plantower sensor and e is the residual error. In addition to Equation 1, we also developed calibration models that include the relative humidity term for each Plantower sensor:

$$Grimm_{PM2.5} = \beta_0 + \beta_1\, Plantower_{PM2.5} + \beta_2\, RH + e \quad \text{(Equation 2)}$$

where RH is the relative humidity measured by the relative humidity sensor inside the indoor air quality monitor. The optimal calibration model for each Plantower sensor was selected based on the Bayesian Information Criterion (BIC) (Kass et al., 1995).

Collection of the time-activity information and estimation of personal $PM_{2.5}$ exposure

As mentioned briefly above, time-activity diaries were used by each participant each day during the air filtration intervention (Appendix III). Participants were asked to record their location and activities at 1-hour intervals. The time-activity diary listed three major microenvironments where we assume people might spend time, and various household activities related to the generation of particles. We calculated the time-weighted average personal $PM_{2.5}$ exposure (C_{TWA}) based on the following equation by mapping the time-activity information with the indoor and outdoor $PM_{2.5}$ monitoring data:

$$C_{TWA} = \frac{\sum_{i=1}^{n} C_i \times t_i}{\sum_{i=1}^{n} t_i} \quad \text{(Equation 3)}$$

where C_i represents the corresponding indoor or outdoor $PM_{2.5}$ concentration at hour t_i and n represents the total number of the microenvironment that a participant spent in a given timeframe. The detailed data source for calculating the time-weighted average exposure was summarized in Appendix IV.

2.4 CARDIOVASCULAR OUTCOME MEASUREMENTS

Daily blood pressure measurement

Two sets of self-administered measurements using an oscillometric Omron Wrist Blood Pressure Monitor (Model BP654; Omron, Kyoto, Japan) were taken at 8 am and 8 pm each day during the air filtration intervention and were recorded in a blood pressure diary (Appendix V). Each set of measurements followed a standardized protocol (Appendix VI). Questions assessing the blood pressure related factors, including stress and diet before or during the blood pressure measurement were included in the diary. The stress was defined as a situation in which a person feels tense, restless, nervous or anxious or is unable to sleep at night, whereas the diet was defined as having breakfast before the morning blood pressure measurement at 8 am or dinner before the evening blood pressure measurement at 8 pm (Elo et al., 2003). In addition to the wrist blood pressure monitor, the participant was required to wear a low-cost smartwatch with a blood pressure sensor (DoSmarter Heart rate intelligent bracelet; DoSmarter, approximate cost $46 USD). A blood pressure reading from the smartwatch was reported every 10 minutes and the data was stored in a compatible mobile phone application. The measuring principle of the watch blood pressure monitor was not provided by the manufacturer.

Validation of the Omron wrist and smartwatch blood pressure monitor

An informal validation was conducted before the air filtration intervention to evaluate the validity of the blood pressure measurement from the wrist and the smartwatch blood pressure monitor in comparison to sphygmomanometer measurements in a convenience sample of healthy adults aged 20 to 65 years old. A total of three measurements were performed by a trained

observer for each participant with a sphygmomanometer, wrist and smartwatch blood pressure monitor, respectively in random order. Each measurement type was separated by at least 5 minutes of seated quiet time and was performed on the left arm for each participant. The protocol of the validation was modified from the Native-Controlling Hypertension And Risk Through Technology (Native-CHART) protocol (https://nchart.wsu.edu; Appendix VII). Participants were advised to use the restroom first and refrain from talking for 5 minutes before BP readings and for the duration of all measurements. For data analysis, the first measurement from each measuring type was discarded and the average of the second and third measurement was used.

2.5 Statistical Analysis

Summary statistics were calculated for demographic variables, exposure and outcome variables as mean and standard deviation for each participant under each type of intervention scenario. We assume no carryover effects between each intervention scenario because of an at least 2-week washout period between them. Selection of the covariates and confounders was based on prior knowledge, including stress before or during the blood pressure measurement and meal before the blood pressure measurement. A mixed-effects model of the following form was used to investigate whether auto-mode filtration and adjustable-mode filtration resulted in statistically lower blood pressure than the sham-mode filtration:

$$BP_{i,t} = \beta_0 + \beta_1 \cdot scenario_{i,t} + \beta_2 \cdot stress_{i,t} + \beta_3 \cdot meal_{i,t}$$
$$+\beta_4 \cdot scenario_{i,t} * day_i + \varepsilon_{i,t} \quad \text{(Equation 4)}$$

where $BP_{i,t}$ is the blood pressure outcome of participant i at time t; β_0 is the intercept of the model; $scenario_{i,t}$ is the dummy variable for the intervention scenario received by participant i at time t (categorical analysis with sham-mode filtration = 0 as reference, and auto-mode filtration and adjustable-mode filtration considered as separate indicators) and β_1 is the corresponding effect; $stress_{i,t}$ is the dummy variable for stress during or before the blood pressure measurement of participant i at time t (0 = not at all (reference), 1 = only a little, 2 = to some extent, 3 = rather much) and β_2 is the corresponding effect; $meal_{i,t}$ is the dummy variable for having a meal before the blood pressure measurement (0 = did not have a meal before the blood pressure measurement (reference), 1 = had a meal before the blood pressure measurement) and β_3 is the corresponding effect; $\varepsilon_{i,t}$ is the random effect. A penalized spline of day was included in the model as an interaction term on scenario ($scenario_{i,t} * day_{i}$) to account for all other unmeasured time-variant confounders. The morning and evening systolic (SBP) and diastolic blood pressure (DBP) were analyzed separately.

We tested whether auto-mode filtration and adjustable-mode filtration resulted in statistically lower indoor $PM_{2.5}$ level than the sham-mode filtration by using the following mixed model:

$$PM_{2.5\,i,t} = \beta_0 + \beta_1 \cdot scenario_{i,t} + \beta_2 \cdot cooking_{i,t} + \varepsilon_{i,t} \quad \text{(Equation 5)}$$

where $PM_{2.5\,i,t}$ is the $PM_{2.5}$ level of household i at time t; β_0 is the intercept of the model; $scenario_{i,t}$ is the dummy variable for filtration scenario (0 = sham-mode filtration as reference and auto-mode filtration and adjustable-mode filtration considered as separate indicators) and β_1 is the corresponding effect; $cooking_{i,t}$ is the cooking event that happened in household i at time

t and β_2 is the corresponding effect; $\varepsilon_{i,t}$ is the random effect. The $PM_{2.5}$ level measured in the living room and the kitchen were analyzed separately.

Finally, we investigated whether personal 12-hour time-weighted average $PM_{2.5}$ exposure was significantly different under different types of intervention scenario with the following mixed model:

$$12 - hr\ TWA\ PM_{2.5\,i,t} = \beta_0 + \beta_1 \cdot scenario_{i,t} + \beta_2 \cdot indoor\ time_{i,t}$$

$$+\beta_3 \cdot scenario_{i,t} * day_i + \varepsilon_{i,t} \quad \text{(Equation 6)}$$

where $12 - hr\ TWA\ PM_{2.5\,i,t}$ is the 12-hour time-weighted exposure calculated based on Equation 3 for participant i at time t; β_0 is the intercept of the model; $scenario_{i,t}$ is the dummy variable for intervention scenario (0 = sham-mode filtration as reference, and auto-mode filtration and adjustable-mode filtration considered as separate indicators) and β_1 is the corresponding effect; $indoor\ time_{i,t}$ is the total time spent in home in the corresponding 12-hour timeframe and β_2 is the corresponding effect; $\varepsilon_{i,t}$ is the random effect. Similarly, a penalized spline of day was included in the model as an interaction term on scenario ($scenario_{i,t} * day_i$) to account for all other unmeasured time-variant confounders.

In the sensitivity analysis, we further tested whether the effects of intervention differed by total time spent in home for the previous 12 hours before each blood pressure measurement using an interaction term on scenario for the mixed model investigating blood pressure (Equation 4). We also explored the inclusion of an interaction term for the day of measurement (weekend or

weekdays) on scenario, since previous studies have shown blood pressure tends to be lower during the weekend (Juhanoja et al., 2016). All statistical tests were two-sided and significance was determined at the 0.05 probability level. The mixed model portion in the analysis was conducted using R package *gamm4* (Wood et al., 2017). R version 3.5.1 was used for all of the analysis.

Chapter 3. RESULTS

3.1 Calibration of the PM Sensors

A total of twelve indoor air quality monitors and a Grimm spectrometer were laid out on a flat table at a height of 60 centimeters. The distance between the tested monitors and the source of testing particles was 2 meters. Two similar cooking events were performed within 2.5 hours, with each one lasted for 40 minutes and 20 minutes, respectively (Figure 1).

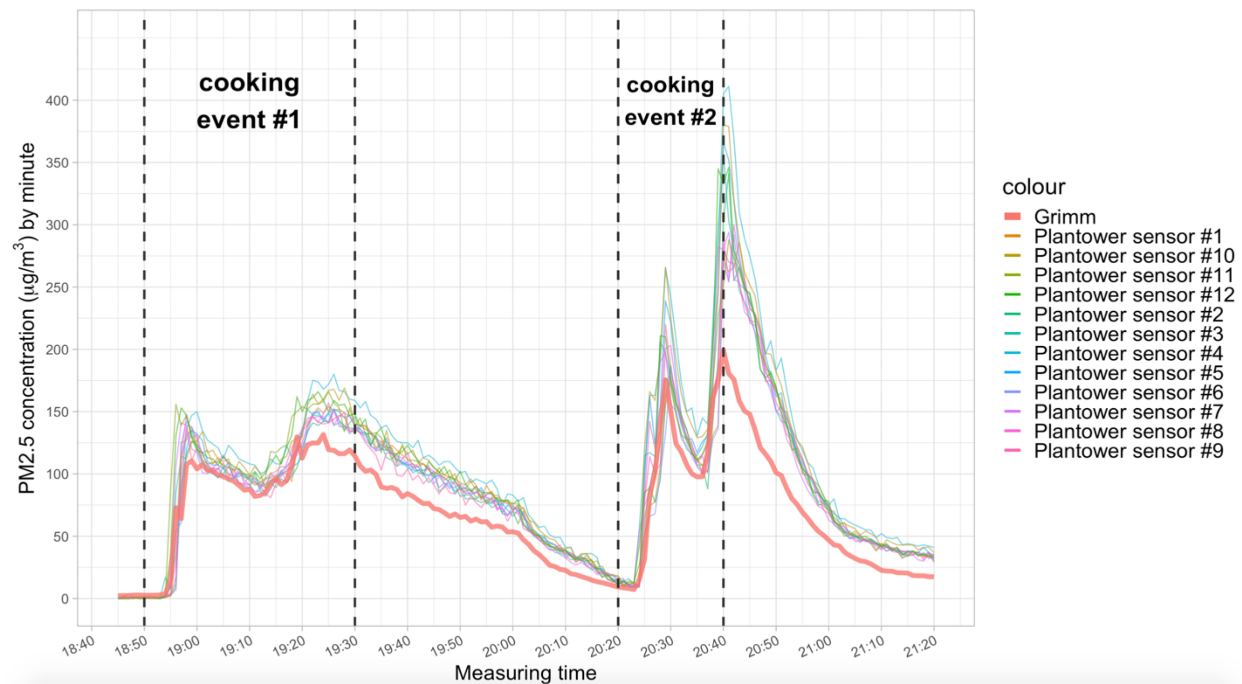

Figure 1. Time-series plot of the 1-minute average $PM_{2.5}$ level measured by the 12 Plantower sensors and the Grimm Spectrometer during the 2.5-hour collocation.

Under these conditions, the BIC of each model after adding a humidity term did not indicate strong evidence favoring a more complex model. Therefore, the optimal calibration model for each Plantower sensor was constructed based on Equation 1 (Appendix VIII). Figure 2 shows the

scatterplot of the relationship of the raw concentrations (the blue line), the calibrated $PM_{2.5}$ concentrations (the red line) of Plantower sensors and the Grimm spectrometer. As can be seen from the plot, the relationship between the calibrated Plantower sensors and the Grimm spectrometer was approximately linear after applying the calibration; however, the Plantower sensor tended to slightly overestimate the $PM_{2.5}$ level when the concentration was between 50 μg/m^3 to 100 μg/m^3, and underestimate the $PM_{2.5}$ level when the concentration at a higher concentration after calibrated.

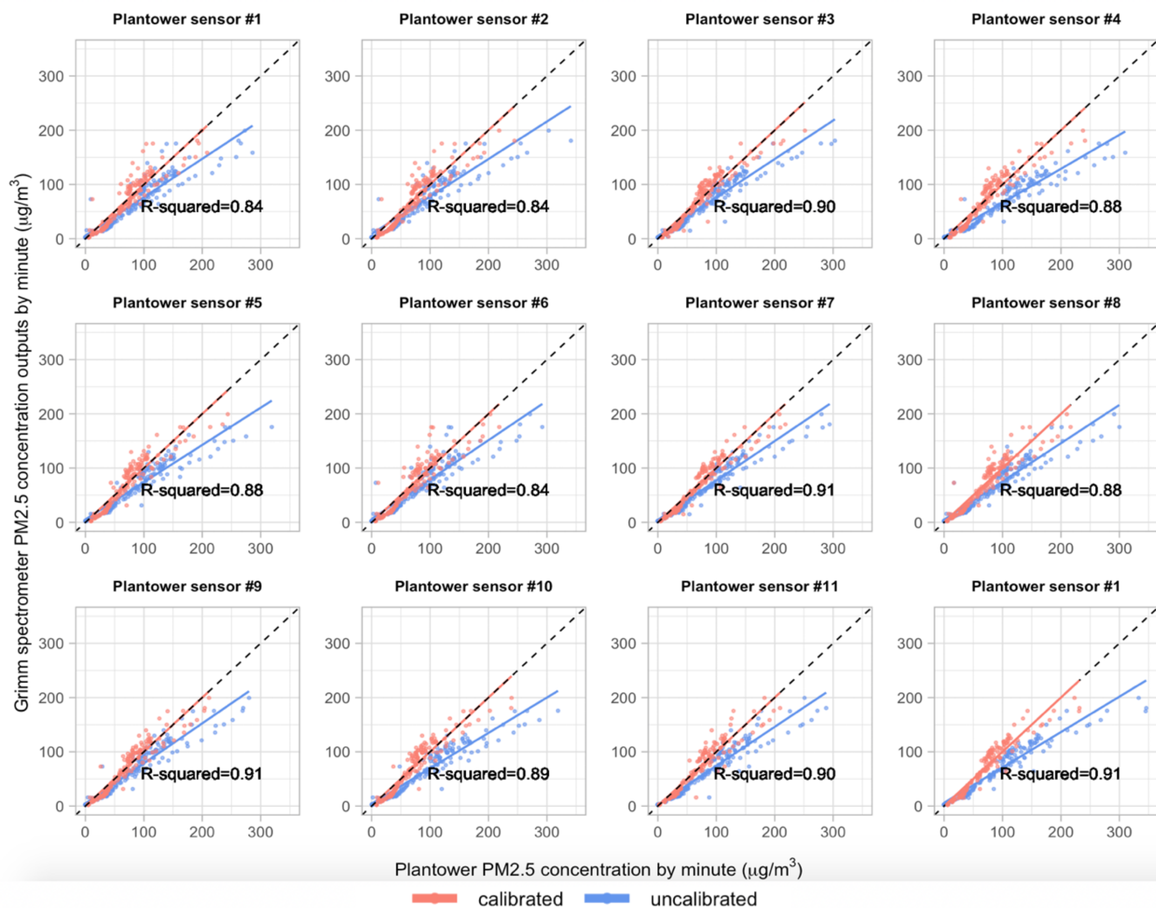

Figure 2. Scatterplots of the raw and calibrated $PM_{2.5}$ concentrations from Plantower sensors and Grimm spectrometer with the corresponding R-squared value of the

calibration model calculated based on least-square regression. The dashed line shows the 1:1 relationship between the Plantower sensor and the Grimm spectrometer.

3.2 Validation of the Wrist and Smartwatch Blood Pressure Monitor

A total of 10 participants were recruited in this informal validation. Figure 3 shows the pairwise correlation between each measurement type. As can be seen from the plot, the correlation between the sphygmomanometer and the Omron wrist blood pressure monitor appeared to be high for both SBP (r= 0.96) and DBP (r=0.98). However, there was no correlation between the measurement of sphygmomanometer, and smartwatch for both SBP and DBP (r≈0). The inspection of the Bland-Altman plot of three measurement types (Appendix IX) shows an increasing mean bias between the sphygmomanometer and smartwatch for both higher SBP and DBP measurement. The magnitude of mean bias between the sphygmomanometer and smartwatch was also larger than the mean bias between the sphygmomanometer and Omron wrist blood pressure monitor.

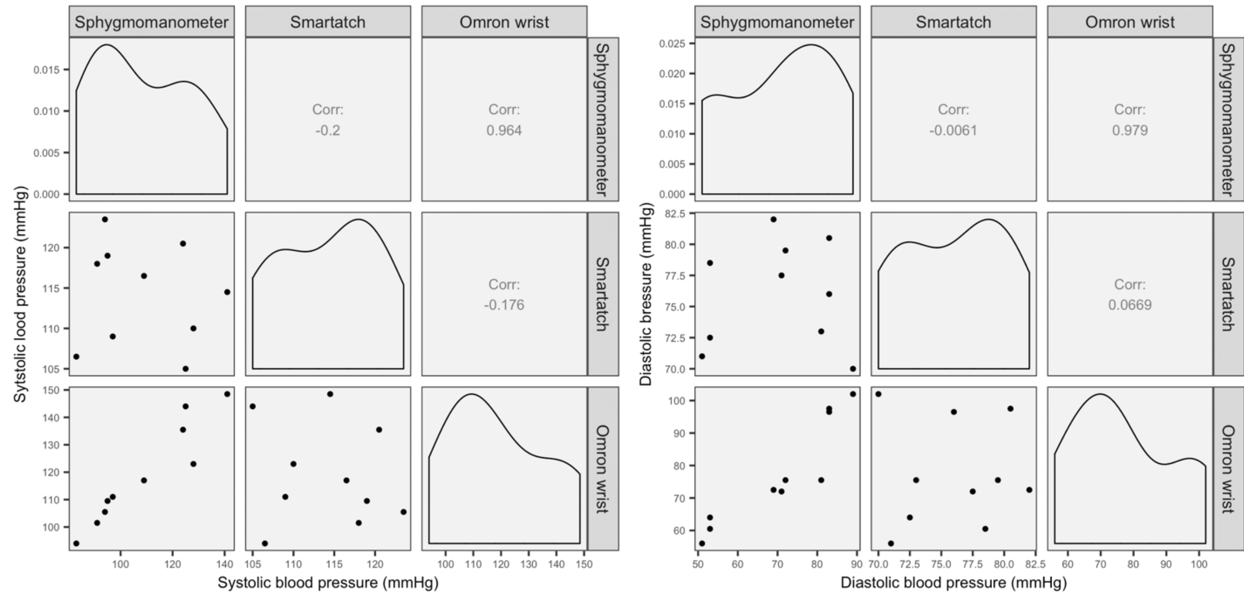

Figure 3. Pairwise Spearman correlation between each measurement type.

3.3 Indoor Air Filtration Intervention Trial

Table 1 summarizes the characteristics of the enrolled participants. A total of 6 healthy, non-smoking people (2 men and 4 women) participated in this study, with a mean (SD) age of 27.3 (4.9) years old. Participants predominantly lived in apartments (66%). 2 participants (30%) had cats in their residence. None of the participants lived with smoker. Under each type of filtration scenario, the participants spent an average of 70 -75% of their time in home (Appendix XI.).

Table 1. Demographic characteristics of 6 participants enrolled.

Variable		Data
Age, mean (SD), years		27.3 (4.9)
Gender, no., (%)		
	Male	2 (30)
	Female	4 (70)
BMI, mean (SD)		20.1 (2.1)
Housing type, no., (%)		
	Apartment	4 (66)
	Townhouse	1 (17)
	House	1 (17)
Pet ownership, no., (%)		2 (30)
Cooking stove used, no., (%)		
	Gas	2 (30)
	Electric	4 (70)
Cooking frequency, no., (%)		
	more than 6 days/week	2 (30)
	3 to 5 days/week	4 (70)
	less than 3 days/week	0 (0)

[a] Based on the self-reporting data.

Abbreviations: BMI, body mass index

Exposure characterization

Figure 4 illustrates an example of the air cleaner power consumption in response to the 1-minute average indoor $PM_{2.5}$ level in the kitchen and the living room in one of the participant's homes under the auto-mode filtration. As can be seen in the plot, the air cleaner was operating under the fan speed 1 and fan speed 2 most of the time, with the corresponding power consumption of about 6 watts and 10 watts. When the $PM_{2.5}$ level reached 28.2 µg/m^3 in the kitchen and 18.2 µg/m^3 in the living room, the air cleaner adjusted the fan speed to turbo level. Overall, the air cleaner power consumption did respond to the increased fan speeds with elevated $PM_{2.5}$ concentration. We also observed some brief periods of increased air cleaner power consumption

when the measured $PM_{2.5}$ level in the kitchen and the living room varied approximately from 7 μg/m^3 to 15 μg/m^3. Under this range, the air cleaner was operating with fan speed 1 and fan speed 2.

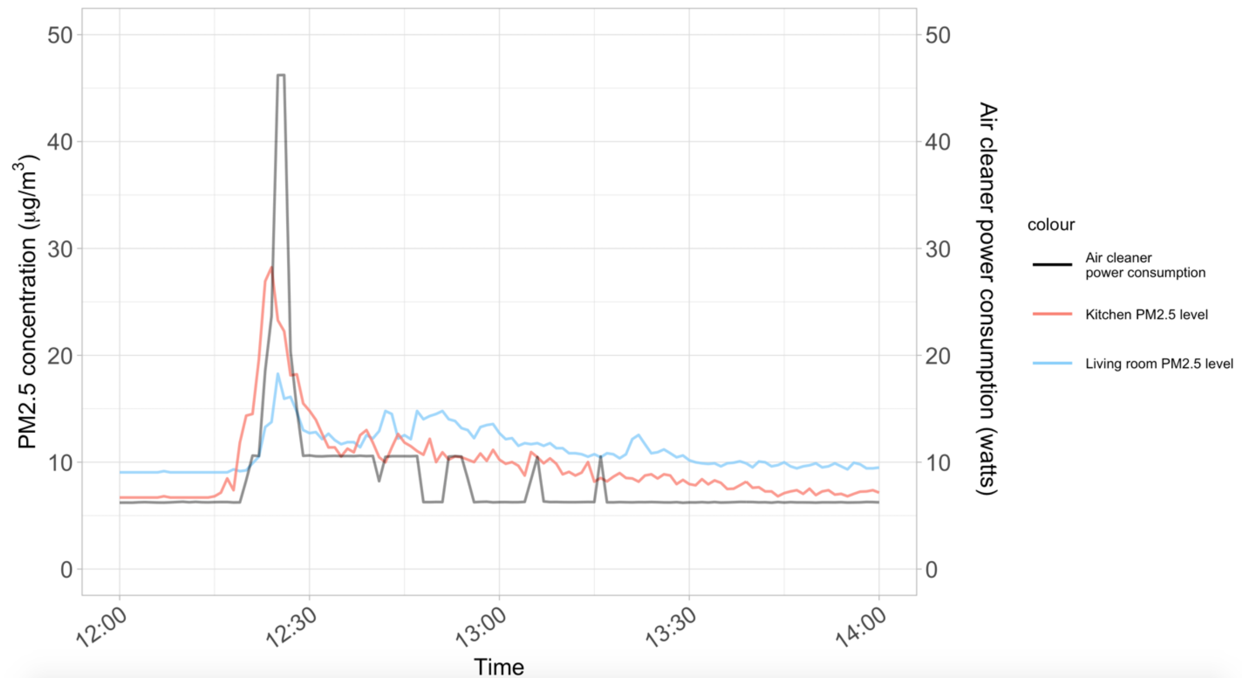

Figure 4. Time-series plot of the air cleaner power consumption and the indoor $PM_{2.5}$ level measured in kitchen and living room under the auto-mode filtration in one of the participant's residence during a two-hour cooking event.

Figure 5 shows a similar time-series plot as Figure 4 in one of the participant's homes, but stratified by different types of intervention scenario. In this case, the participant chose fan speed 1 as the default setting of the air cleaner under the adjustable-mode filtration, and did not adjust it over the 1-week for that scenario according to the power monitoring data. For the 1-week auto-mode scenario, the different heights of the black line corresponding to power consumption suggests that the filter was switching between different fan speeds during this period of

intervention. Several $PM_{2.5}$ peaks (red and blue lines) with steep slopes were observed under both auto-mode and adjustable-mode filtration. In contrast, a plateau-like line shape of the kitchen $PM_{2.5}$ level can be seen during the sham-mode filtration period. This suggests that the air cleaner operated under the auto-mode and adjustable-mode filtration, but did not completely eliminate the peak of the $PM_{2.5}$ level measured in kitchen or living room, but shortened the time required to lower the $PM_{2.5}$ level to the background level as compared to the sham-mode filtration.

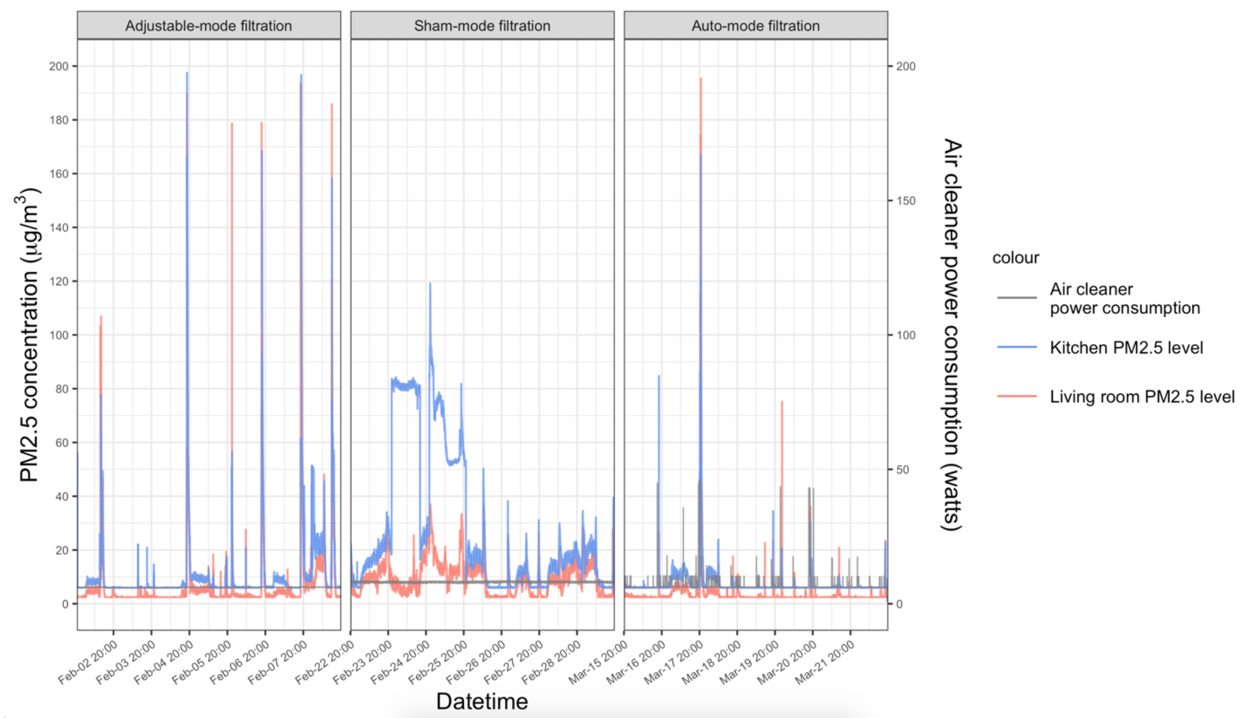

Figure 5. Time-series plot of the air cleaner power consumption and the indoor $PM_{2.5}$ level measured in kitchen and living room in one of the participant's residence, stratified by different types of filtration scenario.

Table 2 shows the summary of exposure variables under each type of intervention scenario. During each intervention scenario, participants reported ≈ 71% of their time in home. The 7-day mean average outdoor $PM_{2.5}$ level, indoor temperature and relative humidity were similar across different types of filtration. The 7-day mean indoor $PM_{2.5}$ level measured in the living room under the auto-mode filtration and the adjustable-mode filtration were 7.8 (SD 2.7) $\mu g/m^3$ and 9.5 (SD 4.4) $\mu g/m^3$, respectively. The result of the mixed model adjusted for indoor cooking events shows that compared with sham-mode filtration, using auto-mode filtration for 7 days decreased the mean indoor $PM_{2.5}$ level in living room and kitchen by 5.05 $\mu g/m^3$ (95% CI [-6.19, -3.91]; $p<0.001$) and 6.60 $\mu g/m^3$ (95% CI [-7.86, -5.34]; $p<0.001$) respectively, whereas using adjustable-mode filtration for 7 days decreased the mean indoor $PM_{2.5}$ level in living room and kitchen by 3.43 $\mu g/m^3$ (95% CI [-4.57, -2.28]; $p<0.001$) and 5.01 $\mu g/m^3$ (95% CI [-6.27, -3.76]; $p<0.001$), respectively. Compared to adjustable-mode filtration, using auto-mode filtration for 7 days decreased the indoor mean $PM_{2.5}$ levels measured in the living room and the kitchen by 1.63 $\mu g/m^3$ (95% CI [-2.76, -0.48]; $p=0.01$) and 1.59 $\mu g/m^3$ (95% CI [-2.84, -0.34]; $p=0.04$) , respectively.

Table 2. Summary of exposure variables under each type of filtration.

Variable		Type of Filtration, mean (SD)		
		sham-mode	**Auto-mode**	**Adjustable-mode**
7-day indoor PM2.5, $\mu g/m^3$				
	Living room	12.8 (9.8)	7.8 (2.7)	9.5 (4.4)
	Kitchen	15.7 (11.6)	9.1 (3.5)	10.8 (5.4)
7-day temperature, °C				
	Living room	28.2 (4.4)	28.0 (5.5)	27.4 (6.6)
	Kitchen	25.3 (6.0)	25.1 (4.3)	25.2 (6.1)
7-day relative humidity, %				
	Living room	27.5 (5.1)	26.6 (3.9)	27.9 (6.8)
	Kitchen	31.5 (9.8)	30.5 (8.4)	31.3 (11.0)
7-day outdoor PM2.5, $\mu g/m^3$ [a]		5.6 (1.7)	5.9 (1.5)	5.6 (1.7)

Abbreviations: PM2.5, particulate matter with an aerodynamic diameter equal to or less than 2.5 μm.

Table 3. Summary of the linear mixed model of indoor living room and kitchen $PM_{2.5}$ level, adjusted for cooking event.

	Living room $PM_{2.5}$ level			Kitchen $PM_{2.5}$ level		
	Estimate	*SE*	*p*	*Estimate*	*SE*	*p*
Intercept	12.28	2.18	<0.001	15.09	2.6	<0.001
Scenario						
Sham-mode	-	-	-	-	-	-
Auto-mode	-5.05	0.58	<0.001	-6.60	0.64	<0.001
Adjustable-mode	-3.43	0.58	<0.001	-5.01	0.64	<0.001
Cooking (1 = yes)	7.93	0.93	<0.001	9.36	1.02	<0.001

Note. R gamm4 package used to estimate the model. Both models adjusted for cooking event (variable "Cooking") happened in each household.

Personal $PM_{2.5}$ exposure

Table 4 demonstrates the summary of 12-hour time-weighted average $PM_{2.5}$ personal exposure under each type of filtration. We calculated the 12-hour time-weighted average exposure right before each blood pressure measurement was conducted. The result of the mixed model without adjusting for total time spent in home shows using auto-mode filtration decreased the 12-hour time-weighted average $PM_{2.5}$ exposure by 5.42 μg/m^3 (95% CI [-9.52, -1.31]; p=0.01), whereas using adjustable-mode filtration decreased the 12-hour time-weighted $PM_{2.5}$ exposure by 4.05 μg/m^3 (95% CI [-8.20, 0.11]; p=0.06). In the mixed model adjusted for total time spent in home within the corresponding 12-hour timeframe and days of receiving the intervention, using auto-mode filtration and adjustable-mode filtration decreased the personal 12-hour time-weighted average $PM_{2.5}$ exposure by 5.45 μg/m^3 (95% CI [-9.51,-1.39]; p=0.01) and 4.26 μg/m^3 (95% CI [-8.37, -0.14]; p<0.05), respectively (Table 5). Adjusted for total time spent in home, the personal 12-hour time-weighted $PM_{2.5}$ exposure under the auto-mode filtration and adjustable-mode filtration was lower comparing to the sham-mode filtration.

Table 4. Summary of 12-hour time-weighted average $PM_{2.5}$ personal exposure under each type of filtration.

Variable	Type of Filtration, mean (SD)		
	Sham-mode	Auto-mode	Adjustable-mode
7-day average 12-hour time-weighted average personal PM2.5 exposure, μg/m³/week [a]	10.8 (6.0)	7.6 (2.6)	9.0 (3.4)
12-hour[b] before morning BP measurement	10.8 (3.6)	7.4 (2.6)	8.3 (2.5)
12-hour[c] before evening BP measurement	10.8 (8.9)	7.9 (3.5)	9.7 (5.4)

Abbreviations: PM2.5, particulate matter with an aerodynamic diameter equal to or less than 2.5 μm; BP, blood pressure.

[a] Time-weighted average personal PM2.5 exposure was calculated according to the time-activity information, indoor $PM_{2.5}$ monitoring data and outdoor PM2.5 monitoring data provided by the Puget Sound Clean Air Agency, WA.

[b] 8:00 pm in the previous day to 7:59 am the next day (right before the morning BP measurement was conducted).

[c] 8:00 am in the previous day to 7:59 pm the next day (right before the evening BP measurement was conducted).

Table 5. Summary of the linear mixed model of 12-hour time-weighted average $PM_{2.5}$ personal exposure.

	Model 1			Model 2		
	Coeff	*SE*	*p*	*Coeff*	*SE*	*p*
Intercept	11.35	2.11	<0.001	8.88	2.32	<0.001
Scenario						
Sham-mode	-	-	-	-	-	-
Auto-mode	-5.42	2.09	0.01	-5.45	2.07	0.01
Adjustable-mode	-4.05	2.12	0.06	-4.26	2.1	0.04
Day	-0.09	0.3	0.78	0.01	0.3	0.97
Indoor time	-	-	-	0.25	0.1	0.01
Scenario*day						
Sham-mode*day	-	-	-	-	-	-
Auto-mode*day	0.49	0.42	0.24	0.47	0.41	0.26
Adjustable-mode*day	0.40	0.42	0.34	0.42	0.42	0.31

Note. R package gamm4 used to estimate the model. Model 1 adjusted for days of receiving the intervention (variable "Day"). Model 2 adjusted for time spent indoor in the corresponding 12-hour time frame (variable "Indoor time") and days of receiving the intervention (variable "Day").

Blood pressure outcome

We first examined the primary outcome, which was the blood pressure measured with the Omron wrist blood pressure monitor. Table 6 shows the summary of the Omron wrist blood pressure

measurement under each type of intervention scenario. It can be observed from Figure 6 that there is no clear pattern for SBP and DBP under different type of intervention scenario regardless for the time of measurement at 8 am or 8 pm.

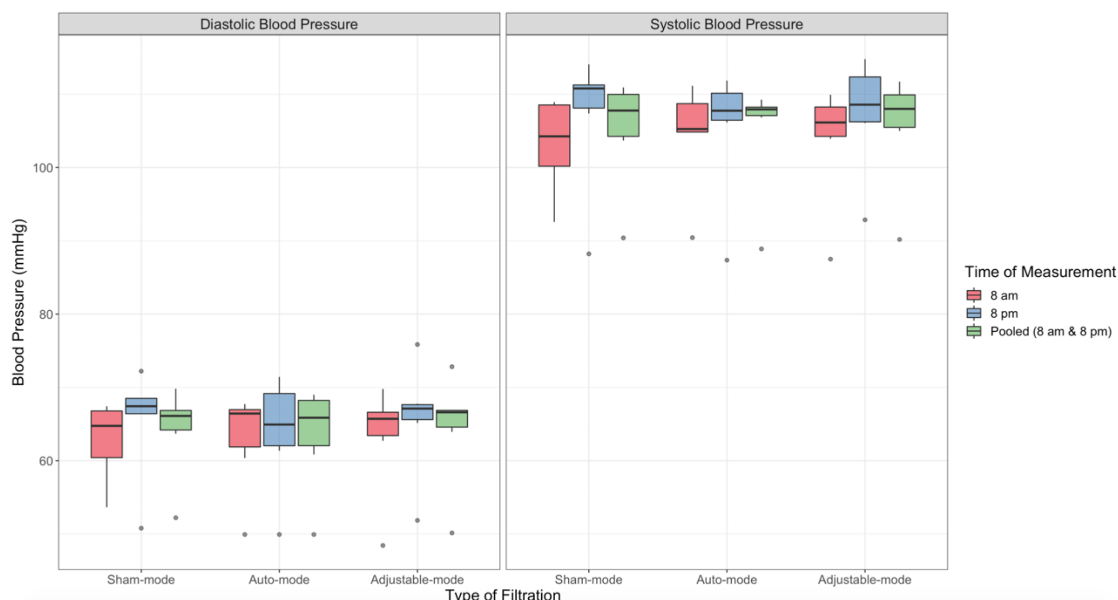

Figure 6. Blood pressure measurement using Omron wrist blood pressure monitor, stratified by time of measurement.

Table 6. Summary of blood pressure under each type of filtration, stratified by time of measurement. [a]

Variable	Type of Filtration, mean (SD)		
	Sham-mode	**Auto-mode**	**Adjustable-mode**
7-day average blood pressure , mm-Hg			
SBP	105.1(7.7)	104.9 (7.9)	105.5 (7.9)
Morning	103.1 (6.5)	104.4 (7.4)	103.7 (8.2)
Evening	107.1 (9.5)	105.3 (9.0)	107.3 (7.9)
DBP	64.1 (6.2)	63.4 (7.2)	64.5 (7.6)
Morning	62.8 (5.4)	63.0 (6.9)	63.2 (7.6)
Evening	65.5 (7.5)	63.8 (7.8)	65.8 (7.8)

Abbreviations: SBP, systolic blood pressure; DBP, diastolic blood pressure.

[a] The measuring time of morning and evening blood pressure is 8 am and 8 pm, respectively.

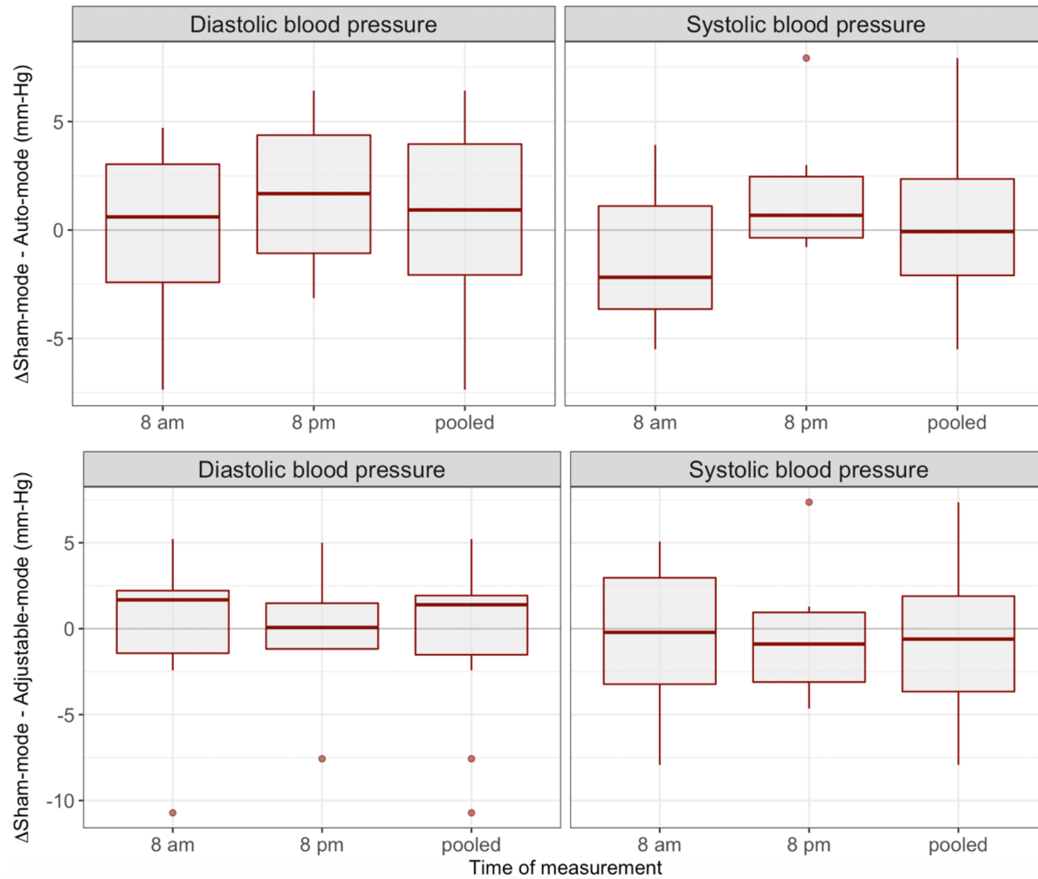

Figure 7. Variation of blood pressure by different types of intervention scenario and time of measurement, averaged within person.

The result of the adjusted linear mixed model shows compared with the sham-mode filtration, using auto-mode filtration for a week decreased morning SBP and morning DBP by 6.13 mm-Hg (95% CI [-12.52, 0.26]; p=0.06) and 3.50 mm-Hg (95% CI [-9.09, 2.09]; p=0.2), respectively; and decreased evening SBP and evening DBP by 2.43 mm-Hg (95% CI [-10.07, 5.21]; p=0.5) and 3.31 (95% CI [-10.37, 3.75]; p=0.4), respectively. Using adjustable-mode filtration for a week decreased morning SBP and morning DBP by 1.81 mm-Hg (95% CI [-8.2, 4.60]; p=0.6) and 1.97 mm-Hg (95% CI [-7.58, 3.64]; p=0.5), respectively; and decreased evening SBP and evening DBP by 5.23 mm-Hg (95% CI [-12.97, 2.51]; p=0.2) and 5.39 (95% CI [-12.50, 1.72]; p=0.1), respectively (Table 7). The result of including a penalized spline of day in the model as

an interaction term on scenario (*scenario*day*) shows that a 1-day increase in the time using auto-mode filtration resulted in significantly higher 1.66 mm-Hg (95% CI [0.31, 3.01]; p=0.02) morning systolic blood pressure as compared to the sham-mode filtration. The result of a sensitivity analysis that included an additional interaction term for total time spent in the home during the 12 hours before the blood pressure measurement or measurement time on the weekend on scenario was robust for both morning and evening blood pressure.

Table 7. Summary of the linear mixed model of systolic blood pressure (SBP) and diastolic blood pressure (DBP) adjusted for the time-varying covariates, including the stress before or during and the meal before the blood pressure measurement.

	Morning SBP			Evening SBP			Morning DBP			Evening DBP		
	Coeff	*SE*	*p*	*Coeff*	*SE*	*p*	*Coeff*	*SE*	*p*	*Coeff*	*SE*	*p*
Intercept	103.3	3.86	<0.001	104.54	4.72	<0.001	60.85	3.21	<0.001	64.19	4.23	<0.001
Scenario												
Sham-mode	-	-	-	-	-	-	-	-	-	-	-	-
Auto-mode	-6.13	3.26	0.06	-2.43	3.9	0.54	-3.5	2.85	0.22	-3.31	3.6	0.36
Adjustable-mode	-1.81	3.27	0.58	-5.23	3.95	0.19	-1.97	2.86	0.49	-5.39	3.63	0.14
Day	-0.31	0.49	0.53	0.21	0.55	0.7	0.02	0.42	0.96	-0.18	0.51	0.72
Stress												
Not at all	-	-	-	-	-	-	-	-	-	-	-	-
Only a little	0.16	2.06	0.94	2.06	1.99	0.3	2.28	1.78	0.2	2.96	1.84	0.11
To some extent	1.49	2.51	0.55	3.92	2.46	0.11	4.12	2.15	0.06	5.87	2.27	0.01
Rather much	5.94	3.69	0.11	4.72	3.79	0.22	6.42	3.18	0.05	4.86	3.49	0.17
Meal												
Did not have a meal before the BP measurement	-	-	-	-	-	-	-	-	-	-	-	-
Had a meal before the BP measurement	1.38	1.42	0.33	0.65	1.58	0.68	-0.7	1.24	0.58	-0.1	1.45	0.95
Scenario*day												
Sham-mode*day	-	-	-	-	-	-	-	-	-	-	-	-
Auto-mode*day	1.66	0.69	0.02	-0.04	0.74	0.96	0.72	0.61	0.24	0.15	0.69	0.83
Adjustable-mode*day	0.44	0.69	0.53	0.87	0.8	0.28	0.24	0.6	0.69	0.88	0.73	0.23

Note. R gamm4 package used to estimate the models. All models adjusted for stress before or during the blood pressure measurement (variable "Stress"), meal before the blood pressure measurement (variable "Meal"), and the day of intervention (variable "Day").

In order to assess the feasibility of using the smartwatch blood pressure monitor, we first examined the correlation between the Omron wrist blood pressure measurement and the watch blood pressure measurement at the matching time point (i.e. the measurement at 8 am and 8 pm from both devices) (Figure 8) (Appendix X). As can be seen from the plot, there was no correlation between the SBP and the DBP measured by the Omron wrist blood pressure monitor and the Smartwatch (r= -0.02 and 0.08, respectively), which was similar to our previous

validation results (Section 3.2). The Pearson's correlation between the smartwatch SBP and DBP was almost 1, indicated it is likely that one of these two parameters was a factor of the other. We also explored the average of the closet 10-minute, 20-minute and 30-minute measurement of the smartwatch to the Omron wrist blood pressure measurement at 8 am and 8 pm on each day However, a similar result was found. There was no correlation between the SBP and DBP measured by the Omron wrist blood pressure monitor and the Smartwatch (r≈0).

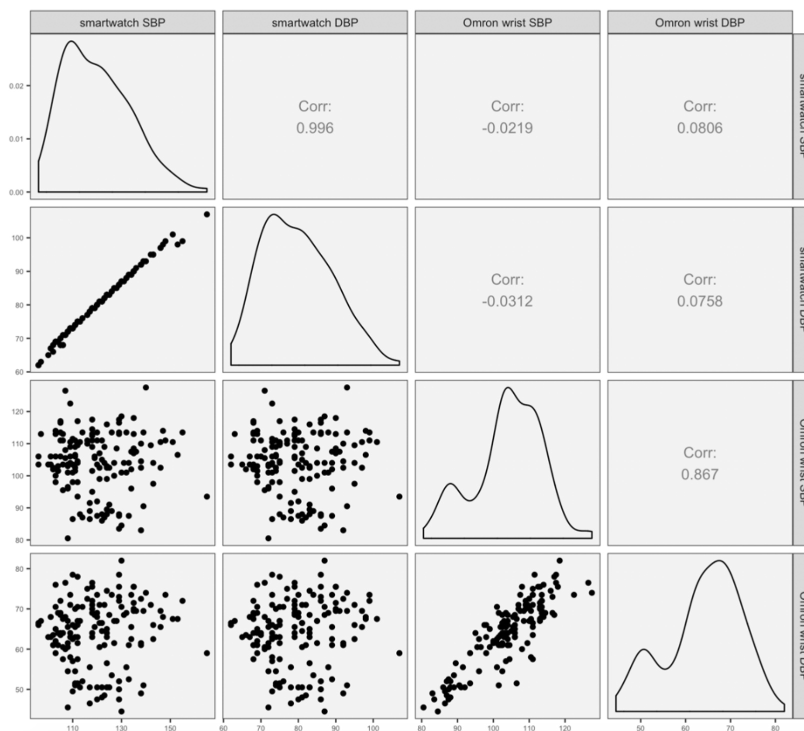

Figure 8. Correlation between smartwatch and Omron wrist blood pressure measurement at the matching time points.

The inspection of the Bland-Altman plot shows that the average difference of the two measurement types for SBP and DBP were 13.8 and 21.7 mm-Hg, respectively (Figure 9), which indicates on average the smartwatch tended to measure 13.8 mm-Hg higher of SBP and 21.7 mm-Hg higher of DBP than the Omron wrist blood pressure monitor. The blue regression line of

mean bias shows that the smartwatch tended to underestimate BP readings when in low BP ranges and overestimate the BP readings in high BP ranges for both SBP and DBP.

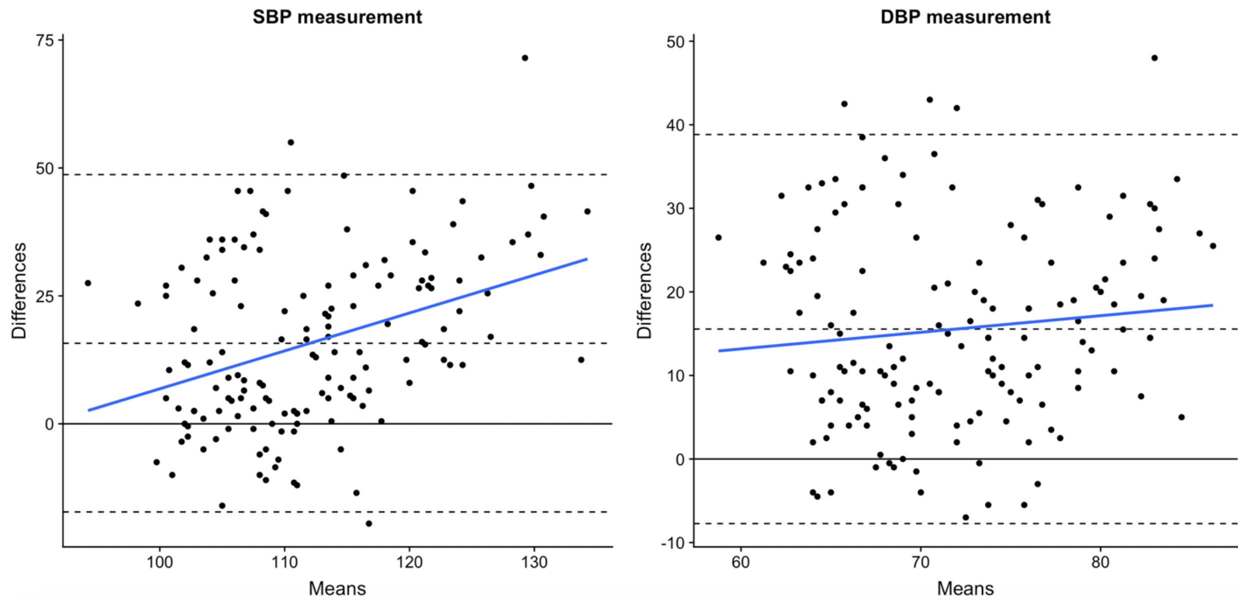

Figure 9. Bland-Altman plot of the Omron wrist and Smartwatch blood pressure measurement.

Chapter 4. DISCUSSION

The ambient mean $PM_{2.5}$ concentration in the US has decreased over the years nationally since 1990 (Zhang et al., 2018). However, the elevated ambient $PM_{2.5}$ level during the wildfire season is still a great concern to public health (Phuleria et al., 2005). Combination of these outdoor-originated wildfire smoke particles (Sapkota et al., 2005) that penetrate indoors and indoor sources can contribute to the exposure of PM indoors. Several crossover intervention studies have evaluated the effects of indoor air filtration on indoor PM exposures and health outcomes among healthy and non-smoking populations in highly polluted Asian countries (Chen et al., 2015; Cui et al., 2018; Li et al., 2017), woodsmoke or traffic-impacted communities (Allen et al., 2011; Kajbafzadeh et al., 2015; Karottki et al., 2013; Padró-Martínez et al., 2015), and urban US environments (Morishita et al., 2018). In these studies, more than 30% significant reductions in indoor $PM_{2.5}$ level (Allen et al., 2011; Chen et al., 2015; Cui et al., 2018; Kajbafzadeh et al., 2015; Karottki et al., 2013; Li et al., 2017), personal $PM_{2.5}$ exposures (Morishita et al., 2018) and particle number concentration (Padró-Martínez et al., 2015) were reported when using either HEPA (Allen et al., 2011; Cui et al., 2018; Kajbafzadeh et al., 2015; Karottki et al., 2013; Li et al., 2017; Morishita et al., 2018; Padró-Martínez et al., 2015) or non-HEPA (Chen et al., 2015) air filtration system for a short term (13 hours to 14 days). For the effect of indoor air filtration on blood pressure in relatively highly polluted locations, inconsistent findings were reported: Chen et al. reported significant reductions in both systolic and diastolic blood pressure among 35 healthy college student using indoor non-HEPA (electret) air conditioner filtration for 2 days. In a study which investigated the effectiveness of HEPA air cleaners on mitigating cardiovascular health effects among 40 older adults in an urban United States location, significant decreases in SBP and DBP were found in groups that were using the HEPA air cleaner for 3 days (Morishita

et al., 2018). In contrast, other crossover studies evaluating the effect of indoor HEPA air filtration on blood pressure in woodsmoke or traffic-impacted communities showed no improvement in systolic and diastolic blood pressure among participants who were exposed to filtered air: Allen et al. found no significant decreases in SBP and DBP among 45 healthy adults exposed to HEPA-filtered air as compared to non-filtered air in a woodsmoke-impacted community (Allen et al., 2011); Karottki et al. reported there were no significant reductions in SBP and DBP among 48 non-smoking elderly using the HEPA air filtration (Karottki et al., 2013) in a traffic pollution impacted community. In a study which evaluated the effectiveness of HEPA air filtration on blood pressure among 20 non-smoking adults in a traffic pollution impacted community, the results showed no evidence that the filtration improved either SBP or DBP (Padró-Martínez et al., 2015). It is worth noting that none of these three aforementioned studies that were conducted in either woodsmoke or traffic impacted communities included a washout period between different types of filtration scenario. Therefore, carryover effects may have influenced the results. These aforementioned studies assessed the blood pressure either with repeated measurement at the same time in the morning during each day of intervention (Karottki et al., 2013; Morishita et al., 2018) or before and immediately after the intervention (Allen et al., 2011; Chen et al., 2015; Cui et al., 2018; Kajbafzadeh et al., 2015; Li et al., 2017; Padró-Martínez et al., 2015).

In this crossover intervention pilot study, we found the short-term use of HEPA air cleaner significantly reduced indoor $PM_{2.5}$ level, which is consistent with the aforementioned air filtration studies. Furthermore, we found using auto-mode filtration demonstrated a higher magnitude of reduction in indoor $PM_{2.5}$ level than the adjustable-mode filtration, which is the

operating mode that relies on people to manually adjust the air cleaner fan speed. This result suggested that the efficacy of the air cleaner under the adjustable-mode filtration highly depends on the behavior of the users. One of the participants reported adjusting the air cleaner to the sleep mode (i.e. the quietest operating fan speed) during the 7-day adjustable-mode filtration due to noise issues, which may contribute to a lower efficacy of particle filtration; another participant adjusted the air cleaner to fan speed 1 during the adjustable-mode filtration due to personal preference, which may limit the ability of air cleaner on reducing indoor $PM_{2.5}$ level when significant pollution sources (e.g. cooking) are present. This demonstrates the efficacy of air cleaner might vary across household due to user's habit, and using auto-mode air cleaner seems to improve real-world effectiveness since it does not rely on the user to adjust the fan speed when the indoor $PM_{2.5}$ levels are elevated.

In this pilot study with six participants, we found no statistically significant lower blood pressure using auto-mode filtration comparing to sham-filtration for one week. However, findings on wrist blood pressure are suggestive for a possible effect of using air cleaner on lowering blood pressure, with morning blood pressure demonstrated a higher reduction comparing to the evening blood pressure when using the auto-mode filtration. Morning blood pressure might be more reflective to the influence of the air filtration intervention, since people spend a relatively long time at home before the morning measurement at 8 am, whereas before the evening blood pressure measurement, people tend to spend most of their time outdoors or in an indoor environment other than home, such as school or office. Our validation of wrist blood pressure monitor and smartwatch showed the measurement of the sphygmomanometer and the wrist blood pressure was in high correlation, which is consistent with a previous study (Deutsch et al., 2014).

For the new smartwatch with blood pressure measurement that we used, however, the results did not show its measurements were in good agreement with either the sphygmomanometer or the Omron oscillometric wrist blood pressure monitor. Furthermore, the correlation of the SBP and DBP measured by the smartwatch was found to be ≈ 1, indicating this smartwatch may convert these two parameters using a crude calculation. The underlying measuring principle was not clear as well. Therefore, our validation testing of the smartwatch did not support its use in our field study or as a proxy for more reliable in-home blood measurement approaches such as oscillometric devices and sphygmomanometer.

Limitation and Strength

To our knowledge, this is the first study to examine the effectiveness and the health benefits of using an auto-mode air cleaner in an urban US location that is compliant with the US National Ambient Air Quality Standards, and where the air pollution level tends to be lower than most Asian countries. Moreover, we considered both indoor sources and outdoor-originated PM exposure in this study. However, our study has some limitations. First, the small sample size limits our power to detect an association between indoor HEPA air filtration and blood pressure. In addition, the characteristics of the study population (healthy young adult students) may also contribute to our null findings on the health benefits of using air filtration. Based on a power calculation, in order to achieve 80% power to detect a 2 mm-Hg difference in blood pressure, a sample size of at least 40 people is required for each intervention group. Third, the estimation of personal exposure in our study only relied on monitoring of two indoor microenvironments (i.e. living room and kitchen), and used data from regional fixed-site monitoring stations as surrogates for out-of-home exposures may have created some exposure estimation error, which

may have reduced our ability to detect statistically significant associations between the intervention and reduced blood pressure. Furthermore, the indoor location which people spend their most time at home is bedroom, only one air cleaner was installed in the living room of each study household may not work well on reducing personal exposure to $PM_{2.5}$ throughout the household. In future studies, we recommend including more PM monitors or using personal PM monitoring to achieve a better exposure assessment and including a PM monitor and/or air cleaner for the bedroom.

Conclusion

In this pilot study, we found suggestive evidence of using auto-mode air cleaner on lowering blood pressure among healthy, young adult students living in an urban location. Our findings suggest using auto-mode filtration may lead to improved real-world effectiveness for reducing indoor $PM_{2.5}$ levels, since auto-mode filtration does not rely on users to turn on the air cleaners when the air is polluted. Future studies should further evaluate the potential health benefits of auto-mode filtration among the susceptible population, such as COPD patients, asthmatic people, elderly, or a wildfire-impacted community.

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APPENDICES

Appendix I. Participant eligibility screening questionnaire.

Pre-screening Questionnaire

A. Basic Subject Information

A1. Subject ID:

A2. Subject's name (First, Last):

A3. Subject's date of birth (mm/dd/yyyy) or age:

A4. Subject's gender:

A4. Subject's weight (kg):

A5. Subject's height (cm):

B. Disease, Medication History and Smoking Status

B1. Have you ever been diagnosed with hypertension?

☐ Yes ☐ No

B2. Are you currently taking anti-hypertensive medication?

☐ Yes ☐ No

B3. Do you currently smoke any tobacco products, cannabis/marijuana, or vape?

☐ Yes ☐ No

C. Baseline Exposure Information

C1. Please write down the address you spend most of the DAY at (office/ school etc.):

____

C2. Please write down the address you spend most of the NIGHT at:

____

C3. Which of the following building type best describes the place you currently live in:

☐ Apartment ☐ House ☐ Dormitory ☐ Condo ☐ Townhouse

☐ Others. Please specify: _____________

C4. How many people live in your home (not include yourself)?

_______________ people

C5. Does any of the people you specify in Question C4. currently smoke in your home?

☐ Yes ☐ No

C6. How often do you cook at your home in a week?

☐ more than 6 days per week

☐ 3 to 5 days per week

☐ less than 3 days per week

☐ I do not cook at home

C7. What kind of cooking appliance do you use most in your home?

☐ Gas ☐ Electric ☐ Others. Please specify: _______________

C8. Do you have any pet in your dwelling unit?

☐ Yes. Please specify the pet you have: _____________________________

☐ No

C9. Do you use a fireplace in you dwelling unit?

☐ Yes ☐ No

C10. If yes, what fuel does it use?

☐ Wood ☐ Gas ☐ Electric ☐ Others. Please specify:___________

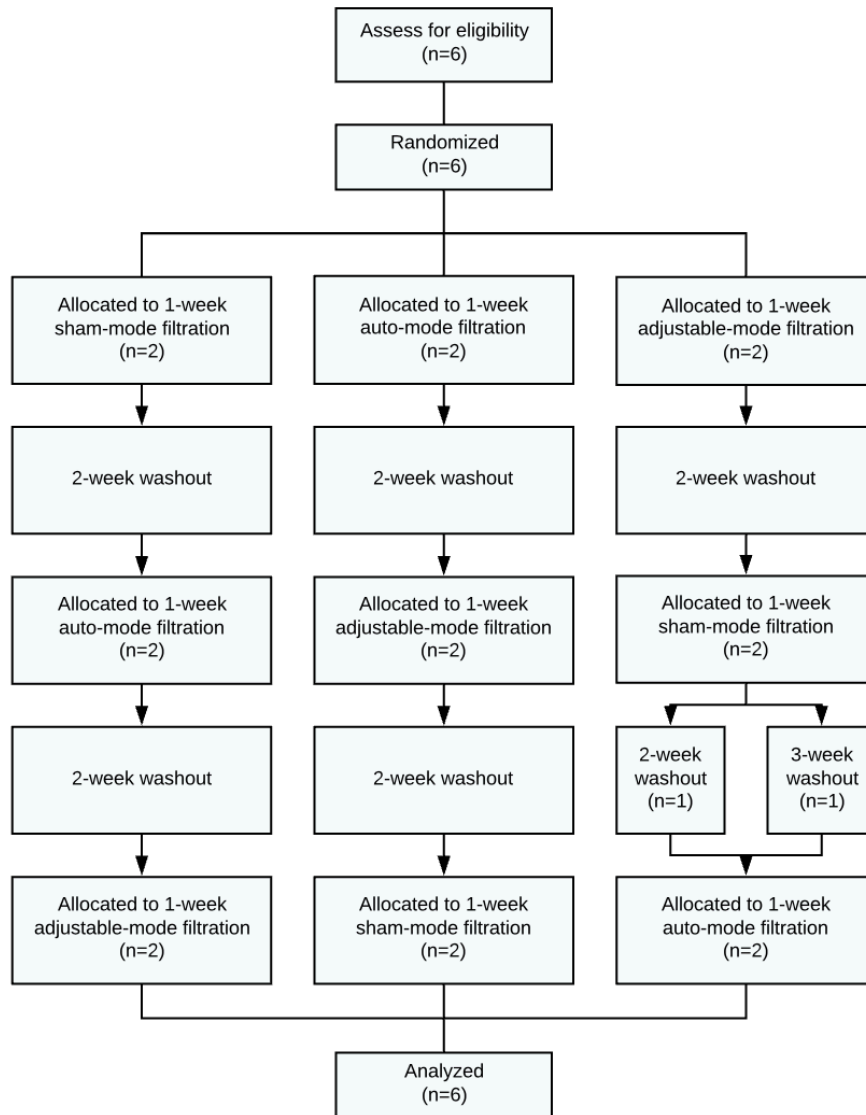
C10. Do you use candles or incense?

☐ Yes ☐ No

C11. How is your home heated?

☐ Wood ☐ Gas ☐ Electric ☐ Others. Please specify:___________

Appendix II. Study flow diagram.



Appendix III. Example of the time-activity diary.

Subject ID: _______ , Subject's name (First, Last): __________

Today's date (MM/DD/YYYY): ___________________

Time-Activity Log

	Time	Location				Activity									
		I am currently in/at...				I'm currently... (check all that apply)									
		home	office	school	Others, please specify	Commuting	cooking	Kitchen ventilation hood	Cooking method	sleeping	vacuuming	Cleaning	using fireplace	burning candle or incense	Others, please specify
Yesterday	20:00 - 20:59							On / off							
	21:00 - 21:59							On / off							
	22:00 - 22:59							On / off							
	23:00 - 23:59							On / off							
Today	00:00 - 00:59							On / off							
	01:00 - 01:59							On / off							
	02:00 - 02:59							On / off							
	03:00 - 03:59							On / off							
	04:00 - 04:59							On / off							
	05:00 - 05:59							On / off							
	06:00 - 06:59							On / off							
	07:00 - 07:59							On / off							
	08:00 - 08:59							On / off							
	09:00 - 09:59							On / off							

Appendix IV. Summary of the data source for calculating the time-weighted average exposure.

Parameter	Monitoring Location	Instrument	Instrument location
Indoor $PM_{2.5}$ Concentration	Home (Kitchen and living room)	The indoor air quality monitor (Plantower PM sensor).	Indoor at each household.
	Other indoor environments, e.g., office, school, vehicle	The fixed outdoor monitoring sites of the Puget Sound Clean Air Agency, using I/O ratio 0.8.	The nearest outdoor air monitoring site to each environment, such as office or school.
Outdoor $PM_{2.5}$ Concentration	Road/ street	The fixed outdoor monitoring sites of the Puget Sound Clean Air Agency.	The nearest outdoor air monitoring site to each location.

Appendix V. Example of the blood pressure diary.

<u>Wrist Blood Pressure Diary</u>

A. Please answer the following questions before you take your measurement:

A1. Were you rushing to get here or physically active right before taking this measurement?

☐ Yes ☐ No

A2. Have you already had your breakfast?

☐ No

☐ Yes, please specify what you had for your breakfast, including drinks and food:

A3. "Stress means a situation in which a person feels tense, restless, nervous or anxious or is unable to sleep at night because his/her mind is troubled all the time. Do you feel this kind of stress these days?"

☐ Very much ☐ Rather much ☐ To some extent ☐ Only a little ☐ Not at all

B. Record your blood pressure measurements:

Date (MM/DD)			Measurement at 8 am
	1st	SBP	
		DBP	
	2nd	SBP	
		DBP	
	3rd	SBP	
		DBP	

Appendix VI. Instruction of Omron wrist blood pressure measurement provided for the study participant.

INSTRUCTION

Before you take the measurement

- Avoid smoking, having a drink containing caffeine or exercise before you take your blood pressure measurement. Use the bathroom before the process.
- Avoid wearing any tight or restrictive clothing around the arm you are measuring your blood pressure in. You should avoid rolling up TIGHT shirt sleeves.
- Rest for at least five minutes before measuring your blood pressure. During this time you should sit with feet flat on the floor, back supported, arm at heart level (preferably on a table surface), try to relax and do not talk.
- Two sets of measurement should be taken per day (at 8 am and 8 pm), with each set consisting of three measurements. Be sure to record all of your measurements in the diary.
- Make sure to record the date under the title of each page before you start your measurement.

Taking the measurements

- Sit down and keep back straight.
- Answer the questions in the diary. (See below)
- Adjust the distance from the top of the seat to the top of the table between 12±2 inches.
- Place the elbow on a table.
- Roll up the sleeve and put the LEFT arm through the cuff loop with the palm facing upward.
- Position the cuff approximately half inch away from the bottom of the palm.
- Align the middle of the monitor with your middle finger.
- Wrap wrist cuff firmly.
- Press the START/STOP button.
- Elevate cuff wrist to heart level until the position indicator turns blue.
- Record the SBP, DBP and the date on the form.
- Repeat the steps above to complete the other two measurements from the wrist BP monitor. After each measurement, write the readings down in the diary and do not round up the number.

Appendix VII. The protocol of the wrist and smartwatch blood pressure monitor validation.

Blood pressure measurement protocol

A. Equipment

(1) A sphygmomanometer

(2) A Stethoscope with a bell

(3) An Omron wrist blood pressure monitor

(4) A Smartwatch blood pressure monitor

(5) A pen

(6) A Measurement tape

(7) A digital timer

B. Method

Part 1: Measurement with the sphygmomanometer (follow the Native-CHART protocol)

B.1 Arm Measurements

The following steps are properly carried out:

(1) Participant standing if possible

(2) Arm bare from elbow to shoulder

(3) Arm at 90 degree angle

(4) Arm length measured from the acromion (or bony extremity of the shoulder girdle) to the olecranon (or tip of the elbow)

(5) Midpoint of arm marked at dorsal aspect

(6) Arm relaxed at side

(7) Circumference measured with tape horizontal

(8) No indentation of skin

(9) Mark at midpoint of arm

(10) Value recorded on study form and checked to ascertain proper cuff size

(11) Proper cuff size checked on study form

B.2 Preparation for BP Readings

(1) Brachial artery palpated

(2) Midpoint of bladder within the cuff located

(3) Cuff applied with midpoint of bladder over brachial artery

(4) Arm positioned with midpoint of cuff width at "heart" level; lower edge 1 inch above crease.

(5) Wait 5 minutes

(6) Sphygmomanometer connected to cuff

(7) Sphygmomanometer scale (midpoint) is at eye level

(8) radial pulse located

(9) cuff is inflated quickly to 80 mm Hg

(10) cuff is further inflated slowly by increments of 10 mm Hg (if pulse present at 80mm Hg) until the pulse is no longer felt.

(11) cuff is quickly and completely deflated

(12) Observed Pulse Obliteration value is correctly recorded on the form

(13) Pulse Obliteration Pressure + 30 are added to get the Peak Inflation Level

B.3 Measurement of Blood Pressure

(1) Brachial artery palpated

(2) Stethoscope in ears (earpieces angled forward)

(3) Bell over artery (may try using diaphragm is sounds heard poorly with bell), without cuff or tubing contact

(4) Cuff inflated quickly and smoothly to the Peak Inflation Level

(5) Deflation at 2 mm Hg/second to 10 mm Hg below K5

(6) Cuff quickly and completely deflated

(7) Cuff disconnected or valve opened fully

(8) Recording of SBP and DBP values

B.4 Between Readings

(1) Cuff removed or tubing disconnected if uncomfortable

(2) Arm raised passively overhead for 15 seconds. (Make sure the patient is not supporting the arm at all)

(3) Arm lowered and cuff replaced (if needed) with attention to proper cuff placement, as above.
Note: There is a total of 30 seconds between readings.

(4) Cuff reconnected if needed

B.5 Second Seated Blood Pressure Reading

(1) Conforms with procedures as in B.3 and B.4 above

B.6 Third Seated Blood Pressure Reading

(1) Conforms with procedures as in B.3 above

B.7 Completion

(1) Complete BP Form

(2) Replace sphygmomanometer for storage

Part 2: Measurement with the Omron wrist blood pressure monitor

(1) Participant rests for 5 minutes before taking the measurement.

(2) Sit down and keeps back straight.

(3) Adjust the distance from the top of the seat to the top of the table between 12±2 inches.

(4) Place the elbow on a table.

(5) Roll up the sleeve and put the left arm through the cuff loop with the palm facing upward.

(6) Position the cuff approximately half inch away from the bottom of the palm.

(7) Align the middle of the monitor with participant's middle finger.

(8) Wrap wrist cuff firmly.

(9) Press the START/STOP button.

(10) Participant elevates cuff wrist to heart level until the position indicator turns blue.

(11) Record the SBP, DBP on the form.

(12) Rest for at least 5 minutes.

(13) Repeat Step (1) to (12) to complete the other two measurements from the wrist BP monitor.

Part 3: Measurement with the smartwatch blood pressure monitor

(1) Participant wears the smartwatch on the left wrist

(2) Participant rests for 5 minutes before taking the measurement.

(3) Sit down and keeps back straight.

(4) Adjust the distance from the top of the seat to the top of the table between 12±2 inches.

(5) Place the elbow on a table.

(6) Open the smartwatch app on cellphone and switch to manual mode blood pressure monitoring.

(7) Press the START button on the app.

(8) Rest for at least 5 minutes.

(9) Repeat Step (1) to (8) to complete the other two measurements from the wrist BP monitor.

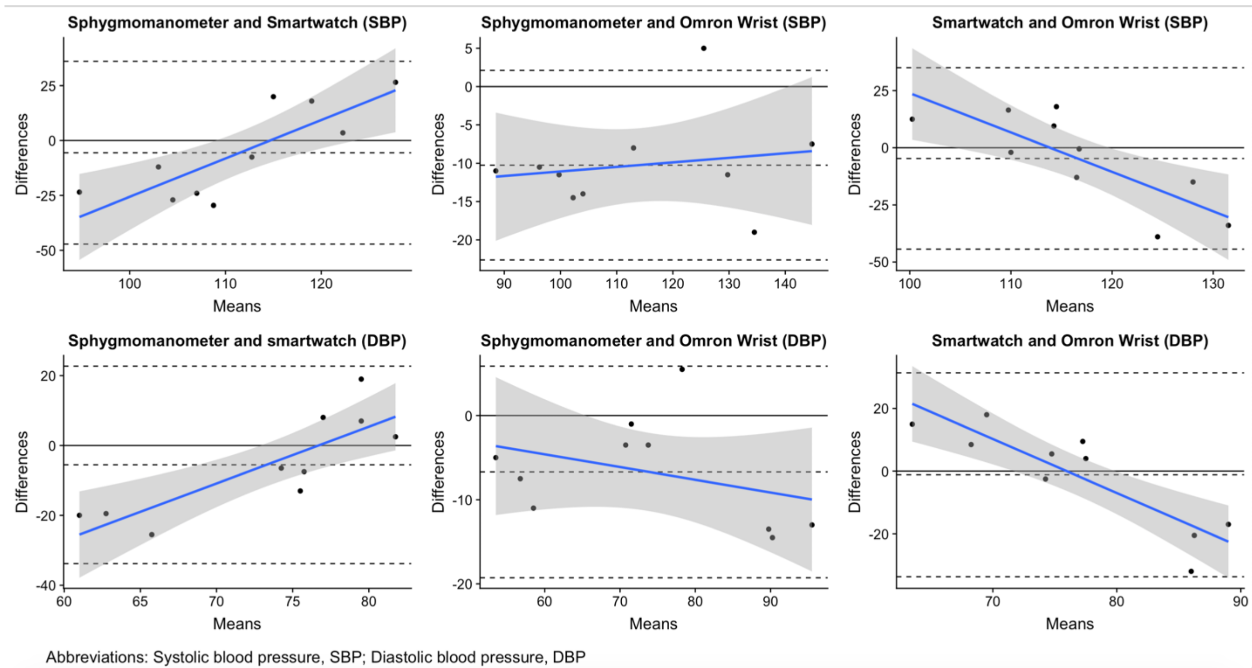
Appendix VIII. Final calibration model for the Plantower sensors.

	sensor #1			sensor #2			sensor #3			sensor #4			sensor #5			sensor #6		
	Coeff	*SE*	*p*	*Coeff*	*SE*	*p*	*Coeff*	*SE*	*p*	*Coeff*	*SE*	*p*	*Coeff*	*SE*	*p*	*Coeff*	*SE*	*p*
Intercept	5.65	2.687	*	8.601	2.618	***	6.693	2.071	**	9.046	2.234	***	9	2.251	***	6.314	2.699	**
$PM_{2.5}$	0.708	0.025	***	0.692	0.024	***	0.686	0.018	***	0.565	0.017	***	0.641	0.019	***	0.726	0.025	***
Adjusted R^2		0.843			0.841			0.9			0.88			0.878			0.84	

	sensor #7			sensor #8			sensor #9			sensor #10			sensor #11			sensor #12		
	Coeff	*SE*	*p*	*Coeff*	*SE*	*p*	*Coeff*	*SE*	*p*	*Coeff*	*SE*	*p*	*Coeff*	*SE*	*p*	*Coeff*	*SE*	*p*
Intercept	4.471	1.988	*	4.856	2.308	*	4.678	2.071	*	7.908	2.197	***	2.439	2.176		5.934	2.018	**
$PM_{2.5}$	0.727	0.018	***	0.705	0.021	***	0.739	0.019	***	0.609	0.018	***	0.718	0.019	***	0.652	0.017	***
Adjusted R^2		0.912			0.882			0.904			0.886			0.899			0.906	

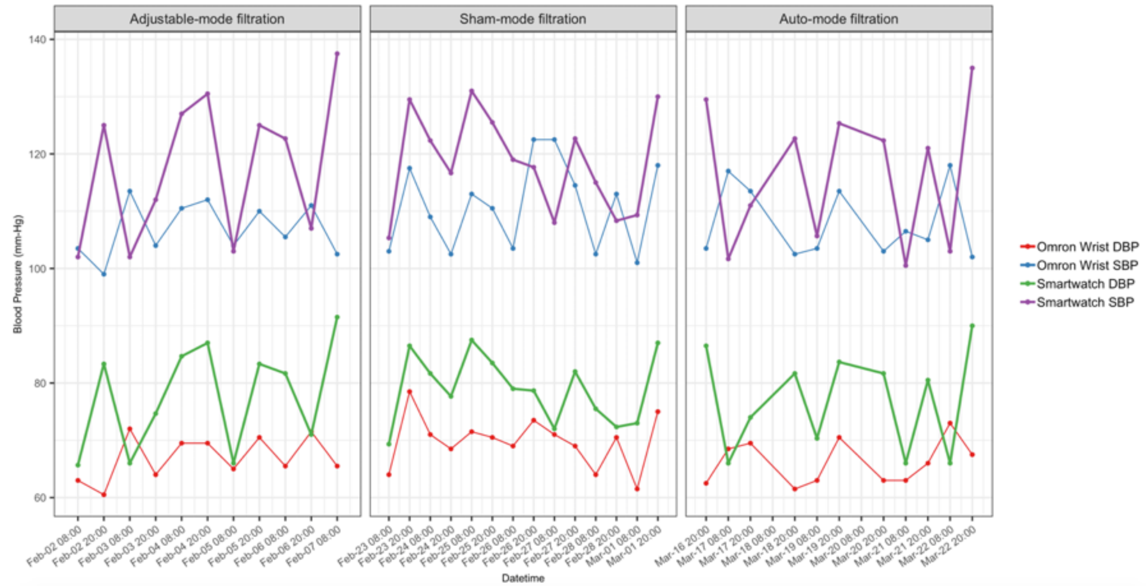
Note. N=156 for each sensor.
** $p<0.05$, ** $p<0.01$, *** $p<0.001$.*

Appendix IX. Bland-Altman plot of three measurement type (sphygmomanometer, Omron wrist blood pressure monitor and Smartwatch) of the validation.



Abbreviations: Systolic blood pressure, SBP; Diastolic blood pressure, DBP

Appendix X. Time-series plot of the Omron wrist and the smartwatch blood pressure measurement of one of the study participant.



Appendix XI. Summary of the average hour participants spent in home, outdoor and other indoor environment under each type of filtration intervention.

Location	Type of Filtration, mean (%)		
	Sham-mode	Auto-mode	Adjustable-mode
Home	116.3 (70)	125.3 (75)	125.2 (75)
Other microenvironment[a]	50 (30)	42.5 (25)	41.8 (25)

[a] Including all outdoor environment and indoor environment other than home (e.g., school, office).