Particle removal effectiveness of portable air purifiers in aged-care centers and the impact on the health of older people

Miao Guo[a,b], Min Zhou[c], Shen Wei[d], Jing Peng[c], Qie Wang[c], Lexiang Wang[a,b], Dandan Cheng[a,b], Wei Yu[a,b*]

[a] Joint International Research Laboratory of Green Buildings and Built Environments (Ministry of Education), Chongqing University, Chongqing 400045, China

[b] National Centre for International Research of Low-carbon and Green Buildings (Ministry of Science and Technology), Chongqing University, Chongqing, China

[c] Department of Geriatrics, Chongqing University Central Hospital, Chongqing Emergency Medical Center, Chongqing, 400014, China

[d] The Bartlett School of Construction and Project Management, University College London, London WC1E 7HB, UK

[*] Corresponding author. E-mail address: yuweixscq@126.com (W. Yu).

Abstract: Airborne particulate matter (PM) is associated with the risk of cardiovascular disease, and the elderly are more susceptible to the adverse effects of PM due to weakened immunity. In China, the use of portable air purifiers is a common method to reduce indoor PM pollution but few studies have evaluated the purification efficiency of portable air purifiers in the aged-care center under real living conditions. To evaluate the PM removal effectiveness of portable air purifiers in aged-care centers and the improvement of cardiovascular function of the elderly, a randomized double-blind crossover study was conducted in 16 rooms of an aged-care center in Yubei District, Chongqing, China in January 2020. The true purifiers and the sham purifiers (just remove filter gauzes) are used alternately in the elderly's room, then the blood pressure and heart rate of elderly participants were tested. The study found that indoor PM concentration decreased rapidly within the first 2 hours after turning on the air purifier, which can make indoor $PM_{2.5}$ concentration lower than the WHO threshold. The air purifiers' mean removal effectiveness of PM in the aged-care center is 73%, which is significantly affected by the window states. According to the multiple linear regression model, the factors predicting the PM concentration in aged-care centers are the usage of air purifiers, weather conditions and window states. Linear mixed-effect models were used to associate blood pressure and heart rate with air purification, which was found that indoor air purification was associated with a significant decrease in heart rate. This study indicates that portable air purifier is effective in improving aged-care center air quality, which is of great significance in improving the elderly cardiovascular health

and providing guidance for the use of air purifiers in aged-care centers.

Keywords: Aged-care center; Indoor PM pollution; Portable air purifiers; Removal effectiveness; Cardiovascular function

1: Introduction

Many existing studies have justified that both short-term and long-term exposures to ambient particulate matter (PM) could increase cardiovascular disease-related morbidity and mortality [1, 2], especially for susceptible people like elderly people [3]. Inhalation of PM can lead to multiple adverse health effects in human beings, depending on their original source of emission or formation, chemical components, varying size, surface areas, and concentrations [4]. Based on the aerodynamic size, PM is generally classified into inhalable (⩽ 10 μm; PM_{10}), coarse (2.5–10 μm; $PM_{2.5–10}$), fine (⩽ 2.5 μm; $PM_{2.5}$), and ultrafine (⩽ 0.1 μm; $PM_{0.1}$) particles. In particular, the smaller particles (e.g., $PM_{2.5}$ and $PM_{0.1}$) may pose a higher risk for cardiovascular disorders [5], as a result of their greater propensity to induce systemic pro-oxidant and pro-inflammatory effects [6].

In China, urban residents spend an average of 87% of their time indoors [7], and therefore the concentration of indoor PM has a significant impact on people's health. Indoor PMs could come from outdoors [8] or be generated indoors [9]. In the past several years, China was suffering greatly from air pollution outdoors, with PM as a major component. According to an official report [10], the average annual $PM_{2.5}$ and PM_{10} concentration in China were 36 μg/m^3 and 63 μg/m^3, respectively, in 2019, which were much higher than the limit sets by the WHO (10 μg/m^3 for $PM_{2.5}$ and 20 μg/m^3 for PM_{10}) [11]. These outdoor PMs can enter indoors mainly through either penetration or ventilation [12, 13], People always promote the increase of air change rates by opening windows, which in turn can increase the infiltration of outdoors PM [14]. Closing external windows can help prevent outdoor PM enter into indoors, many studies have shown that a significant number of particles can still pass the building façade through the cracks around the window [15]. Existing studies have suggested a high correlation between indoor and outdoor pollutant concentrations [16-19]. PM generated indoors from smoking [20], cooking [21], and other sources [9]. Reducing the concentration of atmospheric PM can reduce indoor PM concentration, but reducing atmospheric PM concentration needs the efforts of the whole country and society, which is a long-term process. Fresh air filtration systems can significantly reduce the PM concentration in the fresh air [22]. however, residential buildings mostly use windows to introduce fresh air into the room, and rarely install a fresh air system [23]. Close windows can reduce the penetration of outdoor PM into the indoor, but low ventilation rate will increase the concentration of indoor carbon dioxide, affecting the health of indoor personnel [24]. In China, therefore, to fight indoor PM pollution, a portable air purifier is an effective and universal way in residential buildings to keep people healthy.

The removal efficiency is an important indicator to measure the effect of the air purifier on the improvement of indoor air quality [25].

To test air purifiers' actual removal efficiency of PM, many studies have been carried out in real buildings, especially in conventional residential buildings. Kajbafzadeh et al. [26] have investigated the actual efficiency of High-Efficiency Particulate Air (HEPA) filters in removing traffic- or woodsmoke-relevant pollutants in 44 homes in Vancouver, Canada, with an overall efficiency of 40% identified for $PM_{2.5}$. In another study carried out in Montana, USA, 48 homes using burning biomass fuel were randomly selected and it was found that air purifiers could help to reduce indoor $PM_{2.5}$ concentration by 66% [27]. Based on data collected from 43 residential homes nearby highways, HEPA air purifiers were found to be able to control traffic-related aerosols, for example, with a removal efficiency of 47% for $PM_{2.5}$ [28]. A study on home air quality interventions was carried out in 97 inner-city homes with children, and it was found that air purifiers contributed to a reduction of PM_{10} concentration by 39% [29]. Besides conventional residential buildings, similar studies have been carried out in other building types as well. One of them investigated 102 classrooms in 34 Korean elementary schools and the result showed that the PM level in classrooms using air purifiers was significantly lower (by approximately 35%) than that in classrooms not using them [30]. Another study included 10 Korean child-care centers and the result showed that the average removal efficiency of particulate matters was 75-78% for $PM_{2.5}$ and 72-84% for PM_{10} [31]. In a study carried out in one office in Montana, USA, it was revealed that a portable air cleaner helped to reduce indoor wild-fire sourced $PM_{2.5}$ by 73% and 92% for working and non-working hours, respectively [32].

The above review work reflects that existing studies in terms of filtration efficiency of air purifiers were carried out mostly in conventional residential buildings, with some done in other building types, such as schools, child-care centers and offices. No evidence currently is available from aged-care centers, which are important facilities in many countries, due to the global issue of the aging population [33]. Generally, aged-care centers are arranged differently from other residential building types. For example, in aged-care centers, food is prepared centrally so no kitchen is available in individual rooms, hence with fewer pollutants generated indoors. Additionally, aged-care centers are used by elderly people only and their behavior of using buildings may be quite different from adults or conventional families, and this difference may result in different purifier efficiency. Moreover, indoor particulate matters are more likely to affect the health of the elderly [3], so it is necessary to determine the actual effect of air purifiers in aged-care centers. To fill this knowledge gap, in this study, a randomized double-blind crossover experiment has been conducted in an aged-care center in Chongqing, China. We aim to estimate the actual purification effect of purifiers to PM for aged-care centers; to determine predictive factors for indoor PM concentration in aged-care centers; and to evaluate the impact of PMs on elderly people's healthy conditions based on changes in their blood pressure (BP) and heart rate (HR). The findings from this study are valuable to guide proper design and use of air purifiers in aged-care centers.

2: Methodology

2.1: Case study building

The study was conducted in one aged-care center located in Chongqing, China, in January 2020, when serious outdoor pollution may happen in China [34-36]. Chongqing has a subtropical monsoon humid climate with an annual average temperature of around 18°C and minimum temperature in winter between 6°C and 8°C. The annual average wind speed in Chongqing is 1.12m/s, lower than the average level of China, and therefore may suffer more serious outdoor air pollution. The case study building, as shown in Figure 1(left), has six floors with the main orientation facing to the west. The rooms in the aged-care center are either single or double, and each only has one bedroom and one bathroom. All rooms are equipped with split air conditioners, for both cooling and heating, and there are no central air conditioning systems to control indoor air quality and no portable air purifiers. Additionally, each room has one plastic steel sliding window, which is manually controlled by the room occupants.

Figure 1: The case study building (left) and a typical room (right)

2.2: Data collection

2.2.1: Participant Recruitment and Experimental Process

The participants in the aged-care center were recruited through face-to-face communication and posting recruitment advertisements in the center. These participants were selected according to the following principles: 1) the elderly have not smoked for three years; 2) the elderly have no heart attack in the past three years according to the participants' self-report; 3) the elderly had lived in this aged-care center for more than one year. A total of 26 older people were recruited, however, 2 participants dropped out of the trial, so only 24 people completed the experiment. Table 1 gives the age, gender and body mass index (BMI) of the 24 participants.

Table 1: Characteristics of the 24 study participants

Characteristic	Value
Age, mean (SD) [range], y	82.46 (7.77) [61-97]
Female, No. (%)	12 (50.0)
BMI[a], mean (SD), kg/m^2	24.69 (3.79)

[a] body mass index (calculated as weight in kilograms divided by height in meters squared)

The study followed a randomized double-blind crossover trial method [37]. Double-blind means that neither participants nor researchers know the grouping and the experiment process is arranged and controlled by the designer which can avoid the deviation caused by the subjective factors of the participants and the researchers so that this method makes the experimental results more accurate. In this study, all participants were equally randomized into two groups by sex, namely, Group A and Group B. Figure 2 shows the experimental arrangement and process, each participant went through a 96-hour experiment. In the first 48 hours, Group A was given true air purifiers while Group B was given sham air purifiers (just remove filter gauzes). In the second 48 hours, this arrangement was exchanged between Group A and B. The purifier in each room is placed in a similar location not close to the corner and does not affect personnel activities. Neither participants nor researchers in the trial do not know if the air purifier in their room is true or sham. This double-blind design can avoid the influence of psychological factors and behavioral changes caused by the use of air purifiers on the trial results. To eliminate the influence of the air purifier on the physiological parameters of the elderly, there is a 12-day washout period between two 48-hour trials. The air purifier used in this study was a common portable HEPA air purifier (KJ001, Well Air Love). HEPA filters are an effective technology for removing PM [38]. To be defined as such, a HEPA filter must be able to remove 99.97% of PM greater than or equal to 0.3 μm. In a HEPA air purifier, the air is forced through the HEPA filter, and PM is physically captured. The four key mechanisms through which PM are captured are diffusion, interception, inertial impaction and sieving. Diffusion causes the smallest PM to be removed, whereas interception, inertial impaction and sieving processes are more effective at removing the largest PM [39]. Due to the high health hazards of indoor PM_{10}, $PM_{2.5}$ and PM_1[40], this study focuses on these PM. The air purifier for true purification was equipped with a HEPA filter, while the air purifier for sham purification was not equipped with any filter. Except for the difference in the filter, the air purifier was operated completely in the same state in true and sham intervention. According to the product description, the Clean Air Delivery Rate (CADR) of the air purifier for PM is $350m^3/h$, which is suitable for the testing rooms [34]. To reflect the elderly's cardiovascular health conditions, participants' BP and HR were measured immediately after every 48 hours. All interventions started at 8 am to avoid issues related to diurnal variation. HEPA air purifiers only change the indoor PM concentration, and the concentrations of other air pollutants indoor like nitrogen oxides and ozone had not been changed, therefore, the values of participants' BP and HR in true-purified air and sham-purified air can reflect the impact of indoor PM reduce on the cardiovascular health. The states of windows in each room were recorded manually by researcher from the investigators of this study. If the total length of window-opening time was less than 20%, window state was considered as “closed” during every 48 hours. Otherwise, it was considered as “open”. All participants provided written informed consent before participating in the study. The Ethics Review Committee of Life Sciences at Central China Normal University approved the study protocol. Ethics Ratification ID for the project “pathogenic mechanism of indoor environmental risk factors exposure on COPD among older people” is CCNU-IRB-2019-002.

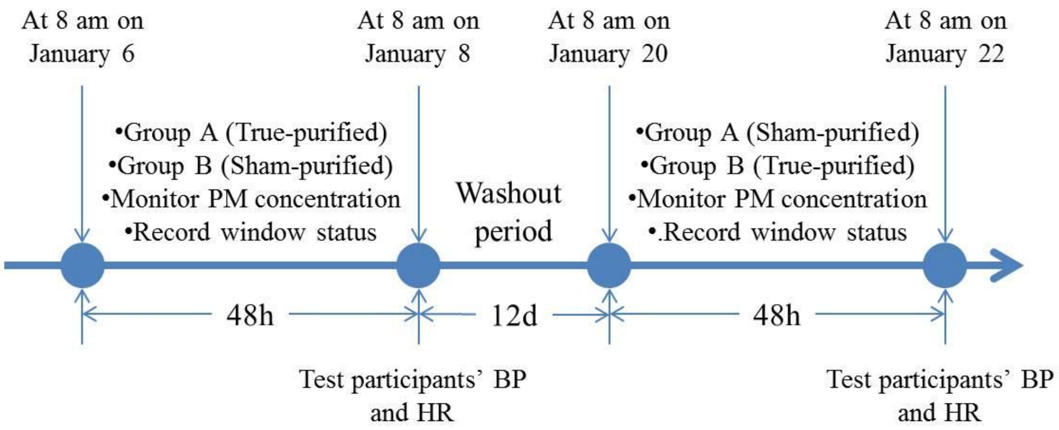

Figure 2: Experimental process

2.2.2: Measurement

The environmental parameters monitored in this study include indoor and outdoor air temperature (T, °C), relative humidity (RH, %), $PM_{1.0}$ concentration (μg/m^3), $PM_{2.5}$

concentration (μg/m^3) and PM_{10} concentration (μg/m^3). The environmental monitoring kit collected and recorded these parameters every minute. In this kit, laser dust sensors (ZH03B) were used to monitor the concentration of PM and digital temperature and humidity modules (MHTRD06) with high polymer wet-sensitive resistor and high precision NTC temperature measuring element were used to monitor air temperature and relative humidity. Before the experiment, all sensors were calibrated against an aerosol monitor (DustTrak 8530) in a calibration room. Table 2 lists the major specifications of all sensors involved in the monitoring kit. According to the "Technical Specifications for Monitoring of Indoor Air Quality" (HJ/T167-2004) [41], one indoor monitoring point was set up and the environmental monitoring equipment was installed at least one meter away from the air purifier. Since the older people often lie or sit indoors, the height of the monitoring point was set between 0.6m and 1.0m to cover the elderly breathing area. Outdoor environmental parameters were collected in the aged-care center yard, 10 meters away from the building.

Table 2: Major specifications of the sensors used in the environmental monitoring kit

Parameter	Range	Accuracy
Air temperature	-40°C~60°C	±0.5°C
Relative humidity	20%~95%	±3%
PM_1	0~1000 μg/m^3	±1 μg/m^3
$PM_{2.5}$	0~1000 μg/m^3	±1 μg/m^3
PM_{10}	0~1000 μg/m^3	±1 μg/m^3

The epidemiological association of PM with cardiovascular morbidity and mortality [42] has been linked to the effects of PM on elevated BP and HR a possible mechanism linking PM to increased risk for cardiovascular diseases in several panel studies [43, 44]. An upper arm electronic sphygmomanometer (OMRrON U15) has been selected to measure participants' HR and BP including systolic pressure and diastolic pressure. The environmental monitoring kit and electronic sphygmomanometer are shown in Figure 3. The state of windows was manually recorded, through hourly observations between 8 am and 8 pm.

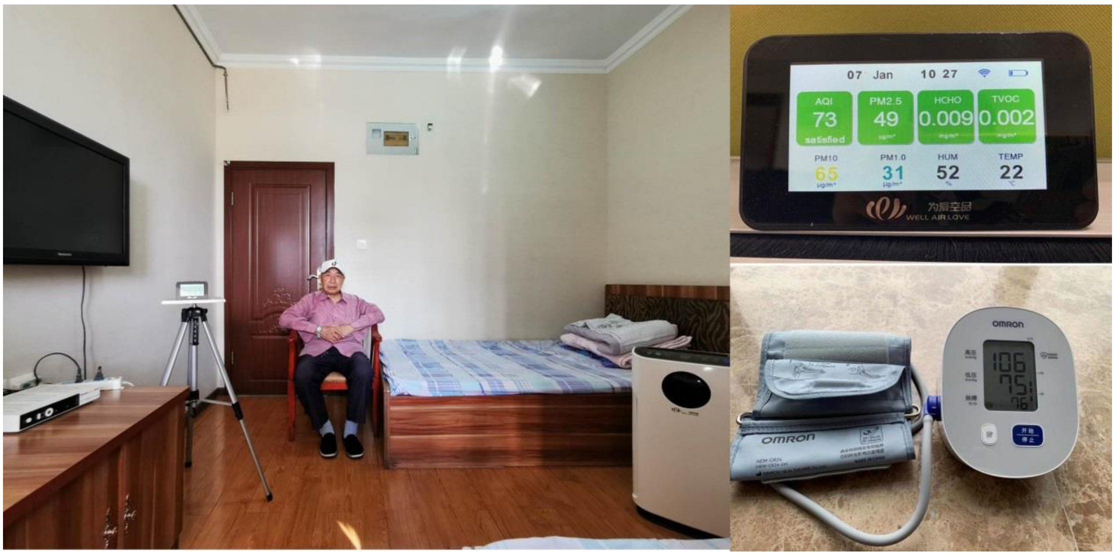

Figure 3: Sample sites and equipment

2.3: Statistical analysis

2.3.1: Air purifier effectiveness

The concept of air purifier effectiveness noted as H, has been defined by Nazaroff [25], as a ratio determined by the PM concentrations with and without air purifiers, as defined in Equation 1,

$$H_{i.j} = \frac{C_{noAC,i} - C_{AC,i,j}}{C_{noAC,i}} \quad (1)$$

where $i = 1, 2$

i represents the experimental stages. There are two experimental stages in this experiment. The first 48 hours (i=1) and the second 48 hours (i=2).

$j = 1,2, \dots ,8$

j represents the 8 true-purified rooms during each experimental stage.

$C_{noAC,i}$ represents the mean PM concentration of 8 Sham-purified rooms in every experimental stage. $C_{AC,i,j}$ represents the PM concentration in each True-purified room in two experimental stages. $H_{i.j}$ represents the effectiveness of HEPA air purifier in a True-purified room at each stage.

2.3.2: Statistical analysis

For statistical analysis, the collected data of PM concentrations were converted from minute-based to hourly-based, with both mean values and corresponding standard deviations were calculated. The indoor and outdoor PM concentrations were skewed distributed according to Kolmogorov Smirnov testing [23] (when $p<0.05$, the variables satisfy a skewed distribution, and when $p>0.05$ the variables satisfy a normal distribution). The data analysis consisted of the following three steps: 1) evaluating the influence and PM-removal effectiveness of HEPA air purifier on PM concentration in the aged-care center; 2) determining the prediction indicators of the indoor PM concentration in the aged-care center; 3) evaluating the improvement of air purification on the elderly's cardiovascular health.

In the first step, the PM concentration differences between indoor and outdoor air during the true purification and sham purification periods were estimated by Wilcoxon signed-rank test, while the differences in indoor and outdoor air PM concentrations between sham filtration and true filtration were estimated by Wilcoxon signed-rank test too[45] (when $p<0.05$, there has significant difference between two samples and when $p \geqslant 0.05$ there is no significant difference between two samples). Wilcoxon signed-rank test was used to test the differences of two paired samples in a skewed distribution. To evaluate the correlation coefficient of PM concentration between indoor air and outdoor air, we calculated Spearman's correlation coefficient (r) [35]. (when $r > 0.8$, the two samples have a strong correlation, when $0.3 \leqslant r \leqslant 0.8$, the two samples have a weak correlation and when $r<0.3$, the two samples have no correlation)

In the second step, to determine the predictive indicators of the PM concentration in the aged-care center, multiple linear regression equation analysis was used and defined in Equation 2 [30]. y_i represent the PM concentrations indoor, x_i represents variables that may affect the indoor PM concentrations. Since the PM concentrations in both true-purified rooms and sham-purified rooms were skewed, the PM concentrations indoor were entered into the regression equation after logarithmic transformation. In the analysis, variables were screened by the stepwise method.

$$y_i = b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_n x_n + \mu_i \tag{2}$$

In the third step, to evaluate the improvement of air purification on cardiovascular health of the older people, linear mixed-effect models were used to evaluate the effect of air purification on the BP and HR and defined in Equation 3 [37]. Where y represents a dependent variable vector, X represents the fixed effect's matrix, Z represents the random effect's matrix, β represents parameter vector of fixed effect, μ represents parameter vector of random effect and ϵ represents the residual vector matrix. In this study, BP and HR are skewed distribution, so they entered into the regression equation after logarithmic transformation. The intervention was coded as a dummy variable (1 for true-purified scenario and 0 for sham-purified scenario). All models estimate adjusted for age, gender, body mass index, indoor relative humidity and temperature, and they were analyzed as fixed effects. All models included random intercepts for subjects to account for correlations between repeated measures from each participant. The significance level during the statistical analysis was selected as 0.05, and all statistical analyses were performed using the "lme4" package of R software (version 4.0.4)

$$\mathrm{y} = \mathrm{X}\beta + \mathrm{Z}\mu + \epsilon \tag{3}$$

3: Results and Discussion

3.1 Outdoor environmental conditions

Figure 4 depicted the outdoor PM concentrations (for $PM_{2.5}$ and PM_{10}) during the experimental period, with a total of 96 hours (4 days). From the data, it could be observed that the average concentrations of $PM_{2.5}$ and PM_{10} outdoors were 60.76 $\mu g/m^3$ and 70.70 $\mu g/m^3$ and there are no obvious fluctuations between daylight and night. According to China National Standard the “Ambient air quality standards” (GB 3095-2012) [46], the 24-hour average concentration limits of $PM_{2.5}$ and PM_{10} are 35 $\mu g/m^3$ and 50 $\mu g/m^3$ respectively, which means the outdoor PM concentrations at the aged-care center exceeds the national limitation so that outdoor PM can enter the room and harm to the elderly health. Ambient PM is produced from many activities including industrial emissions, fuel combustion, road dust, burning biomass, combustion from vehicles and heating boilers [47]. Ambient PM concentration fluctuates irregularly with time as different outdoor conditions and traffic status [48]. Hours 28 and 32, representing 12 noon and 4 p.m., and the beginning of the second 48hours, representing 9 a.m., these periods are commuting peak hours when traffic congestion may be responsible for the rise in outdoor PM_{10} and $PM_{2.5}$ concentrations.

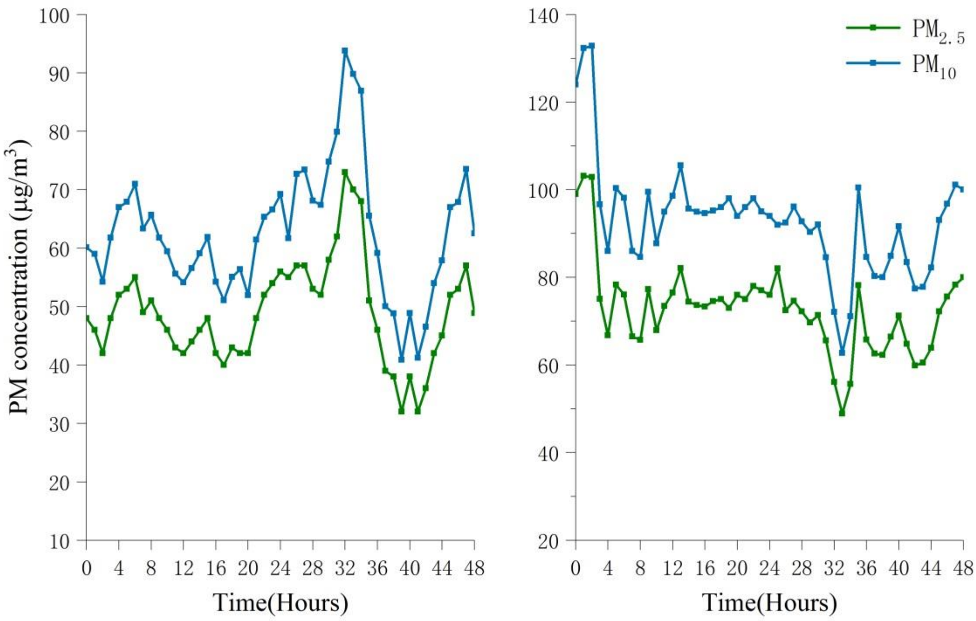

Figure 4: Outdoor PM concentrations during the experimental period. The first 48h (left) and the second 48h (right)

During the experiment period, the outdoor temperature was changing between 7.0ºC and 12.8ºC, with an average value of 10.4ºC, and the outdoor relative humidity was changing between 69% and 98%, with an average relative humidity of 84%. This is a typical winter climatic condition in Chongqing, which is small daily temperature changes and high air relative humidity caused by the humid subtropical monsoon climate.

3.2 The purification effect of air purifiers

Figure 5 depicted the monitored $PM_{2.5}$ concentration in outdoor environment, sham-purified rooms and true-purified rooms, with the green dotted line for the threshold provided in the WHO air quality guidelines for $PM_{2.5}$, which is 25 μg/m^3 [11]. It could be observed that the $PM_{2.5}$ concentration in sham-purified rooms was lower than that in the ambient environment, which may due to the effect of building façade [15], and the difference was significant (Table 3). During the experimental period, the biggest difference was 30.3 μg/m^3, the smallest difference was 0.03 μg/m^3, the average difference was 15.2 μg/m^3. Indoor $PM_{2.5}$ concentration with sham-purified was higher than the threshold provided by the WHO. Additionally, from the close link between indoor and outdoor $PM_{2.5}$ concentration, it could also confirm that the contributions from indoor $PM_{2.5}$ sources were not significant, and this finding was different from what has been observed in conventional residential buildings in [35], where indoor $PM_{2.5}$ concentration was also linked to indoor activities, such as cooking and cleaning.

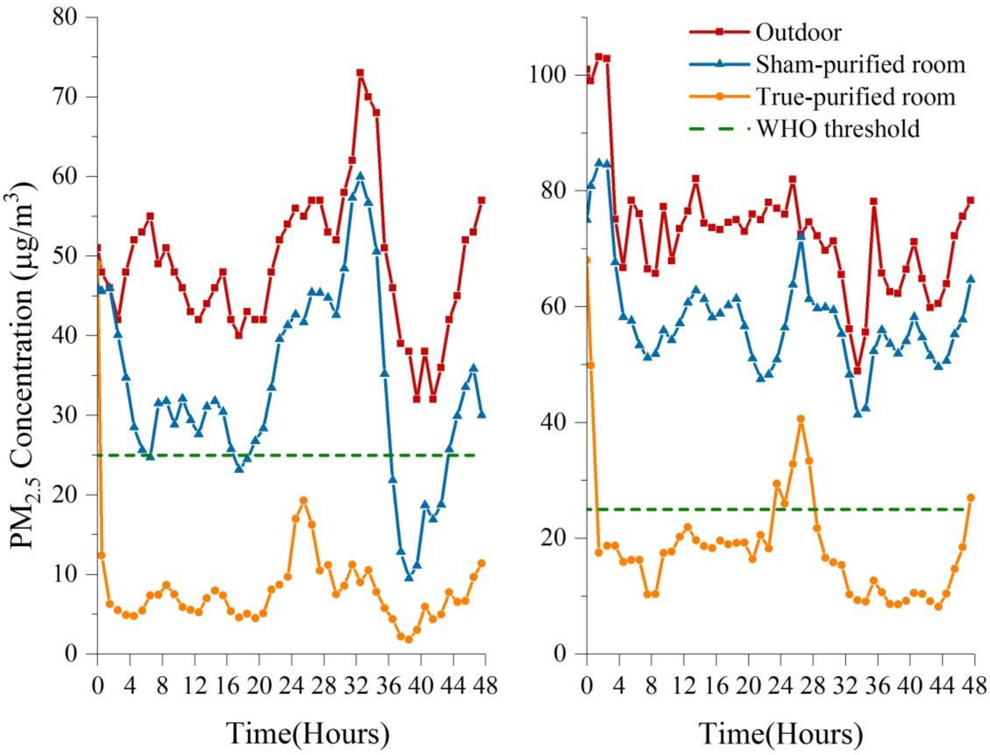

Figure 5: Time-Varying $PM_{2.5}$ Concentration in Outdoor air, Sham-purified indoor air, and True-purified indoor air. The first 48h (left) and the second 48h (right).

Also from Figure 5, it could be observed that the $PM_{2.5}$ concentration in true-purified rooms was much lower than that in sham-purified rooms, with the biggest difference of 67.3 μg/m^3, the smallest difference of 7.0 μg/m^3, the average difference of 32.9 μg/m^3. As both physical properties and occupants' behavior were similar in true-purified rooms and sham-purified rooms, it was obvious that this significant drop of $PM_{2.5}$ concentration was due to the use of air purifiers, and the $PM_{2.5}$ concentration in true-purified room lower than the threshold provided by the WHO. Additionally, there was a significant drop in $PM_{2.5}$ concentrations in the first two hours, due to the start of air purifiers.

Table 3: Comparison of PM concentrations between indoor and outdoor air in Sham-purified rooms and True-purified rooms

Item	Mean±SD		*p*-value	Spearman's rank correlation coefficient (p-value)
	Outdoor	Indoor		
Sham-Purified Indoor Air				
PM_1	37.8±4.5	27.3±4.7	0.000	0.864 (0.000)
$PM_{2.5}$	60.8±6.1	45.6±7.8	0.000	0.898 (0.000)
PM_{10}	77.7±7.5	58.5±10.1	0.000	0.897 (0.000)
True-Purified Indoor Air				
PM_1	37.8±4.5	7.3±3.4	0.000	0.813 (0.000)
$PM_{2.5}$	60.8±6.1	12.7±5.5	0.000	0.879 (0.000)
PM_{10}	77.7±7.5	16.0±7.0	0.000	0.858 (0.000)

The mean values and standard deviations of PM_1, $PM_{2.5}$ and PM_{10} concentration in the ambient environment, sham-purified rooms, and true-purified rooms are shown in Table 3. Similar to $PM_{2.5}$, compared with the Sham-purified room, the concentrations of PM_1 and PM_{10} also decreased significantly in the True-purified room with the biggest difference of 32.6 μg/m^3 and 69.1 μg/m^3, the smallest difference of 15.5 μg/m^3 and 33.0 μg/m^3, the average difference of 20.0 μg/m^3 and 42.5 μg/m^3. The indoor PM_1, $PM_{2.5}$ and PM_{10} concentrations were reduced by 73.3%, 72.1% and 72.6% respectively by using an air purifier and there were significant differences in indoor PM levels between sham-purified rooms and true-purified rooms ($p<0.001$). All correlation coefficients between indoor and outdoor PM concentrations for the sham-purified rooms were larger than those for the true-purified rooms and they all showed a strong correlation (see Table 3).

Figure 6 showed the removal effectiveness of air purifiers for PM_1, $PM_{2.5}$ and PM_{10}, with black dots represent the calculated value of each household. The removal effectiveness for PM_1, $PM_{2.5}$ and PM_{10} were ranging from 0.50~0.90, 0.49~0.89 and 0.50~0.89, with mean values for all 16 rooms were 0.74, 0.73 and 0.74, respectively. Air purifiers have similar removal effectiveness for particles of different sizes. The PM-removal effectiveness in the 1st 11th 15th rooms ranged from 0.49 to 0.55 and except for these three rooms, the removal effectiveness in other rooms is greater than 0.7. Only 4 of 16 rooms had PM removal effectiveness higher than 0.8 which is the US Association of Home Appliance Manufacturers (AHAM) [49] recommended value. This result reflected that to achieve the AHAM recommendation, the CADR of air purifiers used in the aged-care center in Chongqing should be higher than that in the Chinese standard [50].

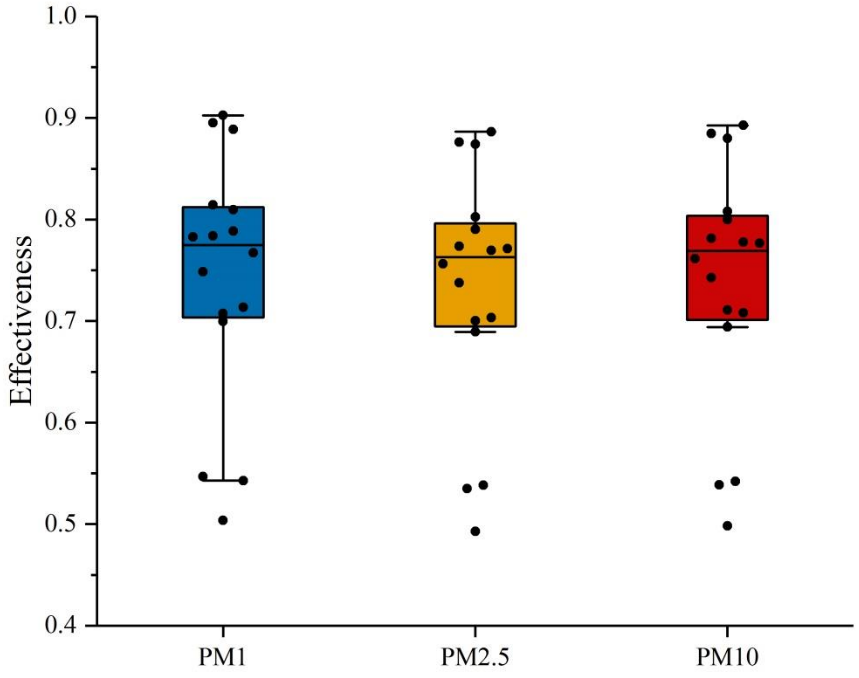

Figure 6: The effectiveness for different size of PM

Table 4 shows the PM-removal effectiveness in all rooms under different conditions during the inspection. On rainy days, the mean removal effectiveness for PM_1, $PM_{2.5}$ and PM_{10} was approximately 0.78, and on sunny days, the value was almost 0.70. The mean removal effectiveness on PM_1, $PM_{2.5}$ and PM_{10} on rainy days was 8.30%, 7.87% and 8.17% higher than that on sunny days. The mean removal effectiveness for PM_1, $PM_{2.5}$ and PM_{10} in the aged-care center with windows closed are 24.8%, 24.5% and 24.4% higher than that with the window opened. Compared to rooms that had opened windows during the inspection, rooms that kept the windows closed had significantly higher PM-removal efficiencies ($p \leqslant 0.001$ given by the independent sample t-test).

Table 4: PM-removal effectiveness in the respected rooms under different conditions

Items	Sample size, n (%)	PM_1	$PM_{2.5}$	PM_{10}
Total	16 (100)	0.74±0.03	0.73±0.03	0.74±0.03
Weather conditions				
Rainy days	8 (50)	0.78±0.05	0.77±0.05	0.78±0.05
Sunny days	8 (50)	0.70±0.04	0.69±0.04	0.70±0.04
Window states				
Opened	10 (62.5)	0.68±0.03	0.67±0.03	0.68±0.03
Closed	6 (37.5)	0.85±0.02	0.83±0.02	0.84±0.02

A random crossover study conducted in 27 dwellings in Denmark [51] has found that the median value of $PM_{2.5}$ removal efficiency of air purifiers was 54.5%. A single-blind cross-over field study was conducted in 20 residences in Chongqing, China [23], given the removal efficiency of portable air purifiers on particles of different particle sizes about 40%. A study on the efficiency of air purifiers in childcare centers in Seoul, South Korea [31] showed that the removal efficiency of air purifiers for indoor $PM_{2.5}$ and PM_{10} ranged from 58% to 85% and 49% to 86% respectively. Compared with these studies, the removal efficiency of PMs in the aged-care center was higher than that in residential buildings and similar to that in childcare centers. This may be because the aged-care centers and childcare centers had similar indoor emission sources of PMs, which are less than residential buildings. Therefore, the PM-removal efficiency of portable air purifiers in aged-care centers is stronger than that in conventional residential buildings.

3.3 Predictive factors for indoor PM concentrations in aged-care centers

The aged-care center selected in this study has no central air conditioning and fresh air systems. In winter, each room uses split air conditioners for heating. Weather conditions, indoor temperature and relative humidity, floors, per capita area, usage of air purifiers and window states were tested and recorded in this study. Table 5 shows the correlations between these factors and indoor PM_1, $PM_{2.5}$, PM_{10} in multiple linear regression analysis, with all variables in the table screened by the stepwise method. Only usage of air purifiers, weather conditions and window states were included in these multiple linear regression equations after the selection by the stepwise method.

The determination coefficients (R^2) of this predictive model of indoor PM_1, $PM_{2.5}$ and PM_{10} were found to be 0.903, 0.916 and 0.914, respectively. Therefore, usage of air purifiers, weather conditions and window states can well be used to predict the PM concentration in aged-care center rooms. From these equations, the PM concentration in aged-care centers reduced on rainy days, closed windows and use of air purifiers (see Table 5). According to the given standardized estimates (see Table 5) from the multiple linear regression, it could be found that usage of air purifiers had the greatest impact on indoor PM_1, $PM_{2.5}$ and PM_{10}, followed by weather conditions and windows states. These three factors have a similar level of influence on indoor PM with different sizes.

Table 5: Stepwise-forward multiple linear regression equations between PM_1, $PM_{2.5}$, PM_{10} and explanatory variables in aged-care center

items	ln PM_1				ln $PM_{2.5}$				ln PM_{10}			
	Estimate	Standardized Estimate	p-value	R^2	Estimate	Standardized Estimate	p-value	R^2	Estimate	Standardized Estimate	p-value	R^2
Experimental period												
Sunny	0.712	0.400	0.000		0.678	0.401	0.000		0.694	0.401	0.000	
Rainy	_	_	_		_	_	_		_	_	_	
Window states												
Opened	_	_	_	0.903	_	_	_	0.916	_	_	_	0.914
Closed	-0.439	-0.246	0.001		-0.409	-0.242	0.000		-0.418	-0.204	0.000	
Purification												
True-purified	-1.419	-0.797	0.000		-1.357	-0.803	0.000		-1.386	-0.801	0.000	
Sham-purified	_	_	_		_	_	_		_	_	_	

3.4 Effect on the cardiovascular function of elderly people using air purifiers

In China, portable air purifiers are an economical and effective way to help control indoor PM concentrations. This study revealed that the $PM_{2.5}$ concentration in the aged-care center was far beyond WHO standard without air purifiers and using air purifiers could help to reduce indoor PM concentration and meet the WHO standard. To study whether short-term air purification can improve cardiovascular function of the elderly, the systolic pressure, diastolic pressure and HR of each participant have been tested twice under both true and sham purification conditions, with finally 144 systolic pressure, diastolic pressure and HR data collected. The pulse pressure was calculated by subtracting the diastolic pressure from the systolic pressure. The geometric mean values and the standard deviation of systolic pressure, diastolic pressure, pulse pressure and HR have been listed in Table 6, according to exposure scenarios. According to the result of the linear mixed-effect models, the HR was significantly associated with air purification. Compared with the sham purification, the HR was significantly reduced by 5.84% under the true purification (95% confidence interval [CI], -10.64% ~ -0.79%; P=0.026). However, there was no significant association between indoor PM concentration with systolic pressure and pulse pressure although there were downward trends in true purification. In both exposure scenarios, the diastolic pressure was barely changed.

Table 6: Summary of health endpoints (Geometric Mean ± SD) in sham-purified indoor air and true-purified indoor air during the intervention periods

Health Endpoints	True-purified Geometric mean ± SD	Sham-purified Geometric mean ± SD	*p*-Value
Systolic pressure	142.34±26.61	144.75±29.49	0.384
Diastolic pressure	87.86±14.36	87.33±13.75	0.608
Pulse pressure	53.11±17.83	55.16±21.88	0.309
HR	70.06±9.62	74.44±12.54	0.011

Some studies have shown that indoor $PM_{2.5}$ levels can lead to elevated HR and BP, which are risk factors for cardiovascular morbidity and mortality [52, 53]. Our results suggest that short-term purification significantly reduced HR in the elderly, and may be beneficial to the cardiovascular function of elderly people. Some studies have shown that inhaled particles can rapidly pass into the blood circulation of human subjects and experimental animals in a few minutes and cause adverse cardiovascular effects directly after exposures [54, 55]. In this study, we believe short-term indoor PM purification could result in BP and HR decrease. Several studies have shown that decreases in human BP and HR are associated with reduced indoor PM concentrations. A study of 60 adults in Taiwan, China, showed that when indoor $PM_{2.5}$ dropped from 24.5 $\mu g/m^3$ to 17.3 $\mu g/m^3$ it led to a drop in BP and HR, but not statistically significant [52]. In our study, the HR change was significant, and this difference may be due to older people are more susceptible to PM exposure [56].

4: Conclusions

Exposure to PM indoors is very harmful to personnel health, especially for elderly people who stay indoors for a long time. In countries with serious PM pollution, portable air purifiers have become an effective way for reducing indoor PM concentrations. Due to the differences in both behavioral characteristics and living environment between older people and young adults, it is important to study the impact of air purifiers on older people's living environment and health conditions. This paper has introduced main findings from a randomized double-blind crossover experiment, which was conducted in an aged-care center located in Chongqing, China, with 24 elder people in 16 rooms monitored for their indoor and outdoor PM concentrations and the older participants' BP and HR. From the study, the main findings could be drawn:

(1) During the experiment, the average concentrations of PM_{10}, $PM_{2.5}$ and PM_1 in Sham-purified room is 58.5 μg/m^3, 45.6 μg/m^3 and 27.3 μg/m^3, while the average concentrations of PM_{10}, $PM_{2.5}$ and PM_1 in True-purified room is 16.0 μg/m^3, 12.7 μg/m^3 and 7.3 μg/m^3. Air purifiers can effectively reduce PM concentrations in aged-care centers, especially in the first 2 hours, to make indoor PM concentrations complied with WHO standards.

(2) The mean PM-removal effectiveness of air purifiers in the aged-care center is 0.73, and this value is higher than that in residential buildings. Compared to rooms that had opened windows, rooms that kept the windows closed had significantly higher PM-removal effectiveness.

(3) The concentrations of indoor PM_1, $PM_{2.5}$ and PM_{10} in aged-care centers are mainly affected by weather conditions, window states and use of air purifiers.

(4) Air purifiers could help to reduce the HR of elderly people by 5.84% significantly and reduce systolic pressure and pulse pressure by 1.85% and 5.71%.

This study has several limitations. First, we only experimented in winter due to atmospheric PM pollution is most serious in winter. The influence of other seasons on the purification effect of air purifiers in the aged-care center has not been analyzed. Second, only the aged-care center located in the urban area was intervened, and those in other outdoor environments were not considered.

Regardless of these limitations, we believe our data generally support the idea that usage of air purifiers in short term can reduce older people's HR, systolic pressure and pulse pressure. The trial environment was well controlled by a randomized, double-blind crossover design so that only the levels of PM differed between the 2 groups, and exposure measurement error was minimized. In China, the use of air purifiers is an economical and effective way to reduce older people's exposure to PM and may improve the cardiopulmonary health of the elderly. These conclusions provide guidelines for the use of air purifiers in the aged-care center.

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Declaration of Competing Interest

None

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