Contribution of indoor-generated and outdoor-generated fine and coarse particles to indoor air in Taiwanese hospitals

Chien-Cheng Jung[1, 2], Pei-Chih Wu[3], Chao-Heng Tseng[4], Charles C.-K. Chou[2], Huey-Jen Su[1*]

[1]*Dept. of Environmental and Occupational Health, College of Medicine, National Cheng Kung University, Tainan City, Taiwan*
[2]*Research Center for Environmental Changes, Academia Sinica, Taipei City, Taiwan*
[3]*Dept. of Occupational Safety and Health, Chang Jung Christian University, Tainan City, Taiwan*
[4]*Inst. of Environmental Engineering and Management, National Taipei University of Technology, Taipei City, Taiwan*

Abstract

This study quantified the contributions of indoor-generated and outdoor-generated particles to indoor air in hospitals and examined whether air conditioning type, working area, working hours, and ambient pollution affect these contributions. Indoor and outdoor fine and coarse particles were measured at 33 hospitals, and building characteristics were recorded. The infiltration factor (F_{inf}) was calculated, and the contributions of indoor-generated and outdoor-generated particles to indoor air were assessed. Additionally, their influencing factors on indoor air were evaluated. The F_{inf} values of fine and coarse particles were higher in hospitals with window and signal split type air conditioning than those in hospitals with other types of air conditioning. No significant differences in the F_{inf} values between working areas were observed. Outdoor-generated fine and coarse particles were major contributors to indoor air, regardless of air conditioning type and working area. Higher contributions of indoor-generated fine and coarse particles to indoor air were recorded in clinic waiting areas and lobbies during working hours than during nonworking hours. Ambient air pollutant emissions and air conditioning characteristics influenced the contributions of indoor-generated and outdoor-generated particles to indoor air according to a regression model. In summary, the contribution of outdoor-generated particles to indoor air must be reduced to improve occupants' health in hospitals.

Keywords: Indoor air; Infiltration factor; Particle; Hospital.

---

[*] Corresponding author. Tel: 886-6-275-2459; Fax: 886-6-274-3748
E-*mail address*: hjsu@mail.ncku.edu.tw

1. INTRODUCTION

Particulate matter (PM) is widely studied because of its effects on human health. Previous studies have identified a link between exposure to PM with aerodynamic diameters less than 2.5 μm ($PM_{2.5}$) and hospital admissions for respiratory diseases (Dominici et al., 2006; Tsai et al., 2014) and cardiovascular diseases (Dominici et al., 2006; Pope et al., 2008). Studies have also determined that $PM_{2.5}$ exposure increases the risk of diabetes mellitus (Pearson et al., 2010; Chen et al., 2013). Particle sizes between 2.5 and 10 μm ($PM_{2.5\text{-}10}$) have also a noticeable effect on human health. Cheng's study found that high $PM_{2.5\text{-}10}$ exposure increases the risk of hospital admission for respiratory diseases on cool days (Cheng et al., 2015). Heart rate variability was associated with $PM_{2.5\text{-}10}$ exposure among older adults with coronary artery disease (Lipsett et al., 2006). Therefore, investigating the characteristics and sources of PM is vital to reduce exposure.

People spend 80-90% of their time indoors, therefore, investigating the characteristics and sources of indoor PM is necessary, especially in hospitals. Hospitals are complex environments and differ from other indoor environments. Many patients and employees stay and work in hospitals. Studies indicated that PM exposure in hospitals was associated with sick building syndrome (Chang et al., 2015). Thus, understanding the characteristics and sources of PM in hospitals is necessary. Studies in Asia and Europe have determined that $PM_{2.5}$ (10-215 μg m^{-3}) and PM_{10} (58-250 μg m^{-3}) levels differ greatly between hospitals (Wang et al., 2006a; Wang et al., 2006b; Slezakova et al., 2012; Lomboy et al., 2015). Additionally, indoor activities (Wang et al., 2006b), carpets, and curtains (Verma and Taneja, 2011) are major sources of indoor PM in hospitals. Other major sources of indoor PM are outdoor $PM_{2.5}$ and PM_{10} (Wang et al., 2006a; Wang et al., 2006b; Slezakova et al., 2012; Lomboy et al., 2015). Studies have shown that both indoor air and outdoor air contribute to the PM inside hospitals. However, no study has measured the contributions of indoor and outdoor air to PM in hospitals for assessing health risks and reducing exposure levels.

Studies have determined that the level of PM varies in different working areas in hospitals. PM_{10} levels were higher in outpatient departments than in inpatient departments (Li et al., 2016) and the level of $PM_{2.5}$ was higher in clinics than in intensive care units (Lomboy et al., 2015). Verma's study found the level of $PM_{2.5}$ or PM_{10} varied in different types of wards (Verma and Taneja, 2011). Air conditioning types also affect the distribution of PM levels in hospitals. A previous study found the levels of $PM_{2.5}$ and PM_{10} were higher in hospitals with window and signal split type than those with central air conditioning (Jung et al., 2015). $PM_{2.5}$ levels were higher in hospitals with natural ventilation than in those with central air conditioning (Lomboy et al., 2015). However, the differences between indoor and outdoor air contributions to indoor PM in hospitals for different air conditioning types and working areas are inadequately understood.

This study investigated the contributions of indoor-generated and outdoor-generated $PM_{2.5}$ and $PM_{2.5\text{-}10}$ to the air in hospitals and assessed whether the air conditioning types and working areas affected the aforementioned contribution. Because hospitals are not accessible on a 7-d, 24-h basis to those who are not staff or patients, this study calculated these contributions at various working hours. Additionally, we used a regression model to analyze the effects of temperature, relative humidity, ambient pollution sources, gaseous pollutants, and air conditioning characteristics on the contributions of indoor-generated and outdoor-generated particles to air in hospitals.

2. MATERIALS AND METHOD

2.1. Hospital selection and building characteristic questionnaire

We used a simple random sampling to select 50 hospitals from the government registry; 33 (average hospital age: 22 years) of the 50 hospitals agreed to participate in the study. From November 2007 to January 2008, we measured indoor air quality (IAQ) at two to four sampling sites within each hospital. We measured IAQ at nurse stations, clinics, clinic waiting areas, lobbies, and wards; the sampling site numbers were 7, 20, 21, 23, and 4, respectively. Outdoor sampling sites where outdoor air entered the hospital were included. Building characteristics, including air conditioning type, working hours, and ambient pollution sources, were also surveyed for each sampling site by the researchers or hospital staffs during the sampling period in accordance with a standardized checklist. Table 1 summarizes the characteristics of the 75 sampling sites from 33 participating hospitals.

2.2. Measurement of indoor and outdoor air pollutants

Indoor samplers were placed in the center of the lobby; at the other sampling sites (viz., nurse stations, clinics, clinic waiting areas, and wards), the indoor samplers were placed near walls (Figure S1). At all sampling sites, instrument inlets were located 1.2-1.5 m above floor level. For the outdoor sampling sites, the samplers were located on balconies in proximity the air inlet of the air conditioner. When a balcony of the hospital was unavailable, the samplers were attached to the windows, and their inlets were used to connect the tubing for outdoor sampling. Indoor and outdoor $PM_{2.5}$ and PM_{10} levels were measured in the study hospitals over 24 h (starting at 09:00), and the $PM_{2.5-10}$ level was calculated by subtracting $PM_{2.5}$ from PM_{10}. Moreover, indoor and outdoor carbon monoxide (CO), carbon dioxide (CO_2), ozone (O_3), temperature, and relative humidity (RH) levels were determined over 24 hours (starting at 09:00).

$PM_{2.5}$ and PM_{10} levels were measured using DUST-TRAK Aerosol Monitors (Model 8520, TSI Corporation, Shoreview, MN, USA). A Q-TRAK Indoor Air Quality Monitor (Model 7575, TSI Corporation, Shoreview, MN, USA) was used to monitor CO, CO_2, temperature, and RH levels. The O_3 level was measured using an Ozone Monitor (Model 202, 2B Technologies, Boulder, CO, USA).

2.3. Infiltration factor estimation

Some studies have used physics models or tracer elements to estimate the contributions of indoor and outdoor air to indoor PM (Meng et al., 2007; Allen et al., 2012; Ji and Zhao, 2015). However, these methods required sampling and analysis of the compositions of PM and thus were relatively expensive and inconclusive (Samek et al., 2016). The infiltration factor (F_{inf}) was employed to ascertain the penetration of outdoor PM into indoor air (Chen and Zhao, 2011). The method only measured the indoor and outdoor PM levels. Some studies have also used the F_{inf} to estimate the contributions of indoor and outdoor air to indoor PM (Kearney et al., 2011; MacNeill et al., 2012).

The F_{inf} can be calculated using Eqs. (1)-(4). The level of indoor PM (C_{in}) is the sum of $C_{out} \times F_{inf}$ and C_{ins} (1), where C_{out} is the outdoor PM level, and C_{ins} is the PM level generated by indoor sources.

$$C_{in} = C_{out} \times F_{inf} + C_{ins} \tag{1}$$

Certain sampling sites were inaccessible to the staffs or patients at night, such as clinic, clinic waiting area, and lobby. At nurse stations and wards, human activity decreased at night. This study assumed that indoor sources could be ignored at night (Long et al., 2001); therefore, equation 1 can be simplified as eq (2). We used indoor and outdoor PM levels between 02:00 and 06:00 to calculate the F_{inf}.

$$F_{inf} = \frac{C_{in}}{C_{out}} \qquad (2)$$

The contributions of the indoor-generated and outdoor-generated particles to indoor air were estimated according to Eqs. (3) and (4); where C_{outs} is an indoor particle level which is contributed by the outdoor source.

$$C_{outs} = C_{out} \times F_{inf} \qquad (3)$$

$$C_{ins} = C_{in} - C_{outs} \qquad (4)$$

2.4. Statistical analysis

This study used one-way analysis of variance (one-way ANOVA) to analyze the differences in F_{inf} values of $PM_{2.5}$ or $PM_{2.5\text{-}10}$ for different air conditioning types or working areas. Additionally, ANOVA was also used to test the differences in the contribution levels of indoor-generated or outdoor-generated particles to indoor air according to different air conditioning types or working areas. Furthermore, the t-test was used to analyze the contribution of indoor-generated particles to indoor air during various periods.

A predictive model of indoor-generated and outdoor-generated $PM_{2.5}$ and $PM_{2.5\text{-}10}$ contributions to indoor air was analyzed using a step-wise regression model (backward elimination) and variables were required to be $p < 0.05$. We analyzed the associations between all variables and indoor-generated and outdoor-generated particles and removed variables that were statistically nonsignificant in the regression model. We repeated this process until no more variables could be removed without a statistically significant change in the regression model. SAS (v 9.3) was used for data analysis.

3. RESULT

3.1. Hospitals characteristics and IAQ

Hospital characteristics are shown in Table 1. Most sampling sites from study hospitals near main roads (81%), parking lot entrances (68%), or with plant growth (55%) exhibited susbtantial emission of particles. Over two-fifths of the sampling sites were located near loading docks (43%) or restaurants (40%). The other characteristics can be found in Table 1.

The average indoor $PM_{2.5}$, $PM_{2.5\text{-}10}$, CO, CO_2, O_3 temperature, and RH levels are 12.1 ± 5.3 μg m^{-3}, 11.6 ± 5.2 μg m^{-3}, 2.9 ± 1.6 ppm, 647 ± 169 ppm, 33.8 ± 8.6 ppb, 23.5 ± 1.0℃, and 59.0 ± 5.1%, respectively. The indoor pollutant levels were all within Taiwanese regulations for IAQ

($PM_{2.5}$: 35 μg m^{-3}; CO: 9 ppm; CO_2: 1000 ppm; O_3: 60 ppb) (Environmental Protection Administration, 2011). These results indicated that the IAQ is acceptable in Taiwanese hospitals. Additionally, the average outdoor $PM_{2.5}$, $PM_{2.5\text{-}10}$, CO, CO_2, O_3, temperature, and RH levels were 20.6 ± 7.4 μg m^{-3}, 24.0 ± 9.4 μg m^{-3}, 2.3 ± 1.3 ppm, 491 ± 77 ppm, 38.3 ± 9.8 ppb, 23.4 ± 2.3°C, and 64.9 ± 7.3%, respectively.

The indoor $PM_{2.5}$ and $PM_{2.5\text{-}10}$ levels for various air conditioning types and working areas are presented in Tables S1 and S2, respectively. Indoor $PM_{2.5\text{-}10}$ levels differed with air conditioning type ($p < 0.05$), indicating that air conditioning type affects the characteristics of indoor $PM_{2.5\text{-}10}$ in hospitals. No significant differences were observed in the indoor $PM_{2.5}$ levels between air conditioning types or the levels of $PM_{2.5}$ and $PM_{2.5\text{-}10}$ between working areas. Tables S1 and S2 indicate that temperature and RH did not significantly differ between air conditioning types or working areas. These results imply that air conditioning usage controls the temperature and RH to within a stable range in Taiwanese hospitals. The characteristics of gaseous pollutants for different air conditioning types and working areas were ascertained in our previous study (Jung et al., 2015).

3.2. Infiltration factor estimates

The average F_{inf} values of $PM_{2.5}$ and $PM_{2.5\text{-}10}$ were 0.63 and 0.54, respectively. The F_{inf}

values of $PM_{2.5}$ and $PM_{2.5\text{-}10}$ for air conditioning types and working areas are reported in Table 2. Hospitals with window and signal split type have higher F_{inf} values of $PM_{2.5}$ and $PM_{2.5\text{-}10}$ ($p < 0.05$) than those with other air conditioning types. No statistical significance was observed for the F_{inf} values of $PM_{2.5}$ and $PM_{2.5\text{-}10}$ between working areas.

3.3. Indoor-generated and outdoor-generated particles

Table 3 presents the contributions of indoor-generated and outdoor-generated particle levels to indoor air. The contributions of indoor-generated and outdoor-generated $PM_{2.5}$ to indoor air were 2.0 μg m^{-3} (14%) and 12.0 μg m^{-3} (86%), respectively, and the outdoor contribution was significantly higher ($p < 0.05$). A similar result was found for indoor-generated and outdoor-generated $PM_{2.5\text{-}10}$ (indoor: 2.6 μg m^{-3} (18%); outdoor: 12.1 μg m^{-3} (82%), $p < 0.05$). The contributions of indoor-generated and outdoor-generated $PM_{2.5}$ and $PM_{2.5\text{-}10}$ to indoor air were calculated for air conditioning types and working areas in Table 3. Our data shows that outdoor-generated $PM_{2.5}$ and $PM_{2.5\text{-}10}$ were major contributors to indoor air for different air conditioning types and working areas.

Table 4 reveals higher contributions of indoor-generated $PM_{2.5}$ and $PM_{2.5\text{-}10}$ to indoor air in both the clinic waiting areas and lobbies during working hours than during nonworking hours (*p*

< 0.05). Additionally, higher contributions of indoor-generated $PM_{2.5}$ and $PM_{2.5\text{-}10}$ to indoor air were recorded during working hours than during nonworking hours at nurse stations, clinics, and wards; however, statistical significance was not attained for this result. Figure 1 reveals that the average contribution of indoor-generated and outdoor-generated $PM_{2.5}$ and $PM_{2.5\text{-}10}$ in all study spaces ($N = 75$) increased gradually from 08:00 and steadily declined from 16:00.

3.4. Effect factors of indoor-generated and outdoor-generated particles

A step-wise regression model was used to analyze the factors (ambient pollution, air conditioning characteristics, and weather) affecting the contributions of indoor-generated and outdoor-generated PM to indoor air (Table 5). Obstacles in the air outlet ($\beta = 2.82$) and lack of a return air pathway ($\beta = 2.15$) were major factors affecting the contribution of indoor-generated $PM_{2.5}$ (42% explained). The lack of a return air pathway ($\beta = 2.64$) was also a major factor affecting the contribution of indoor-generated $PM_{2.5\text{–}10}$ (11% explained). Moreover, being located near a restaurant ($\beta = 4.92$) affected the contribution of outdoor-generated $PM_{2.5}$ (17% explained). The lack of a return air pathway ($\beta = 5.46$) and outdoor CO level ($\beta = 1.42$) were major factors affecting the contribution of outdoor-generated $PM_{2.5\text{-}10}$ (17% explained).

4. DISCUSSION

This study determined that the F_{inf} is higher in hospitals with window and signal split type air conditioning than those with air conditioning types. Moreover, outdoor-generated $PM_{2.5}$ and $PM_{2.5-10}$ were the principal contributors to indoor air, regardless of air conditioning types and working areas. During working hours, higher contributions of indoor-generated $PM_{2.5}$ and $PM_{2.5-10}$ were recorded in both clinic waiting areas and lobbies than during nonworking hours. Air conditioning characteristics affected the contribution of indoor-generated particles to indoor air. The outdoor CO level, ambient pollution sources, and air conditioning characteristics influenced the contributions of outdoor-generated particle to indoor air.

The mean $PM_{2.5}$ level recorded in the present study was lower than that recorded in other studies (Wang et al., 2006a; Wang et al., 2006b; Li et al., 2016), however, the $PM_{2.5-10}$ levels recorded in the present study were similar to those recorded in the aforementioned studies. In their studies (Wang et al., 2006a; Wang et al., 2006b; Li et al., 2016), the hospitals were closed to the main roads, restaurants, and industrial areas, and the mean outdoor $PM_{2.5}$ levels were higher (86-105 $\mu g\ m^{-3}$). Moreover, their studies also found that the ratios of indoor and outdoor (I/O ratio) PM levels were below 1.0 and suggested that outdoor-generated PM was an important source to indoor PM. This was the reason for the higher level of indoor PM in the previous studies.

In a previous study, the F_{inf} (nighttime I/O) of $PM_{2.5}$ and $PM_{2.5\text{-}10}$ ranged from 0.1 to 1.2 and from < 0.1 to 0.9, respectively (Long et al., 2001). Daily median F_{inf} values of censored I/O and sulfur I/O for $PM_{2.5}$ were 0.55 and 0.49, respectively, in winter, and 0.80 and 0.83, respectively, in summer (MacNeill et al., 2012). Our estimation was similar to the previous studies. Therefore, our results reflected that the F_{inf} estimation was reasonable and can be used to calculate the contributions of indoor-generated and outdoor-generated PM to indoor air.

Table 2 shows that the F_{inf} values of $PM_{2.5}$ and $PM_{2.5\text{-}10}$ were higher in hospitals with window and signal split type air conditioning than in those with other types of air conditioning. We speculate that more window openings were present in hospitals with this type of air conditioning, increasing the F_{inf} values. Studies have indicated that window opening increased the F_{inf} values (Long et al., 2001; MacNeill et al., 2012). Moreover, in this study, the correlation between the indoor and outdoor $PM_{2.5}$ level in hospitals with window and signal split type air conditioning was superior to that of central air conditioning (Supplementary Table 3). Hospitals with central air conditioning install air filters to remove PM from the outdoor air. One study also found that the level of aerosol was lower in indoor spaces with central air conditioning with high-efficiency particulate air filters than in those with signal split type air conditioning (Chuaybamroong et al., 2008). Thus, the F_{inf} value was higher in hospitals with window and signal split type air conditioning than in those with other types of air conditioning, because outdoor air was more directly combined with indoor air.

In this study, most of the hospitals used central air conditioning, and less window opening occurred. Therefore, we hypothesized that the contributions of indoor-generated particles to indoor air were dominant. However, our results reveal that outdoor-generated $PM_{2.5}$ and $PM_{2.5\text{-}10}$ contributions to indoor air were the principal contributions in terms of contribution levels and percentage (Table 3). This result contradicted our hypothesis and the findings of a previous study (MacNeill et al., 2012). In MacNeill's study, they conducted the measurement on homes and found that oven use, candle burning, and wood fireplaces are associated with the contribution of indoor-generated fine particles. However, no indoor burning occurs in our study hospitals; therefore, the contribution of indoor-generated particles was lower. Our data indicated that the I/O ratios of $PM_{2.5}$ and $PM_{2.5\text{-}10}$ were below 1.0 ($PM_{2.5}$: 0.70; $PM_{2.5–10}$: 0.61); these results were similar to those of previous studies (Wang et al., 2006a; Wang et al., 2006b; Slezakova et al., 2012; Lomboy et al., 2015). Therefore, outdoor air is a key source of indoor PM in Taiwanese hospitals. However, the correlation between indoor PM and outdoor PM in hospitals with central air conditioning was low (Table S3). A time delay may affect this association. Similar results were found for the contributions of outdoor-generated particles to indoor air between different working areas (Table 3). These results suggest that the effect of outdoor PM on indoor air in hospitals should not be ignored, regardless of the air conditioning types or working areas.

To the best of our knowledge, this is the first study to investigate the different contributions of indoor-generated particles to indoor air for various working hours in hospitals (Table 4). The contributions of the indoor-generated $PM_{2.5}$ and $PM_{2.5\text{-}10}$ to indoor air were high during working hours, and statistically significant differences were observed in both the clinic waiting areas and lobbies. The concentrations of indoor-generated $PM_{2.5}$ and $PM_{2.5\text{-}10}$ gradually increased after 08:00 and gradually declined after 18:00 (Figure 1). Human activities, such as walking and cleaning, may be influencing factors. Ferro's study used a mathematical model to calculate the effect of human activity on the level of PM (Ferro et al., 2004). They found PM levels gradually increased during human activity, such as walking, dancing on carpeted surfaces, and dancing on noncarpeted surfaces. One study indicated that cleaning behavior also increased the particle emission rate using a chamber test (Géhin et al., 2008). Thus, human activities increase the PM level during working hours.

Ambient pollution (Massey et al., 2012; Chithra and Nagendra, 2013), air conditioning characteristics (Chithra and Nagendra, 2012), and weather (Chithra and Nagendra, 2012; Massey et al., 2012) have been demonstrated to affect indoor PM concentration. A regression model was used and determined that obstacles in the air outlet and lack of a return air pathway increased the contribution of indoor-generated $PM_{2.5}$, and the lack of a return air pathway increased the contribution of indoor-generated $PM_{2.5\text{-}10}$ (Table 5). The PM level should increase in air conditioning systems without a return air pathway. Moreover, obstacles in the air outlet prevented the air flow from effectively removing PM (Hu et al., 2014), therefore, these obstacles may influence variations in indoor PM concentrations in hospitals.

Hospitals near to the restaurants were associated with the contribution of outdoor-generated $PM_{2.5}$ to indoor air. A previous study indicated that particulate matter emission from restaurants affected the air quality (Lung et al., 2011). Moreover, our results indicated that the outdoor CO level and lack of a return air pathway were positively associated with the contribution of outdoor-generated $PM_{2.5-10}$. Studies have indicated CO is a marker for traffic-related air pollution (Jo and Lee, 2006; Both et al., 2013), and that traffic pollution produces particulate air pollutants (Charron and Harrison, 2005; Both et al., 2013; Oakes et al., 2016). Moreover, 81% of sampling sites from study hospitals in this study near a main road. Therefore, traffic pollution could be an important factor contributing to the outdoor-generated PM and the resulting indoor air. In hospitals, particulate air pollutants from the outdoor air can infiltrate indoor air through air conditioning. The lack of a return air pathway may hinder particulate air pollutant removal in indoor air and lead to a higher contribution of outdoor-generated $PM_{2.5-10}$ to indoor air.

Several limitations affected this study. First, the air exchange rate was not measured to calculate the F_{inf} value. Calculation of the F_{inf} value used the levels of indoor and outdoor PM between 02:00 and 06:00; we assumed that indoor sources of PM were negligible in these periods.

Therefore, measuring the air exchange rate to calculate F_{inf} value was unneccesary. Moreover, the previous study successfully used the same equations to calculate the F_{inf} value (Long et al., 2001) and our value was also similar to those of previous studies (Long et al., 2001; MacNeill et al., 2012). Therefore, the value was reasonable to calculate the contribution of indoor-generated or outdoor-generated PM to indoor air. Secondary, we did not complete the sampling over four seasons to characterize seasonal variations in F_{inf} value. In this study, 88% of the sampling sites used central air conditioning to control the temperature and air flow. The temperature and air flow are generally stable when central air conditioning is used; therefore, the F_{inf} estimation may remain stable across seasons.

5. CONCLUSIONS

This is the first study to calculate the infiltration factors and the contributions of indoor-generated and outdoor-generated fine and coarse particles to indoor air in hospitals. Our study found that air conditioning type affects the infiltration factor. Outdoor air was a primary source of indoor PM. The air conditioning characteristics and ambient pollution influence the contributions of indoor-generated and outdoor-generated fine and coarse particles to indoor air. This paper provides valuable suggestions for reducing PM exposure and effectively assessing the health risks of occupants in hospitals.

ACKNOWLEDGMENTS

We would like to thank the Minister of Health and Welfare for financially supporting this study under contract no. 96B6114.

REFERENCES

Allen, R.W., Adar, S.D., Avol, M.C., Curl, C.L., Larson, T., Liu, L.-J.S., Sheppard, L. and Kaufman, J.D. (2012). Modeling the Residential Infiltration of Outdoor Pm2. 5 in the Multi-Ethnic Study of Atherosclerosis and Air Pollution (Mesa Air). *Environmental health perspectives* 120: 824.

Both, A.F., Westerdahl, D., Fruin, S., Haryanto, B. and Marshall, J.D. (2013). Exposure to Carbon Monoxide, Fine Particle Mass, and Ultrafine Particle Number in Jakarta, Indonesia: Effect of Commute Mode. *Science of the Total Environment* 443: 965-972.

Chang, C.-J., Yang, H.-H., Wang, Y.-F. and Li, M.-S. (2015). Prevalence of Sick Building Syndrome-Related Symptoms among Hospital Workers in Confined and Open Working Spaces. *Aerosol Air Qual. Res* 15: 2378-2384.

Charron, A. and Harrison, R.M. (2005). Fine (Pm2. 5) and Coarse (Pm2. 5-10) Particulate Matter on a Heavily Trafficked London Highway: Sources and Processes. *Environmental science & technology* 39: 7768-7776.

Chen, C. and Zhao, B. (2011). Review of Relationship between Indoor and Outdoor Particles: I/O Ratio, Infiltration Factor and Penetration Factor. *Atmospheric Environment* 45: 275-288.

Chen, H., Burnett, R.T., Kwong, J.C., Villeneuve, P.J., Goldberg, M.S., Brook, R.D., van Donkelaar, A., Jerrett, M., Martin, R.V. and Brook, J.R. (2013). Risk of Incident Diabetes in Relation to Long-Term Exposure to Fine Particulate Matter in Ontario, Canada. *Environmental Health Perspectives (Online)* 121: 804.

Cheng, M.-H., Chiu, H.-F. and Yang, C.-Y. (2015). Coarse Particulate Air Pollution Associated with Increased Risk of Hospital Admissions for Respiratory Diseases in a Tropical City, Kaohsiung, Taiwan. *International journal of environmental research and public health* 12: 13053-13068.

Chithra, V. and Nagendra, S.S. (2012). Indoor Air Quality Investigations in a Naturally Ventilated School Building Located Close to an Urban Roadway in Chennai, India. *Building and Environment* 54: 159-167.

Chithra, V. and Nagendra, S.S. (2013). Chemical and Morphological Characteristics of Indoor and Outdoor Particulate Matter in an Urban Environment. *Atmospheric Environment* 77: 579-587.

Chuaybamroong, P., Choomseer, P. and Sribenjalux, P. (2008). Comparison between Hospital Single Air Unit and Central Air Unit for Ventilation Performances and Airborne Microbes. *Aerosol Air Qual Res* 8: 28-36.

Dominici, F., Peng, R.D., Bell, M.L., Pham, L., McDermott, A., Zeger, S.L. and Samet, J.M. (2006). Fine Particulate Air Pollution and Hospital Admission for Cardiovascular and Respiratory Diseases. *Jama* 295: 1127-1134.

Environmental Protection Administration (2011). Indoor Air Quality Act, Environmental Protection Administration, Taiwan.

Ferro, A.R., Kopperud, R.J. and Hildemann, L.M. (2004). Source Strengths for Indoor Human Activities That Resuspend Particulate Matter. *Environmental science & technology* 38: 1759-1764.

Géhin, E., Ramalho, O. and Kirchner, S. (2008). Size Distribution and Emission Rate Measurement of Fine and Ultrafine Particle from Indoor Human Activities. *Atmospheric Environment* 42: 8341-8352.

Hu, S.-C., Shiue, Y.-Y., Shiue, A. and Tsai, M.-H. (2014). Removal Characteristics of Particulate Matter with Different Return Air System Designs in a Nonunidirectional Cleanroom for Integrated Circuit (Ic) Testing Processes. *HVAC&R Research* 20: 162-166.

Ji, W. and Zhao, B. (2015). Contribution of Outdoor-Originating Particles, Indoor-Emitted Particles and Indoor Secondary Organic Aerosol (Soa) to Residential Indoor Pm2. 5 Concentration: A Model-Based Estimation. *Building and Environment* 90: 196-205.

Jo, W.K. and Lee, J.Y. (2006). Indoor and Outdoor Levels of Respirable Particulates (Pm10) and Carbon Monoxide (Co) in High-Rise Apartment Buildings. *Atmospheric Environment* 40: 6067-6076.

Jung, C.-C., Wu, P.-C., Tseng, C.-H. and Su, H.-J. (2015). Indoor Air Quality Varies with

Ventilation Types and Working Areas in Hospitals. *Building and Environment* 85: 190-195.

Kearney, J., Wallace, L., MacNeill, M., Xu, X., VanRyswyk, K., You, H., Kulka, R. and Wheeler, A. (2011). Residential Indoor and Outdoor Ultrafine Particles in Windsor, Ontario. *Atmospheric environment* 45: 7583-7593.

Li, R., Fu, H., Hu, Q., Li, C., Zhang, L., Chen, J. and Mellouki, A.W. (2016). Physiochemical Characteristics of Aerosol Particles in the Typical Microenvironment of Hospital in Shanghai, China. *Science of The Total Environment* 580: 651-659.

Lipsett, M.J., Tsai, F.C., Roger, L., Woo, M. and Ostro, B.D. (2006). Coarse Particles and Heart Rate Variability among Older Adults with Coronary Artery Disease in the Coachella Valley, California. *Environmental Health Perspectives*: 1215-1220.

Lomboy, M.F.T.C., Quirit, L.L., Molina, V.B., Dalmacion, G.V., Schwartz, J.D., Suh, H.H. and Baja, E.S. (2015). Characterization of Particulate Matter 2.5 in an Urban Tertiary Care Hospital in the Philippines. *Building and Environment* 92: 432-439.

Long, C.M., Suh, H.H., Catalano, P.J. and Koutrakis, P. (2001). Using Time-and Size-Resolved Particulate Data to Quantify Indoor Penetration and Deposition Behavior. *Environmental Science & Technology* 35: 2089-2099.

Lung, S.-C., Liu, C.-H., Fu, C.B., Wen, T.-Y. and Huang, S.-Y. (2011). Exposures and Potential

Risks in the Neighborhoods of 5 Different Restaurants Emitting Particulate Polycyclic Aromatic Hydrocarbons. *Epidemiology* 22: S90.

MacNeill, M., Wallace, L., Kearney, J., Allen, R., Van Ryswyk, K., Judek, S., Xu, X. and Wheeler, A. (2012). Factors Influencing Variability in the Infiltration of Pm 2.5 Mass and Its Components. *Atmospheric environment* 61: 518-532.

Massey, D., Kulshrestha, A., Masih, J. and Taneja, A. (2012). Seasonal Trends of Pm 10, Pm 5.0, Pm 2.5 & Pm 1.0 in Indoor and Outdoor Environments of Residential Homes Located in North-Central India. *Building and Environment* 47: 223-231.

Meng, Q.Y., Turpin, B.J., Lee, J.H., Polidori, A., Weisel, C.P., Morandi, M., Colome, S., Zhang, J., Stock, T. and Winer, A. (2007). How Does Infiltration Behavior Modify the Composition of Ambient Pm2. 5 in Indoor Spaces? An Analysis of Riopa Data. *Environmental science & technology* 41: 7315-7321.

Oakes, M.M., Burke, J.M., Norris, G.A., Kovalcik, K.D., Pancras, J.P. and Landis, M.S. (2016). Near-Road Enhancement and Solubility of Fine and Coarse Particulate Matter Trace Elements near a Major Interstate in Detroit, Michigan. *Atmospheric Environment* 145: 213-224.

Pearson, J.F., Bachireddy, C., Shyamprasad, S., Goldfine, A.B. and Brownstein, J.S. (2010). Association between Fine Particulate Matter and Diabetes Prevalence in the Us. *Diabetes* *care* 33: 2196-2201.

Pope, C.A., Renlund, D.G., Kfoury, A.G., May, H.T. and Horne, B.D. (2008). Relation of Heart Failure Hospitalization to Exposure to Fine Particulate Air Pollution. *The American journal of cardiology* 102: 1230-1234.

Samek, L., Stegowski, Z. and Furman, L. (2016). Preliminary Pm2. 5 and Pm10 Fractions Source Apportionment Complemented by Statistical Accuracy Determination. *Nukleonika* 61: 75--83.

Slezakova, K., da Conceição Alvim-Ferraz, M. and do Carmo Pereira, M. (2012). Elemental Characterization of Indoor Breathable Particles at a Portuguese Urban Hospital. *Journal of Toxicology and Environmental Health, Part A* 75: 909-919.

Tsai, S.-S., Chiu, H.-F., Liou, S.-H. and Yang, C.-Y. (2014). Short-Term Effects of Fine Particulate Air Pollution on Hospital Admissions for Respiratory Diseases: A Case-Crossover Study in a Tropical City. *Journal of Toxicology and Environmental Health, Part A* 77: 1091-1101.

Verma, N. and Taneja, A. (2011). Particulate Matter Exposure in Hospitals of Urban City Lo-Cated in Northern Central India. *The Indian Journal of environmental protection* 31: 627-634.

Wang, X., Bi, X., Chen, D., Sheng, G. and Fu, J. (2006a). Hospital Indoor Respirable Particles and Carbonaceous Composition. *Building and environment* 41: 992-1000.

Wang, X.H., Bi, X.H., Sheng, G.Y. and Fu, H.M. (2006b). Hospital Indoor Pm10/Pm2.5 and Associated Trace Elements in Guangzhou, China. *Science of the Total Environment* 366: 124-135.

Table 1. Hospital characteristics (N = 75)

Hospital characteristic	**n (yes)**	**%**
Close to ambient pollution source		
Main road	61	81
Parking lot entry	51	68
Loading dock	32	43
Plant growth	41	55
Restaurant	30	40
Laundry and car wash facility	7	9
Incinerator	2	3
Air conditioning		
Insect or leaf in air intake	3	4
Air intake within 8 meters of cooling tower	3	4
Air intake within 8 meters of air outlet	10	13
Air intake within 8 meters of restaurant chimney	3	4
Air intake from engine room of the air conditioning system	18	24
Air filter with mildew	10	13
Duct of air outlet with dust	14	19
Duct of return air with dust	16	25
Lack of return air pathway	21	28
Obstacle in air outlet	3	4

Table 2. Infiltration factor of particles for different air conditioning type and working area (mean)

	F_{inf} ($PM_{2.5}$)	F_{inf} ($PM_{2.5-10}$)		F_{inf} ($PM_{2.5}$)	F_{inf} ($PM_{2.5-10}$)
All (N = 75)	0.63	0.54			
Air conditioning type			**Working area**		
AHU mix FCU (n = 41)	0.54	0.46	**Nurse station (n = 7)**	0.58	0.42
AHU (n = 12)	0.75	0.55	**Clinic (n = 20)**	0.64	0.61
FCU (n = 13)	0.69	0.63	**Clinic waiting area (n = 21)**	0.64	0.52
Window and signal split type (n = 9)	0.80	0.73	**Lobby (n = 23)**	0.60	0.55
p-value*	< 0.05	< 0.05	**Ward (n = 4)**	0.79	0.42
			p-value*	0.71	0.50

AHU: air handing unit; **FCU:** fan cooling unit.

*One-Way ANOVA was used to examine the differences in F_{inf} values of $PM_{2.5}$ or $PM_{2.5-10}$ in different air conditioning types or working areas (statistical significant was set at $p < 0.05$).

Table 3. Contribution levels of indoor-generated and outdoor-generated particles to indoor air for different types of air conditioning and working areas (μg m^{-3} (%))

	$PM_{2.5}$			**$PM_{2.5-10}$**		
	Indoor	**Outdoor**	***p-value*****	**Indoor**	**Outdoor**	***p-value*****
All (N = 75)	2.0 (14)	12.0 (86)	< 0.05	2.6 (18)	12.1 (82)	< 0.05
Air conditioning types						
AHU mix FCU	2.2 (16)	11.5 (84)	< 0.05	2.6 (20)	11.4 (80)	< 0.05
AHU	1.6 (10)	14.0 (90)	< 0.05	2.4 (15)	12.7 (85)	< 0.05
FCU	2.3 (14)	12.9 (86)	< 0.05	2.4 (14)	13.0 (86)	< 0.05
Window and signal split type	1.4 (11)	10.5 (89)	< 0.05	3.5 (16)	13.0 (84)	< 0.05
p-value*	0.49	0.40		0.61	0.83	
Working areas						
Nurse station	2.3 (18)	12.6 (82)	< 0.05	3.0 (23)	9.4 (77)	< 0.05
Clinic	1.6 (12)	10.8 (88)	< 0.05	2.1 (15)	12.4 (85)	< 0.05
Clinic waiting area	2.2 (14)	11.9 (86)	< 0.05	2.6 (17)	11.1 (83)	< 0.05
Lobby	2.4 (15)	12.2 (85)	< 0.05	3.3 (20)	13.5 (80)	< 0.05
Ward	0.7 (4)	16.7 (96)	< 0.05	1.2 (10)	11.7 (90)	< 0.05
p-value*	0.26	0.43		0.24	0.64	

AHU: air handing unit; **FCU:** fan cooling unit.

*One-Way ANOVA was used to examine the differences in the contribution levels of $PM_{2.5}$ or $PM_{2.5-10}$ in different air conditioning types or working areas (statistical significant was set at $p < 0.05$).

**T-test was used to examine the differences in the contribution levels of indoor-generated and outdoor-generated $PM_{2.5}$ or $PM_{2.5-10}$ according to air conditioning types or working areas (statistical significant was set at $p < 0.05$).

Table 4. Contribution level of indoor-generated particles to indoor air for different periods according to various working areas (μg m^{-3} (%))

Working area	**$PM_{2.5}$**		***p-value****	**$PM_{2.5-10}$**		***p-value****
	Working hour	**Non-working hour**		**Working hour**	**Non-working hour**	
Nurse station	3.0 (23)	1.8 (17)	0.28	4.0 (30)	2.3 (27)	0.26
Clinic	1.9 (15)	1.4 (14)	0.38	2.6 (20)	1.7 (15)	0.22
Clinic waiting area	3.3 (24)	1.4 (11)	< 0.05	3.8 (26)	1.7 (15)	< 0.05
Lobby	3.9 (24)	1.4 (12)	< 0.05	5.1 (29)	2.0 (18)	< 0.05
Ward	0.6 (3)	0.8 (5)	0.73	1.9 (13)	0.7 (8)	0.44

* T-test was used to examine the differences in the contribution levels of indoor-generated $PM_{2.5}$ or $PM_{2.5-10}$ in different working hours according to working areas (statistical significant was set at $p < 0.05$).

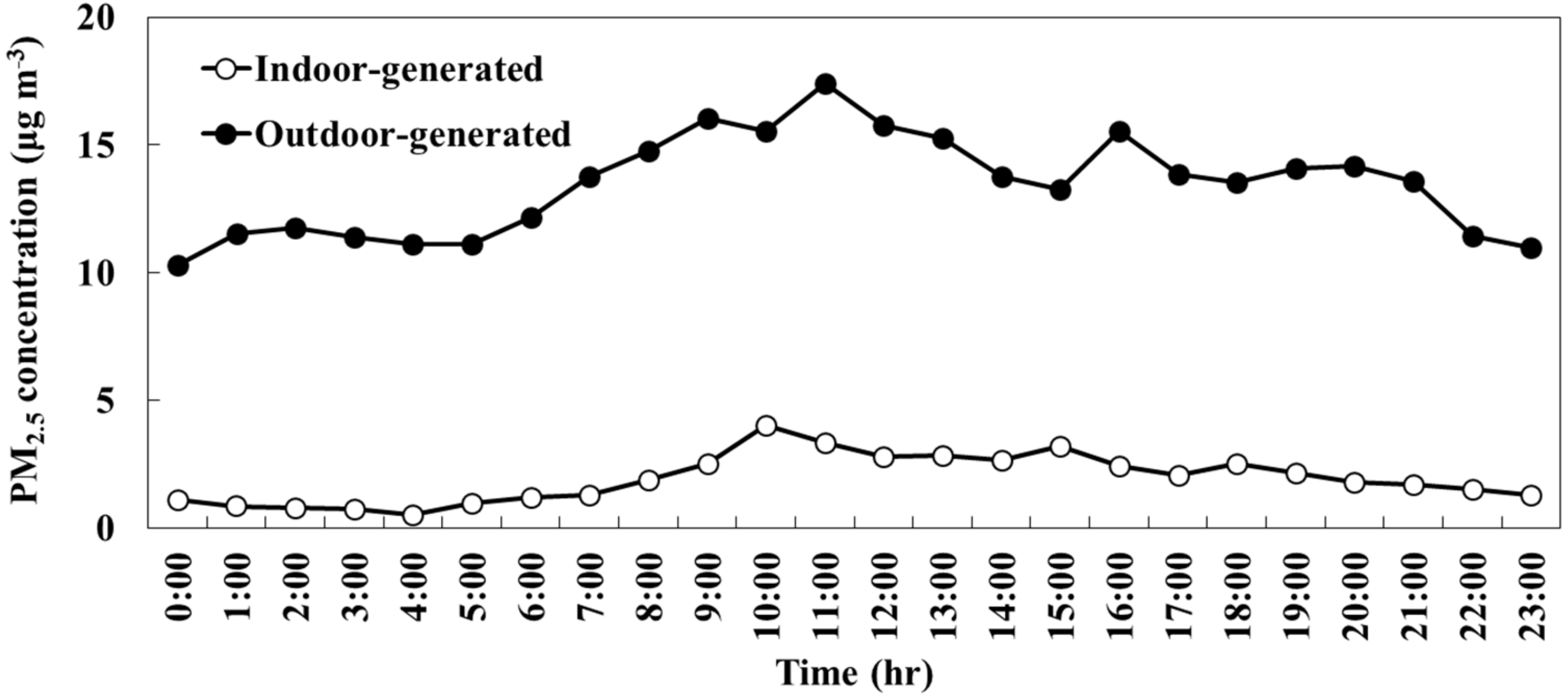
Table 5. Predictive model for the contribution levels of indoor-generated and outdoor-generated $PM_{2.5}$ and $PM_{2.5-10}$ to indoor air

Fixed effect*	**Parameter estimate (β)**	**Standard error (σ)**	**Proportion of explained (%)**	**Fixed effect***	**Parameter estimate (β)**	**Standard error (σ)**	**Proportion of explained (%)**
Indoor-$PM_{2.5}$				**Indoor-$PM_{2.5-10}$**			
Intercept	1.40	0.26	42	Intercept	2.30	0.30	11
Obstacle in air outlet	2.82	0.55		Lack of a return air pathway	2.64	1.15	
Lack of a return air pathway	2.15	0.89					
Outdoor-$PM_{2.5}$				**Outdoor-$PM_{2.5-10}$**			
Intercept	10.57	1.28	17	Intercept	6.85	2.22	17
Close to the restaurant emission	4.92	1.65		Outdoor CO level (ppm)	1.42	0.67	
				Lack of a return air pathway	5.46	2.16	

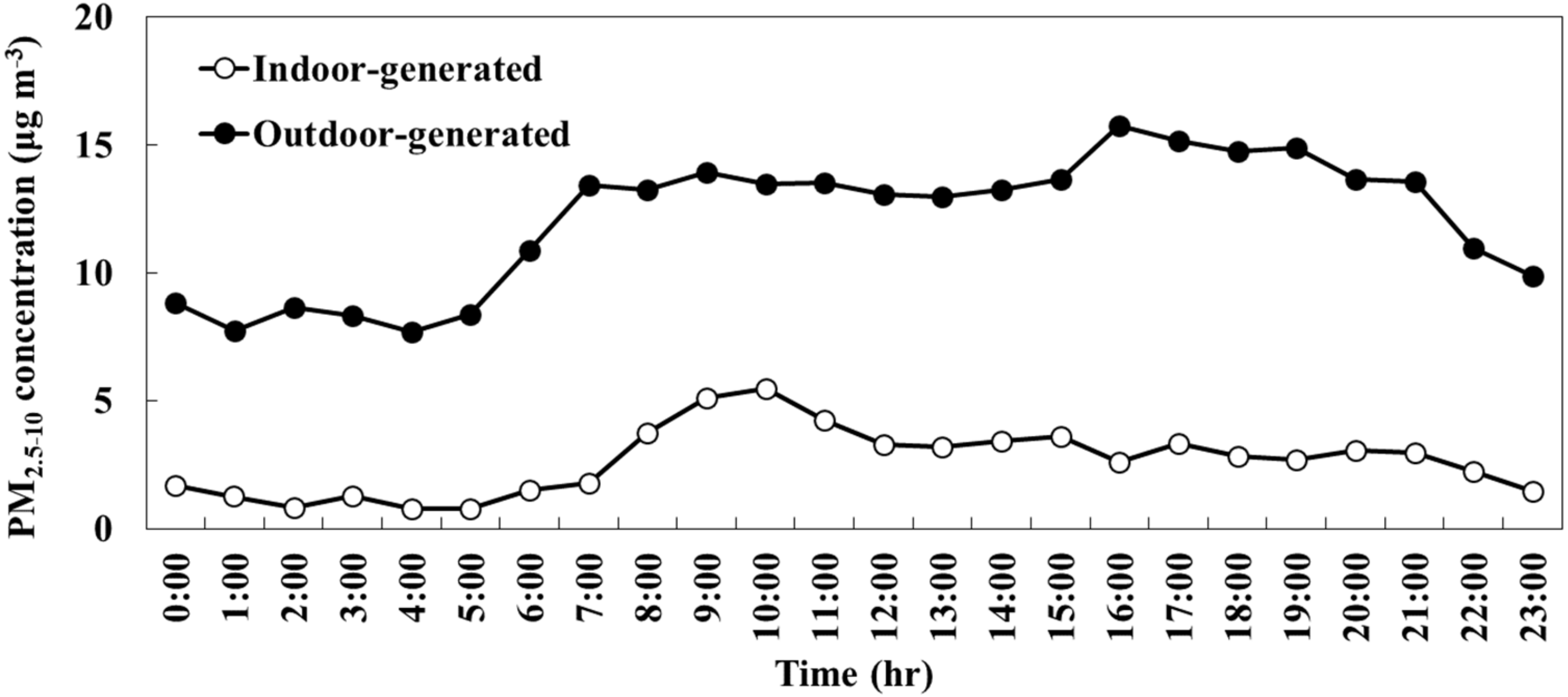
*The effect was selected into the final model when the $p < 0.05$ by a step-wise regression model.

Figure Captions

Fig. 1. Diurnal patterns of average hourly indoor-generated and outdoor-generated particles in all study spaces (N = 75). (a) $PM_{2.5}$ and (b) $PM_{2.5\text{-}10}$.


Indoor-generated
Outdoor-generated
PM$_{2.5}$ concentration (µg m^{-3})
20
15
10
5
0
0:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
Time (hr)

(a) PM$_{2.5}$



(b) $PM_{2.5-10}$

Fig. 1. Diurnal patterns of average hourly indoor-generated and outdoor-generated particles in all study spaces (N = 75). (a) $PM_{2.5}$ and (b) $PM_{2.5-10}$.