Infiltration of fine particles in urban buildings

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Abstract. Singapore is a tropical country that can be affected by outdoor fine particle air pollution. Little information is available on the penetration of outdoor fine particles into daycare environments. Our study attempted to address the following objectives: to measure indoor infiltration factor \( F_{\text{inf}} \) of PM2.5 from outdoor fine particles and to determine the building parameters that modifies the indoor PM2.5. We collected indoor/outdoor 1-min PM2.5 from 50 daycare environments. We noted high indoor and outdoor concentrations of fine particles due to the presence of regional haze pollution. Indoor and outdoor fine particle concentrations are significantly highest for daycares located near highways while indoor to outdoor ratios were significantly lower for air-conditioning use in daycares. Mean \( F_{\text{inf}} \pm \text{SD} \) of 0.65±0.19 in daycare rooms which are naturally ventilated and lower \( F_{\text{inf}} \pm \text{SD} \) values of 0.46±0.22 for those that are air-conditioned. The penetration coefficients and air exchange rates were higher in naturally ventilated daycares (0.78 vs 0.61 and 1.47 vs 0.86 h⁻¹ respectively). Our findings show that children remaining indoor in daycares where air conditioning is used can reduce PM2.5 exposures during outdoor pollution episodes.

1. Introduction

Numerous epidemiological studies have demonstrated the adverse impacts of fine particles exposures on various human morbidity and mortality outcomes [1,2]. Among the various sub-groups, children are particularly susceptible to harmful exposures of particle exposures [3]. In Singapore, Chew has demonstrated a link between outdoor particles concentration with asthma exacerbations among children [4]. However, considering that children spend the majority of their time indoors [5], their exposures to fine particles of outdoor origin may occur indoors. For preschool children, a large proportion of would spend up to 11 hours in a day in daycares. Consequently, there is an increasing interest in determining reducing outdoor fine particles ingress into buildings [3, 5].

The fraction of outdoor fine particles that penetrates indoors and remains suspended under steady-state conditions is defined as the infiltration factor \( F_{\text{inf}} \) [6,7]. \( F_{\text{inf}} \) variations within and between buildings is very important in determining the fraction of total exposure due to outdoor fine particles [7]. Epidemiological studies that estimate the effect of outdoor fine particles on health have typically used outdoor measurements from central monitoring sites [8]. The assumption here is that the outdoor concentrations are a good surrogate for the personal exposures of the entire population within the vicinity. Unfortunately, a poor correlation between outdoor fine particle concentration and personal exposure to fine particles of outdoor origin can result in a poor estimate of the associated health effect [7].

In view of the above-mentioned knowledge gaps, this study aims to determine the penetration behaviour of outdoor fine particles into urban daycare environments in Singapore and determine the building parameters that modifies the indoor fine particle levels. The results from this study have important implications concerning preschool children’s exposure to outdoor fine particles and their possible health consequences.
2. Materials and methods

2.1. Measurements
The experimental measurements were conducted in 50 urban daycare classrooms. These daycares are located near traffic sources from various parts of Singapore. Indoor and outdoor fine particle (PM$_{2.5}$) levels were measured using a pair of aerosol monitors (Dust-Trak, Model 8520, TSI, Inc., St. Paul, MN) fitted with 2.5 $\mu$m size-selective inlets. The Dust-Traks were programmed to sample every minute. Research performed elsewhere reported that side-by-side sampling indicated that DustTrak was highly correlated with gravimetric instrument (Wheeler et al., 2011). Indoor measurements were performed in the middle of the classroom near the breathing zone of children (approximately 0.5–0.7 m). Sampling was designed to evaluate the ‘typical’ indoor exposure levels in each daycare. As such, measurements were conducted in the middle of the week and during the day from 9 a.m. to 5 p.m. An outdoor location for each daycare center was simultaneously monitored. Indoor and outdoor CO$_2$ was continuously measured using monitors (Telaire, Santa Barbara, CA, USA) based on non-dispersive infrared technology. The precision of measurements ranged between 0 and 4,000 ppm CO$_2$ is ±50 ppm. Using the measured CO$_2$ as a tracer gas, the daycare center air change rates were estimated using in accordance with ASTM E 741.

2.2. Data analysis
The relationship between indoor and outdoor fine particles was examined using time series indoor and outdoor plots and calculating longitudinal correlations between the indoor and outdoor fine particles for daycare center. Based on mass-balanced principles, the steady state indoor fine particle concentrations for a given daycare center under a well-mixed condition can be described by the following equation [7]:

$$C_i = C_o \cdot \frac{Pa}{(a+k)} + \frac{S}{(a+k)V}$$  \hspace{1cm} (1)

Where $C_o$ is the outdoor fine particle concentration ($\mu$g/m$^3$), and $C_i$ is the indoor fine particle concentration ($\mu$g/m$^3$), $P$ is the outdoor fine particle penetration efficiency (unitless), $a$ is the air change rate (1/h), $k$ is the composite deposition rate (1/h), $S$ is the indoor generation rate ($\mu$g/h) and $V$ is the volume (m$^3$). Here, the composite deposition rate $k$ is a composite of at least two processes: 1) deposition on interior surfaces and/or mechanical ventilation system or air-conditioning units; and 2) removal via filtration. In the absence of indoor sources, the infiltration factor, $F_{inf}$ (unitless) can be obtained as [7]:

$$F_{inf} = \frac{C_i}{C_o} = \frac{Pa}{(a+k)}$$  \hspace{1cm} (2)

To estimate the daily infiltration factors for each daycare, we relied on linear regression analysis of the indoor fine particle concentrations against the outdoor fine particle concentrations as follows:

$$C_i = \beta_1 C_o + \beta_0$$  \hspace{1cm} (3)

where $\beta_i$ are the regression estimates. Comparing the regression with the mass balanced model equitation, one can relate $\beta_1$ with $Pa/(a + k)$ term and $\beta_0$ with $S/V \cdot (a + k)$ term. Note also that $\beta_1$ is the infiltration factor, of outdoor fine particles, $F_{inf}$, is equivalent to indoor fine particles source strengths multiplied with volume, air exchange and deposition rates terms.

3. Results and Discussion

3.1. Indoor and outdoor fine particle levels
The summary data are provided in Table 1. Of the 50 daycare classrooms, thirty-nine are naturally ventilated while eleven are air-conditioned. There is no difference in occupant density between naturally ventilated and air-conditioned daycares ($p>0.10$) (average is 0.39 person/m$^2$). All the windows for the naturally ventilated and air conditioned daycares were opened and closed respectively during the study. Twenty-three are located outside a small urban road, eleven outside a major road and fourteen near a
highway. Research elsewhere [9] have shown the impact of fine particles from traffic sources on the indoor concentration levels. The mean indoor levels in the daycares are comparable to those in US and Holland buildings with high levels of indoor smoking [7]. The elevated indoor and outdoor fine particle levels due to regional biomass burning resulting in concentrations that are comparable to those reported during light haze, moderate-haze and severe-haze values (indoor: 42, 88 and 121 µg m⁻³; outdoor: 47, 101 and 134 µg m⁻³ respectively) events that commonly occurs in Singapore [10]. In our study, the indoor and outdoor fine particle concentrations are significantly (ANOVA; p < 0.001) highest for daycares located near highways, followed by those situated near major roads and lastly those outside small roads. Indoor to outdoor ratios were significant difference for air-conditioning use in daycares (student’s t-test; p < 0.05) and building types (ANOVA; p < 0.01).

Figure 1 and 2 illustrates hourly boxplots of indoor and outdoor fine particles concentrations in air conditioned and naturally ventilated daycares. The indoor profiles of fine particles from naturally ventilated daycares closely follow the trend of the outdoor levels. Within the day, the median indoor-outdoor fine particles correlations were 0.81 (range: 0.01 to 0.99) and 0.20 (range: -0.10 to 0.94) for naturally ventilated and air-conditioned daycares respectively. The daily mean fine particle indoor to outdoor concentrations grouped according to air-conditioning status shows a slightly higher gradient for naturally ventilated daycares (Figure 3). The intercepts indicate a relatively low contribution of indoor sources to fine particles. The median hourly COV within each daycare for indoor fine particles was 13% in air-conditioned centers compared with 20% in naturally ventilated centers, also indicating more variation in the indoor levels over time in the latter compared with the former.

### Table 1. Indoor and outdoor fine particle concentrations and their indoor-outdoor ratios.

| Characteristics | No | Indoor (µg m⁻³) | Outdoor (µg m⁻³) | Indoor-Outdoor Ratio |
|-----------------|----|----------------|------------------|----------------------|
|                 | No | mean SD | mean SD | mean SD |
| Total           | 50 | 69 32 71 34 | 1 0.2 |
| Building Type   |    |          |          |          |
| Public Residential | 20 | 69 29 | 73 29 | 0.9 0.1 |
| Office          | 3  | 45 21 | 69 12 | 0.6* 0.2 |
| Private Residential | 19 | 64 19 | 62 22 | 1.1 0.2 |
| Institutional   | 8  | 87 57 | 90 61 | 1 0.1 |
| Traffic outside building |   |          |          |          |
| Small street    | 24 | 56 23 | 58 23 | 1 0.1 |
| Major road      | 22 | 70 28 | 76 28 | 0.9 0.2 |
| Highway         | 4  | 89* 39 | 92* 44 | 1 0.2 |
| Air-Conditioning | no | 39 31 | 72 32 | 1.0* 0.1 |
|                 | yes| 11 37 | 68 41 | 1 0.3 |
Figure 1. Temporal indoor and outdoor fine particle concentrations in naturally-ventilated daycares.

Figure 2. Temporal indoor and outdoor fine particle concentrations in air-conditioned daycares.
Figure 3. Scatter plot of mean indoor and outdoor fine particle concentrations in naturally ventilated and air-conditioned daycares.

Table 2 provides summary statistics on the daily $F_{inf}$ estimates, penetration factor, air exchange rates and removal rates of fine particles. These parameters are also presented under air-conditioned and naturally ventilated daycares as well for daycares located in different road types. Our daily $F_{inf}$ values are comparable to those measured in homes during summer where window openings are prevalent (0.69 – 0.8) [11,12]. Indeed, significantly different (p<0.05) average $F_{inf}$ values of 0.65 ± 0.19 and 0.46 ± 0.22 were noted for naturally ventilated and air-conditioned daycares respectively. These $F_{inf}$ values suggest that naturally ventilated daycares do not provide optimum protection against exposure to outdoor-generated fine particle exposure. Our observations of higher $F_{inf}$ values in naturally ventilated daycares may be explained by the statistically higher air exchange rates and to a lesser extent penetration factor. The estimated mean deposition rate for fine particles in the daycares is 0.75 h$^{-1}$ (range: 0.13-2.26). This result is within the range of those reported in residences: Ozkaynak et al. [13] estimated a deposition rate of 0.39 h$^{-1}$ for the PTEAM study; Lachenmyer and Hidy [14] reported a deposition rate of 0.6 h$^{-1}$; and Meng et al [9] reported a mean k value of 0.79 h$^{-1}$ in the ROPA study. Indeed, the wide range of values between studies could be related to the surface-to-volume ratio, building type, boundary layer air flows, turbulence, particle size distribution and air conditioning use [7].

Table 2. Infiltration factor estimates, penetration factor, air exchange and deposition rates.

|                  | $F_{inf}$ | $P$     | $A$ (h$^{-1}$) | $k$ (h$^{-1}$) |
|------------------|-----------|---------|----------------|----------------|
|                  | Mean      | SD      | Mean           | SD             | Mean       | SD          |
| Total            | 0.6       | 0.21    | 0.74           | 0.24           | 1.34       | 0.95        | 0.75       | 0.48          |
| Air-Conditioning |           |         |                |                |             |             |
| no               | 0.65*     | 0.19    | 0.78*          | 0.23           | 1.47*      | 1.01        | 0.67       | 0.43          |
| yes              | 0.46      | 0.22    | 0.61           | 0.26           | 0.86       | 0.53        | 1.03*      | 0.55          |
| Traffic outside building | | | | | | | |
| Small street     | 0.65      | 0.2     | 0.7            | 0.24           | 1.47       | 0.94        | 0.72       | 0.47          |
| Major road       | 0.56      | 0.26    | 0.84           | 0.24           | 1.06       | 0.77        | 0.71       | 0.37          |
| Highway          | 0.57      | 0.19    | 0.74           | 0.24           | 1.32       | 1.11        | 0.82       | 0.57          |
4. Conclusion
Singapore is a tropical country that can be affected by outdoor fine particle air pollution. Little information is available on the penetration of outdoor fine particles into daycare environments. Our study attempted to address the following objectives: to measure indoor infiltration factor ($F_{\text{inf}}$) of PM$_{2.5}$ from outdoor fine particles and to determine the building parameters that modifies the indoor PM$_{2.5}$. We collected indoor/outdoor 1-min PM$_{2.5}$ from 50 daycares. We noted high indoor and outdoor concentrations of fine particles due to the presence of regional haze pollution. Indoor and outdoor fine particle concentrations are significantly highest for daycares located near highways while indoor to outdoor ratios were significant difference for air-conditioning use in daycares. Mean $F_{\text{inf}} \pm \text{SD}$ of 0.65±0.19 in daycare rooms which are naturally ventilated and lower $F_{\text{inf}} \pm \text{SD}$ values of 0.46±0.22 for those that are air-conditioned. The penetration coefficients and air exchange rates were higher in naturally ventilated daycares (0.78 vs 0.61 and 1.47 vs 0.86 h$^{-1}$ respectively). Our findings show that children remaining indoor in daycares where air conditioning is used can reduce PM$_{2.5}$ exposures during outdoor pollution episodes.

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