Exposure Assessments for Children in Homes and in Daycare Centers to NO₂, PMs and Black Carbon
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ABSTRACT Indoor air quality was investigated in homes and daycares located in areas with heavy traffic in Seoul, South Korea from November 2013 to January 2014. Indoor and outdoor air quality measurements were collected for 48 hours in four children's homes and daycare centers. The I/O ratio (Indoor to outdoor ratio) for each major air pollutant (NO₂, black carbon, PM₁₀, and PM₂.₅) was calculated, and NO₂ and PM₁₀ concentration profiles were analyzed based on indoor activity diaries recorded during the 48 hours. Most I/O ratios for NO₂, black carbon, PM₁₀, and PM₂.₅ at daycare centers were less than one. At homes, I/O ratios for black carbon, PM₁₀, and PM₂.₅ were less than one; however, most I/O ratios for NO₂ were greater than one due to the usage of gas stoves. The children's exposure to indoor air pollutants was calculated using a time-weighted average exposure method, and the daily intake level for each pollutant was determined.

KEY WORDS Indoor air quality, Air pollutants, Children, I/O ratio, Exposure assessment

1. INTRODUCTION

Air pollutants are known to influence allergic diseases, respiratory illnesses, and cardiovascular diseases (Zanobetti et al., 2011). Traffic related emissions are one of the major outdoor sources of pollutants that affect human health. Thus, it is important to investigate indoor and outdoor air quality in areas with heavy traffic.

Among traffic related air pollutants, NO₂, black carbon, and particulate matter have been frequently studied due to their impacts on human health (Buonanno et al., 2013; Habil et al., 2013; Massey et al., 2013, 2012, 2009; Tian et al., 2012; Pénard-Morand et al., 2010;Lee et al., 2008; Martuzevicius et al., 2008; Hwang et al., 2005; Janssen et al., 2003; Brauer et al., 2002; Fisher et al., 2000; Studnicka et al., 1997; van Vliet et al., 1997). NO₂ is the most effective indicator of proximity to traffic. The exposure to NO₂ has received a lot of attention due to its toxicity in humans. Previous studies demonstrated how indoor and outdoor NO₂ concentrations change and affect personal exposure (Kornartit et al., 2010). In a study conducted by Vanderstraeten et al. (2011), black carbon was a more effective indicator of local traffic than particulate matter, and showed a strong correlation with NO. Janssen et al. (2011) also reported that black carbon is an important indicator of air...
quality with regard to health risks. For particulate matter, previous studies reported that PM$_{10}$ and PM$_{2.5}$ are capable of carrying allergens and polycyclic aromatic hydrocarbons (PAHs), and can penetrate deep lung tissue (Krugly et al., 2014; Liu et al., 2004; Ormstad, 2000). Therefore, particulate matter can cause adverse respiratory effects (Happo et al., 2013). Liu et al. (2004) and Hassanvand et al. (2014) reported that particulates in indoor air primarily originate from outdoor sources, such as heavy traffic and construction activities; thus, particulate concentrations can also be used to elucidate the relationship between outdoor and indoor air quality. Based on previous studies, this study focused on indoor and outdoor levels of NO$_2$, black carbon, PM$_{10}$, and PM$_{2.5}$.

Because children are more susceptible to the adverse health effects of air pollution than adults, studies concerning indoor air quality in daycares and schools have been conducted. Krugly et al. (2014) investigated indoor and outdoor concentrations of PAHs in primary schools during winter, and showed that indoor PAHs originated from outdoor sources. Pegas et al. (2012) reported that outdoor NO$_2$ concentrations were higher than those indoors, while indoor PM$_{10}$ and volatile organic compound (VOC) concentrations were lower than those outdoors on weekdays in both suburban and city center elementary schools in Aveiro, Portugal. Tippayawong et al. (2009) showed that in school classrooms with natural ventilation, the presence of indoor particulates was attributed to penetration of outdoor particles. Habil and Taneja (2011) also reported that particulate matter concentrations inside of classrooms were higher than those outside of classrooms in India. Zuraimi and Tham (2008) investigated the indoor air quality of childcare centers in Singapore, and determined that outdoor concentrations of PM$_{2.5}$, floor type, toy type, presence of curtains, renovation, and cleaning frequency were directly related to indoor PM$_{2.5}$ levels. Demirel et al. (2014) showed that personal, indoor, and outdoor concentrations of NO$_2$ and benzene, toluene, ethylbenzene, and xylene (BTEX) were higher in primary schools located in urban areas with heavier traffic than those in suburban areas with less traffic in Turkey. Janssen et al. (2001) also reported that concentrations of PM$_{2.5}$, NO$_2$, and benzene inside and outside of schools in the Netherlands increased as traffic around the school increased.

A few studies examined indoor air quality in homes and daycare centers simultaneously. Roda et al. (2011) measured endotoxin and NO$_2$ concentrations in child daycare centers and homes in Paris, and found that the concentrations were higher in daycare centers than in homes, while VOC concentrations were higher in homes than in daycare centers. Langer et al. (2010) measured phthalates and PAHs in Danish daycare centers and in homes. They reported that phthalate concentrations were higher in daycare centers, and PAH concentrations were similar in homes and daycare centers. In addition, Wichmann et al. (2010) measured indoor PM$_{2.5}$, soot, and NO$_2$ concentrations in homes, preschools, and schools in Sweden. They found that NO$_2$ concentrations were highest in preschools, while soot and PM$_{2.5}$ concentrations were highest in homes. However, there is still

Table 1. Child, home, and daycare center information.

| Child | Gender | Age (years) | Degree of symptoms | Daycare | | | Home | | |
|-------|--------|-------------|-------------------|---------| | | Type of home | Area (m$^2$) | Cooking type and smoker |
|       |        |             |                   | # of Classroom | Area (m$^2$/child) | | | |
| A     | Female | 3           | Moderate          | 5        | 0.28 | | 2-story residence (1st floor)* | 90 | Gas stove; non-smoking |
| B     | Female | 4           | Severe to moderate| 13       | 0.29 | | High-rise apartment (25th floor)* | 84 | Gas stove; non-smoking |
| C     | Male   | 2           | Moderate to weak  | 6        | 0.15 | | High-rise apartment (18th floor)* | 109 | Gas stove; non-smoking |
| D     | Male   | 2           | Moderate to weak  | 4        | 0.31 | | High-rise apartment (19th floor)* | 115 | Gas stove; non-smoking |

*Parenthesis indicates the actual floor where the child is living.
a dearth of studies measuring indoor air quality of daycare centers and homes simultaneously, and estimating the total exposure levels for children.

This study examined indoor air quality of homes and daycare centers where four children with atopic dermatitis were living and attending. Based on the outdoor and indoor air pollutant concentrations, the relationship between the indoor and outdoor environment at homes and daycares located in traffic-concentrated areas in Seoul were investigated. Lastly, a time-weighted averaging method was used to assess the exposure for each child, and daily intake levels of pollutants were calculated.

2. METHODS

2.1 Subject Information

Four children with atopic dermatitis were screened and tested by dermatologists at the Samsung Medical Center in Seoul, Korea. The children lived in homes and attended daycare centers near main roads with heavy traffic in Seoul. Children were selected based on availability for measuring indoor air quality both in their homes and in the daycare centers they attended. Table 1 displays general information about the children, their homes, and the daycare centers. The severity of atopic dermatitis symptoms was divided into three categories: weak, moderate, and severe. As shown in Table 1, three of the four children lived in high-rise apartments, which are the most common type of accommodation in Seoul. The locations of the homes and daycare centers were marked on a map of Seoul as shown in Fig. S1. The locations of air quality monitoring stations (AQMS) in Seoul are also identified in Fig. S1.

2.2 Measurements of NO2, Black Carbon, and Particulate Matter (PM10 and PM2.5)

Forty-eight-hour measurements were conducted at each home and daycare center from November 12, 2013 to January 23, 2014. The measurement schedule is detailed in Table 2. For each period, the indoor and outdoor measurements were taken simultaneously. At the high-rise apartments, the measurement devices for

| Table 2. Meteorological parameters at each site. |
|-----------------------------------------------|
| Child | Site | Date       | Average temp (°C) | Precipitation (mm) | Relative humidity (%) | Average wind speed (m/s) |
|-------|------|------------|-------------------|--------------------|-----------------------|--------------------------|
| A     | Daycare | Nov. 12–14, 2013 | 3.4               | −                   | 36.1                  | 2.7                       |
|       |        | Nov. 19–21, 2013 | 1.1               | −                   | 5.9                   | 4.4                       |
| B     | Daycare | Nov. 26–28, 2013 | 2.1, 0.0          | 1.5, 1.7           | 60.9, 66.8            | 2.5, 3.4                  |
|       |        | Nov. 3–5, 2013   | 6.7               | −                   | 62.6                  | 1.6                       |
|       |        | Dec. 16–18, 2013 | −3.6, −0.3        | −                   | 52.6, 52.4            | 1.8, 1.5                  |
|       | Home*  | Jan. 6–7, 2014   | 0.8, 3.0          | −                   | 50.4, 56.0            | 1.6, 1.7                  |
| C     | Daycare | Jan. 14–16, 2014 | −4.3, −2.9        | −                   | 33.8, 42.0            | 2.2, 1.7                  |
|       | Home   | Jan. 21–23, 2014 | −5.5, −3.9        | 0.7                | 62.6, 60.0            | 2.4, 1.6                  |

*Due to an undisclosed issue, measurements were collected for 24 hours.
outdoor air quality were located on a front balcony, which was assumed to be the nearest place exposed to outdoor air. At the 2-story residence, they were located in the front yard. Indoor air quality measurement devices were placed in the middle of the living room.

To measure NO$_2$ concentrations, an NO-NO$_2$-NO$_x$ analyzer (Thermo 42i, USA) was used inside, and an NH$_3$ analyzer (Teledyne Technologies 201E, USA) was used outside. The analyzer monitored NO, NO$_2$, and NO$_x$ concentrations in real time with a recording interval of 1 minute. An aethalometer (Magee Scientific AE51, USA) and a dust monitor (Grimm Technologies 1.109, Germany) were used to measure black carbon concentrations and particulate concentrations, respectively. These monitors also reported the real-time concentrations every minute. All measurement systems were placed on a tray at 1 m above the floor.

Meteorological parameters, such as temperature, precipitation, relative humidity, and wind velocity, were obtained from the Korea Meteorological Administration for each day that measurements were taken. They are summarized in Table 2.

### 2.3 Time-weighted Average Exposure

To determine the child’s exposure over two days, we used a time-weighted average micro-environmental exposure method (Eq. (1)) (Kornartit et al., 2010). The child’s home, daycare, and outside of these areas were used as the microenvironments; the time the child spent in each microenvironment was used to calculate the exposure level for two days. We assumed that two consecutive days were sufficient to represent the typical pollutant concentration trends at the home and daycare.

$$E_i = \sum_j C_j t_{ij}$$ (1)

where $E_i =$ time-weighted average exposure for person i over the specified time period; $C_j =$ pollutant concentration in microenvironment j; $t_{ij} =$ time that person i spends in microenvironment j; J = total number of microenvironments.

On weekdays, children were generally at the daycare from 9 am to 5 pm, and spent the rest of the time at home. We assumed that all of the children followed this time schedule, and calculated the NO$_2$, black carbon, and particulate matter concentrations that the children could potentially be exposed to for 48 hours at daycare centers and at homes. The time for outdoor activities, such as commute and play time, was not considered in this study.

### 2.4 Daily Intake

In this study, we calculated each child’s daily intake of NO$_2$, black carbon, PM$_{10}$, and PM$_{2.5}$ using the following equation.

$$DI = \frac{C_{air} \cdot IR \cdot ET}{BW}$$ (2)

where $C_{air} =$ contaminant concentration in air (μg/m$^3$); IR = inhalation rate (m$^3$/h), for a 1-3-year-old child IR = 7.6 m$^3$/h; ET = exposure time (h/d); BW = body weight (kg), for a 1-3-year-old child BW = 19 kg. The inhalation rate and body weight for a 1-3-year-old child were obtained from Guo and Kannan (2011) and Zhang et al. (2014).

### 3. RESULTS AND DISCUSSION

#### 3.1 Relationship between Indoor and Outdoor Air Pollution Levels at Daycare Centers and Homes

As seen in Table 3, most I/O ratios of indoor pollutants in daycare centers were less than one, with the exception of NO$_2$ concentrations in child D’s daycare center. In child D’s daycare center, the indoor concentration of NO$_2$ was higher than the average outdoor NO$_2$ concentration. For the children’s homes shown in Table 4, I/O ratios for black carbon, PM$_{10}$ and PM$_{2.5}$ were less than one, while I/O ratios for NO$_2$ were greater than one, with the exception of child B’s home. This indicates that there was an indoor source of NO$_2$ in the homes. The use of gas stoves and candle burning are potential indoor sources of NO$_2$.

Fig. 1 and Fig. 2 show the indoor and outdoor NO$_2$ concentrations that were measured at daycares and homes, along with the hourly NO$_2$ concentrations reported from urban AQMS. To analyze the relationship between indoor activities and indoor air quality, we consulted the indoor activity diaries recorded by the children’s parents, and denoted the indoor activities carried out during the measurement period in the figures. The indoor peak concentrations of NO$_2$ generally occur when gas stoves are on, and when doors are open...
Asian Journal of Atmospheric Environment, Vol. 12, No. 3, 204-214, 2018

In South Korea, the usage of gas stoves is much more common than that of electric stoves. Combustion from cooking processes is one of the dominant causes of increased NO2 concentrations indoors. Garrett et al. (1998), Smith et al. (2000), and Belanger et al. (2006) reported that NO2 exposure due to the usage of gas stoves was positively associated with respiratory symptoms and asthma.

In Fig. 1(d), based on the indoor activity diaries, the peak concentrations of NO2 at daycare occurred when windows were opened and closed for ventilation. Since the classroom where the indoor measurement systems were located was near a loading zone for trucks, the increase of NO2 concentrations when the windows opened could have been caused by exhaust gases from trucks. Table 3.

Table 3. Pollutant concentrations and I/O ratios at daycare centers.

| Child | NO2 (ppb) | Black carbon (μg/m3) | PM10 (μg/m3) | PM2.5 (μg/m3) |
|-------|-----------|----------------------|---------------|---------------|
|       | Indoor    | Outdoor              | I/O           | Indoor        | Outdoor      | I/O           | Indoor        | Outdoor      | I/O           |
| A     | 36.11 ± 9.20 | 40.38 ± 11.77       | 0.89          | 3.11 ± 1.74   | 4.39 ± 2.65   | 0.71          | 42.12 ± 24.64 | 54.27 ± 20.82 | 0.78          | 24.61 ± 9.13  | 36.24 ± 13.89 | 0.68          |
| B     | 21.11 ± 6.12 | 21.27 ± 7.42       | 0.99          | 0.97 ± 0.33   | 1.97 ± 1.97   | 0.49          | 21.42 ± 20.67 | 1.42 ± 1.42   | 0.49          | 9.64 ± 4.19   | 36.24 ± 13.89 | 0.27          |
| C     | 37.59 ± 5.78 | 44.33 ± 9.20       | 0.85          | 2.74 ± 1.24   | 4.78 ± 2.22   | 0.57          | 33.21 ± 15.90 | 72.05 ± 22.83 | 0.46          | 24.95 ± 8.50  | 64.54 ± 20.85 | 0.39          |
| D     | 54.82 ± 20.88 | 42.02 ± 10.03      | 1.30          | 1.89 ± 0.80   | 3.12 ± 1.80   | 0.61          | 30.93 ± 14.55 | 58.53 ± 31.54 | 0.53          | 25.67 ± 11.00 | 50.50 ± 27.21 | 0.51          |

*Measurements were not available due to equipment malfunction.

Table 4. Pollutant concentrations and I/O ratios at homes.

| Child | NO2 (ppb) | Black carbon (μg/m3) | PM10 (μg/m3) | PM2.5 (μg/m3) |
|-------|-----------|----------------------|---------------|---------------|
|       | Indoor    | Outdoor              | I/O           | Indoor        | Outdoor      | I/O           | Indoor        | Outdoor      | I/O           |
| A     | 23.52 ± 11.11 | 17.92 ± 5.52       | 1.31          | 0.80 ± 0.31   | 1.35 ± 0.75   | 0.59          | 17.35 ± 24.24 | 26.14 ± 5.75   | 0.66          | 9.08 ± 7.68   | 17.82 ± 4.84   | 0.51          |
| B     | 22.51 ± 5.65 | 47.50 ± 7.03       | 0.47          | 2.67 ± 1.12   | 6.24 ± 3.29   | 0.43          | 39.16 ± 8.11  | 77.52 ± 15.63  | 0.51          | 34.62 ± 5.79  | 71.33 ± 15.36  | 0.49          |
| C     | 61.40 ± 21.72 | 52.87 ± 8.25       | 1.16          | 3.83 ± 1.39   | 6.38 ± 2.11   | 0.6           | 44.88 ± 12.60 | 102.95 ± 9.06  | 0.44          | 38.42 ± 8.99  | 86.49 ± 6.22   | 0.44          |
| D     | 73.72 ± 30.98 | 69.05 ± 58.13      | 1.07          | 2.10 ± 1.12   | 3.30 ± 2.01   | 0.64          | 36.17 ± 16.04 | 62.28 ± 21.11  | 0.58          | 32.15 ± 12.98 | 61.20 ± 23.70  | 0.53          |

*Twenty-four-hour measurements taken due to an undisclosed issue.

Fig. 1. Profile of NO2 concentrations over 48 hours at each daycare center. Missing data points are due to equipment malfunction. (1), (2), (3), and (4) represent major indoor activities such as opening/closing the main door for entering or leaving, cooking, as opening/closing the main door for entering or leaving, cooking, and vacuum cleaning, respectively.
trucks. Generally, the loading zones were full of trucks during the morning (approximately 9 am to 12 pm), and the indoor NO$_{2}$ concentrations in the classroom increased more at that time. Outdoor measurement systems were located on the opposite side of the daycare from the loading zone due to limitations of the measurement system installation; thus, our measured outdoor NO$_{2}$ concentrations could not represent the degree of NO$_{2}$ pollution at the loading zone. In this case, even though the I/O ratio was greater than one, we cannot specify that outdoor sources affected the elevated indoor NO$_{2}$ concentrations.

In Fig. 1 and Fig. 2, most trends of outdoor NO$_{2}$ concentrations closely followed that of the AQMS NO$_{2}$ concentrations, with the exception of child D’s home. At child D’s home, outdoor NO$_{2}$ concentrations measured on the balcony were higher than those measured at the nearest AQMS. Possible reasons for this phenomenon may be the traffic characteristics and wind direction near the residence.

To observe the effects of indoor activities on particulate matter concentrations, Fig. 3 and Fig. 4 illustrate the indoor and outdoor PM$_{10}$ concentrations at daycare centers and homes. Concentration data exported from the AQMS are also shown in these figures.
care centers, PM$_{10}$ concentrations were only elevated during the opening hours (approximately 9 am to 7-8 pm). This might have been due to the children’s indoor activities, which could keep the particles suspended in the air. However, at homes, several indoor activities, such as cooking, opening main doors, and cleaning, caused elevated indoor PM$_{10}$ concentrations. Interestingly, unlike the NO$_2$ concentration profile at homes and daycares, the indoor PM$_{10}$ concentrations were lower than the outdoor concentrations and the AQMS data, despite the occurrence of indoor activities.

3.2 Time-weighted Average Exposure for Children with Atopic Dermatitis

As shown in Table 5, time-weighted average exposures of NO$_2$, black carbon, PM$_{10}$, and PM$_{2.5}$ for each child were calculated. The average concentrations at home are displayed from 5 pm to 9 am, while the concentrations at daycares are displayed from 9 am to 5 pm. Note that at child C’s home, air pollutant concentrations were measured for only 24 hours, and the data was used twice to calculate the time-weighted average exposures for 48 hours; therefore, the total calculated exposure concentrations may be overestimated or underestimated. Child D had the highest estimated NO$_2$ exposure among all of the children, followed by child C, child A, and child B. Child C had the highest estimated black carbon exposure, followed by child B, child A, and child D. Child C also had the highest estimated PM$_{10}$ exposure, followed child B, child D, and child A. Child B had the highest estimated exposure to PM$_{2.5}$, followed by child C, child D, and child A.

Based on the estimated exposure levels in Table 5, we calculated each child’s daily intake of NO$_2$, black carbon, PM$_{10}$, and PM$_{2.5}$ and summarized in Table 6 (Demirel et al., 2014; Krol et al., 2014; Zhang et al., 2014). Based on the exposure assessments, the severity of atopic dermatitis symptoms in the four children (Table 1) was not proportional to the estimated exposure levels. This may be because there are many other factors that determine the severity of atopic dermatitis. Such factors may include age, sex, and parental history. In addition, there were limitations in this exposure study. First, the pollutant con-

![Fig. 4. Profile of PM$_{10}$ concentrations over 48 hours at each child’s home. Blue solid line indicates indoor PM$_{10}$ concentrations and red dotted line indicates outdoor PM$_{10}$ concentrations. Green line with circles indicates PM$_{10}$ concentrations reported from regional AQMS. Missing data points are due to equipment malfunction. (1), (2), (3), and (4) represent major indoor activities such as cooking (gas stove), opening/closing the main door, incense burning, and vacuum cleaning, respectively.]

| Table 5. Time-weighted average exposure for each child. |
|-----------------------------------------------|
| **Child** | **NO$_2$ (ppb)** | **Black carbon (μg/m$^3$)** | **PM$_{10}$ (μg/m$^3$)** | **PM$_{2.5}$ (μg/m$^3$)** |
| | **Home** | **Daycare** | **Total** | **Home** | **Daycare** | **Total** | **Home** | **Daycare** | **Total** |
| A | 23.31 | 43.14 | 29.92 | 0.73 | 4.15 | 1.87 | 18.77 | 70.07 | 35.87 | 9.35 | 31.55 | 16.75 |
| B | 24.15 | 28.23 | 25.51 | 3.04 | 1.06 | 2.38 | 39.3 | 44.01 | 40.87 | 34.55 | 28.07 | 32.39 |
| C* | 54.21 | 35.79 | 48.07 | 3.21 | 2.55 | 2.99 | 40.96 | 42.1 | 41.34 | 35.38 | 23.41 | 31.39 |
| D | 66.99 | 68.88 | 67.62 | 1.46 | 2.54 | 1.82 | 37.04 | 40.34 | 38.14 | 32.2 | 28.03 | 30.81 |

*For C’s home, measurements were collected for 24 hours due to an undisclosed issue.*
4. DISCUSSION

In this study, indoor and outdoor levels of NO$_2$, PMs and black carbon were measured at four children’s homes and daycare centers. Based on the measurement data, we calculated time-weighted average exposures and daily intakes of air pollutants for four children. In addition, we calculated the I/O ratio for each air pollutant and analyzed NO$_2$ and PM$_{10}$ concentration profiles based on indoor activity diaries. According to the result, the I/O ratios of NO$_2$, PM$_{2.5}$, PM$_{10}$ and black carbon were typically less than one. This result indicates that those indoor air pollutants were originated from outdoor sources, and thus it is better to keep doors and windows closed for indoor air quality. However, the I/O ratios of NO$_2$ at children’s homes were typically more than one due to indoor sources such as gas stoves. To reduce the indoor NO$_2$ levels, it is better to use electric stoves instead of gas stoves. In addition, a proper ventilation is necessary during cooking and vacuum cleaning.

This study has a few limitations. First, this study only aimed to measure indoor and outdoor air concentrations for the atopic dermatitis patients. Thus, it is not possible to compare the environments for children with and without atopic dermatitis. In addition, the measurements were conducted during fall and winter. Therefore, it is not possible to examine the seasonal variations in the air pollutant concentrations. Lastly, this study only measured homes and daycare centers of four children. The exposure characteristics for those children may not represent the exposure for children in Seoul.

5. CONCLUSIONS

In this paper, indoor air qualities of homes and daycare centers were measured, and the exposure assessment of children with atopic dermatitis was studied. The major findings of this work can be summarized as follows:

- At daycare centers and homes located in traffic-concentrated areas, I/O ratios for black carbon, PM$_{10}$, and PM$_{2.5}$ were all less than one. However, I/O ratios for NO$_2$ at homes were mostly greater than one due to the usage of gas stoves for cooking.
- According to the real-time air quality measurements conducted at homes and daycare centers, indoor activities such as cooking and door opening contribute to the indoor pollutant concentrations.
- Children’s exposures were estimated using the time-weighted average exposure method, and the daily intake of pollutants was calculated. We found that the exposure amount was not proportional to the severity of atopic dermatitis symptoms. This may be due to other confounding factors such as age, sex, and parental history.

In this study, an exposure assessment was conducted by measuring the indoor air quality in microenvironments (homes and daycare centers), and applying the time-weighted average exposure method. This process can help to accurately estimate the pollutant exposure of children, and to further analyze the association between exposure and diseases in children.

ACKNOWLEDGEMENT

This project was supported by the Korean Ministry of Environment’s Environmental Health Action Program (Project NO. 2013001360004).

REFERENCES

Belanger, K., Gent, J.F., Triche, E.W., Bracken, M.B., Leaderer, B.P. (2006) Association of indoor nitrogen dioxide exposure with respiratory symptoms in children with asthma.

| Pollutant (μg/(kg·d)) | Child A | Child B | Child C | Child D |
|-----------------------|--------|--------|--------|--------|
| NO$_2$                | 548.6  | 467.8  | 881.4  | 1239.9 |
| Black carbon          | 18.0   | 22.8   | 28.7   | 17.5   |
| PM$_{10}$             | 344.4  | 392.4  | 396.9  | 366.1  |
| PM$_{2.5}$            | 160.8  | 310.9  | 301.3  | 295.8  |
American Journal of Respiratory and Critical Care Medicine 173, 297-303.

Brauer, M., Hoek, G., Van Vliet, P., Mielke, K., Fischer, P.H., Wijga, A., Koopman, L.P., Neijens, H.J., Gerritsen, J., Kerkhof, M., Heinrich, J., Bellander, T., Brunekreef, B. (2002) Air pollution from traffic and the development of respiratory infections and asthma and allergic symptoms in children. American Journal of Respiratory and Critical Care Medicine 166, 1092-1098.

Buonanno, G., Stabile, L., Morawska, L., Russi, A. (2013) Child exposure assessment to ultrafine particles and black carbon: the role of transport and cooking activities. Atmospheric Environment 79, 53-58.

Demirel, G., Özden, Ö., Dögeroğlu, T., Gaga, E.O. (2014) Personal exposure of primary school children to BTEx, NO2, and ozone in Eskisehir, Turkey: relationship with indoor/outdoor concentrations and risk assessment. Science of the Total Environment 473-474, 537-548.

Fisher, P.H., Hoek, G., Van Reeuwijk, H., Briggs, D.J., Lebret, E., van Wijnen, J.H., Kingham, S., Elliott, P.E. (2000) Traffic-related differences in outdoor and indoor concentrations of particles and volatile organic compounds in Amsterdam. Atmospheric Environment 34, 3713-3722.

Garrett, M.H., Hooper, M.A., Hooper, B.M., Abramson, M.J. (1998) Respiratory symptoms in children and indoor exposure to nitrogen dioxide and gas stoves. American Journal of Respiratory and Critical Care Medicine 158, 891-895.

Guo, Y., Kannan, K. (2011) Comparative assessment of human exposure to phthalate esters from house dust in China and the United States. Environmental Science and Technology 45, 3788-3794.

Habil, M., Taneja, A. (2011) Children’s Exposure to Indoor Particulate Matter in Naturally Ventilated Schools in India. Indoor and Built Environment 20, 430-448.

Habil, M., Massey, D., Taneja, A. (2013) Exposure of children studying in schools of India to PM levels and metal contamination: sources and their identification. Air Quality, Atmosphere and Health 6, 575-587.

Happo, M., Markkanen, A., Markkanen, P., Jalava, P., Kuuspalo, K., Leskenen, A., Sippula, O., Lehtinen, K., Jokiniemi, J., Hirvonen, M.R. (2013) Seasonal variation in the toxicological properties of size-segregated indoor and outdoor air particulate matter. Toxicology in Vitro 27, 1500-1501.

Hassanvand, M.S., Naddaf, K., Faridi, S., Arhami, M., Nabizadeh, R., Sowlat, M.H., Pourpak, Z., Rastkari, N., Momeniha, F., Kashani, H., Gholampour, A., Nazmara, S., Allihammadim, M., Goudarzi, G., Yunesian, M. (2014) Indoor/outdoor relationships of PM10, PM2.5, and PM1 mass concentrations and their water-soluble ions in a retirement home and a school dormitory. Atmospheric Environment 82, 375-382.

Hwang, B.F., Lee, Y.L., Jaakkola, J.K.J., Guo, Y.L. (2005) Traffic related air pollution as a determinant of asthma among Taiwanese school children. Thorax 60, 467-473.

Janssen, N.A.H., van Vliet, P.H.N., Aarts, F., Harssema, H., Brunekreef, B. (2001) Assessment of exposure to traffic related air pollution of children attending schools near motorways. Atmospheric Environment 35, 3875-3884.

Janssen, N.A.H., Brunekreef, B., van Vliet, P., Aarts, F., Meliefste, K., Harssema, H., Fischer, P. (2003) The relationship between air pollution from heavy traffic and allergic sensitization, bronchial hyperresponsiveness, and respiratory symptoms in Dutch schoolchildren. Environmental Health Perspectives 111, 1512-1518.

Janssen, N.A.H., Hoek, G., Simic-Lawson, M., Fischer, P., van Bree, L., ten Brink, H., Keuken, M., Atkinson, R.W., Anderson, H.R., Brunekreef, B., Cassee, F.R. (2011) Black carbon as an additional indicator of the adverse health effects of airborne particles compared with PM10 and PM2.5. Environmental Health Perspectives 119, 1691-1699.

Kornaritis, C., Sokhi, R.S., Burton, M.A., Ravindra, K. (2010) Activity pattern and personal exposure to nitrogen dioxide in indoor and outdoor microenvironments. Environment International 36, 36-45.

Krugly, E., Martuzevicius, D., Sidaravicute, R., Ciuzas, D., Prasauskas, T., Kauneliene, V., Stasiulaitiene, I., Kliucininkas, L. (2014) Characterization of particulate and vapor phase polycyclic aromatic hydrocarbons in indoor and outdoor air of primary schools. Atmospheric Environment 82, 298-306.

Langer, S., Weschler, C.J., Fischer, A., Bekö, G., Toftum, J., Clausen, G. (2010) Phthalate and PAH concentrations in dust collected from Danish homes and daycare centers. Atmospheric Environment 44, 2294-2301.

Lee, Y.L., Su, H.J., Sheu, H.M., Yu, H.S., Guo, Y.L. (2008) Traffic-related air pollution, climate, and prevalence of eczema in Taiwanese school children. Journal of Investigative Dermatology 128, 2412-2420.

Liu, Y., Chen, R., Shen, X., Mao, X. (2004) Wintertime indoor air levels of PM10, PM2.5, and PM1 at public places and their contributions to TSP. Environment International 30, 189-197.

Martuzevicius, D., Grinshpun, S.A., Lee, T., Hu, S., Biswas, P., Reponen, T., LeMasters, G. (2008) Traffic-related PM2.5 aerosol in residential houses located near major highways: Indoor versus outdoor concentrations. Atmospheric Environment 42, 6575-6585.

Massey, D., Masih, J., Kulshrestha, A., Habil, M., Taneja, A. (2009) Indoor/outdoor relationship of fine particles less than 2.5 μm (PM2.5) in residential homes locations in central Indian region. Building and Environment 44, 2037-2045.

Massey, D., Kulshrestha, A., Masih, J., Taneja, A. (2012) Seasonal trends of PM10, PM2.5 and PM1 in indoor and outdoor environments of residential homes located in North-Central India. Building and Environment 47, 223-231.

Massey, D., Kulshrestha, A., Taneja, A. (2013) Particulate matter concentrations and their related metal toxicity in rural residential environment of semi-arid region of India. Atmospheric Environment 67, 278-286.

Ormsund, H. (2000) Suspended particulate matter in indoor air: adjuvants and allergen carriers. Toxicology 152, 53-68.

Pegas, P.N., Nunes, T., Alves, C.A., Silva, J.R., Vieira, S.L.A., Caseiro, A., Pio, C.A. (2012) Indoor and outdoor characterization of organic and inorganic compounds in city centre and suburban elementary schools of Aveiro, Portugal.
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Atmospheric Environment 55, 80-89.
Pénard-Morand, C., Raherison, D., Charpin, D., Kopfer-schmitt, C., Lavaud, F., Caillaud, D., Annesi-Maesano, I. (2010) Long-term exposure to close-proximity air pollution and asthma and allergies in urban children. European Respiratory Journal 36, 33-40.

Roda, C., Barral, S., Ravelomanantsoa, H., Dusséaux, M., Tribout, M., Moullec, Y.L., Momas, I. (2011) Assessment of indoor environment in Paris child day care centers. Environmental Research 111, 1010-1017.

Smith, B.J., Nitschke, M., Pilotto, L.S., Ruffin, R.E., Pisaniello, D.L., Wilson, K.J. (2000) Health effects of daily indoor nitrogen dioxide exposure in people with asthma. European Respiratory Journal 16, 879-885.

Studnicka, M., Hackl, E., Pischinger, J., Fangmeyer, C., Haschke, N., Kühr, J., Urbanek, R., Neumann, M., Frischer, T. (1997) Traffic-related NO₂ and the prevalence of asthma. European Respiratory Journal 10, 2275-2278.

Tian, L., Zhang, W., Lin, Z.Q., Zhang, H.S., Xi, Z.G., Chen, J.H., Wang, W. (2012) Impact of traffic emissions on local air quality and the potential toxicity of traffic-related particulates in Beijing, China. Biomedical and Environmental Sciences 25(6), 663-671.

Tippayawong, N., Khuntong, P., Nitatwichit, C., Khunatorn, Y., Tantakitti, C. (2009) Indoor/outdoor relationships of size-resolved particle concentrations in naturally ventilated school environments. Building and Environment 44, 188-197.

Vanderstraeten, P., Forton, M., Brasseur, O., Offer, Z.Y. (2011) Black carbon instead of particle mass concentration as an indicator for the traffic related particles in the Brussels Capital Region. Journal of Environmental Protection 2, 525-532.

van Vliet, P., Knape, M., de Hartog, J., Janssen, N., Harssema, H., Brunekeerf, B. (1997) Motor vehicle exhaust and chronic respiratory symptoms in children living near freeways. Environmental Research 74, 122-132.

Wichmann, J., Lind, T., Nilsson, M.A.M., Bellander, T. (2010) PM$_{2.5}$, soot and NO$_2$ indoor-outdoor relationships at homes, pre-schools and schools in Stockholm, Sweden. Atmospheric Environment 44, 4536-4544.

Zanobetti, A., Baccarelli, B., Schwartz, J. (2011) Gene-air pollution interaction and cardiovascular disease: a review. Progress in Cardiovascular Diseases 53, 344-352.

Zhang, L., Wang, F., Ji, Y., Jiao, J., Zou, D., Liu, L., Shan, C., Bai, Z., Sun, Z. (2014) Phthalate esters (PAEs) in indoor PM$_{10}$/PM$_{2.5}$ and human exposure to PAEs via inhalation of indoor air in Tianjin, China. Atmospheric Environment 85, 139-146.

Zuraimi, M.S., Tham, K.W. (2008) Indoor air quality and its determinants in tropical child care centers. Atmospheric Environment 42, 2225-2239.
**Fig. S1.** The locations of target homes, daycare centers and AQMSs respectively marked using circles, triangles and squares. (a) A map of Seoul is shown along with the four boxes each of which indicates the area where each child is living. (b)-(e) Enlarged maps of the boxed area shown in (a), where Child A-D are living, respectively (scale of map - 1:11399). Gangnam-go, Seocho-gu, Songpa-gu, and Youngdeungpo-gu are the name of the borough the child A-D are living, respectively. Red lines indicate the nearby major roads and railroad.