보건학석사 학위논문

Correlation between Personal Exposure and Ambient Concentration of PM_{10} and $PM_{2.5}$ with Control of Time-activity Pattern

시간활동패턴의 영향을 통제한 PM_{10} 과 $PM_{2.5}$ 의 개인노출과 대기농도의 연관성

2017 년 8 월

서울대학교 보건대학원

환경보건학과 환경보건학 전공

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지도 교수 이 기 영

이 논문을 보건학석사 학위논문으로 제출함

2017 년 5 월

서울대학교 보건대학원

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2017 년 6 월

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ABSTRACT

Correlation between personal exposure and ambient concentration of PM_{10} and $PM_{2.5}$ with control of time-activity pattern

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Introduction: Ambient particulate matter (PM) concentration at ambient air monitoring station was often used as an indicator of population exposure to PM in epidemiological studies. The correlation between personal exposure and ambient concentration of PM varies because of diverse time-activity patterns. The aim of this study was to determine the correlation between personal exposure and ambient concentration of PM_{10} and $PM_{2.5}$ with attempts to control impact of time-activity pattern on personal exposure. Personal PM_{10} and $PM_{2.5}$ exposures with a fixed time-activity pattern were measured on several times.

Methods: Performance of personal environmental monitor (MicroPEM, Model 3.2A, RTI incorporated, USA) was evaluated by co-location of ambient air monitors for PM_{10} and $PM_{2.5}$ for 3 days, 12 hours per a day. A field technician carried out personal exposure measurements of PM_{10} and $PM_{2.5}$ for 24 hours with a fixed time-activity pattern over 26 days in Seoul, Korea. The time-activity pattern was simulated to a fixed scenario including five microenvironments (office, home, bus, cafeteria, and walking). Ambient PM concentrations were obtained from the closest air monitoring station.

Results: The relationship between MicroPEM and central-site monitor had a good linearity. The mean personal and ambient PM_{10} concentrations were 37.9 ± 31.9 μg/m^3 and 72.5 ± 37.9 μg/m^3, respectively. The mean personal and ambient $PM_{2.5}$ concentrations were 28.5 ± 24.1 μg/m^3 and 36.1 ± 30.2 μg/m^3, respectively. The correlation between personal exposure and ambient concentration for $PM_{2.5}$ (R^2=0.81) was significantly higher than for PM_{10} (R^2=0.44). The personal to ambient ratio of $PM_{2.5}$ was approximately 1, while the ratio of PM_{10} was approximately 0.5. The office to ambient ratio of $PM_{2.5}$ and PM_{10} were approximately 1 and 0.5, respectively. The finding implied a high infiltration rate of $PM_{2.5}$ and low infiltration of PM_{10}. The relationship between personal exposure and ambient concentration of PM_{10} and $PM_{2.5}$ was different by characteristics of high level episodes. In the Asian dust episode, the personal to ambient ratio of PM_{10} was 0.2. However, the personal to ambient ratio of $PM_{2.5}$ approximated 1 during the fine dust advisory episode.

Conclusions: Personal exposure and ambient concentrations of $PM_{2.5}$ were highly correlated with fixed time-activity pattern compared with PM_{10}. The personal to ambient ratio of PM_{10} was much lower than the ratio of $PM_{2.5}$. With regards to the Asian dust episode, staying indoors might reduce personal exposure to PM_{10}. However, personal exposure to $PM_{2.5}$ could not be reduced by staying indoors during the high level episode. It is necessary to manage high ambient $PM_{2.5}$ concentrations to prevent excessive personal exposure to fine particles.

Keywords: Ambient, Correlation, Microenvironment, $PM_{2.5}$, PM_{10}, Personal exposure

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Ⅰ. Introduction

Exposure to particulate matter (PM) has been associated with increased mortality in numerous epidemiologic studies (Dockery et al., 1993; Schwartz and Dockery, 1992; Wallace, 2000). Analysis of 15,000 deaths from 1974 to 1984 found that an increase in daily TSP concentrations from 36 $\mu g/m^3$ to 209 $\mu g/m^3$ was associated with 6 % increase in daily mortality (Schwartz and Dockery, 1992). A cohort study of 8,000 adults in six cities demonstrated that an increase in the annual average $PM_{2.5}$ concentration from 10 to 30 $\mu g/m^3$ was associated with an increase in total mortality by 26 % and lung and heart disease mortality by 37 % (Dockery et al., 1993).

Exposure to PM was associated with morbidity. A cohort study of 295,000 individuals in 50 cities demonstrated that an increase in the annual average $PM_{2.5}$ concentration by 24.5 $\mu g/m^3$ was associated with a 31 % increase in lung and heart diseases (Pope III et al., 1995). Another cohort study assessed the relationship between ambient PM_{10} concentration and morbidity among 3.8 million babies, and determined that there was a 40% increase in respiratory disease when ambient air PM_{10} concentrations was higher than 45.5 $\mu g/m^3$ (Woodruff et al., 1997).

Most epidemiological studies assessing PM exposure were based on ambient air pollution using urban air quality monitoring networks. Better understanding of the relationship could provide accurate association between ambient PM concentrations and health effects. However, regional air quality monitoring data may not represent personal exposure of individuals living near the monitoring station. The correlation between personal exposure and ambient concentration of PM can be affected by various factors. Therefore, it is necessary to assess the validity of ambient concentration as a surrogate for personal exposure.

Several large population-based studies had been conducted to assess the relationship between personal exposure and ambient concentration of PM in large population-based studies. These studies included Particle Total Exposure Assessment Methodology (PTEAM), Air Pollution Exposure Distributions of Adult Urban Populations in Europe (EXPOLIS), and the Relationships of Indoor, Outdoor and Personal Air (RIOPA) study.

PTEAM was the first large population-based PM exposure study (Thomas et al., 1993). PTEAM collected PM_{10} and $PM_{2.5}$ stationary monitoring data both in and outside homes of 178 people in Riverside, California during autumn 1990. Each subject wore a personal exposure monitor (PEM) for PM_{10} over two consecutive 12 hour periods of daytime (7 AM - 7 PM) and nighttime (7 PM - 7 AM). Correlation of personal exposure data and fixed site PM_{10} concentration was lower during the daytime compared with nighttime. The observation suggested that personal activities were more important determinants of personal exposure. Subjects might participate in more activities during the daytime and thus are exposed to a greater proportion of PM. At nighttime, they spend most of their time sleeping and generating a relatively small amount of PM.

EXPOLIS was conducted from summer of 1996 to winter of 1997-98 in six European cities assessing 500 adults from Athens, Basel, Grenoble, Helsinki, Milan and Prague (Kruize et al., 2003). The personal and microenvironmental exposure to $PM_{2.5}$ was measured by PEM over 48 hours. The relationship between ambient and personal exposure could only be determined for Helsinki. Workday PEM filter (work and commuting) were measured for 2 sessions of between 8–10 h, and the leisure time filter measured the remaining time. The correlation of personal $PM_{2.5}$ exposures with fixed site ambient concentrations ranged from 0.15 (personal workday) to 0.48 (personal leisure time). Low activity levels (leisure time exposures) resulted in a relatively higher $PM_{2.5}$ correlation than high activity levels (workday exposure).

RIOPA was conducted from summer 1999 to spring 2001 in three areas of the US (Elizabeth NJ, Houston TX, and Los Angeles CA) in 100, 105, and 105 homes, respectively (RIOPA research report, version posted 2007). Integrated indoor, outdoor, and personal air samples were collected with 48 hour resolution for $PM_{2.5}$. Each personal sample was collected using a PEM. The coefficients of determination (R^2) between ambient and personal $PM_{2.5}$ concentration ranged from 0.01 to 0.19 (Elizabeth NJ and Houston TX) and from 0.21 to 0.44 (Los Angeles CA). There was a wide range in the correlation between personal exposure and ambient concentration of PM depending on the region. Each of the three cities in distinct locations had different geography, climates and housing characteristics, which affected distribution of air change rate (AER), room volume, house age and other variable.

The correlation between personal exposure and ambient concentration of PM was different according to study subjects. In cross-sectional or short-term studies, study subjects included adults (Broich et al., 2012; Janssen et al., 1999; Kousa et al., 2002; Lioy et al., 1990; Monn et al., 1997; Oglesby et al., 2000; Thomas et al., 1993), children (Crist et al., 2008; Janssen et al., 1997; Janssen et al., 1998; Michikawa et al., 2014; Wallace et al., 2011), the elderly (Allen et al., 2003; Janssen et al., 2000), and even patients (Bahadori et al., 1999; Janssen et al., 2005; Rojas-Bracho et al., 2004; Wallace et al., 2011). Several studies on personal exposure were measured by field technicians (Chang et al., 2000; Gulliver and Briggs, 2004; Urso et al., 2015). Correlation R values ranged from from -0.41 to 0.92 for adult, 0.04 to 0.94 for children, from -0.12 to 0.97 for the elderly, from 0.64 to 0.96 for patients, and from 0.62 to 0.86 for the field technician. Correlation R values had a wide range because these subjects have different time-activity patterns including various microenvironment with different PM sources and time spent in these locations. Various time-activity patterns could contribute to interpersonal or intrapersonal variation in personal exposure to PM.

The correlation between ambient and personal exposure levels was different by particle size. Several studies have simultaneously incorporated the relationship between ambient and personal exposure by particle size for PM_{10} and $PM_{2.5}$ (Broich et al., 2012; Michikawa et al., 2014; Rojas-Bracho et al., 2004). They have shown that the correlation between personal exposure and ambient concentration of $PM_{2.5}$ is higher than for PM_{10}. This is because PM has different physic-chemical characteristics and origin depending on particle size. Although there is a trend in correlation coefficients, it is hard to determine whether there is a clear relationship due to scattered correlation in different subjects and regions.

Recent studies had used continuous monitors to investigate the correlation between personal exposure and ambient PM concentration (Broich et al., 2012; Gulliver and Briggs, 2004; Wallace et al., 2011). Previous correlation studies mostly used gravimetric monitors such as PEM. These monitors have low time resolution capabilities and can only provide daily average PM exposure in one site. A continuous monitor can provide high time resolution and useful information for real-time distribution of PM concentration, location, and time spent in various activities in more detail. Using continuous monitor can determine a more accurate correlation between personal exposure and ambient concentration of PM.

Purpose of this study

The correlation between personal exposure and ambient concentration can be influenced by time-activity pattern. When personal exposure with fixed time-activity pattern is measured, the correlation between personal exposure and ambient concentration of PM can be determined independent of time-activity pattern. The aim of this study was to determine the correlation between personal exposure and ambient concentration of PM_{10} and $PM_{2.5}$ mitigating for impact of various time-activity patterns on personal exposure. A field technician followed a fixed time-activity pattern while measuring personal exposure to PM. The personal exposure measurement with a fixed time-activity pattern was repeated by one technician. Simultaneous measurements of PM_{10} and $PM_{2.5}$ ascertained correlation by particle size.

Ⅱ. Materials and Methods

2.1. Personal exposure to PM measurements

Personal exposures over 24 hours were measured in Seoul between March 10 and June 18, 2014. The number of total sampling days was 26 days. A field technician carried out 24 hour measurement of personal exposure to PM_{10} and $PM_{2.5}$ following a fixed time-activity pattern. The fixed-activity pattern, shown in Table 1, was modified from average time-activity pattern of the office worker population in Seoul, Korea (NIER, 2010).

Microenvironments in this study were classified into five different groups such as time in the office, home, bus, cafeteria, and walking. Time spent in the office, home, bus, cafeteria and walking were 11 h 48 min, 8 h 56 min, 2 h, 40 min and 28 min, respectively.

Table 1. Fixed time-activity patterns for personal exposure to particulate matter.

Start time	End time	Total time	Microenvironment
0:00	7:30	7:30	Home
7:30	7:32	0:02	Transport (Walk)
7:32	8:32	1:00	Transport (Bus)
8:32	8:34	0:02	Transport (Walk)
8:34	12:00	3:26	Office
12:00	12:07	0:07	Transport (Walk)
12:07	12:27	0:20	Cafeteria
12:27	12:34	0:07	Transport (Walk)
12:34	18:00	5:26	Office
18:00	18:07	0:07	Transport (Walk)
18:07	18:27	0:20	Cafeteria
18:27	18:34	0:07	Transport (Walk)
18:34	21:30	2:56	Office
21:30	21:32	0:02	Transport (Walk)
21:32	22:32	1:00	Transport (Bus)
22:32	22:34	0:02	Transport (Walk)
22:34	0:00	1:26	Home

Personal exposures to PM_{10} and $PM_{2.5}$ were measured at the near breathing zone using two v3.2 MicroPEM monitors with different inlet (PM_{10} and $PM_{2.5}$) (Figure 1). This instrument is the real-time monitor that operates a class 1 (<5 mW) 780 nm infrared laser nephelometer operating technique. The MicroPEM has continuous operating time of 40 hours on 3 AA batteries. Prior to the experiments, the inlets were zero-calibrated with a HEPA (High-Efficiency Particulate Air) filter and cleaned once a day. The air flow rate was set to 0.5 L/min using a flowmeter (TSI 4100 series, TSI Inc., MN, USA). The MicroPEM also allows gravimetric measurement of personal exposure. Preweighed 3.0 μm polytetrafluoroethylene (PTFE) 25 mm TEFLO filters (Zefon International, Ocala, FL) was placed in MicroPEM filter cassette during sampling. Due to the low flow rate, particulate mass on the filter was collected for 2 days. Measurement data are downloaded via a USB connection using MicroPEM Docking Station software (RTI International, Research Triangle Park, NC). Table 2 explains the v3.2 MicroPEM validation criteria.

Figure 1. Personal environment monitor (MicroPEM v3.2A, RTI incorporated, USA)

Table 2. Specification of the MicroPEM v.3.2

	Specification
Principle	Light-scattering (continuous nephelometer)
Weight	240 g
Noise level	3 dB over ambient at a distance of 1 m
Measurement target	PM_{10}, $PM_{2.5}$
Minimum size response	Response down to 90 nm
Inlet D50 cut point	<10% for PM_{10}, $PM_{2.5}$
Operating time	>40 hours using 3 alkaline AA batteries
Operating range	3 - 15000 $\mu g/m^3$
Operating resolution	3 $\mu g/m^3$
Flow rate	0.5 L/min
Precision	<10% variability
Accuracy	<15% for any given unit using default settings

2.2. Co-location of the personal environmental monitor and ambient air monitor

The personal environmental monitor (MicroPEM) for PM_{10} and $PM_{2.5}$ were co-located for evaluation with monitor at the ambient air monitoring site. PM concentration from the MicroPEM was co-located with ambient air monitor for 3 days, 12 hours per a day. Ambient PM concentrations (an hourly average) over the same time period were obtained from the air monitoring station. Air quality data was provided by the South Air Korea Environment Corporation and the Seoul Clean Air Pollution Information (AirKorea, 2014). Ambient PM concentrations in air monitoring station were measured by a beta attenuation monitor.

2.3. Data analysis

All PM concentrations were summarized to 1 hour average prior to analysis. Statistical analysis was conducted using the Statistical Package for the Social Sciences (IBM SPSS Statistics for Windows version 22.0; IBM Corp., Armonk, NY, USA). Graphs were drawn in SigmaPlot 10.0 (Systat Software Inc., Chicago, IL, USA). A *p*-value less than 0.05 was considered statistically significant.

During entire sampling periods, comparisons of average PM concentration between personal exposure and ambient concentration were conducted by Student's *t*-test. Simple linear regression analysis was conducted to identify the PM concentration of personal exposure from ambient PM concentration. The independent variable was ambient PM concentration and the dependent variable was the PM concentration of personal exposure. Spearman correlation was used to assess the relationship between ambient level and personal exposure. The relationship was confirmed using the non-parametric tests. The average PM concentrations were compared between episodes (general, fine dust advisory, and Asian dust) using analysis of variance (ANOVA) and Tukey's test in *post-hoc* comparison.

Ⅲ. Results

3.1. Evaluation of the personal environmental monitor by colocation with ambient air monitor

The personal environmental monitor (MicroPEM) for PM_{10} and $PM_{2.5}$ were evaluated by co-location with monitor at the ambient air monitoring site (Figures 2 and 3, respectively). The results showed a strong linear relationship. The intercept was not included in the linear regression analysis. The coefficients of determination (R^2) were 0.893 for PM_{10} and 0.930 for $PM_{2.5}$. Linear regression slopes were 0.813 for PM_{10} and 0.772 for $PM_{2.5}$.

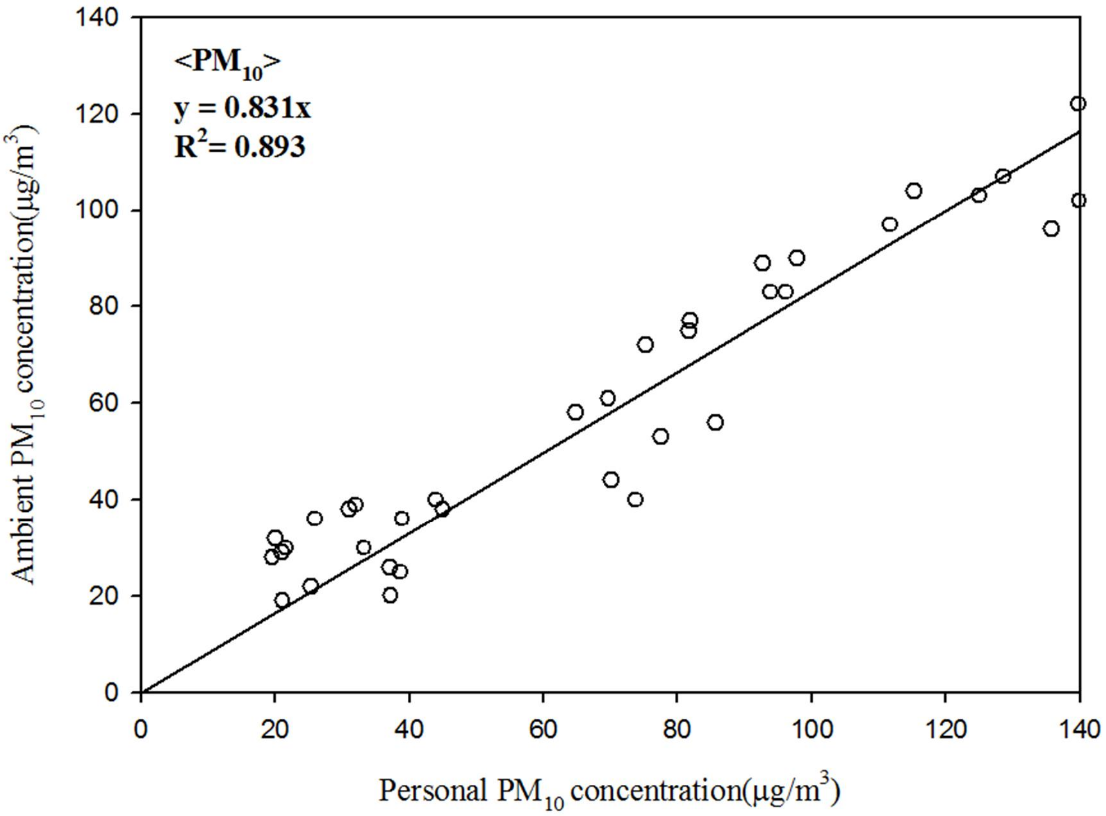


Figure 2. Correlation between ambient air monitor and MicroPEM for PM_{10} measurements

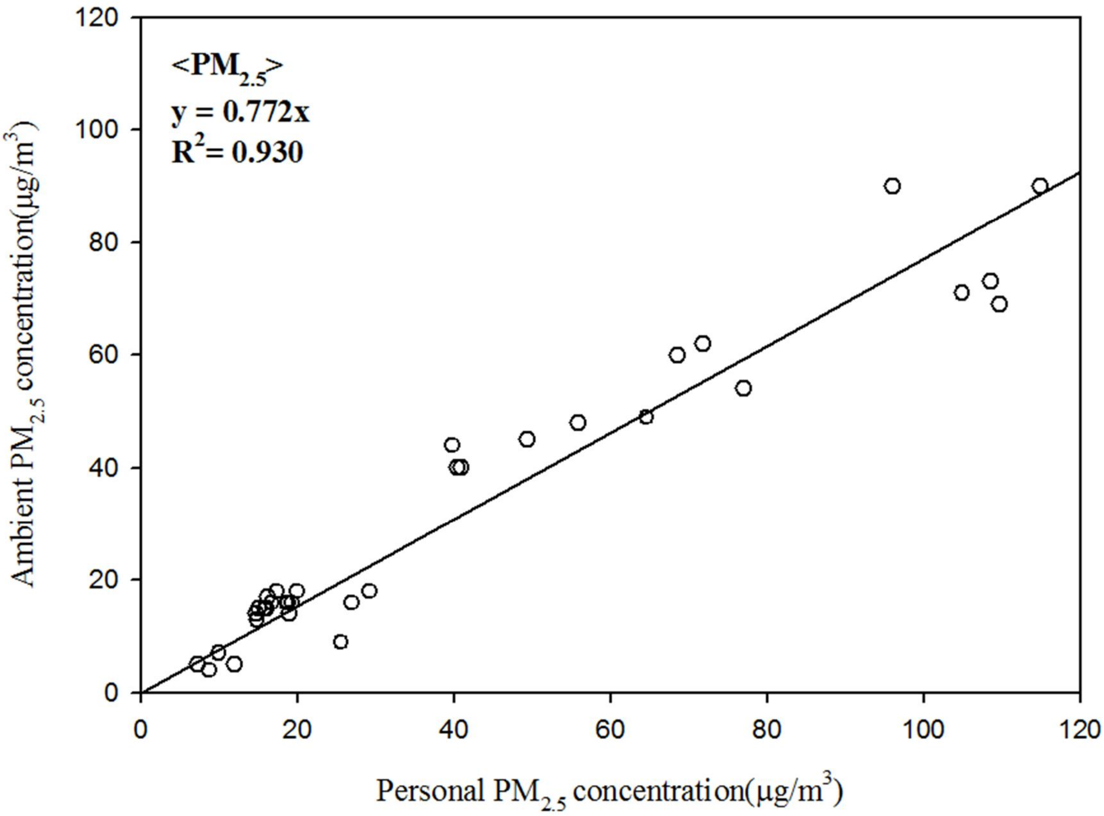
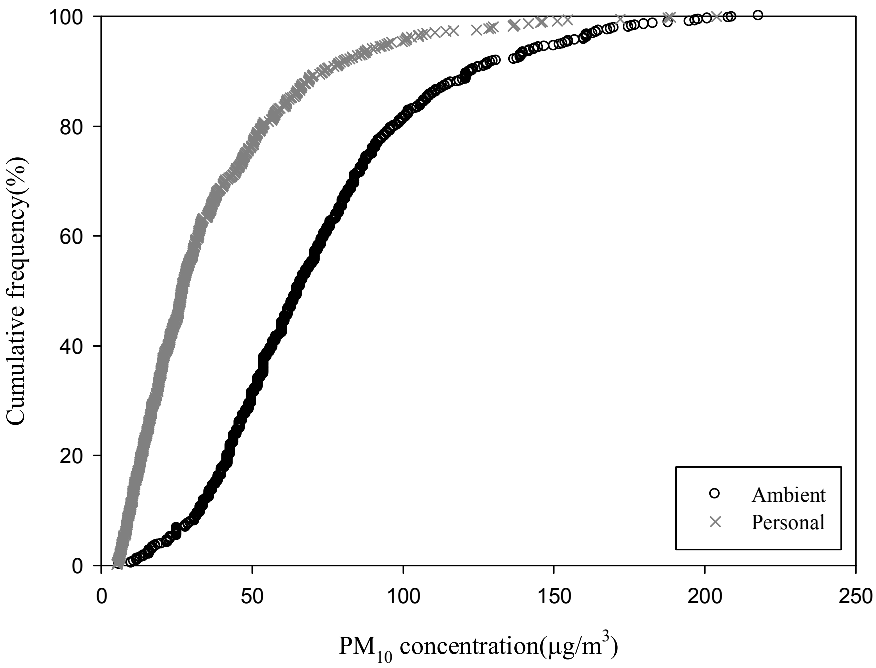


Figure 3. Correlation between ambient air monitor and MicroPEM for $PM_{2.5}$ measurements

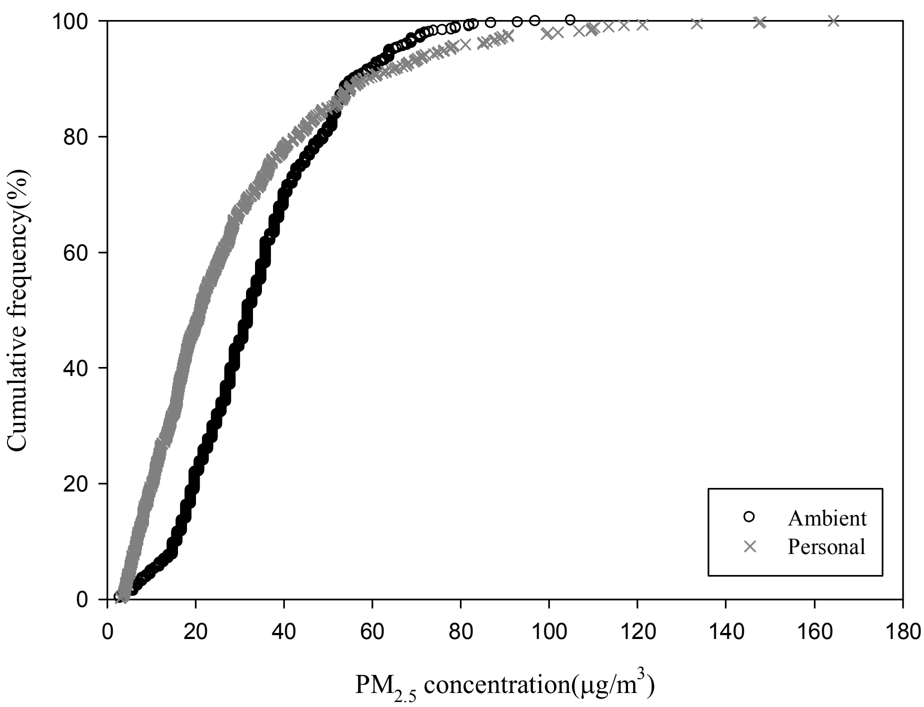
3.2. Distribution between personal exposure and ambient concentration of PM_{10} and $PM_{2.5}$

A total of 26 days using hourly average personal exposure data were collected. The average personal exposures and ambient concentrations of PM_{10} were 37.9 ± 31.9 μg/m^3 and 72.5 ± 37.9 μg/m^3, respectively. Personal exposures to PM_{10} ranged from 3.0 to 105.0 μg/m^3 and ambient PM_{10} concentrations ranged from 6.0 to 218.0 μg/m^3. The personal exposures and ambient concentrations of PM_{10} were significantly different (p<0.001). The average personal exposures and ambient concentrations of $PM_{2.5}$ were 28.5 ± 24.1 μg/m^3 and 36.1 ± 30.2 μg/m^3, respectively. Personal exposures to $PM_{2.5}$ ranged from 3.0 to 164.3 μg/m^3 and ambient $PM_{2.5}$ concentrations ranged from 5.2 to 164.3 μg/m^3. The personal exposures and ambient concentrations of $PM_{2.5}$ were significantly different (p<0.05).

The cumulative frequencies of ambient concentration and personal exposure for PM_{10} and $PM_{2.5}$ are shown in Figure 4 using hourly average. Since there is no Korea Ambient Air Quality Standard (KAAQS) for the hourly average, the distribution of personal exposure could not be directly compared with a KAAQS. The daily average for PM_{10} KAAQS was 100 μg/m^3 and this was exceeded in 18.5% of the ambient concentrations and 3.7% of the personal exposures. The daily average for $PM_{2.5}$ KAAQS was 50 μg/m^3 and this was exceeded in 11.1% of the ambient concentrations and 14.8% of the personal exposures.



(a) PM_{10}



(b) $PM_{2.5}$

Figure 4. Cumulative frequency of personal exposure and ambient concentration of PM_{10} and $PM_{2.5}$

3.3. The relationship between personal exposure and ambient concentration of PM_{10} and $PM_{2.5}$

The linear regression analyses between daily average personal exposure and ambient concentration are presented in Figure 5. The R^2 value between personal exposure and ambient concentration of PM_{10} was 0.44 (p<0.0001). The slope of PM_{10} was 0.50 and the 95% CI ranged from 0.26 to 0.74 (p<0.001). The intercept of PM_{10} was -0.29 and the 95% confidence intervals (CI) ranged from -19.1 to 18.5 (p=0.97). The R^2 value between personal exposure and ambient concentration of $PM_{2.5}$ was 0.81 (p<0.0001). The slope of $PM_{2.5}$ was 1.32 and the 95% CI ranged from 1.05 to 1.59 (p<0.0001). The intercept of $PM_{2.5}$ was -16.57 and the 95% CI ranged from -26.29 to -6.85 (p=0.0018). The slope of $PM_{2.5}$ concentration was twice as high as that of the PM_{10} concentration. The relationship between personal exposures and ambient concentrations of PM_{10} and $PM_{2.5}$ are shown in the subsequent equations.

$$\mathbf{PM_{10}\ (personal) = -0.29 + 0.50\ PM_{10}\ (ambient)\ (R^2 = 0.44)}$$

$$\mathbf{PM_{2.5}\ (personal) = -16.57 + 1.32\ PM_{2.5}\ (ambient)\ (R^2 = 0.81)}$$

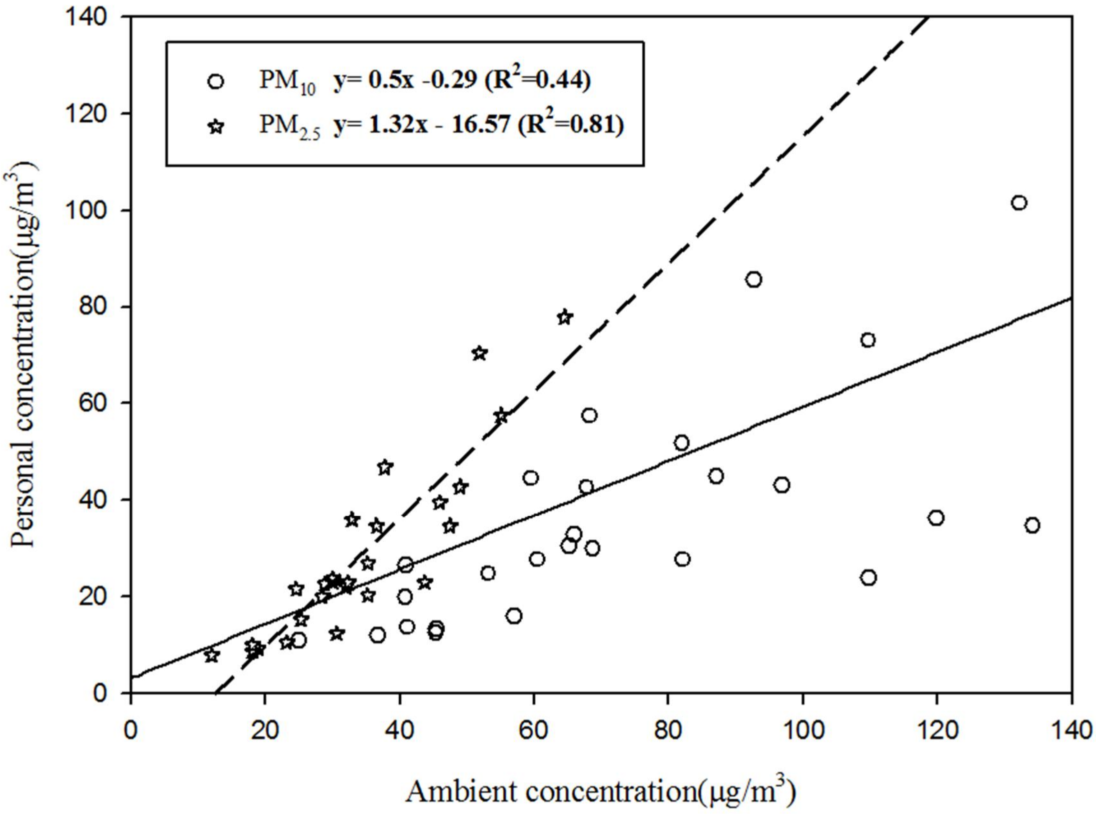


Figure 5. Relationship between personal exposure and ambient concentration of PM_{10} and $PM_{2.5}$ using the daily average

3.4. The relationship between microenvironmental concentration and ambient concentration of PM_{10} and $PM_{2.5}$

The average PM_{10} and $PM_{2.5}$ concentrations at the office, in the home, on the bus, in the cafeteria, and while walking varied. The average PM_{10} concentrations were 38.4 ± 29.5 μg/m^3 at the office, 23.9 ± 13.5 μg/m^3 in the home, 60.7 ± 38.1 μg/m^3 on the bus, 60.5 ± 36.8 μg/m^3 in the cafeteria and 65.0 ± 35.0 μg/m^3 while walking. The average $PM_{2.5}$ concentrations were 30.7 ± 24.0 μg/m^3 at the office, 19.1 ± 11.4 μg/m^3 in the home, 45.5 ± 30.9 μg/m^3 on the bus, 47.1 ± 29.5 μg/m^3 in the cafeteria and 48.6 ± 26.8 μg/m^3 while walking (Table 3). The highest PM_{10} and $PM_{2.5}$ exposures were observed while walking and the lowest were observed in the home. The PM_{10} microenvironmental concentrations while walking were significantly higher than at home by approximately 2.7 fold (p<0.001). The $PM_{2.5}$ microenvironmental concentrations while walking were significantly higher than at home by approximately 2.5 fold (p<0.001).

The proportion of personal exposures to PM_{10} and $PM_{2.5}$ by each microenvironment is shown in Table 3. Time spent at the office, in the home, on the bus, in the cafeteria and while walking were 49.2 %, 37.2 %, 8.3 %, 2.8 %, and 2.5 %, respectively. The percentage PM_{10} contributions at the office, in the home, on the bus, in the cafeteria and while walking were 48.6 %, 26.7 %, 14.9 %, 4.8 % and 4.9 %, respectively. The percentage $PM_{2.5}$ contributions at the office, in the home, on the bus, in the cafeteria and while walking were 48.9 %, 27.3 %, 14.3 %, 4.8 % and 4.7 %, respectively. The time contributions of personal exposures decreased at the office and in the home and increased on the bus, in the cafeteria and while walking.

Table 3. Time spent and personal exposures to PM_{10} and $PM_{2.5}$ concentrations by each microenvironment

Microenvironments	Time spent (min)	Percentage of total time (%)	PM_{10} concentration ($\mu g/m^3$)	Contribution of total personal exposure (%)	$PM_{2.5}$ concentration ($\mu g/m^3$)	Contribution of total personal exposure (%)
Office	708	49.2	38.4 ± 29.5	48.6 ± 10.1	30.7 ± 24.0	48.9 ± 11.3
Home	536	37.2	23.9 ± 13.5	26.7 ± 7.6	19.1 ± 11.4	27.3 ± 8.6
Transport (Bus)	120	8.3	60.7 ± 38.1	14.9 ± 4.0	45.5 ± 30.9	14.3 ± 4.5
Cafeteria	40	2.8	60.5 ± 36.8	4.8 ± 1.3	47.1 ± 29.5	4.8 ± 1.4
Transport (Walk)	36	2.5	65.0 ± 35.0	4.9 ± 1.1	48.6 ± 26.8	4.7 ± 1.3

*Contribution of total personal exposure (%) : Time spent in each microenvironment x PM concentration/Total time spent x PM concentration in 24 hours

Only three microenvironmental concentrations at the office, in the home and on the bus were compared with ambient concentrations, since measurement intervals were different. While microenvionomental concentration was measured at 1-minute intervals, ambient PM concentrations were provided by an hourly average. Since PM concentrations in the cafeteria and while walking did not have any segment that exceed 1 hour, the PM concentrations in the cafeteria and while walking were not able to match up with ambient concentration measurements.

The relationship between personal exposure and ambient concentrations of PM_{10} and $PM_{2.5}$ at the three microenvironments are shown in Figure 6 and 7, respectively. The R^2 values of PM_{10} were 0.42 at the office, 0.28 in the home, and 0.23 on the bus, respectively. The R^2 values of $PM_{2.5}$ were 0.56 at the office, 0.44 in the home, and 0.36 on the bus, respectively. The regression between personal exposure and ambient concentration of PM_{10} and $PM_{2.5}$ at the office had the strongest relationship in the aforementioned microenvironments. The largest slopes of PM_{10} and $PM_{2.5}$ were 0.51 and 1.06 for the bus, respectively. The lowest slopes of PM_{10} and $PM_{2.5}$ were 0.22 and 0.52 at the home, respectively. When the intercept was removed, the slope of PM_{10} and $PM_{2.5}$ increased.

The relationship between personal exposure and ambient concentration of PM_{10} and $PM_{2.5}$ at the three microenvironments are shown in the subsequent equations.

$$\textbf{Office : } PM_{10}\ (office) = -0.14 + 0.51 * PM_{10}\ (ambient)\ (R^2=0.42)$$

$$\textbf{Home : } PM_{10}\ (home) = 8.17 + 0.22 * PM_{10}\ (ambient)\ (R^2=0.28)$$

$$\textbf{Bus : } PM_{10}\ (bus) = 17.81 + 0.51 * PM_{10}\ (ambient)\ (R^2=0.23)$$

$$\textbf{Office : } PM_{2.5}\ (office) = -9.79 + 1.15 * PM_{2.5}\ (ambient)\ (R^2=0.56)$$

$$\textbf{Home : } PM_{2.5}\ (home) = 1.85 + 0.52 * PM_{2.5}\ (ambient)\ (R^2=0.44)$$

$$\textbf{Bus : } PM_{2.5}\ (bus) = 4.99 + 1.06 * PM_{2.5}\ (ambient)\ (R^2=0.36)$$

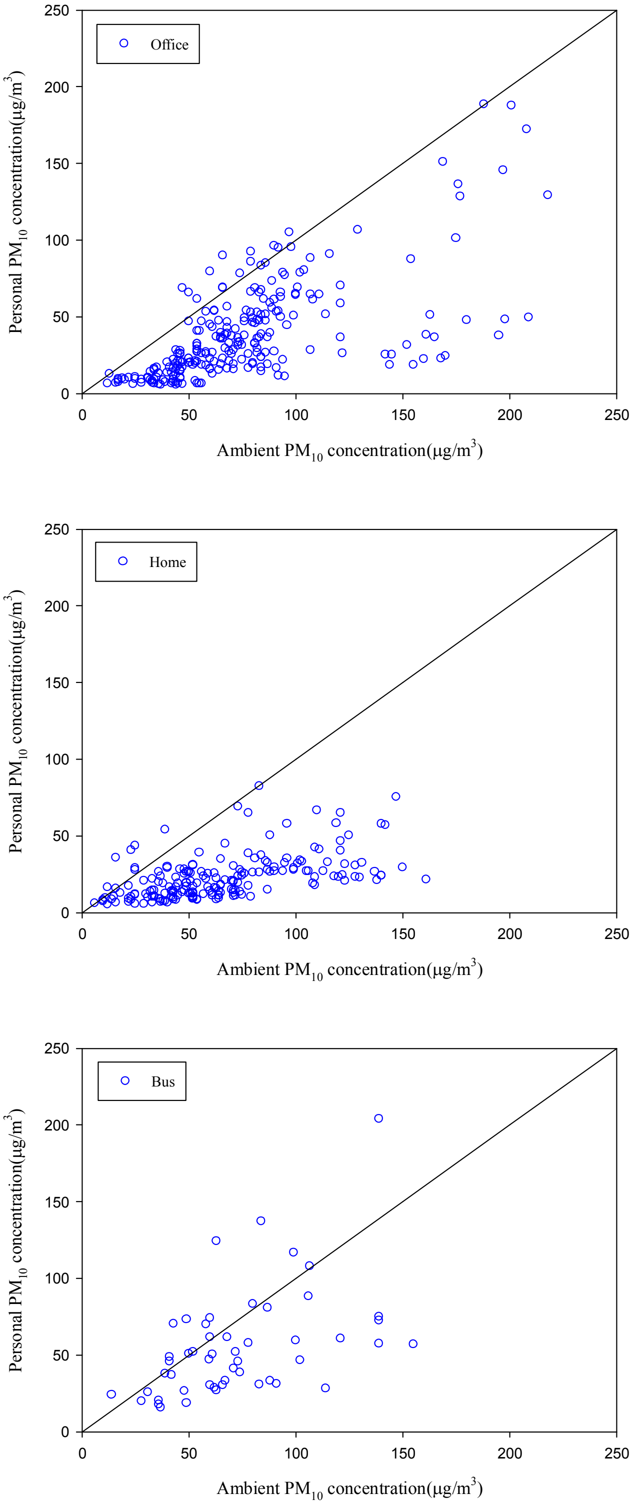


Figure 6. The relationship between personal exposure and ambient concentration of PM_{10} at the office, in the home and on the bus (hourly data)

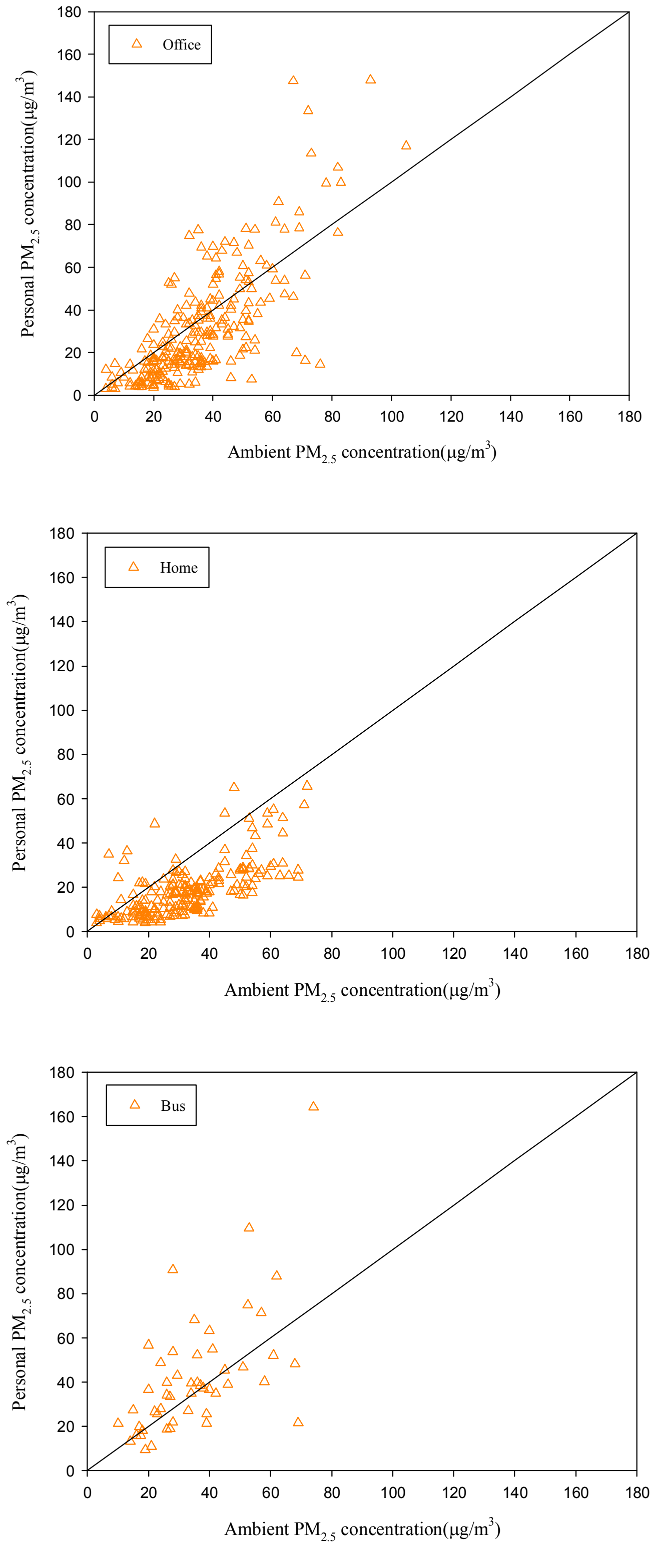


Figure 7. The relationship between personal exposure and ambient concentration of $PM_{2.5}$ at the office, in the home and on the bus (hourly data)

3.5. The relationship between personal exposure and ambient concentrations of PM_{10} and $PM_{2.5}$ in three episodes

During sampling periods, personal PM exposures were measured for 4 days during the Asian dust episode and for 7 days where there was the fine dust advisory episode. The average personal exposure and ambient concentrations of PM in these episodes are shown in Table 4. The personal PM_{10} and $PM_{2.5}$ exposures were 30.9 ± 17.5 μg/m^3 and 22.5 ± 11.5 μg/m^3 in Asian dust, respectively. The ambient PM_{10} and $PM_{2.5}$ levels were 114.9 ± 38.9 μg/m^3 and 35.6 ± 15.5 μg/m^3 in Asian dust, respectively. The personal PM_{10} and $PM_{2.5}$ exposures were 62.0 ± 38.5 μg/m^3 and 49.9 ± 30.1 μg/m^3 in the fine dust advisory, respectively. The ambient PM_{10} and $PM_{2.5}$ levels were 95.8 ± 36.5 μg/m^3 and 50.2 ± 15.1 μg/m^3 in the fine dust advisory, respectively. The average personal exposure and ambient concentration of PM were significantly different in episodes (p<0.0001), except for $PM_{2.5}$ in the fine dust advisory.

Table 4. Ambient concentration and personal exposure to PM_{10} and $PM_{2.5}$ by episodes

Mean ± SD (μg/m^3)		Ambient	Personal	*p*-value
General	PM_{10}	55.8 ± 23.6	29.0 ± 22.8	<0.0001
	$PM_{2.5}$	29.4 ± 13.9	23.1 ± 18.7	
Asian dust	PM_{10}	114.9 ± 38.9	30.9 ± 17.5	<0.0001
	$PM_{2.5}$	35.6 ± 15.5	22.5 ± 11.5	
Fine dust advisory	PM_{10}	95.8 ± 36.5	62.0 ± 38.5	<0.0001
	$PM_{2.5}$	50.2 ± 15.1	49.9 ± 30.1	0.4158

The relationship between personal exposure and ambient concentration during these episodes is shown in Figure 8, 9, and 10, respectively. The R^2 values for PM_{10} concentration were 0.35 in the general atmosphere, 0.20 during the Asian dust episode, and 0.53 during the fine dust advisory, respectively. The R^2 values for $PM_{2.5}$ concentration were 0.38 in the general atmosphere, 0.21 during the Asian dust episode, and 0.42 during the fine dust advisory, respectively. The regression between personal exposure and ambient concentration of PM_{10} and $PM_{2.5}$ had the strongest linearity in the fine dust advisory episode. However, the regression between personal exposure and ambient concentration of PM_{10} and $PM_{2.5}$ showed the lowest linearity and slopes of 0.20 and 0.34 in the Asian dust episode, respectively. The intercept for PM_{10} during Asian dust was 9.08 and the 95% CI ranged from -2.38 to 20.29 (p=0.12). The intercept for $PM_{2.5}$ during the fine dust advisory was 10.28 and the 95% CI ranged from 4.87 to 15.92 (p=0.0003). The intercept for PM_{10} during the fine dust advisory was -11.50 and the 95% CI ranged from -23.84 to 1.02 (p=0.07). The intercept for $PM_{2.5}$ during the fine dust advisory was -14.29 and the 95% CI ranged from -27.73 to -0.94 (p=0.036). The relationship between personal exposure and ambient concentration of PM_{10} and $PM_{2.5}$ by episodes are shown in the subsequent equations.

General : PM_{10} (personal) = -3.77 + 0.58*PM_{10} (ambient) (R^2=0.35)

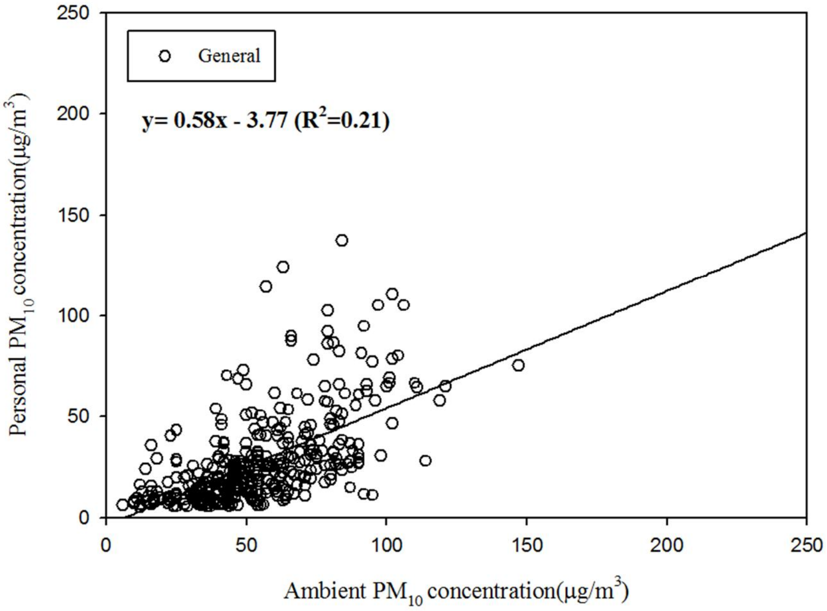
Asian dust : PM_{10} (personal) = 9.08 + 0.20*PM_{10} (ambient) (R^2=0.20)

Fine dust advisory : PM_{10} (personal) = -11.50 + 0.77*PM_{10} (ambient) (R^2=0.53)

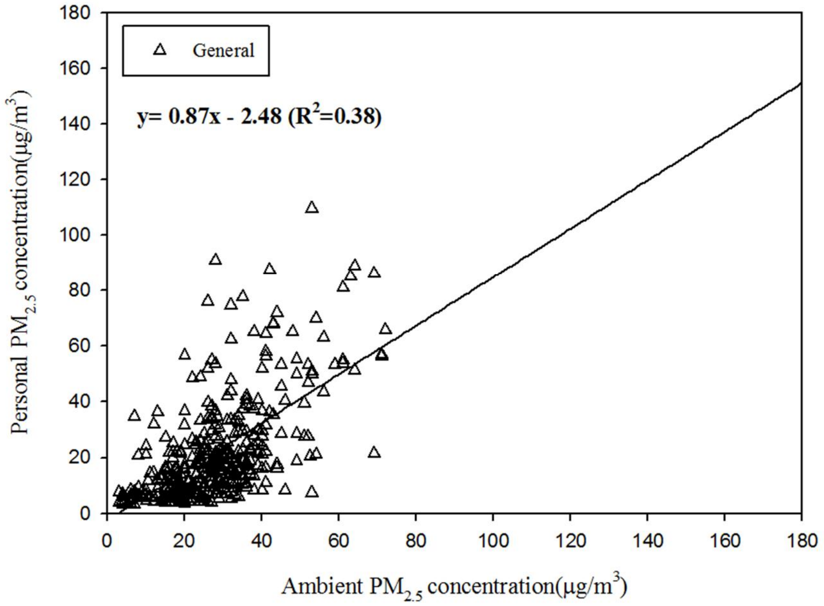
General : $PM_{2.5}$ (office) = -2.48 + 0.87*$PM_{2.5}$ (ambient) (R^2=0.38) Asian dust :

$PM_{2.5}$ (bus) = 10.28 + 0.34*$PM_{2.5}$ (ambient) (R^2=0.21)

Fine dust advisory : $PM_{2.5}$ (home) = -14.29 + 1.28*$PM_{2.5}$ (ambient) (R^2=0.42)

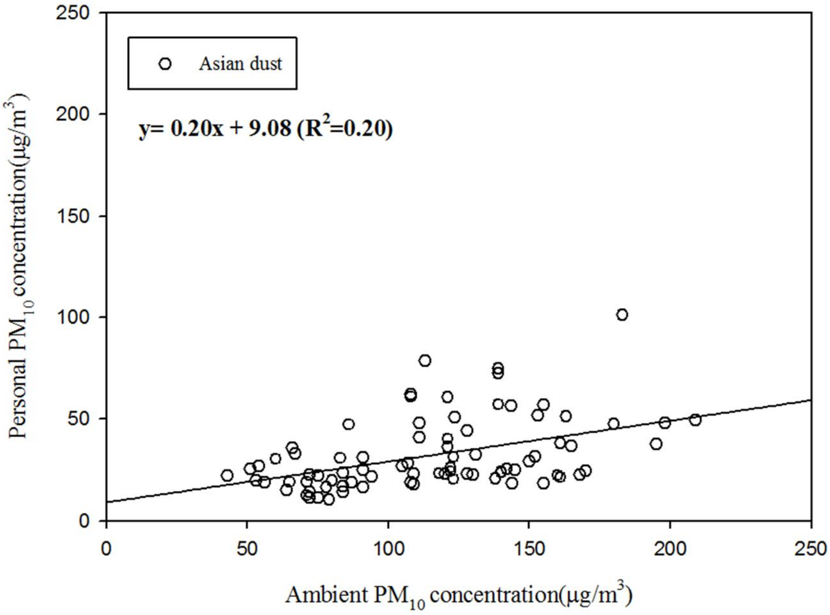


<PM_{10}>

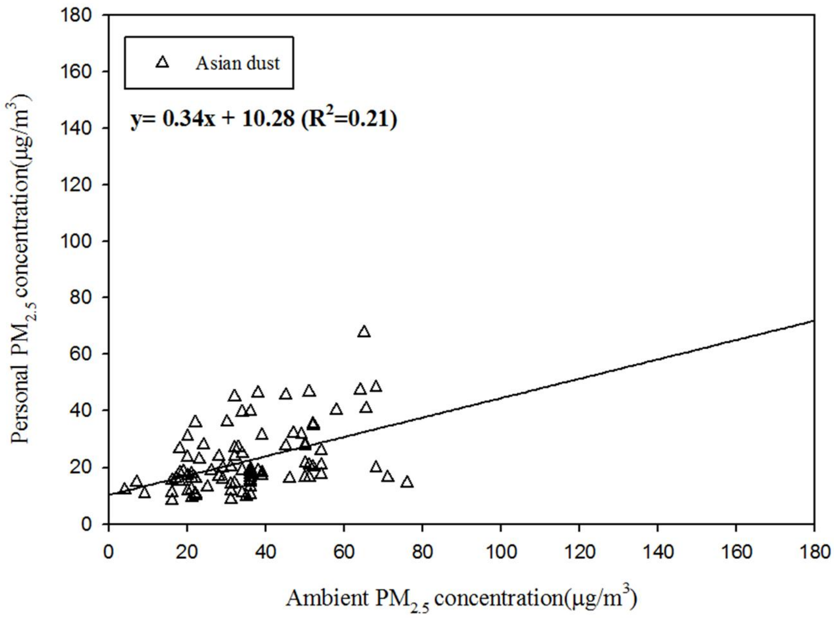


<$PM_{2.5}$>

Figure 8. Relationship between personal exposure and ambient concentrations of PM_{10} and $PM_{2.5}$ in the general atmosphere

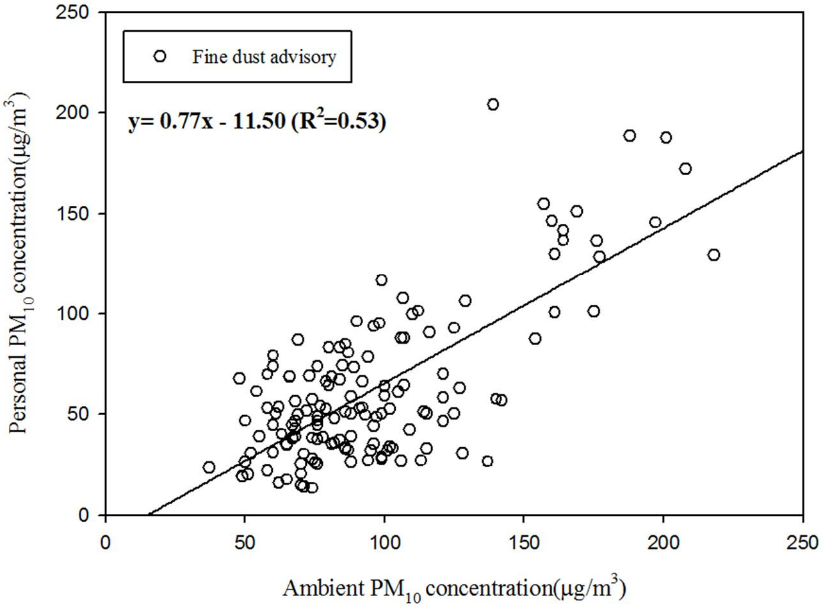


<PM_{10}>

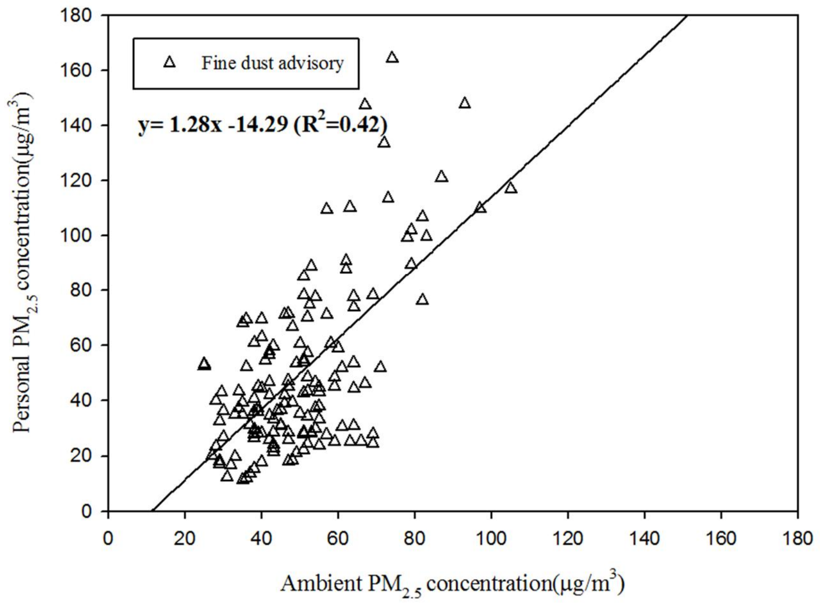


<$PM_{2.5}$>

Figure 9. Relationship between personal exposure and ambient concentrations of PM_{10} and $PM_{2.5}$ in the Asian dust episode



<PM$_{10}$>



<PM$_{2.5}$>

Figure 10. Relationship between personal exposure and ambient concentrations of PM_{10} and $PM_{2.5}$ in the fine dust advisory episode

IV. Discussion

Performance of MicroPEM was evaluated by co-location with central site ambient air monitor for PM_{10} and $PM_{2.5}$. The relationship between MicroPEM and ambient air monitor of PM_{10} and $PM_{2.5}$ had good linearity. However, the slopes of regression were different from 1 for PM_{10} and $PM_{2.5}$ because MicroPEM operating principle was different with ambient air monitor. Although ambient air monitor did not provide gravimetric analysis, the MicorPEM was able to adjust PM concentrations using gravimetric measurement analysis. The correlation of two monitors was similar to a study conducted by EPA in U.S (EPA, 2014). Measurements of MicroPEM and the Federal Equivalent Method (FEM) were highly correlated for $PM_{2.5}$ (R^2>0.81). The MicroPEM to ambient air monitor ratio was higher than that of a US study. Since a light-scattering MicroPEM monitor was affected by the characteristics of the PM, the calibration factor could be different by locations.

In this study, the fixed time-activity pattern was simulated while simultaneously measuring personal exposures to PM_{10} and $PM_{2.5.}$ With a fixed time-activity pattern, the impact of time-activity pattern on personal exposure could be minimized. In previous large population-based studies (PTEAM, EXPOLIS, RIOPA), they had found that personal exposure and ambient concentration were poorly correlated. In cross-sectional or short term studies, correlations were better in specific subjects than in large population. However, correlation widely varied from -0.41 to 0.97 by subject characteristic (Allen et al., 2003; Janssen et al., 1997; Oglesby et al., 2000; Rojas-Bracho et al., 2004). Several studies have simultaneously determined the correlation between ambient and personal exposure by particle size (Broich et al., 2012; Michikawa et al., 2014; Rojas-Bracho et al., 2004). However, the correlation was varied due to the diverse subjects.

Personal PM exposure levels were lower than ambient concentrations. In this study, personal exposure was measured for office worker. Office workers tended to stay longer in the office, which usually results in low incidence of the indoor source and low activity levels. The difference of personal exposure and ambient concentration were similar in other studies for subjects who had relatively low indoor exposure levels, including children (Branis and Kolomaznikova, 2010; Ryan et al., 2015), the elderly (Arhami et al., 2009; Williams et al., 2000), and patients (Janssen et al., 2005; Wallace et al., 2011). However, many studies reported that personal exposure was higher than ambient concentration (Crist et al., 2008; Janssen et al., 2000; Koistinen et al., 2001; Meng et al., 2005; Williams et al., 2003). These studies measured personal exposure for a general population. Most of the general population spends the majority of their time in indoor, and they could be exposed to many indoors environments with higher concentration of PM. Such high PM exposure in indoor implied various indoor PM sources.

The correlation between personal exposure and ambient concentration was different by particle size. The linearity of regression between personal exposure and ambient concentration was higher for $PM_{2.5}$ but lower for PM_{10}. Personal exposure to $PM_{2.5}$ was closely correlated with ambient concentration due to high infiltration rate of $PM_{2.5}$. These results were observed in other studies. In the Netherlands, the correlation coefficient for the relationship between personal and outdoor environments was 0.79 for

$PM_{2.5}$ and 0.50 for PM_{10} (Janssen et al., 2000; Janssen et al., 1998). In Japan, the correlation between personal exposure and ambient concentrations was 0.62 for $PM_{2.5}$ and 0.58 for PM_{10} (Michikawa et al., 2014). The personal to ambient ratio for $PM_{2.5}$ was higher than for PM_{10}. Personal $PM_{2.5}$ exposure was similar to ambient concentration, while personal PM_{10} exposure was approximately half of the ambient concentration. Ambient $PM_{2.5}$ concentration was similar to the level in the office environment. Since the office did not have $PM_{2.5}$ sources, this relationship indicated infiltration of ambient $PM_{2.5}$ levels to indoor spaces. A study found that it was relatively easy for $PM_{2.5}$ to infiltrate indoors (Monn, 2001). In indoor environments without apparent sources, a study found that outdoor particles contributed to approximately 75% of the indoor $PM_{2.5}$ concentration and 66% of the indoor PM_{10} concentration (Ozkaynak et al., 1995). The intercept of regression for PM_{10} was not significantly different from zero. However, the intercept for $PM_{2.5}$ was significantly different from zero. The large intercept for $PM_{2.5}$ implies significant source of personal exposure other than ambient concentration.

Although time spent in the cafeteria was less than one hour in a day, the average $PM_{2.5}$ levels in the cafeteria were highest. The high $PM_{2.5}$ concentration levels at cafeteria were mainly due to cooking activity. Fine PM concentrations in the kitchen were higher than levels in general ambient air (Van Vliet et al., 2013). The highest increases in indoor concentrations and personal exposure were attributable to cooking (Wallace et al., 2006).

The relationship between personal exposure and ambient concentration of PM_{10} and $PM_{2.5}$ was different by characteristics of high level episodes. Asian dust episode in Korea was defined when the PM_{10} concentration over 400 $\mu g/m^3$ lasted at least 2 hours.

In the Asian dust episode, personal PM_{10} exposure was not high despite a high ambient PM_{10} concentration. Increased PM_{10} concentrations during the Asian dust episode were more significant for the coarse fraction than for the fine particle fraction (Kim et al., 2003). The relatively low personal exposure was associated with low indoor PM_{10} concentration due to limited infiltration of PM_{10}.

A fine dust advisory episode in Korea was defined when the $PM_{2.5}$ concentration over 120 μg/m^3 lasted at least 2 hours. In the fine dust advisory episode, personal $PM_{2.5}$ exposure was similar to ambient $PM_{2.5}$ concentration. However, the intercept for $PM_{2.5}$ was significantly different from zero. The relationship might be determined due to high infiltration of $PM_{2.5}$ and significant sources in personal $PM_{2.5}$ exposure. The findings suggested that staying indoors during the Asian dust episode could have reduced personal exposure to PM_{10}. However, staying indoors could not reduce personal exposure to $PM_{2.5}$ during the fine dust advisory episode. It is necessary to reduce high ambient $PM_{2.5}$ concentration to prevent excessive personal exposure. Air pollution for $PM_{2.5}$ arises by combustion sources such as automobiles and power plants (Pires and Querol, 2004). To reduce $PM_{2.5}$ exposure in the high level episodes, it is necessary to implement national policies to include management of air pollution sources.

The limitation of this study was the lack of PM data in the cafeteria and while walking. Times spent in the cafeteria and while walking were less than one hour in our sampling. The results of this study could not assess the correlation between two microenvironmental concentrations and ambient concentrations of PM_{10} and $PM_{2.5}$. However, the times in the other three microenvironments were sufficient to establish the correlation. A follow-up study will be able to elucidate further correlations using more time resolution parameters in other microenvironments.

V. Conclusions

Personal exposure and ambient concentrations of $PM_{2.5}$ were highly correlated for an office worker with fixed time-activity pattern compared with PM_{10}. The personal to ambient ratio of $PM_{2.5}$ was much higher than the ratio of PM_{10}. With Asian dust episode, staying indoors might reduce personal exposure to PM_{10}. However, staying indoors during high level episodes could not reduce personal exposure to $PM_{2.5}$. It is necessary to manage high ambient $PM_{2.5}$ concentration to prevent excessive personal exposure to fine particles.

References

Air KOREA. Available: http://www.airkorea.or.kr/autoStatistic. [Accessed 1 April 2017].

Allen, R., Larson, T., Sheppard, L., Wallace, L., Liu, L.-J.S., 2003. Use of real-time light scattering data to estimate the contribution of infiltrated and indoor-generated particles to indoor air. Envion. Sci. Technol. 37, 3484-3492.

Arhami, M., Polidori, A., Delfino, R.J., Tjoa, T., Sioutas, C., 2009. Associations between personal, indoor, and residential outdoor pollutant concentrations: Implications for exposure assessment to size-fractionated particulate matter. J. Air Waste Manag. Assoc. 59, 392-404.

Bahadori, T., Suh, H., Koutrakis, P., 1999. Issues in human particulate exposure assessment: Relationship between outdoor, indoor, and personal exposures. Hum. Ecol. Ris. Assess. 5, 459-470.

Branis, M., Kolomaznikova, J., 2010. Monitoring of long-term personal exposure to fine particulate matter ($PM_{2.5}$). Air Qual. Atmos. Hlth. 3, 235-243.

Broich, A.V., Gerharz, L.E., Klemm, O., 2012. Personal monitoring of exposure to particulate matter with a high temporal resolution. Environ. Sci. Pollut. Res. 19, 2959-2972.

Chang, L.-T., Koutrakis, P., Catalano, P.J., Suh, H.H., 2000. Hourly personal exposures to fine particles and gaseous pollutants-results from Baltimore, Maryland. J. Air Waste Manag. Assoc. 50, 1223-1235.

Crist, K.C., Liu, B., Kim, M., Deshpande, S.R., John, K., 2008. Characterization of fine particulate matter in Ohio: Indoor, outdoor, and personal exposures. Environ. Res. 106, 62-71.

Dockery, D.W., Pope, C.A., Xu, X., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris Jr, B.G., Speizer, F.E., 1993. An association between air pollution and mortality in six US cities. N. Engl. J. Med. 329, 1753-1759.

EPA, U.S., 2014. Evaluation of Field-deployed Low Cost PM Sensors. EPA/600/R-14/464. www.epa.gov/ord.

Gulliver, J., Briggs, D.J., 2004. Personal exposure to particulate air pollution in transport microenvironments. Atmos. Environ. 38, 1-8.

Janssen, N., Hoek, G., Harssema, H., Brunekreef, B., 1997. Childhood exposure to PM_{10}: relation between personal, classroom, and outdoor concentrations. Occup. Environ. Med. 54, 888-894.

Janssen, N., Lanki, T., Hoek, G., Vallius, M., De Hartog, J., Van Grieken, R., Pekkanen, J., Brunekreef, B., 2005. Associations between ambient, personal, and indoor exposure to fine particulate matter constituents in Dutch and Finnish panels of cardiovascular patients. Occup. Environ. Med. 62, 868-877.

Janssen, N.A., de Hartog, J.J., Hoek, G., Brunekreef, B., Lanki, T., Timonen, K.L., Pekkanen, J., 2000. Personal exposure to fine particulate matter in elderly subjects: relation between personal, indoor, and outdoor concentrations. J. Air Waste Manag. Assoc. 50, 1133-1143.

Janssen, N.A., Hoek, G., Brunekreef, B., Harssema, H., Menswik, I., Zuidhof, A., 1998. Personal sampling of particles in adults: relation among personal, indoor, and outdoor air concentrations. Am. J. Epidemiol. 147, 537-547.

Janssen, N.A., Hoek, G., Harssema, H., Brunekreef, B., 1999. Personal exposure to fine particles in children correlates closely with ambient fine particles. Arch. Environ. Occup. Health. 54, 95-101.

Kim, K.-H., Choi, G.-H., Kang, C.-H., Lee, J.-H., Kim, J.Y., Youn, Y.H., Lee, S.R., 2003. The chemical composition of fine and coarse particles in relation with the Asian Dust events. Atmos. Environ. 37, 753-765.

Koistinen, K.J., Hänninen, O., Rotko, T., Edwards, R.D., Moschandreas, D., Jantunen, M.J., 2001. Behavioral and environmental determinants of personal exposures to $PM_{2.5}$ in EXPOLIS – Helsinki, Finland. Atmos. Environ. 35, 2473-2481.

Kousa, A., Oglesby, L., Koistinen, K., Künzli, N., Jantunen, M., 2002. Exposure chain of urban air $PM_{2.5}$—associations between ambient fixed site, residential outdoor, indoor, workplace and personal exposures in four European cities in the EXPOLIS-study. Atmos. Environ. 36, 3031-3039.

Kruize H, Hänninen O, Breugelmans O, Lebret E, Jantunen M., 2003. Description and demonstration of the EXPOLIS simulation model: Two examples of modeling population exposure to particulate matter. J. Expo. Sci. Environ. Epidemiol. 13, 87-99.

Lioy, P., Waldman, J., Buckley, T., Butler, J., Pietarinen, C., 1990. The personal, indoor and outdoor concentrations of PM_{10} measured in an industrial community during the winter. Atmos. Environ. Part B. Urban Atmos. 24, 57-66.

Meng, Q.Y., Turpin, B.J., Korn, L., Weisel, C.P., Morandi, M., Colome, S., Zhang, J., Stock, T., Spektor, D., Winer, A., 2005. Influence of ambient (outdoor) sources on residential indoor and personal $PM_{2.5}$ concentrations: analyses of RIOPA data. J. Expo. Sci. Environ. Epidemiol. 15, 17-28.

Michikawa, T., Nakai, S., Nitta, H., Tamura, K., 2014. Validity of using annual mean particulate matter concentrations as measured at fixed site in assessing personal exposure: An exposure assessment study in Japan. Sci. Tot. Environ. 466–467, 673-680.

Monn, C., 2001. Exposure assessment of air pollutants: a review on spatial heterogeneity and indoor/outdoor/personal exposure to suspended particulate matter, nitrogen dioxide and ozone. Atmos. Environ. 35, 1-32.

Monn, C., Fuchs, A., Högger, D., Junker, M., Kogelschatz, D., Roth, N., Wanner, H.U., 1997. Particulate matter less than 10 μm (PM_{10}) and fine particles less than 2.5 μm ($PM_{2.5}$): relationships between indoor, outdoor and personal concentrations. Sci. Tot. Environ. 208, 15-21.

NIER. Research for personal exposure assessment by time activity patterns on a nation. Korea National Institute of Environmental Research. 2010

Oglesby, L., Künzli, N., Röösli, M., Braun-Fahrländer, C., Mathys, P., Stern, W., Jantunen, M., Kousa, A., 2000. Validity of ambient levels of fine particles as surrogate for personal exposure to outdoor air pollution—results of the European EXPOLIS-EAS Study (Swiss Center Basel). J. Air Waste Manag. Assoc. 50, 1251-1261.

Ozkaynak, H., Xue, J., Spengler, J., Wallace, L., Pellizzari, E., Jenkins, P., 1996. Personal exposure to airborne particles and metals: results from the Particle TEAM study in Riverside, California. J. Expo. Anal. Environ. Epidemiol. 6, 57-78.

Pires, M., Querol, X., 2004. Characterization of Candiota (South Brazil) coal and combustion by-product. Int. J. Coal Geol. 60, 57-72.

Pope III, C.A., Thun, M.J., Namboodiri, M.M., Dockery, D.W., Evans, J.S., Speizer, F.E., Heath Jr, C.W., 1995. Particulate air pollution as a predictor of mortality in a prospective study of US adults. Am. J. Respir. Crit. Care Med. 151, 669-674.

Rojas-Bracho, L., Suh, H.H., Catalano, P.J., Koutrakis, P., 2004. Personal exposures to particles and their relationships with personal activities for chronic obstructive pulmonary disease patients living in Boston. J. Air Waste Manag. Assoc. 54, 207-217.

Ryan, P.H., Son, S.Y., Wolfe, C., Lockey, J., Brokamp, C., LeMasters, G., 2015. A field application of a personal sensor for ultrafine particle exposure in children. Sci. Tot. Environ. 508, 366-373.

Schwartz, J., Dockery, D.W., 1992. Particulate air pollution and daily mortality in Steubenville, Ohio. Am. J. Epidemiol. 135, 12-19.

Thomas, K.W., Pellizzari, E., Clayton, C.A., Whitaker, D.A., Shores, R.C., Spengler, J., Ozkaynak, H., Froehlich, S.E., Wallace, L., 1993. Particle Total Exposure Assessment Methodology (PTEAM) 1990 study: method performance and data quality for personal, indoor, and outdoor monitoring. J. Expo. Anal. Environ. Epidemiol. 3, 203-226.

Urso, P., Cattaneo, A., Garramone, G., Peruzzo, C., Cavallo, D.M., Carrer, P., 2015. Identification of particulate matter determinants in residential homes. Buil. Environ. 86, 61-69.

Van Vliet, E.D.S., Asante, K., Jack, D.W., Kinney, P.L., Whyatt, R.M., Chillrud, S.N., Abokyi, L., Zandoh, C., Owusu-Agyei, S., 2013. Personal exposures to fine particulate matter and black carbon in households cooking with biomass fuels in rural Ghana. Environ. Res. 127, 40-48.

Wallace, L., 2000. Correlations of personal exposure to particles with outdoor air measurements: a review of recent studies. Aerosol Sci. Technol. 32, 15-25.

Wallace, L., Williams, R., Rea, A., Croghan, C., 2006. Continuous weeklong measurements of personal exposures and indoor concentrations of fine particles for 37 health-impaired North Carolina residents for up to four seasons. Atmos. Environ. 40, 399-414.

Wallace, L.A., Wheeler, A.J., Kearney, J., Van Ryswyk, K., You, H., Kulka, R.H., Rasmussen, P.E., Brook, J.R., Xu, X., 2011. Validation of continuous particle monitors for personal, indoor, and outdoor exposures. J. Expo. Sci. Environ. Epidemiol. 21, 49-64.

Williams, R., Creason, J., Zweidinger, R., Watts, R., Sheldon, L., Shy, C., 2000. Indoor, outdoor, and personal exposure monitoring of particulate air pollution: the Baltimore elderly epidemiology-exposure pilot study. Atmos. Environ. 34, 4193-4204.

Williams, R., Suggs, J., Rea, A., Leovic, K., Vette, A., Croghan, C., Sheldon, L., Rodes, C., Thornburg, J., Ejire, A., Herbst, M., Sanders Jr, W., 2003. The Research Triangle Park particulate matter panel study: PM mass concentration relationships. Atmos. Environ. 37, 5349-5363.

Woodruff, T.J., Grillo, J., Schoendorf, K.C., 1997. The relationship between selected causes of postneonatal infant mortality and particulate air pollution in the United States. Environ. Health Perspect. 105, 608.

국문초록

Correlation between personal exposure and ambient concentration of PM_{10} and $PM_{2.5}$ with control of time-activity pattern

시간활동패턴의 영향을 통제한 PM_{10}과 $PM_{2.5}$의 개인노출과 대기농도의 연관성

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많은 역학연구에서 PM_{10}과 $PM_{2.5}$의 노출은 유병률과 사망률의 증가와 관련있다고 보고되었다. 하루동안 개인이 노출되는 PM_{10}과 $PM_{2.5}$를 정확하게 파악하기 위해서는 개인노출을 측정하여야 한다. 하지만 직접 측정하여 개인노출을 파악하는 것은 시간적, 경제적 등의 제약이 따른다. 이런 제한점을 극복하고자 대기측정망에서 측정된 대기농도를 이용하여 개인노출을 파

악하려는 시도들이 있었다. 개인노출은 다양한 미세환경에서의 노출을 추정할 수 있는 노출평가로, 개인이 머무른 미세환경에서의 농도와 그 미세환경에서 머문 시간의 곱으로 표현이 된다. 여기서, 미세환경에서 머문 시간은 개인이 생활하는 시간활동패턴 (Time-activity pattern)에 따라 영향을 받게 된다. 대기측정망의 PM_{10}과 $PM_{2.5}$ 대기농도를 이용하여 개인노출을 추정하려면 둘의 정확한 연관성을 파악해야 하는데 다양한 시간활동패턴에 대한 영향을 최소화 하는 것이 필요하다. 동일한 시간활동패턴으로 개인노출을 측정하면 그 변이를 최소화 할 수 있다. 따라서 본 연구의 목적은 개인노출의 측정에서 시간활동패턴에 대한 영향을 통제하여 PM_{10}과 $PM_{2.5}$의 개인노출과 대기농도의 연관성을 알아보는 것이다.

연구방법은 2014년 3월부터 6월까지 26일동안 연구자가 동일한 시간활동패턴으로 PM_{10}과 $PM_{2.5}$ 농도에 대한 24시간 개인노출 측정을 진행하였다. 시간활동패턴은 서울의 사무실 근로자의 시간활동패턴을 근거로 하였으며 각 미세환경은 집, 사무실, 식당, 버스, 도보 총 5가지 행동패턴을 유지하였다. 각 미세환경별 소요 시간은 24시간 중 연구실 11시간 52분(49.6%), 집 9시간(37.5%), 버스 2시간(8.3%), 식당 40분(2.7%), 도보 28분(1.9%) 이었다. 측정기기는 직독식 측정기기인 MicroPEM (version 3.2A, RTI, USA)을 사용하여 실시간 PM_{10}과 $PM_{2.5}$의 개인노출 질량농도를 측정하였다. 측정간격은 1분, 공기유량은 0.5L/min으로 유지하였으며 측정 전 기기의 영점보정을 실시하였다.

개인노출 측정에 앞서 PM_{10}과 $PM_{2.5}$의 대기측정망의 대기농도와 MicroPEM 농도간의 상관성을 분석한 결과 모두 좋은 직성성 (Linearity)을 나타내었다. PM_{10}의 개인노출 농도는 37.9 ± 31.9 $\mu g/m^3$ 이었고, 대기농도는 72.4 ± 37.4 $\mu g/m^3$ 이었다. $PM_{2.5}$의 개인노출 농도는 30.2 ± 25.9 $\mu g/m^3$ 이었고, 대기농도는 34.9 ± 16.8 $\mu g/m^3$ 이었다. 개인노출과 대기농도의 연관성은 $PM_{2.5}$ (R^2=0.81)가 PM_{10} (R^2=0.44) 보다 유의하게 높게 나타났다. 개인노출/대기농도 ratio는 $PM_{2.5}$는 1이었고 PM_{10}은 0.5 이

었다. 이는 $PM_{2.5}$가 PM_{10}보다 실내로 더 쉽게 침투 (Infiltration)된다는 것을 증명한다. 대기의 특징별로 연관성을 분석한 결과 개인노출과 대기농도의 연관성이 다르게 나타났다. 황사주의보 일 때 대기 중 주요 미세먼지 입자크기인 PM_{10}의 대기농도와 개인노출의 연관성은 낮았다. 반면, 미세먼지 주의보일 때 $PM_{2.5}$의 대기농도와 개인노출의 연관성은 높게 나타났다.

시간활동패턴을 고정시켰을 때, 개인노출과 대기농도의 연관성은 $PM_{2.5}$가 PM_{10}보다 더 높게 나타났다. 황사일 때는 실내에 머무는 것으로 PM_{10}에 대한 개인노출을 줄일 수 있지만 미세먼지 주의보일 때는 실내에 머무는 것으로 $PM_{2.5}$의 개인노출을 줄일수가 없다. 따라서, 높은농도의 $PM_{2.5}$ 개인노출을 줄이기 위해서는 국가 정책적인 대기오염의 관리가 필요하다.

주요어: PM_{10}, $PM_{2.5}$, 개인노출, 대기측정망, 미세먼지, 초미세먼지,

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