Atmospheric Environment 175 (2018) 192–198

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Contribution of microenvironments to personal exposures to PM_{10} and $PM_{2.5}$ in summer and winter

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ARTICLE INFO

Keywords:
Particulate matter
Time-activity pattern
Personal exposure
Exposure contribution
Microenvironmental model

ABSTRACT

Personal exposure to particulate matter (PM) can be affected by time–activity patterns and microenvironmental concentrations. Particle size is closely associated with potential health problems, where smaller particles have greater effects on health. We investigated the effects of time–activity patterns on personal exposure and the contribution of the microenvironment to personal exposure to PM with maximal diameters of 10 μm and 2.5 μm (PM_{10} and $PM_{2.5}$, respectively) in summer and winter. Technicians carried a nephelometer to detect various sizes of PM while engaging in one of nine scripted time–location–activity patterns. The scripted activities were based on the time–activity patterns of nine groups of inhabitants of Seoul, Korea. The monitoring was repeated in summer and winter to assess seasonal variation. The differences of personal exposures to PM_{10} and $PM_{2.5}$ in summer and winter were not significant. The greatest PM concentrations occurred in restaurants. The $PM_{2.5}/PM_{10}$ ratios were varied from 0.35 at schools to 0.92 at stores. In both seasons, the residential indoor microenvironment was the largest contributor to personal PM exposure. The other major contributors were restaurants, offices, schools, buses, and walking, although their contributions differed by season and particle size. The different microenvironmental contributions among the activity pattern groups suggest that personal exposure significantly differs according to activity pattern.

1. Introduction

Particulate matter (PM) is a major pollutant associated with a variety of adverse health outcomes, including respiratory illnesses, cardiovascular events, hospitalization, and mortality (Carugno et al., 2016; Minichilli et al., 2016; Phung et al., 2016; Shaughnessy et al., 2015; Vaduganathan et al., 2016). Personal exposure to PM depends on a combination of indoor and outdoor factors. Furthermore, the effects of personal exposure tend to differ by particle size. For example, the deposition of inhaled airborne PM in the respiratory system is controlled by particle size, driven by the complex mechanisms of aerosol deposition (Hinds, 1999), and finer particles can reach deep into the alveoli, causing serious health outcomes (EPA, 2009).

Studies have shown that personal exposure to PM varies by human activity, such as cooking, vacuuming, and walking. For example, PM emitted during cooking largely contributes to $PM_{2.5}$ and ultrafine particle exposure (Buonanno et al., 2009, 2011). A study conducted in Hong Kong found that cooking increased PM levels by four times the background levels (Wan et al., 2011). When operating a vacuum cleaner on polyvinyl chloride (PVC) flooring, the mean maximum concentration of PM was 6×10^3 particles/cm^3 (Glytsos et al., 2010). Furthermore, walking leads to particle resuspension. Ferro et al. (2004) found that an individual walking on carpet led to a $PM_{2.5}$ concentration of 15 μg/m^3 in a California residence. In another study, a period of walking elevated PM_{10} concentrations in a house by 32 ± 13 μg/m^3 (Qian et al., 2008).

Personal exposure to PM is influenced by microenvironmental concentrations and the time spent in various microenvironments. When the Stochastic Human Exposure and Dose Simulation (SHEDS-PM) model was applied in a case study of daily $PM_{2.5}$ exposure in Philadelphia, PA, USA, indoor residential exposure made up the greatest proportion of total exposure (Burke et al., 2001), and exposure across the population varied from less than 10 μg/m^3 in the least-exposed group of people to greater than 59 μg/m^3 in the most-exposed population. Meanwhile, personal exposure in Seoul, Korea, ranges from 9.8 to 43.1 μg/m^3, depending on time–activity patterns (Lim et al., 2012).

In addition, personal exposure to PM can differ by season. Liu et al. (2003) showed that personal $PM_{2.5}$ exposure was greater during winter, as were indoor and outdoor $PM_{2.5}$ concentrations. In both seasons, the

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https://doi.org/10.1016/j.atmosenv.2017.12.009
Received 2 April 2017; Received in revised form 3 December 2017; Accepted 5 December 2017
Available online 14 December 2017

mean personal exposure to PM was greater than the mean residential indoor or outdoor concentrations (Rojas-Bracho et al., 2004), suggesting the possibility of greater exposure in other microenvironments. Li et al. (2016) reported that greater concentrations of PM during the heating season resulted in higher exposures to PM compared to the non-heating season.

In this study, we investigated how PM_{10} and $PM_{2.5}$ exposure varied by time–activity patterns, and examined the contributions of various microenvironments to personal PM exposure by season. PM_{10} and $PM_{2.5}$ exposures were measured simultaneously while trained technicians followed scripted activity patterns, which were based on time–activity patterns derived from the Seoul population. This study has developed a new and effective approach to estimate population exposure. Time-activity pattern of the population and actual measurement with simulated time-activity pattern were used to estimate population exposure.

2. Methods

During the summer and winter of 2013, five non-smoking field technicians collected PM_{10} and $PM_{2.5}$ measurements while engaging in scripted time–location–activity patterns. The scripted patterns were based on the time–activity patterns of 2358 inhabitants (4849 person-days) of Seoul, Korea.

2.1. Time–activity patterns

Time–location data were collected by Statistics Korea. Data from 2358 Seoul inhabitants were classified into nine population groups based on similarities in their time–location–activity patterns (Hwang et al., 2016). Randomly selected 1000 monitored days of activity data were used for cluster analysis. Four-digit codes were generated from the three-digit activity codes and one-digit location codes for every 10 min. Cluster analysis with K-mean method was conducted using similarity matrixes from this four-digit codes. Groups 1 and 3 did not appear to commute. Group 3 included people who left their residences early in the morning and returned home before 7 p.m. Groups 2, 4, 5, 6, and 9 had similar morning commuting patterns and stayed outside their residences during the day. However, these groups exhibited different afternoon and evening commuting patterns. While the majority of individuals in Group 2 returned home in early evening, the other groups showed delayed evening patterns. Group 7 showed no specific commuting pattern throughout the day. Group 8 remained outside their residences at night. The characteristics of the nine population groups and activity patterns applied in this simulation study are shown in Table 1. Demographic characteristics of the 9 groups were explained in previous paper (Hwang et al., 2016). Groups 1 and 3 were mainly housewives; Group 2 consisted of office workers; Group 4 was mainly made up of elementary, junior high, and high school students; and Groups 5, 6, and 9 comprised the working population. Group 7 showed no specific commuting pattern throughout the day. Group 8 was made up of night shift workers. We applied the summer patterns in both summer and winter because the time-activity pattern data were collected once in September (late summer).

Table 1
Time-activity patterns of nine population groups based on data from Seoul, Korea.

Group	Proportion of population (%)	Residential indoor (hour)	Transportation (hour)	Others (hour)
1	22.8	19.0 ± 3.9	1.5 ± 1.8	3.5 ± 2.8
2	20.6	11.2 ± 1.6	2.1 ± 1.0	10.7 ± 1.6
3	14.9	16.9 ± 4.4	2.1 ± 2.3	5.0 ± 3.5
4	13.2	12.8 ± 2.4	1.7 ± 1.0	9.5 ± 2.2
5	11.1	11.4 ± 2.3	2.6 ± 1.6	10.0 ± 2.6
6	7.0	10.7 ± 2.8	2.7 ± 1.6	10.6 ± 2.6
7	4.4	14.7 ± 6.1	2.1 ± 2.0	7.2 ± 5.3
8	2.7	9.7 ± 7.5	2.6 ± 3.3	11.7 ± 7.8
9	2.7	10.0 ± 2.5	3.4 ± 2.2	10.6 ± 2.4

2.2. PM monitoring

For each population group, exposure was measured over 5 consecutive days by trained technicians. A total of 45 person-days of exposure data were collected in both summer and winter. A pre-printed, real-time diary was used to record movement by the minute, following a written protocol, to match each data point to the appropriate activity, microenvironment, and aerosol sources (smokers, candle or cooking). The field technicians recorded their actual time schedules in the diary. Although they could not follow the activity patterns exactly, differences were usually within a few minutes of the scripted schedule (Table S1).

A real-time portable aerosol spectrometer (Model 1.109, Grimm, Ainring, Germany) was used to measure the mass concentrations of PM_{10} and $PM_{2.5}$. The technicians carried the monitors so that the inlet of the monitor was positioned as close to the breathing zone as possible. For all measurements, the logging interval of the spectrometer was set to 1 min. The monitor continuously measured, in real time, the particle number concentrations of the 31 size channels ranging from 0.25 μm to 32 μm. The sampling flow rate was 1.2 L/min. The data were saved as 1 min averages. A gravimetric correction factor was applied using the particle weight gained from 47 mm polytetrafluoroethylene filters during the monitoring runs. Zero calibration of the spectrometer was conducted before each measurement. The PM_{10} and $PM_{2.5}$ concentrations were downloaded using the software GRIMM 1177 v.3.

2.3. Statistical analyses

The SPSS ver. 23 package for Windows was used for statistical analyses. Exposure to PM_{10} and $PM_{2.5}$ for each group and season and the average concentration in each microenvironment were calculated. Because the distributions of PM concentrations were skewed, the data were log-transformed. The seasonal differences were analyzed by Student's t-test. Paired *t*-test was applied for comparing the seasonal differences of $PM_{2.5}/PM_{10}$ in each group. All statistical procedures used a significance level of 0.05. The PM_{10} and $PM_{2.5}$ data from summer and winter were used to apportion PM_{10} and $PM_{2.5}$ personal exposure by microenvironment using the population fraction of each group in Seoul. The average time spent in each microenvironment per group was determined from the scripted activity pattern of each population group. The product of the population fraction of each group and average time spent in the microenvironment was calculated to determine the total time spent in the microenvironment, and it was multiplied by the average PM_{10} and $PM_{2.5}$ concentrations of each microenvironment in the two seasons. The products of the population fraction, average time, and average PM_{10} and $PM_{2.5}$ concentrations were used to determine the contribution of each microenvironment. The apportionment of each microenvironment was calculated as the product of the microenvironment divided by the sum of all products, as shown in equation (1).

$$Contribution_m = C_m \times \frac{\sum_{n=1}^{9} (Population\ proportion_n \times T_{(m,n)})}{\sum_{m=1}^{13} \{\sum_{n=1}^{9} (C_m \times Population\ proportion_n \times T_{(m,\,n)})\}} \quad (1)$$

where $Contribution_m$ is the contribution of the microenvironment m (%) to PM exposure, C_m is the mean PM concentration of microenvironment m, $Population\ proportion_n$ is the population fraction of time–activity pattern group n, and $T_{(m,n)}$ is the average time spent in microenvironment m of time-activity group n. The measured microenviornments in this study were consisted of thirteen categories as seen in Tables 3–5.