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Characterization of personal exposure concentration of fine particles for adults and children exposed to high ambient concentrations in Beijing, China

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Abstract

In China, the health risk from overexposure to particles is becoming an important public health concern. To investigate daily exposure characteristics to $PM_{2.5}$ with high ambient concentration in urban area, a personal exposure study was conducted for school children, and office workers in Beijing, China. For all participants (N = 114), the mean personal 24-hr exposure concentration was 102.5, 14.7, 0.093, 0.528, 0.934, 0.174 and 0.703 μg/m^3 for $PM_{2.5}$, black carbon, Mn, Al, Ca, Pb, and Fe. Children's exposure concentrations of $PM_{2.5}$ were 4–5 times higher than those in related studies. The ambient concentration of $PM_{2.5}$ (128.5 μg/m^3) was significantly higher than the personal exposure concentration ($P < 0.05$), and exceed the reference concentration (25 μg/m^3) of WHO air quality guideline. Good correlation relationships and significant differences were identified between ambient concentration and personal exposure concentration. The relationships indicate that the ambient concentration is the main factor influencing personal exposure concentration, but is not a good indicator of personal exposure concentration. Outdoor activities (commute mode, exposure to heating, workday or weekend travel) influenced personal exposure concentrations significantly, but the magnitude of the influence from indoor activities (exposure to cooking) was masked by the high ambient concentrations.

Key words: personal exposure; $PM_{2.5}$; high ambient concentration

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Introduction

Fine particles (particulate matter with diameter less than 2.5 μm) are responsible for harmful effects on human health. A series of epidemiology studies reported that there are robust associations between short-term and long-term exposure to $PM_{2.5}$ and adverse health effects, including cardiac and respiratory morbidity and mortality. In 2002, the American Cancer Society determined that a 6% increase in the risk of mortality occurs for every 10 μg/m^3 increase in $PM_{2.5}$ (Pope et al., 2002). In 2008, a new relative risk factor was developed by the California Air Resource Board for $PM_{2.5}$ that reflects a 10% increase in the risk of premature death per 10 μg/m^3 increase in exposure to $PM_{2.5}$ concentrations (CARB, 2008).

All individuals are potentially affected, but as a subpopulation children are more prone to suffer health effects due to ambient particulate matter, since their lung structure and immune system are not fully developed when compared to adults. Most studies involving children focused on the effects of $PM_{2.5}$ exposure on asthmatic symptoms (Wallace et al., 2003; Wu et al., 2005), while other studies attempted to identify possible $PM_{2.5}$ exposure sources such as traffic pollution (Van Roosbroeck et al., 2007), outdoor air concentration (Janssen et al., 1999), and indoor sources (Lung et al., 2007). Recently, a comprehensive review pointed out that the microenvironments of active children are significantly different from those of adults, and therefore, children's personal exposures to air pollutants differ from adults' (Ashmore and Dimitroulopoulou, 2009). Research comparing these two groups is needed along with work to identify the factors accounting for variations in exposure. Further, in considering children's health on a global basis, there is an urgent need to apply personal exposure assessment technologies not only in North America and Europe, but also in areas where the effects of air pollution are much more serious, e.g., developing countries.

In developing countries, the health risk from overexposure to particles is becoming an important public health concern due to the high density of population, the rapid development of smokestack industries, and the large increases in motor vehicles (HEI, 2004). In some megacities, such as Beijing and Shanghai, large amounts of aerosols are emitted from both anthropogenic and natural sources, which cause a high ambient concentration and health burden (Kan et al., 2009). According to the results reported by fixed-site monitoring in Beijing, annual $PM_{2.5}$

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averages for 2005, 2006 and 2007 were 86.5, 93.5, and 84.4 μg/m^3, respectively (Zhao et al., 2009). This was approximately 10 times the concentration in Edinburgh of 8.5 μg/m^3 (Heal et al., 2005), seven times the concentration in New York City of 13 μg/m^3 (Qin et al., 2006), and 4 times the concentration in Tokyo of 20 μg/m^3 (Minoura et al., 2006).

High ambient concentrations of fine particles will threaten the human health in urban areas. Personal exposure measurement can provide insight into the routes and amounts of the pollutants to which the human population is directly exposed. However, in China there are few studies that document the personal exposure concentration to $PM_{2.5}$ and its components such as black carbon (BC) and metals. For a comparison between adults and children, there are no related studies. To better characterize exposure to $PM_{2.5}$, BC, and metals, a personal exposure study was conducted in Beijing. Participants in the study were school children and their teachers in a primary school, and office workers. This study is the first of its kind to report personal exposures of children in China, and to compare the exposure features of adult and child populations. Further, results reported here characterize $PM_{2.5}$ exposure concentrations in Beijing, where air quality is a concern, and analyze the possible influence factors.

1 Materials and methods

1.1 Study design

Personal exposure concentration is a function of the concentrations within various microenvironments visited as well as the time spent in those microenvironments. It can be defined by Eq. (1):

$$C_{\mathrm{E}} = (\sum C_i t_i)/t \quad (1)$$

where, C_{E} is the time-weighted concentration for personal exposure to a pollutant, C_i is the concentration of a pollutant in microenvironment i, and t_i is the fraction of modeled time spent in microenvironment i. t is the total exposure time. Our objective is to estimate the group difference between actual exposure concentrations of adults and children, and the relationship between personal exposure concentration and ambient concentration.

In Beijing, the personal exposure sampling was carried out in October, 2006 and November, 2007. During this period, participants were fitted with Personal Exposure Monitors (PEM) for 13 days, including 9 workdays and 4 weekend days. Fixed-site sampling of ambient $PM_{2.5}$ concentration occurred during the same time period. All participants were volunteers, who were drawn from two groups: school children and office workers from one primary school and three office buildings. The primary school and one office building are located in Qing Huayuan (QHY) Community, a residential area on the main part of a university's campus, is located northwest of Beijing's central urban area, outside the 4th Ring Road. The other two office buildings are located in the central business district near the east 3rd Ring Road.

School children, 10 to 11 years old, were invited children to participate in the study. The children were provided a demonstration of the personal exposure sampler (PEM), and given a written questionnaire requesting personal information, including age, gender, home address, telephone number, mode of transportation to school, transport time, and whether or not a smoker resided in the household. Based upon the questionnaire, a total of 29 children ultimately participated in the study, and from them, 43 child samples of 24-hr personal sampling periods were collected with the help of their teacher and parents. Forty one office workers (25–28 years old) were recruited. A total of 68 adult samples of 24-hr $PM_{2.5}$ exposure periods were collected. Four children and five adults participated the multiple days of sampling in order to provide a parallel comparison. In total, 114 personal samples were collected. This study complied with Tsinghua University's guidelines regarding the participation of human subjects in research.

To ensure consistency among the groups, all of the adults in this study were non-smokers, and both the school and office buildings had similar ventilation systems during the sampling period. The locations of volunteers' home, primary school, office buildings, and fixed monitoring site are shown in Fig. 1. Their home locations spanned the Beijing urban area to provide representation of the samples.

1.2 Sampling and analytical methods

$PM_{2.5}$ was collected with a $PM_{2.5}$ personal exposure monitor (PEM) (SKC Inc., USA) powered by portable pump (Research Triangle Institute, USA) using pre-weighed 37 mm Teflon filters (Pall Corp., USA). Each individual participating in the study was outfitted with a waist pack containing a PEM. $PM_{2.5}$ for personal samples was collected during 24-hr sampling periods by PEM. Concurrent with the personal sampling, ambient air was sampled by a dichotomous Model 241 sampler (TSI Inc., USA) located in the study community as shown in Fig. 1. All of the participants were asked to wear the backpack monitor at all times with the exception of bathing, sleeping, or changing clothes. Due to the bulky nature of the PEM and its possible restriction of movement, school children were asked to leave the personal samplers in the classroom during physical education class. Therefore, the samples from children exclude the influence of physical education activities at school.

$PM_{2.5}$ was analyzed in the lab of Research Triangle Institute by a gravimetric method (Lawless and Rodes, 1999). The filters were pre-weighed before sampling and re-weighed in the same laboratory; pre-weights were subtracted from the final weight to determine the total mass of $PM_{2.5}$ collected. Black carbon (BC) was analyzed by RTI using a multi-wavelength optical absorption technique (Lawless et al., 2004). The samples were then shipped to the Nuclear Laboratory at the University of Montreal for analysis of Mn, Al, and Ca by neutron activation analysis (NAA). Details regarding analysis by NAA may be found elsewhere (Pellizzari et al., 2001). Following analysis by NAA, the samples were returned to RTI for analysis of Pb,

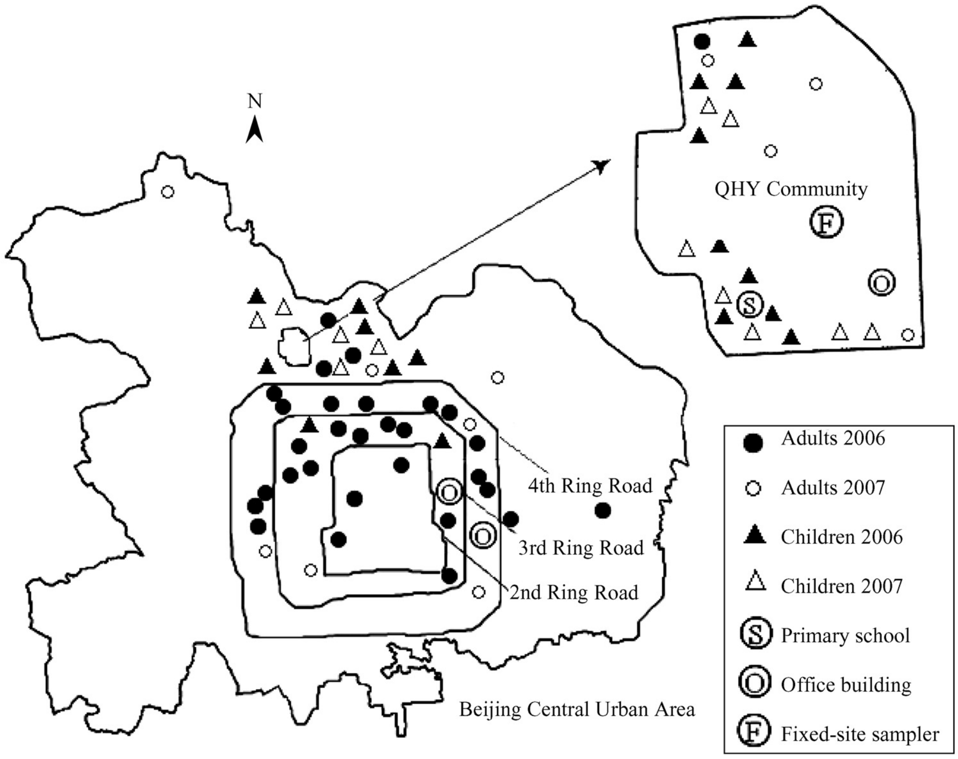

Fig. 1 Map for locations of volunteers' home, primary school, office building and fixed-site sampler.

and Fe by ICP-MS analysis.

1.3 Quality assurance and quality control

At the beginning of each sampling session, the pump flow rate was measured with a Drycal Lite flow meter (Bios Int., USA), and adjusted to 2 L per minute (± 5%). At the end of each sampling session, the flow was measured again. The pre- and post-sampling flow rates were averaged to calculate the $PM_{2.5}$ air concentrations. A PEM loaded with a blank filter was carried in the workplace for every 10 personal exposure samples. This PEM was placed in a sealed plastic bag and kept in the pump case during monitoring. Before and after the monitoring period, each PEM was stored in a plastic bag to avoid contamination during transport to and from the field sites. For gravimetric analyses, the balance was located in a constant temperature (± 1°C) and relative humidity (± 5%) chamber. Filters were hand-carried to the laboratory from the field-sampling locations. The limit of detection (LOD) for $PM_{2.5}$ was 2.5 μg/m^3. The LOD for Mn, Al, and Ca by NAA was 0.2, 1, 1 μg, respectively. For Pb, and Fe by ICP-MS, the LOD was 0.375, 150 ng, respectively. The minimum detection limit for BC on a filter was 0.3 g.

1.4 Questionnaire

Participants completed a time-activity diary (TAD) when they returned the PEM. Children were also asked to fill out the TAD. The TAD recorded their personal information and time-activity patterns, including age, home location, sampling time, traffic-related information and possible indoor and outdoor emission sources.

1.5 Statistical analysis

Statistical analysis was performed using the statistical software program SPSS (version 15.0). The Kolmogorov-Smirnov test was used to check for normal distribution. Differences of means were tested by the Wilcoxon Signed Ranks Test. Spearman Correlation was used to determine the association between two variables.

2 Results

2.1 Exposure characteristics

Personal exposures and ambient concentrations of $PM_{2.5}$ were high in our study. Concentration of $PM_{2.5}$, BC and metals for ambient and personal samples are summarized in Tables 1 and 2. For the 114 personal $PM_{2.5}$ samples, the overall personal mean exposure was 102.5 μg/m^3, which is significantly lower than the fixed-site concentrations ($P < 0.05$). In China, there is no ambient air quality standard for $PM_{2.5}$. Air quality guidelines of World Health Organization established 25 μg/m^3 as a reference concen-

Table 1 Statistic parameters of $PM_{2.5}$, blank carbon (BC) and metals for ambient samples (N = 13) (unit: μg/m^3)

Chemical	Mean	Max	Min	SD
$PM_{2.5}$	118.5	372.8	28.5	95.0
BC	11.0	21.2	3.6	4.7
Mn	0.107	0.220	0.038	0.054
Al	0.683	1.130	0.251	0.276
Ca	1.139	1.792	0.498	0.466
Pb	0.211	0.694	0.070	0.172
Fe	0.748	1.398	0.244	0.374

Table 2 Statistic parameters of $PM_{2.5}$, BC and metals for personal samples (N = 114) (unit: μg/m^3)

Chemical	Mean	Max	Min	SD	Spearman correlation		Wilcoxon signed ranks test
					R	P^a	P^b
$PM_{2.5}$	102.5	355.1	6.2	68.4	0.81	0.00	0.00
BC	14.7	29.6	0.3	6.8	0.61	0.00	0.00
Mn	0.093	0.203	0.011	0.043	0.67	0.00	0.00
Al	0.528	1.329	0.000	0.341	–0.14	0.13	0.01
Ca	0.934	3.93	0.000	0.718	0.20	0.03	0.01
Pb	0.174	1.251	0.006	0.174	0.54	0.00	0.00
Fe	0.703	2.691	0.000	0.439	0.29	0.00	0.00

[a] Spearman correlation between personal and fixed-site samples, $P < 0.05$ means significant association.
[b] Wilcoxon signed ranks test between personal and fixed-site samples, $P < 0.05$ means significant difference.

tration (RfC) for $PM_{2.5}$ (WHO, 2005). In this study, all of the $PM_{2.5}$ concentrations of ambient samples exceed the RfC value, and the average ambient concentration exceeds four times the RfC value.

2.2 Background data and personal activities information

The ambient concentrations and meteorological information during the sampling periods are shown in Table 3. There were four foggy days during the sampling period. The ambient concentrations on those days were much higher than the other non-foggy days in the same community. Wind speed, which was low on the foggy days and one other day, indicating the role of wind in the dispersal process of $PM_{2.5}$. In 2006, children and adults were sampled on different days, and the office buildings are located in east 3rd Ring Road, outside the QHY community. In 2007, children and adults were sampled simultaneously and the primary school and office building are located in the same community, as shown in Table 3.

Table 4 gathers the basic results of TAD in the study. In 2007, 20 adults and 16 school children were sampled simultaneously on workdays. The average exposure concentration for adults (121.4 μg/m^3) was 10.1 μg/m^3 higher than for children (111.3 μg/m^3) on workdays. It may be related to their time activity pattern. On average, the adults spent 39.6%, 54.2%, 6.2% of 24 hours in office, home, and traffic, respectively. Meanwhile, the children spent 33.1%, 62.4%, 4.5% of 24 hours in school, home, and traffic, respectively.

As shown in Fig. 2, adults in our study were typically young with an average age of 26, and their time-activity

Table 3 Ambient conditions during sampling periods

Date	Temperature (°C)	Wind speed (m/sec)	Relative humidity (%)	Other	Ambient fixed-site $PM_{2.5}$ (μg/m^3)	Subject
21 Oct, 2006	14	3	50	Rainy	38.5	Adults
23 Oct, 2006	10	1	60	No	125.5	Adults
25 Oct, 2006	10	2	46	Rainy	54.3	Adults
28 Oct, 2006	14	2	54	No	70.0	Adults
30 Oct, 2006	13	1	66	No	153.3	Adults
1 Nov, 2006	13	1	68	Foggy	139.7	Children
2 Nov, 2006	14	1	60	Foggy	139.4	Children
1 Nov, 2007	7	3	30	No	49.3	Both
3 Nov, 2007	10	2	47	No	64.2	Both
6 Nov, 2007	8	1	86	Foggy	372.8	Both
8 Nov, 2007	10	2	57	No	28.5	Both
10 Nov, 2007	7	1	51	No	171.3	Both
12 Nov, 2007	7	1	77	Foggy	155.1	Both

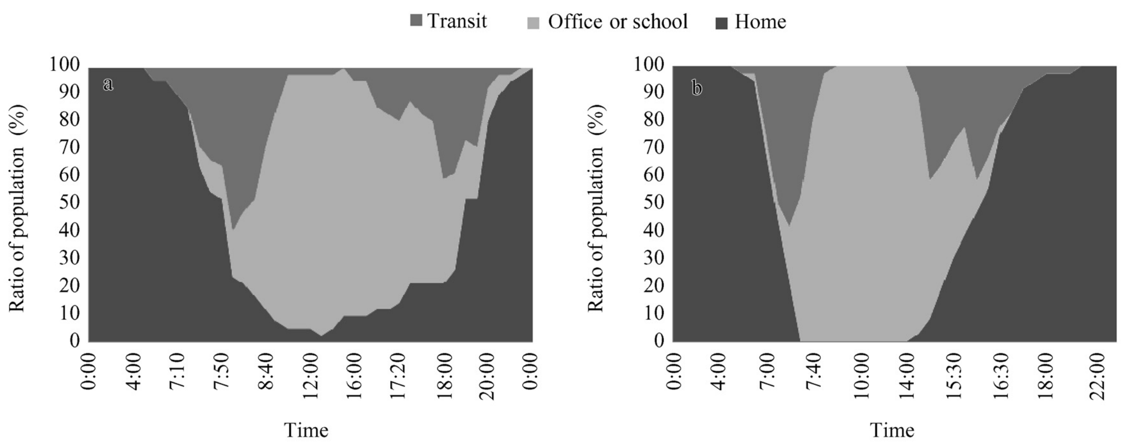

Fig. 2 Time activity patterns for adults and children. (a) time allocation of adults; (b) time allocation of children.

Table 4 Basic information of time activity diary

Category	Adult	Child
Sample size	71	43
Age (SD)	26.2 (3.3)	10.2 (0.5)
Exposed to smoking	6	5
Exposed to cooking	19	37
Residential heating	15	32

diary showed they were present in a traffic environment during two daily periods, 6 to 9 a.m. and 5 to 7 p.m. However, the children avoided the prime traffic rush hours; they were in traffic environments from 6 to 7 a.m. and 3 to 5 p.m. Moreover, adults spent 25 min more than children in traffic environments. These details may affect the microenvironment exposures.

As shown in Table 5, personal $PM_{2.5}$ concentrations were classified by different personal activities, including commute mode, sampling day (weekday or weekend) and exposure to heating and cooking. Building heating is provided by central heating system station in each community, so exposure to heating is considered to be an outdoor activity.

Table 5 Comparison of $PM_{2.5}$ exposure unit: levels according to different personal activities (unit: μg/m^3)

Personal activities		*N*	Mean	SD
Commute mode[c]	By bus and car[a]	39	129.2	86.3
	By bike and wal k[b]	34	91.8	54.6
Sampling day[c]	Workday	80	115.7	75.4
	Weekend	34	71.5	31.3
Heating[c]	Yes	47	115.8	67.2
	No	67	91.8	68.0
Cooking	Yes	56	112.4	94.9
	No	58	97.6	50.4

[a] Average commute time per day is 93 min, [b] average commute time per day is 42 min; [c] $P < 0.05$, statistical tests used were Wilcoxon rank test.

2.3 Personal exposure concentrations versus fixed-site concentrations

The relationship of $PM_{2.5}$ concentrations of the fixed-site monitor versus the personal sampler is described by Spearman Correlation, which is shown in Table 2 for $PM_{2.5}$, BC and metals. For overall samples in this study, the correlation coefficient of fixed-site ambient concentrations compared to the personal measurements of $PM_{2.5}$ is 0.81. Personal exposure concentrations of BC were significantly higher than fixed-site concentrations ($P <$ 0.05), and fixed-site concentrations of Mn, Al, Ca, Pb and Fe were significantly higher than personal exposures ($P <$ 0.05). This result reveals a strong association relationship between fixed-site concentration and personal exposure concentration, which shows ambient concentration having a dominate role in personal exposure to fine particles and some of its components.

2.4 Personal exposure concentrations for different groups

As shown in Fig. 3, in 2006, the mean $PM_{2.5}$ exposure concentrations of adults and children were: (86.8

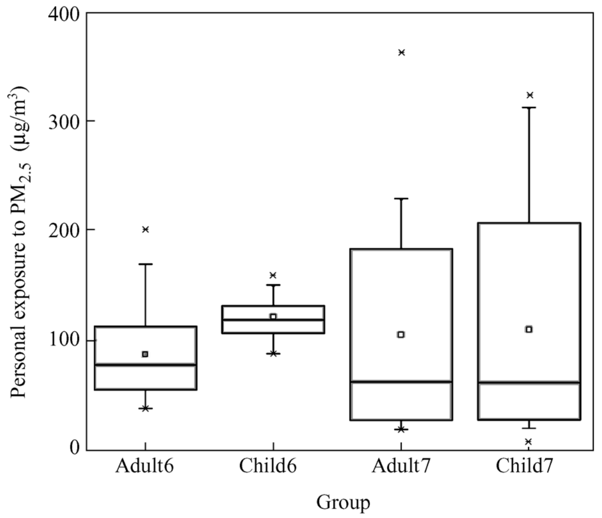

Fig. 3 Personal exposure concentrations of $PM_{2.5}$ for different groups.

± 37.7) μg/m^3, and (121.5 ± 19.0) μg/m^3, respectively. The exposure concentrations of adults were significantly different from those of children ($P < 0.05$). In 2007, the mean $PM_{2.5}$ exposure concentrations of adults and children were: (105.2 ± 87.2) μg/m^3, and (109.8 ± 99.8) μg/m^3, respectively. However, there is no significant difference between exposure concentrations of adults and children ($P > 0.05$), but a significant association between exposure concentrations of these two groups (adult1 and adult2) (P < 0.05).

In 2007, two office workers (adult1 and adult2), two school children (child1 and child2) and the teacher participated simultaneously in the whole process of personal exposure sampling to observe parallel trends. The 24-hr exposures for these five participants and fixed-site monitoring results are shown in Fig. 4. It illustrates an obviously consistent trend for these six types of mass concentrations. Table 6 lists the result of Spearman correlation analysis for these parallel samples, which provides evidence of a strong association between exposure concentrations of adults and children in the study. Therefore, in 2006, the significant difference of $PM_{2.5}$ exposure concentrations

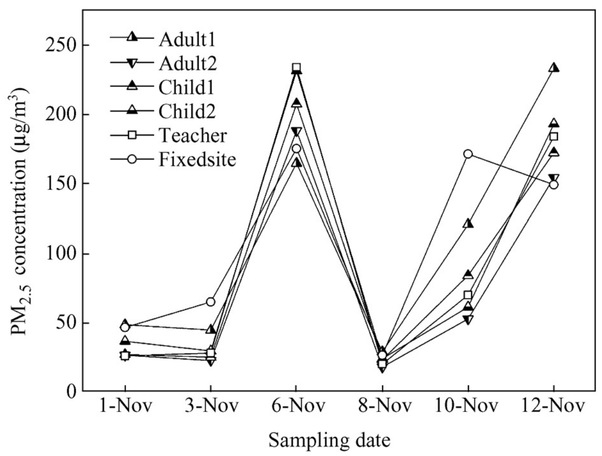

Fig. 4 Time series plots of ambient fixed-site concentration and personal exposure to $PM_{2.5}$.

Table 6 Spearman Correlation for personal parallel samples and ambient samples

Category	Adult1	Adult2	Child1	Child2	Teacher	Fixed-site
Adult1	1.000	0.885*	0.909*	0.883*	0.880*	0.832*
Adult2	0.885*	1.000	0.992**	1.000**	0.999**	0.774
Child1	0.909*	0.992**	1.000	0.988**	0.995**	0.842*
Child2	0.883*	1.000**	0.988**	1.000	0.997**	0.757
Teacher	0.880*	0.999**	0.995**	0.997**	1.000	0.795
Fixedsite	0.832*	0.774	0.842*	0.757	0.795	1.000

* $P < 0.05$; ** $P < 0.01$.

between adults and children were mainly influenced by ambient concentrations of different sampling days, not by the different groups of people.

3 Discussion

3.1 Influence of ambient concentration

To better understand the results reported here, it is helpful to consider the components of personal exposures. Total personal exposure can be considered the sum of two components: ambient and non-ambient exposures (Ott et al., 2000). The ambient component includes exposure to the ambient PM concentration that exists outdoors and exposure to ambient PM that has infiltrated indoors. The non-ambient component refers to exposure from personal activity to PM generated by indoor sources, such as cooking (Lung et al., 2007).

Several studies investigated the contribution of the ambient component in recent years. Some studies found that outdoor PM concentration was a poor indicator of personal exposure (*r* in the range of 0.25–0.54) (Kousa et al., 2002; Williams et al., 2008), while other studies have shown reasonable correlations between ambient fixed-site monitoring and personal exposures (*r* in the range of 0.75–0.82) (Janssen et al., 1999; Landis et al., 2001). In our exposure study, outdoor $PM_{2.5}$ was found to have a strong correlation with personal exposure ($r = 0.81$). This result is consistent with the Baltimore study and Wageningen study, and revealed that the ambient component was the dominant contributing source to personal exposure.

Some studies focus on the relationship between disease responses and particulate matter exposure levels in children living in developed countries (Janssen et al., 1999; Wu et al., 2005; Nikasinovic et al., 2006; Van Roosbroeck et al., 2007). The greater sensitivity of children than adults to particulate matter is justification for these studies. As shown in Table 7, the $PM_{2.5}$ exposure levels for children in this study were 4–5 times higher than those in the related studies. The ambient concentrations were also significantly higher, thus, indicating the need for additional studies of health outcomes of childhood exposures in developing nations.

3.2 Influence by personal activities

Some non-ambient factors may contribute to particle exposure. In our study, the personal exposure concentrations on workdays were 44.2 μg/m^3, being higher than those on weekend days ($P < 0.05$), as shown in Table 5. Additionally, Fig. 4 reveals the different trends between weekend and workday. On weekends (November 3 and November 10), all of the personal exposure levels were much lower than the fixed-site concentrations. However, on workdays, some personal samples were higher than the fixed-site concentrations. Especially on November 12, all of the personal exposures were higher than the fixed-site concentrations. According to the TAD, over 90% of sampled subjects stayed at home on weekends. Therefore, their exposure levels were less affected by outdoor concentrations on weekends than on workdays. If the personal exposure concentration during weekends in our study is taken as an indicator of indoor exposure concentration, and fixed site concentration is considered to be outdoor concentration, ratios of indoor to outdoor (I/O) may be estimated. The average ratio of I/O was 0.81 for $PM_{2.5}$ on weekends. As reported in the publications (Kingham et al., 2000; Crist et al., 2008; Johannesson et al., 2007, Balasubramanian et al., 2007), the I/O values were 0.8–2.98. Compared to other cities during the sampling period, indoor air was much cleaner than outdoor, and the high ambient concentration of $PM_{2.5}$ was the key influence factor for personal exposure in Beijing.

Studies of microenvironments offer strong evidence that traffic contributes to personal $PM_{2.5}$ exposures. In London, UK, a comprehensive study showed that the cyclists had the lowest exposure levels; bus and car were slightly higher (Adams et al., 2001). Recent research implemented in Beijing, which measured PM_{10} in buses, taxis, subways and railway cars in Beijing from 2004 to 2006 showed that

Table 7 Result of related studies on children exposures to $PM_{2.5}$

Personal		Ambient		Reference
Concentration (μg/m^3)	*N*	Concentration (μg/m^3)	*N*	
115.3	43	118.5	13	This study, 2007
28.3	77	17.1	13	Janssen et al., 1999
24.2	202	10.8	58	Wu et al., 2005
30.4 (42.4)	41 (44)	24.0 (PM_{10})	N.A.*	Nikasinovic et al., 2006
27, 40, 20, 23	46, 38, 53, 55	19, 19, 17, 17	10,10,13,13	Van Roosbroeck et al., 2007

* N.A. means the study did not offer the data.

bus interiors have the worst air quality (Li et al., 2008). Table 5 illustrates that personal exposure concentration of the group commuting by bike and walking was 37.4 μg/m^3 lower than those traveling by bus and car ($P < 0.05$). This result indicates that the higher ambient PM concentrations in traffic microenvironments contributed to personal exposures, which is similar to related studies.

Cooking is also reported as an indoor source of particles (Wallace, 2003; Lung, 2007). Chinese cooking using hot oil often creates more smoke than typical Western cooking. A study in Taiwan showed that the population who cooked or spent time in the kitchen during the sampling period had on average 22.9 μg/m^3 higher exposure concentration of PM_{10} than those who did not (Lung, 2007). All of the participants in our study used natural gas or electric stoves rather than biomass or coal stoves for cooking. Table 5 shows that adults who cooked at home averaged 14.8 μg/m^3 higher exposures to $PM_{2.5}$ than those who did not cook. However, the difference between the cooking and non-cooking groups is not statistically significant. This might be related to the extra high ambient concentration, which masked the contribution caused by personal activity to the daily exposure.

4 Conclusions

The result reported here is the first to compare human $PM_{2.5}$ exposure concentrations for children and adults who reside in Beijing, a mega-city of China. It covers basic exposure information for the specific subjects. The results suggest that the average value of personal exposure concentration was 102.5 μg/m^3, and the mean fixed-site concentration was 118.5 μg/m^3. The ambient $PM_{2.5}$ concentrations during sampling period were above the 25 μg/m^3 WHO air quality guideline for $PM_{2.5}$. There is no significant difference between exposure concentrations of adults and children sampled simultaneously.

Additionally, the result of this study shows the $PM_{2.5}$ ambient concentration, which was measured by a fixed-site monitor, was the dominant factor in personal exposure during the sampling period. A strong correlation relationship was found between fixed-site concentration and personal exposure concentration (overall samples, $r = 0.81$), indicating outdoor sources as an important contributor to personal $PM_{2.5}$ levels. The personal exposure concentrations of BC, Mn, Ca, Pb and Fe were also significantly correlated with the fixed-site concentrations.

However, the ambient concentration is not a good indicator of personal exposure concentration because there is significant difference between them. Personal activities, such as commute mode, exposure on workday or weekend days, exposure to heating and to cooking influenced exposure concentrations. The outdoor activities influenced the personal exposure concentrations significantly. But the magnitude of the influence from indoor activity (cooking) is likely concealed by high ambient PM concentrations.

An investigation into the influence of indoor activities on PM exposure would require a decrease in the ambient outdoor exposures, in order to make effective policies to decrease the personal exposure level and protect human health.

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