RESEARCH ARTICLE
doi: 10.2306/scienceasia1513-1874.2005.31.359

Exposure to PM-10 of Shop House Dwellers in Bangkok, Thailand

Pensri Watchalayann,[a] Thares Srisatit,[b*] Daniel J. Watts[c] and Pichaya Rachadawong[b]

[a] National Research Center for Environmental and Hazardous Waste Management, Chulalongkorn University, Bangkok 10330, Thailand.
[b] Department of Environmental Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand.
[c] Otto H. York Center for Environmental Engineering and Science, New Jersey Institute of Technology, Newark, New Jersey 07102-1982, USA.

* Corresponding author, E-mail: fentss@eng.chula.ac.th

Received 8 Dec 2004
Accepted 17 Jun 2005

ABSTRACT: Relationships between personal PM-10 exposure and indoor and outdoor PM-10 concentrations were investigated among 28 non-smoking participants who lived in roadside buildings. The nine repeated measurements covered 3 seasons and were conducted with individuals living in 14 shop houses on Sukhumvit Road, Bangkok. The averages of personal exposure, and indoor and outdoor PM-10 concentrations were 81.6, 74.6 and 130.7 $\mu g/m^3$ respectively. The overall mean of the outdoor concentrations exceeded both the indoor and personal PM-10 exposure concentrations, and the levels were higher in winter than in the summer or rainy seasons. Variations in the indoor PM-10 concentrations were found from floor to floor, with the highest levels measured on the first floor of the shop house. Even for people living in the same houses, personal PM-10 exposure concentrations could be different. Nonetheless, the result showed that the personal PM-10 exposure level was well correlated with the outdoor concentration. The correlation between personal exposure and outdoor PM-10 concentration was moderate with a median Pearson's R correlation of 0.706. Excluding a house with a parking space, the median Pearson's R correlation increased to 0.760. In addition to the contributions from the outdoor PM-10 concentrations, the personal PM-10 exposure concentrations tended to be higher under conditions of incense burning, exposure to tobacco smoke, door opening, and during the winter season. However, sleeping in a bedroom with an air conditioning system tended to lower the personal PM-10 exposure concentrations. This finding supported a conclusion that outdoor PM-10 concentration could be used as an exposure surrogate in a health impact epidemiological study for people living this life-style.

KEYWORDS: Particulate Matter, PM-10, Personal Exposure, Person – Outdoor Relationship, Shop House.

INTRODUCTION

Particulate matter air pollution is comprised of solid or liquid forms of various chemicals of chemical and physical properties (such as size, shape, density and composition), surrounded by air molecules.[1] Typically, the size distribution of particles in ambient air is presented as consisting of two modes. The coarse mode usually refers to particles with aerodynamic diameters between 2.5 and 10 μm (PM-10), and the fine mode refers to particles with aerodynamic diameter less than 2.5 μm (PM-2.5). Particulate matter is currently studied extensively because several recent epidemiological studies of particulate exposure have concluded that there are relationships between ambient particulate air pollution and adverse health outcomes.[2,3,4,5] A recent analysis of epidemiologic data in China allowed derivation of a coefficient that indicates an increase of 0.03% in all-cause mortality per an increase of every $\mu g/m^3$ of PM-10 over normal background.[6] The paper compared the projected increase found in the China studies with previous studies in Europe and the United States and concludes that the increase in mortality may be even greater in areas with lower background PM-10 levels. As a point of reference for PM-10 levels in an area with no industrial activity and low traffic, a study in Finland reported a mean ambient PM-10 level over a 57 day period of 13 $\mu g/m^3$ in a suburban community in winter.[7] Similarly, a study[8] in Hong Kong has reported that for the fall and winter seasons the mean indoor PM-10 concentration was 63.3 $\mu g/m^3$, while the corresponding outdoor level was 69.5$\mu g/m^3$. Several approaches both direct and indirect, have been used to estimate personal exposure to PM.[9,10,11]

In most existing studies of PM-10 and health effects, the ambient particulate concentrations obtained from fixed site air monitoring networks are typically used as representatives of the totality of the PM-10 concentrations that people are presumed to be exposed to during all aspects of their daily lives. However, the validity and reliability of this presumption remain to be determined by comparison with the results of personal exposure measurement.[12] The results of previous studies on the relationship between personal exposure and outdoor PM concentrations have suggested that the correlations are likely to vary in a wide range and cross-sectional correlations ($R = -0.08$ to 0.62) are typically smaller than longitudinal correlations ($R = 0.26$ to 0.68).[13,14,15,16,17] Personal exposure to PM, which varies from day to day and from person to person, is likely to depend on geographical location, climate, seasonal conditions, and building construction as well as individual activity patterns.[18,19,20]

Most of the recent studies were conducted widely in residential areas in several countries. However the information is still quite limited for a city like Bangkok, which is different in culture, living style and climate from the areas where the previous studies have been carried out. In spite of the significant decline of TSP and PM-10 in the general areas of Bangkok since 1995, the average PM-10 concentrations measured at roadside stations in the city have not significantly changed. At present, the Thailand National Ambient Air Quality Standards (NAAQS) estimated the levels of 24-hour average PM-10 and annual average (arithmetic mean) PM-10 to be 120 and 50 g/m^3 respectively. The percentages of measurements where PM-10 exceeded the 24 hr standard limit value in 1998, 1999 and 2000 are 6.38, 8.0 and 12.8 respectively.[21] Public health and public environmental policy issue can best be moved forward based upon a clear understanding of the possible exposure of people to these air contaminants. This study was prompted by a need to understand the possible exposure of residents of specialized housing/ occupational buildings in Bangkok.

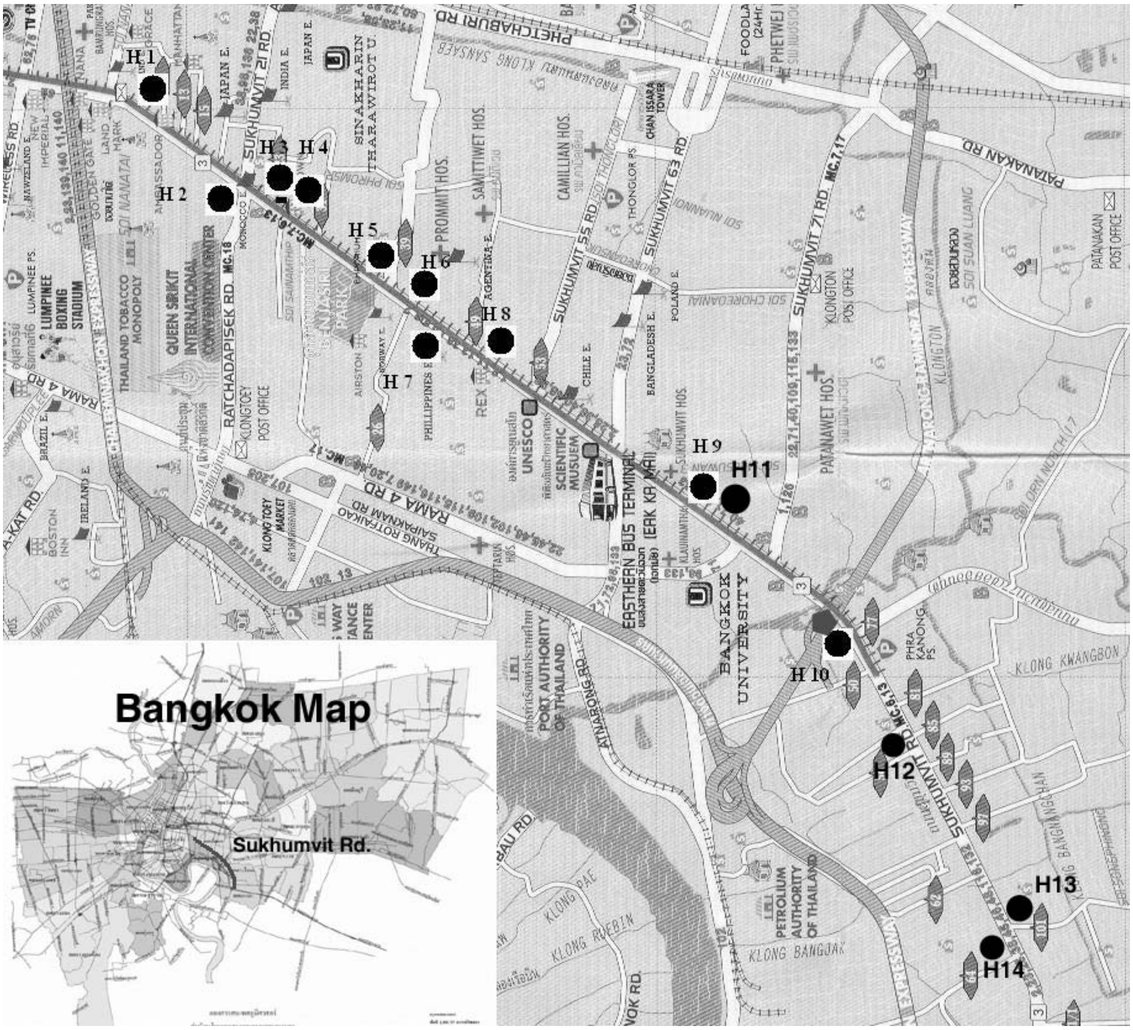

Fig 1. Location of the 14 shop houses: and the On-Nuch roadside station:

Typically along many roads in Bangkok, there are numbers of commercial curbside buildings called "shop houses" where the same people both work and live. This group of people could be one of the high-risk groups with regards to PM-10 air pollution even though they spend most of their time indoors. However, there are few studies that provide simultaneous measurement of PM-10 concentrations representative of personal exposure as well as indoor and outdoor air levels. In one study on indoor/outdoor PM-10 and PM-2.5 concentrations in Bangkok, personal exposure, which was calculated from indirect microenvironment measurement, suggested that the ambient PM-10 concentrations were moderately correlated with the indoor concentrations and had potential for estimating personal exposure for residents living in areas with no indoor sources.[22] Another investigation on roadside particulate air pollution in Bangkok found that the exposure of police officers to roadside PM-10 during their work periods was well correlated with the PM-10 level monitored at the roadside ($R = 0.93$).[23] While the existing ambient concentrations taken at street level have significant value, a question still remains as to whether they could be used as a PM-10 exposure surrogate for individuals in the "shop house" life-style situation. The aims of this study were: (1) to determine within the same time frame PM-10 concentrations representative of personal exposure, as well as indoor and outdoor air (2) to investigate the relationships between PM-10 concentrations obtained from personal exposure, indoor and outdoor measurements; and (3) to determine the additional factors influencing on personal PM-10 exposure of shop house dwellers in Bangkok.

Materials and Methods

Sampling Site

Sukhumvit Road is one of the roads in Bangkok with both a large traffic burden and a representative distribution of building types and styles of life along its length. Along the road from Soi 1 to Soi 105 (which are side streets), a distance of approximately 11 km running from the inner zone to the outer zone of Bangkok, there are large numbers of shop houses on both sides of the road. The Pollution Control Department of Thailand, PCD, has monitored the ambient air quality in the Sukhumvit area for several years using both the general station at Bangna and the roadside station at On-Nuch. Based on their willingness to volunteer and the location of their homes, the occupants of 14 shop houses in which the owners and/or workmen live upstairs, were invited to participate in this study, especially those residing in non-smoking households. All the houses are within a radius of approximately 7 km from the On-Nuch ambient roadside monitoring station as shown in Figure 1.

Study Design

For each participating house, four types of PM-10 measurements, namely indoor air, outdoor air, personal monitoring and ambient roadside air, were performed simultaneously and repeatedly for 3 consecutive days per season and only on weekdays. Measurements were conducted in all three seasons from December 2002 to August 2003 (winter: December to January, summer: March to May and the rainy season: June to August). Thus a total of nine measurements per subject/sampling location were obtained. All samples were programmed to be collected for 24 hrs from 10:00 a.m. of the first day to 10:00 a.m. of the next day.

For indoor measurements, three sampling locations were selected in each shop house on the 1^{st,} 2nd and 4th floors. The measurements were taken by placing Personal Environmental Monitor (PEM) instruments at about 1.5 m height from the floor. The 1st floor or ground floor normally was the shop area, whereas the 2nd and 4th floor contained living or bed rooms. The outdoor measurement was made by placing a PEM outside the building on the 2nd floor balcony about 5 m above ground level. The ambient roadside measurement was taken at the On-Nuch station using a High Volume PM-10 Air Sampler.

To obtain an estimate of personal PM-10 exposure concentrations, 2 participants in each shop house were instructed to carry the PEM instrument, which consisted of an air sampler pump set in an acoustic leather bag, for a 24 hr period. They were instructed further to attach the impactor near their breathing zone during the daytime and to place the instrument near their beds during the night. Questionnaires were used to obtain information about household characteristics including floor plan, air conditioning usage, potential indoor sources of particulates, cooking fuel and time-activity pattern of the participants. In addition, the subjects were interviewed after each day of measurements for recording of their daily activities such as incense usage, cooking, cleaning, time spent outdoor, exposure to tobacco smoke, and similar issues.

Sampling Equipment and Materials

A Personal Environmental Monitor Model 200 (PEM^{TM}, MSP Corporation, USA.), containing a single-stage impactor in which particles smaller than 10 μm are collected on a 37 mm filter (2 μm PTFE filter with PMP support ring, SKC Inc., USA.), was connected to a personal air sampler pump (model 224-PCXR 8, SKC). To obtain a 24 hr integrated measurement while preventing filter overloading and battery failure, the sampler pumps were programmed for 23 hr 30 min of sampling periods with intermittent operation (1 min on and 1 min off). The batteries of the pumps were modified by using 3000 mAh metal hydride batteries to achieve sampling for an entire day without need for battery charging. The pump flow rate was calibrated with an automatic flow meter (Dry Cal, Bios.) to 4±0.05 l/min before sampling and was also checked again after sampling. The average flow rate and the sampling time were used to compute the sample volume.

The filters were analyzed gravimetrically by using a microbalance with 1 μg reading precision (Sartorius MC5, Germany). The filters, both before and after sampling, were desiccated for 24 hr and weighed twice to determine the weight (net mass) gain of sample in the controlled room at a temperature of 23±5 °C and relative humidity of 45±5%. Laboratory filter blanks 3/50 were desiccated and used as controls in the same weighing procedure in cases where the change of mass of the lab blanks was within 10 μg. A field blank was obtained for each day of measurements by placing a clean filter near the indoor sampling location for 24 hr. The field blank PM mass was 11.5±8.3 μg (n = 135). All PM-10 mass data were corrected with the corresponding field blanks.

A High Volume Air Sampler for PM-10 (ASI/GMW Model 1200) with Volumetric Flow Controller (VFC) was used to collect roadside PM-10 for 24 hr. The sampler was calibrated by an orifice transfer standard (GMW 25A) to ensure a flow rate of 1.13 m^3/min. The 8 x 10 inch quartz fiber filters (SKC), both before and after sampling, were conditioned for 24 hr in a desiccator and then weighed in a humidity and temperature-controlled room at the laboratory of PCD.

Field Comparison and Data Analysis

Because of the difference in the two PM-10 measurement methods, High volume PM-10 Sampler and PEM instruments, these two methods were assessed to determine the data comparability by placing a PEM instrument near the High Volume PM-10 sampler at On-Nuch station for a 24 hr collocation sampling study. The correlation coefficient, r, was 0.98 (n = 18) and the estimated regression equation was PEM = 1.304 x Hi-Volume. The results indicated that these two instruments could reflect the day to day variation of PM-10 consistently and was comparable, although the PM 10 concentration obtained from the PEM was higher than that from the High Volume PM-10 Sampler. There are reproducible differences between PM-10 measurements made by different instrumental techniques. For example Williams et al.[24] reported that differences for the ratio of PEM to other measurements ranged up to 1.22, which is comparable to the factor of 1.3 found in this study. Their explanations for the difference (which is an unavoidable result of differing instrumentation) include differences in cut-points, potential ammonium nitrate losses in the high volume samplers, influence of wind speed, and losses in semi-volatile carbon compounds as a result of the higher velocity in the high volume samplers. In this study the comparison was made to determine whether there was a correlation between the two measurement techniques, not to demonstrate an exact match between the PM-10 levels.

To determine the precision of the PEM instrument under these conditions, 5 sets of PEM equipment were set up to perform the 24 hr PM-10 sampling in the same room and the resulting PM-10 concentrations were calculated. This operation was run 3 times. The relative standard deviations of the results for the three runs were 4.05, 3.72 and 5.1%, indicating that the PEM instrument was reliable for measuring PM-10 concentration with high precision. In addition, a High Volume PM-10 Sampler from PCD and the identical one from this study were placed close together for 10 days. The result showed that the PM-10 measurement by this method in this study is in good agreement with the PCD measurement (γ = 0.998; n= 7).

The descriptive statistical method was used to evaluate levels and distribution of outdoor, indoor and personal exposure concentrations. Analysis of Variance and paired T- tests were applied for comparison between indoor and personal exposure concentration. The individual longitudinal correlations between personal exposure, indoor and outdoor PM-10 levels were investigated by simple linear regression. Factors influencing personal exposure concentrations were determined by multiple step-wise regression analysis.

RESULTS

Personal Exposure, Indoor, Outdoor and Roadside PM-10 Concentrations

Among the 14 shop houses in this study, ten shop houses are 4-story buildings, two of them are 3- story, and the remainder are 5 and 2 story buildings. Twelve of the shop houses still run their businesses as usual. All the houses use LPG as fuel for cooking and most of them do cooking once a day. The kitchens were at the 1st floor except for H1, H5 and H9 that had their kitchens on the 2nd floor. A total of 28 individuals participated in the study with ages ranging from 20 to 75 years old. The interviews revealed that most of the participants spent more than 95% of their time indoors with little exercise and going outside. The average time spent indoors was about 23 hrs 13 minutes and the average time spent outdoors was about 47 minutes (range between 0 to 600 min).

For each house/participant, the individual mean of indoor, outdoor, ambient roadside and personal PM-

Table 1. Descriptive statistics of the overall mean of indoor, 1st floor, 2nd floor and 4th floor, outdoor, ambient roadside and personal PM-10 exposure concentrations.

Sampling site	N	# ( )*	PM-10 concentrations: $\mu g/m^3$ Mean	SD	Median	Range
1st floor	14	134 (1)	87.5	31.5	81.8	37.7 to 163.8
2nd floor	14	130 (5)	67.1	18.6	64.4	38.9 to 101.7
4th floor	12	111 (6)	63.8	13.3	61.3	39.8 to 84.3
Indoor	14		74.6	19.5	73.1	38.7 to 122.1
Outdoor	14	131 (4)	130.7	39.0	115.5	91.4 to 207.8
Ambient	1	133 (2)	155.0	29.7	156.1	85.2 to 248.1
Person	28	259 (11)	81.6	14.3	81.5	41.0 to 155.4

* # Total number of observations, ( ) Numbers of missing data.

10 exposure concentrations were calculated using eight to nine measurements except for H3 where fifteen to eighteen measurements were obtained. Three indoor sampling locations were on the 1st, 2nd and 4th floors, except for H1 and H 6 where there were only 2 indoor sampling sites on the 1st and 2nd floors. In these two cases, H1 permitted sampling no higher than the 2nd floor and H6 is a 2 story building. H7 and H8 are 3 story buildings so their 3rd floor PM-10 concentrations were used as the 4th floor concentrations. To get a single indoor concentration, the 1st, 2nd and 4th floor PM concentrations for each day were averaged. Summarized distribution of the individual average concentrations of PM-10 measured in shop houses are shown in Table 1.

The overall mean of outdoor PM-10 concentration significantly exceeded the personal exposure and indoor concentrations as tested by t-test ($p < 0.001$) but the mean personal and indoor concentrations showed no statistical difference ($p = 0.428$). Comparison of the 1st, 2nd and 4th floor PM-10 concentrations by Two-Way ANOVA and Multiple Comparison: Least-Significant Difference method, revealed that the overall mean PM-10 level on the 1st floor was significantly different from the 2nd and 4th floor means ($p < 0.001$), whereas the overall mean PM-10 concentration on the 2nd floor was similar to that of the 4th floor ($p = 0.297$). The mean outdoor concentration was less than the mean of the ambient roadside concentration ($p = 0.037$). The ambient roadside PM-10 concentration had an average value of about 155.0 $\mu g/m^3$. The average of ambient PM-10 concentrations in winter was higher than those in the hot and rainy seasons, which were 189.3, 141.7 and 133.8 $\mu g/m^3$ respectively. Based on comparison with the Thailand National Ambient Air Quality Standards (NAAQS), the average of ambient PM-10 concentration exceeded the NAAQS for a 24 hr average and for an annual average, while the average exposure concentration, of 81.6 $\mu g/m^3$, was higher than the NAAQS for annual average of PM-10.

Investigation of indoor PM-10 concentrations showed that the PM-10 indoor levels fluctuated widely from house to house and from floor to floor (Table 2). The highest indoor concentration was found in H12, while the lowest was in H7. The differences in PM-10 levels on different floors in each house were also examined using Random Block Design-Analysis of Variance (RBD-ANOVA) except that H1 and H6 were tested using Paired T-Test. The results showed that for, 12 of the 14 houses, PM-10 levels on each floor were statistically different ($p < 0.05$) as shown in Table 2.

All 28 participants completed the personal PM-10 measurements. The variations in personal exposure to PM-10 among participants were substantial, ranging from 41.0 to 155.4 $\mu g/m^3$ (Table 3). The mean difference between two personal exposure concentrations was 10.5 $\mu g/m^3$, with a range from 0.2 to 43.3 $\mu g/m^3$. Comparing personal exposure concentrations in each house by Paired T-Test, revealed that there were 4 houses, namely H3, H6 and H10 and H14 where the personal PM-10 exposure concentrations between two participants were significantly different ($p < 0.05$).

The Relationships among Personal Exposure, Indoor and Outdoor PM-10 Concentrations

Regression and correlation analyses were used to determine the relationship between personal exposure,

Table 2. Indoor PM-10 concentrations on the 1st, 2nd and 4th floor for each house.

	PM-10 concentration ($\mu g/m^3$); Mean±SD: n=9 1st floor	2nd floor	4th floor	P-Value (RBD-ANOVA)
H1	61.3±13.6	84.0±16.4	NA	0.006 (Paired t-test)
H2	59.5±19.2	43.6±13.4[a]	56.0±24.7	0.005
H 3	87.5±25.5[b]	62.6±17.0[c]	56.0±12.0[d]	0.000
H 4	69.5±18.5	66.1±14.5	59.5±14.9[a]	0.026
H 5	66.8±25.9	56.7±31.0[a]	58.8±17.1	0.082
H 6	117.4±30.1	46.8±16.7	NA	0.000 (Paired t-test)
H 7	37.7±16.6[a]	38.9±13.2	39.8±13.5	0.425
H 8	77.7±31.4	58.9±25.7	63.0±21.5	0.032
H 9	114.9±35.3	73.2±24.5	78.3±22.9	0.000
H 10	103.7±70.8	72.4±24.8[a]	75.0±39.7[a]	0.039
H 11	76.0±19.6	101.7±33.9	84.3±29.5	0.023
H 12	163.8±48.1	97.9±33.6[a]	76.8±24.8[a]	0.000
H 13	85.9±18.4	73.4±14.7	69.5±17.5	0.000
H14	103.2±47.3	62.8±37.2	48.1±18.2	0.000

a: number of observation = 8; missing data = 1,
b: number of observation = 18,
c: number of observation = 17; missing data = 1,
d: number of observation = 15; missing data = 3.

Table 3. Comparison of personal PM-10 exposure concentrations between the participants in the same shop house.

	Mean of personal PM-10 concentration; $\mu g/m^3$				P1 vs. P2	
	n	Person1: P1	n	Person2: P2	P-Value	n*
H 1	8	44.6±10.5	8	44.8±10.9	0.814	8
H 2	9	89.7±23.6	8	72.7±17.9	0.067	8
H 3	16	78.7±18.9	16	88.3±23.1	0.015	14
H 4	9	69.1±21.0	9	84.6±30.8	0.067	9
H 5	9	65.1±24.4	9	64.7±23.0	0.953	9
H 6	9	66.6±35.1	8	103.8±38.0	0.009	8
H 7	8	41.4±17.4	9	44.1±17.7	0.699	8
H 8	9	65.0±26.5	9	74.4±31.4	0.224	9
H 9	9	101.2±32.8	9	106.9±37.7	0.451	9
H 10	9	95.0±61.1	9	102.6±68.9	0.041	9
H 11	9	103.3±34.3	9	97.7±27.9	0.208	9
H 12	9	154.7±48.5	9	155.4±33.4	0.953	9
H 13	8	96.2±32.7	8	84.2±16.3	0.834	7
H 14	9	41.03±19.4	9	49.8±16.7	0.007	9

* Number of paired observation data.

indoor and outdoor concentrations in the three following models: model 1 (person-outdoor), model 2 (person-indoor) and model 3 (indoor-outdoor). The distribution of individual correlations is not normal (Shapiro-Wilk Statistic, $p < 0.01$), as presented in Table 4. Median regression and correlation coefficients for the three models were statistically significant (p 0.001), but the median intercepts for the three models were not significant ($p > 0.05$).

The median correlation coefficient of model 2 was higher than that determined for model 1, indicating that personal exposure concentrations were in better agreement with indoor rather than outdoor PM-10 levels. Examination into individual correlation coefficients for model 1 revealed that there were three negative correlation coefficients (-0.049, -0.772 and -0.798) of which the two highest values belonged to participants in H14 where their cars were typically parked inside the house. In contrast, the correlation coefficients for model 2 (person-indoor) of H14 were strongly positive (0.846 and 0.938). Excluding data from H14, the median correlation coefficient was increased from 0.706 to 0.760 for model 1 and from 0.824 to 0.828 for model 3, while the median correlation coefficient for model 2 was not changed from 0.865.

Factors Affecting Personal PM-10 Exposure Concentrations

The results showed that the indoor concentrations were lower than the personal PM-10 exposure concentrations, while the outdoor concentrations exceeded the personal PM-10 exposure levels. Thus outdoor PM-10 levels could serve as a basis for estimation of personal exposure. Aside from the outdoor PM-10 levels, other environmental factors and personal activities were determined to contribute

Table 4. Correlation and regression for the relationship between personal exposure, indoor and outdoor PM-10 concentrations.

	Model 1 (n= 28) $PM10_{person}=PM10_{outdoor}$		Model 2 (n= 28) $PM10_{person}=PM10_{indoor}$		Model 3 (n= 14) $PM10_{indoor}=PM10_{outdoor}$	
	Median	Range	Median	Range	Median	Range
Intercept $\mu g/m^3$*	21.2	-114.8, 78.9	2.9	-50.2, 78.8	4.6	-67.6,131.4
Slope**	0.488	-0.167,1.503	1.071	0.485,1.718	0.461	-0.289,1.066
Pearson's R**	0.706	-0.798,0.937	0.865	0.548, 0.980	0.824	-0.826,0.981

* Median intercepts for three models were not significant (Wilcoxon Signed Rank Test; p = 0.05)
** Median regression and correlation coefficients for three models were significant (Wilcoxon Signed Rank Test; p = 0.05).

Table 5. Categorized variables examined in multiple step-wise regression analysis.

Environmental Factors: Characteristic examined	P-Value	Personal activities: Characteristic examined	P-Value
Outdoor concentration; $\mu g/m^3$	0.000	Cleaning; Yes/No	0.132
Season: Winter	0.000	Cooking; Yes/No	0.287
: Summer	0.051	Gold sleeve paper burning; Yes/No	0.315
: Rainy	0.051	Incense burning; Yes/No	0.001
Under Sky train station alignment; Yes/No	0.509	Exercise; Yes/No	0.560
Bedroom; at 1st floor or Else	0.345	Expose to tobacco Smoke; Yes/No	0.000
House location; Left/Right(of the road)	0.063	Time spent outdoors; Minutes	0.645
Raining on the measurement day; Yes/No	0.166		
Door of 1st floor; Opened/Closed	0.000		
Air conditioned bedroom; Yes/ No	0.000		

to the personal PM-10 exposure concentrations as listed in Table 5. Six variables namely outdoor concentration, winter season, door on the 1st floor kept open, bedroom with air conditioning system, incense burning and exposure to tobacco smoke; have significant influences on personal PM-10 exposure concentrations ($p \leq 0.001$). The other 9 factors, for example cooking, exercise, time spent outdoors, cleaning, building location and proximity to the Sky Train station (an elevated electric light rail system), were not significant contributing effects to personal PM-10 exposure levels ($p > 0.05$).

The most influential factor affecting personal exposures was outdoor PM-10 concentrations with a standardized coefficient of 0.312 (Table 6). Measurement in the winter as well as exposure to tobacco smoke was shown to be similarly correlated to the personal PM-10 exposure levels. Although, participants were non-smokers with no smokers in their households, they could still be exposed to tobacco smoke from their friends or customers or elsewhere. Incense burning also contributed to increases in the personal PM-10 exposure levels. Conversely, sleeping in a bedroom with an air conditioning system had a negative effect on the personal PM-10 exposure levels indicating that living in a room equipped with an air conditioning system tended to lower the personal PM-10 exposure levels. All these six factors accounted for 42% of the variability in personal exposure concentrations. Nonetheless, the intercept of the exposure model was significant. This suggested that other activities not included in this study, such as time in vehicle, time spent on each floor or moving rate, may influence the personal PM-10 exposure levels.

Discussion

Personal PM-10 exposure concentrations lie between the outdoor and indoor PM-10 concentrations. While variation occurred throughout the sampling locations on identical sampling days, most of the outdoor PM-10 concentrations exceeded the indoor and personal PM-10 exposure concentrations. Only 1 outdoor concentration of a total of 131 samples was lower than the corresponding indoor concentration. About 15% of the personal PM-10 exposure concentrations exceeded the corresponding outdoor concentrations (38 personal exposure concentrations out of a total of 251 samples), whereas approximately 67% of personal exposure concentrations were higher than the indoor levels on the same day measurements (174 out of a total of 259 samples). This result was quite different from the previous studies, in which personal exposure concentrations typically exceeded both outdoor concentrations and indoor concentrations.[13-15] This is possibly due to the vast difference in setting and living styles in these Bangkok residences as compared with the locations of the previous studies. This study was performed in a high traffic urban area where the average outdoor concentration was about two times higher than the values in those studies. Compared with the previous study conducted in Bangkok[22], the average indoor and outdoor PM-10 concentrations of the shop houses on Sukhumvit Road were lower than those measured at Odean, which is also a high traffic area, but similar to those measured at a university hospital campus.

According to the results, there were significant differences among PM-10 concentrations on each floor of the shop houses, especially the PM-10 level on the first floor which was approximately 20%-40% higher than the levels on the other floors (Table 2). This finding was not consistent with the study of PTEAM[13] where room-to-room variation was less than 10%. Consequently, in order to obtain a more reliable representation of indoor PM-10 concentration for shop houses, more than one sampling site in the house was required. The reason could be due to the fact that the 1st floor of the shop houses was a shop area with a door usually opened widely, resulting in possible easy exchange of indoor and outdoor air. The other floors,

Table 6. Estimation of factors affecting personal concentrations (n=251)*.

	Parameter Estimate	Std Error	Standardized coefficients	95% CI[a] for Parameter
Intercept [b]	40.67	6.20		28.44 to 52.89
Expose to tobacco smoke	19.53	5.06	0.205	9.56 to 29.51
Winter season	17.98	4.50	0.205	9.10 to 26.85
Outdoor PM-10 conc.	0.23	0.40	0.312	0.15 to 0.31
Door of 1st floor open/closed	25.38	4.32	0.309	18.87 to 33.90
Bedroom with A/C system	-18.63	4.36	-0.214	-27.21to -10.05
Incense	30.45	9.26	0.171	12.21 to 48.69

* Correlation of Model: r = 0.645, r2 = 0.415, adjusted r2 = 0.401.
a Confidence interval.
b Intercept was significant (p = 0.000).

in general, were bedrooms or other living areas and were mostly air conditioned, leading to less air exchange. In addition, the difference between two personal PM-10 exposure concentrations within the same house was up to 43.3 μg/m^3 and there were four households where personal PM-10 exposure concentrations between the two participants were statistically different (Table 3). This result supported the conclusion that personal activities could possibly affect personal exposure, leading to the variation in personal PM-10 exposure concentrations even for individuals living in the same household.

The study showed that the personal exposure concentrations were highly correlated with the outdoor PM-10 concentrations. Excluding the house with a strong interior PM source (parking car inside the house), the individual correlation coefficients ranged from slightly negative to strongly positive values with the median Pearson's *R* coefficient of 0.760 (range from -0.049 to 0.937). However, the correlation coefficients for the personal-indoor relationships (model 2) with median Pearson's *R* coefficient of 0.865 (range from 0.548 to 0.980) was somewhat higher than those of the personal-outdoor relationship (model 1) meaning that the personal PM-10 exposure concentration was more highly correlated with the indoor rather than the outdoor PM-10 concentrations. The median slope was about 0.46 for model 1 and model 3 and approximately 1.1 for model 2. The results were comparable with the previous studies by PTEAM, THEES and Janssen,[17] and can be that the outdoor PM-10 concentrations could be used as a surrogate measure of personal exposure to PM-10 for epidemiological study, even in the very different setting and living styles of Bangkok residents.

The personal PM-10 exposure concentrations, however, were lower than the outdoor concentrations although most exceeded the indoor concentrations. This led to ruling out the indoor concentrations as explanatory of the personal PM-10 exposure levels. Multiple regressions analyses showed that in addition to the outdoor PM-10 concentrations, keeping the door to the outside on the 1st floor open was a major determinant of an increase in the personal PM-10 exposure levels (Table 6). Personal exposures were increased by 25 μg/m^3 in these cases, because the outdoor PM-10 could easily penetrate into the building, resulting in increases in the personal PM-10 exposure and concentrations. The personal PM-10 exposure concentrations in the winter season were about 18 μg/m^3 higher than those in the summer or rainy seasons, because the roadside PM-10 levels were higher in winter than in the other seasons. Incense burning also contributed to increases in the personal PM-10 exposure concentrations although there was a smaller influence. In contrast, the personal exposure concentrations of participants whose bedroom was fitted with an air conditioning system appeared to be lower than for those without air conditioning, because the outdoor air could penetrate only slightly into the bedroom with an air conditioning system and the windows tightly closed. However, some personal activities, such as cleaning, cooking or exercise, and some household characteristics, such as the location of the buildings on the right or left side of the road or their proximity to a sky train station, did not contribute a significant effect to personal exposure concentrations.

Conclusions

The results of this study generally support a finding that the relationships among the personal exposure, indoor and outdoor PM-10 concentrations are significantly correlated. The personal PM-10 exposure was more closely associated with the indoor rather than outdoor concentrations. The correlation coefficients and slope were quite similar to previous studies. This consistent result supported the conclusion that the outdoor PM-10 concentration could reliably be used as a representative of personal exposure even in the very different setting and living style of Bangkok residents, as compared to the locals of the previous studies. However, the overall mean of the personal PM-10 exposure was ranked between the means of the outdoor and indoor concentrations. The average of the indoor PM-10 concentrations an the 1st floor was higher than those on the other floors of the building. This difference suggested that the indoor PM-10 concentration depended on the floor level and the characteristics of the house. Moreover, the personal PM-10 exposure levels of the two participants living in the same house were significantly different in four houses, supporting the concept that personal activities could produce a significant effect on the personal exposure concentrations. The result of regression analyses showed that personal exposure could also be influenced by some personal activities (e.g. incense usage and exposure to tobacco smoke), house characteristics and the season. By comparison, however, house location and proximity to the sky train station and some other personal activities such as exercise or cleaning, have no significant contributions to personal PM-10 exposure concentrations.

Acknowledgements

The authors are grateful to the study participants and to the shop houses owners for their invaluable cooperation. They especially thank the Pollution Control Department, Electric Generating Authority of Thailand, Health Science Department of Thammasat

University, Bureau of Occupational and Environmental Disease of Ministry of Public Health, Dr. Supol Durongwatana of Chulalongkorn University and Dr. Nares Chuersuwan of Suranaree University of Technology for their supports and assistance. This research has been funded by the National Research Center for Environmental and Hazardous Waste Management Program and the Rachadapisek Sompoch Endowment, Chulalongkorn University.

References

1. Whitby, K.T. 1975. Modeling of atmospheric aerosol particle size distributions. Particle Technology Laboratory. Environmental Division, Mechanical Engineering Department, University of Minnesota.
2. Dockery, D.W., Schwartz, J., Spengler, J.D., 1992. Air pollution and daily mortality: Associations with particulates and acid aerosols. *Environmental Research* **59**, 362-73.
3. Pope, C.A., Schwartz, J., Ransom, M.R., 1992. Daily mortality and PM-10 pollution in Utah valley. *Archives of Environmental Health* **47 (3)**, 211-7.
4. Ostro, B., Chestnut, L., Vichit-Vadakan, N., Laixuthai, A., 1999. The impact of particulate matter on daily mortality in Bangkok, Thailand. *Journal of Air and Waste Management Association* **49**, 100-7.
5. Moolgavkar, S.H., 2000. Air pollution and daily mortality in three U.S. counties. *Environmental Health Perspective* **50**, 1287-98.
6. Aunan, K., Pan, X., 2004. Exposure-response functions for health effects of ambient air pollution applicable for China: a meta-analysis. *Science of the Total Environment* **329**, 3-16.
7. Timonen, K., Pekkanen, J., 1997. Air pollution and respiratory health among children with asthmatic or cough symptoms. *American Journal of Respiratory and Critical Care Medicine* **156**, 546-52.
8. Chao, C., Wong, K., 2002. Residential indoor PM10 and PM2.5 in Hong Kong and the elemental composition. *Atmospheric Environment* **36**, 265-77.
9. Mage, T.D., 1985. Concepts of human exposure assessment for airborne particulate matter. *Environmental International* 1, 407-12.
10. Ott, W.R., 1982. Concepts of human exposure to air pollution. *Environment International* **7**, 179-96.
11. Lioy, P.J., 1995. Measurement methods for human exposure analysis. *Environmental Health Perspectives* **103 (Suppl. 3)**, 35-43.
12. 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. *Atmospheric Environment* **35**, 1-32.
13. Ozkaynak, H., Xue, J., Spengler, J.D., Wallace, L, Pellizzari, E., Jenkin, P., 1996b. Personal exposure to airborne particles and metals: Results from the Particle Team Study in Riverside, C.A. *Journal of Exposure Analysis and Environmental Epidemiology* **6,** 57-78.
14. Lioy, P.J., Waldman, J.M., Buckley, T., Butler, J., Pietarinen, C., 1990. The personal, indoor and outdoor concentrations of PM-10 measured in an industrial community during the winter. *Atmospheric Environment* **24B,** 57-66.
15. Janssen, N.A., Hoek, G., Brunekreef, B., Harssema, H., Mensink, I., Zuidhof, A., 1998. Personal sampling of particles in adults: Relationship among personal, indoor and outdoor air concentrations. *American Journal of Epidemiology* **147**, 537-47.
16. Janssen, N.A., Hoek, G., Harssema, H., Brunekreef, B., 1997. Childhood exposure to PM-10: Relation between personal, classroom and outdoor concentrations. *Occupational and Environmental Medicine* **54**, 888-94.
17. Wallace, L., 2000. Correlations of personal exposure to particles with outdoor measurements: A review of recent studies. *Aerosol Science and Technology* **32 (1)**, 15-25.
18. Morawska, L., He, C., Hitchins, J., Gilbert, D., Parappukkaran, S., 2001. The relationship between indoor and outdoor airborne particles in the residential environment. *Atmospheric Environment* **35**, 3463-73.
19. Rea, A.W., Zufall, M.J., Williams, R.W., Sheldon, L., Howard-Reed, C., 2001. The influence of human activity patterns on personal PM exposure: A comparative analysis of filter-based and continuous particle measurements. *Journal of Air and Waste Management Association* **51**, 1271-9.
20. Lachenmyer, C., Hidy, G.M., 2000. Urban measurements of outdoor-indoor PM2.5 concentrations and personal exposure in the Deep South. Part I. pilot study of mass concentrations for nonsmoking subjects. *Aerosol Science and Technology* **32 (1)**, 34-51.
21. Air and Noise Management Division, 2000. *Report on Environmental situation and management of air and noise pollution in Thailand*. PCD.03-038. Pollution Control Department. Ministry of Science Technology and Environment. Bangkok, Thailand.
22. Tsai, C.F., Smith, R.K., Vichit-Vadakan, N., Ostro, D.B., Chestnut, L., Kungskulniti, N., 2000. Indoor/outdoor PM-10 and PM-2.5 in Bangkok, Thailand. *Journal of Exposure Analysis and Environmental Epidemiology* **10**, 15-26.
23. Jinsart, W., Tamura, K., Loetkamonwit, S., Thepanondh, S., Karita, K., Yano, E., 2002. Roadside Particulate Air Pollution in Bangkok. *Journal of Air and Waste Management Association* **52**, 1102-10.
24. Williams, R., Suggs, J., Rodes, C., Lawless, P., Zweidinger, R., Kwok, R., Creason, J., et al., 2000. Comparison of PM2.5 and PM10 monitors. *Journal of Exposure Analysis and Environmental Epidemiology* **10**, 494-505.