



Indoor/outdoor PM₁₀ and PM_{2.5} in Bangkok, Thailand

FENG C. TSAI,^a KIRK R. SMITH,^a NUNTAVARN VICHIT-VADAKAN,^b BART D. OSTRO,^c
LAURINE G. CHESTNUT^d AND NIPAPUN KUNGSKULNITI^e

^aSchool of Public Health, University of California, Berkeley, California

^bCollege of Public Health, Chulalongkorn University, Bangkok, Thailand

^cCalifornia Environmental Protection Agency, Berkeley, California

^dStratus Consulting Inc., Boulder, Colorado

^eFaculty of Public Health, Mahidol University, Bangkok, Thailand

Twenty-four-hour averaged PM₁₀ and PM_{2.5} concentrations were obtained by using 4-liter-per-minute-pumps and impactors in microenvironments of a busy shopping district and a university hospital campus. In both areas, most people live directly adjacent to their worksites — minimizing the need to measure commuting exposure as part of total daily exposure. Co-located samplers were set in indoor microenvironments, the near-ambient zone of the households, and at nearby streetside central ambient monitoring stations. Smoking and use of other indoor PM sources were recorded daily via questionnaires. Consistent with previous studies, smoking and the use of charcoal stoves increased indoor particulate matter levels. The sampled air-conditioned hospital area had substantially lower particle concentrations than outdoors. A simple total exposure model was used to estimate the human exposure. The averaged ratios of co-located PM_{2.5}/PM₁₀ concentrations in various microenvironments are reported for each location. A single daily indoor average PM₁₀ concentration for all households measured in a given sampling day is calculated for correlation analysis. Results showed that day-to-day fluctuations of these calculated indoor PM₁₀ levels correlated well with near-ambient data and moderately well with ambient data collected at the nearby central monitoring site. This implies that ambient monitors are able to capture the daily variations of indoor PM levels or even personal exposure and may help explain the robust association of ambient PM levels and health effects found in many epidemiological studies. Absolute PM exposures, however, were substantially underestimated by ambient monitors in the shopping district, probably because of strong local sources. *Journal of Exposure Analysis and Environmental Epidemiology* (2000) 10, 15–26.

Keywords: Bangkok, indoor-outdoor relationship, particulate matter.

Introduction

In 1990, a risk ranking study funded by USAID (Agency for International Development) and the USEPA (Environmental Protection Agency) examined a range of environmental health hazards in Bangkok and found that ambient particulate matter constituted “the most serious threat to public health” (ABT Associates and Sobotka, 1990). According to that study, there were 300–1400 excess deaths and 9–51 million restricted activity days annually resulting from annual average outdoor concentrations of total suspended particulates (TSP) ranging from 90 to 200 $\mu\text{g}/\text{m}^3$ (Table 1). The results were derived by extrapolating from epidemiological studies of ambient particulate levels

performed in the United States. Since that time, dozens of additional epidemiological studies have been published across the world that show a strong association of various kinds of ill health with particulate air pollution at these levels or even much lower. Among other tentative conclusions of these studies is that the health effects seem to be most closely related to particles of smaller sizes, i.e., less than 10 μm in diameter (PM₁₀) or, even those less than 2.5 μm (PM_{2.5}).

Epidemiological studies on health effects of air pollution typically use concentrations measured by fixed-site ambient monitors as the indicator of human exposures in the surrounding urban areas. People spend most of their time indoors, however, and it is well-established that indoor levels of pollutants may be different from outdoor levels. This raises the question of how well ambient concentrations reflect actual human exposure, which is the best indicator of potential ill health. The fact that the studies, mostly done in developed countries, seem to find good correlations between ambient concentrations and health effects indicates that at least the *changes* in total exposure seem to be adequately reflected by *changes* in ambient air pollution levels. The relationship between outdoor and indoor

1. Abbreviations: N1, first sampling session in nurses' dorms; N2, second sampling session in nurses' dorms; MEM, microenvironmental monitor; PCD, Pollution Control department; PM, particulate matter; S1, first sampling session in Odean shops; S2, second sampling session in Odean shops; S3, third sampling session in Odean shops.

2. Address all correspondence to: Dr. Kirk R. Smith, School of Public Health, 140 Warren Hall, Berkeley, CA 94720-7360. Tel.: (510)643-0793. Fax: (510)642-5815. E-mail: krsmith@uclink4.berkeley.edu

Received 6 January 1999; accepted 16 May 1999.

Table 1. Ambient TSP measurements in Bangkok in the 1980s^a.

Particle size	Averaged concentration ($\mu\text{g}/\text{m}^3$)	Average time	Sampling location	Reference
TSP	180 (1980)	Annual arithmetic mean	Three GEMS ambient stations	United Nations Environment Programme and World Health Organization (1992)
	190 (1981)			
	190 (1982)			
	200 (1983)			
	220 (1984)			
	200 (1985)			
	240 (1986)			
	190 (1987)			
	200 (1988)			
	170 (1989)			
TSP	90–120 (1983)	Annual geometric mean ^b	Seven ONEB ambient stations in Bangkok	ABT Associates and Sobotka (1990)
	100–140 (1984)			
	90–120 (1985)			
	80–200 (1986)			

^aThese data represent annual geometric means from the seven stations operated by the Office of the National Environmental Board (ONEB) and annual arithmetic means for the three stations designated as part of the Global Environmental Monitoring System (GEMS).

^bThe 24-h TSP was measured routinely every 3 days by the ONEB in Thailand.

concentrations is hard to generalize, however, because it depends on local characteristics, including building construction, ventilation, and existence of indoor sources. Thus, the apparent ability to predict changes in health effects based on changes of ambient levels that has been found in many studies in the cities of the U.S. and Europe may not necessarily be applicable to cities in different climates and economic circumstances, where air pollution source patterns and building characteristics may result in quite different indoor/outdoor relationships. This raises additional questions about the validity of extrapolating epidemiological results from developed to developing country settings, beyond the problems created by differences in such factors as health burden, competing risks, access to medical care, and nutritional status of the various populations.

Our study was designed to investigate these indoor/outdoor particulate matter (PM) relationships in Bangkok, Thailand. It is part of a larger PM epidemiological study funded by the World Bank (Chestnut et al., 1998), pursuant

to performing more detailed calculations of the health and other benefits of air pollution control for the city.

The two principal research questions of this study are the following.

(1) What are the indoor/outdoor particulate matter relationships for both PM₁₀ and PM_{2.5}? Does the ratio vary with particle size? How do indoor sources and outdoor particulate matter levels affect indoor concentrations?

(2) What is the correlation of indoor/outdoor particulate matter (for both sizes) over time? As long as indoor and outdoor particulate matter concentrations fluctuate similarly day by day, even if at different absolute concentrations, outdoor monitor data could still serve as an approximate indicator for daily fluctuations in personal exposure in epidemiological studies that are also monitoring daily fluctuations in health effects.

Study design

This study was conducted with a subset of participants from the larger epidemiological study who lived and worked in two locations of Bangkok — the Odean Circle, a shopping area with heavy traffic, and at Chulalongkorn Hospital, which is adjacent to a large busy city street on one side and the relatively quiet Chulalongkorn University campus on the other. These sites were advantageous from an exposure assessment standpoint because the inhabitants' homes and work sites are in close proximity, i.e., there is essentially no commuting exposure, which is difficult to measure. Odean is an area of "shop houses" in which the owners live upstairs in homes that extend two to four stories above the shop itself, which is on the street level. At Odean, monitors were placed in homes, shops, and outdoors near the shops. At the hospital site, we monitored the nurses' dormitories, which are directly adjacent to the hospital, outdoors near the dormitories, and a bit in the hospital itself. Personal sampling would undoubtedly be more accurate, but was beyond the financial and logistic capabilities of the project. These indirect microenvironmental measurements were used to assess total exposure levels¹ and the relationships between outdoor and indoor particulate matter concentrations.

Sampling was conducted for 9 consecutive days in each session for five sessions from January 22 to March 7, 1996. A total of 12 shop houses in Odean (four per session) and 12 dorm rooms (six per session) at Chulalongkorn Hospital were selected for indoor PM monitoring in closely located clusters of varying distances to heavily trafficked roads. Survey participants were in families also involved in a

¹By "exposure level" or "exposure concentration", we mean the average concentration experienced by someone in that microenvironment or combination of microenvironments for the period in question.

concurrent study of daily health symptoms with a fairly complete diary response to date.

A background questionnaire was administered about the household including general questions on cooking fuel usage, air conditioning usage, and smoking. In addition, descriptive information about the configuration of the shop homes was recorded by the interviewers. A second questionnaire was a short list of questions designed to determine if there were any unusual circumstances during

the day of monitoring that might affect indoor PM concentrations. A consent form with a description of the research purpose and approach was signed by a household member before starting the field work. Each household received monetary compensation for the electricity used and their time and inconvenience.

The first session in the Odean shops (S1) was in shop houses on moderately busy streets; the second session in Odean (S2) was in shop houses near busy streets; the third

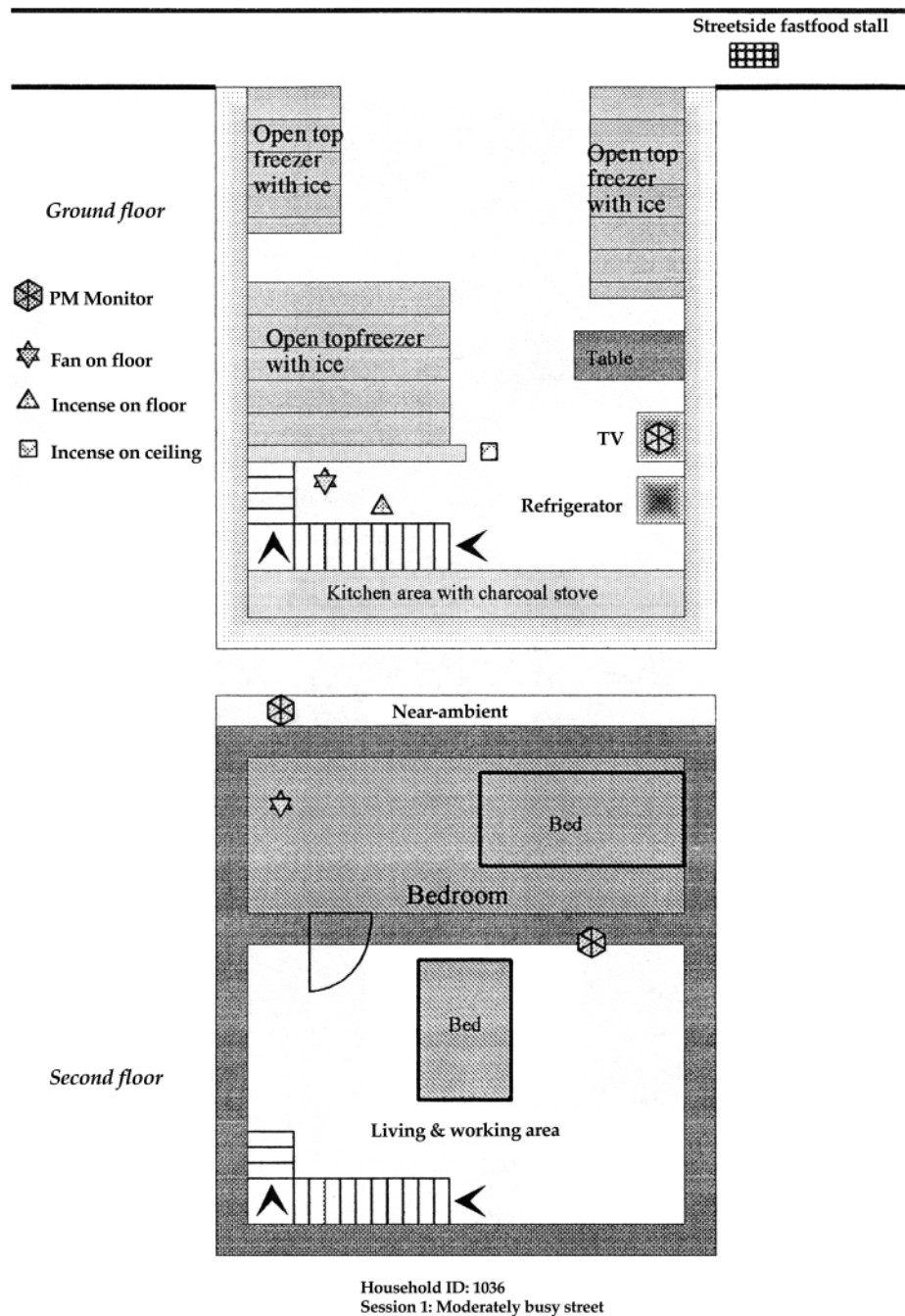


Figure 1. An example of the floor plan in a shophouse.

session (S3) was in houses near less busy streets. The first session (N1) in the Chulalongkorn Hospital nurses' dorms was in dorm rooms facing the street; the second session (N2) was in those facing away from the street.

Each sample was collected for 22–24 hours using a Personal Environmental Monitor Model 200 (PEM, MSP), which is a single-stage impactor that collects either PM₁₀ or PM_{2.5} on a 37-mm filter at constant flow rate of 4 liters per minute (lpm). Since we did not use the PEM for personal monitoring, we called it MEM (MicroEnvironmental Monitor). Both Teflon-coated glass fiber filters (Pallflex) and Teflon membrane filters (Gelman) with support pads were used as collection media. Pre- and post-weights were taken in a temperature-controlled room at the Bangkok Municipal Pollution Control Department (PCD) laboratory. Filters were handled with gloves and forceps in the field and laboratory. The support pads were changed daily. Two field blanks per day were placed near the randomly selected sampling location in Petri dishes. Lab blanks, 1/20 samples, were kept in Petri dishes at the PCD laboratory. Loaded filters were placed in the Petri dishes and kept in desiccator cabinets for at least 48 h before pre- and post-weighing (initial weighings after 24 h showed instability). During weighing sessions, every 7th filter was reweighed and if more than 0.05 mg were different, the entire seven were reweighed. Nineteen pumps made by SKC (model: 224-PCXR7) and Gilian (model: GilAir 5) were used. The SKC pumps can sample intermittently, e.g., repeatedly turning on for 1 min and off for 2 min. This characteristic is useful in high PM areas to prevent overloading filters while still determining 24-h integrated averages. Researchers visited the households at about the same time every day to change filters, check equipment, and administer household questionnaires.

To compare the MEMs and the PCD's ambient stationary monitors, one pair of collocated PM₁₀/PM_{2.5} MEMs was set inside the nearby ambient stations in both locations. Pumps were placed inside the PCD equipment hut and the impactors were hung through an outside vent over which a wire cage was installed to protect them from theft. At these ambient stations, there were a dichotomous sampler (PM_{2.5} and PM₁₀), a high-volume PM₁₀ sampler, a beta-gauge PM₁₀ sampler, and other pollutant monitors routinely operated by PCD.

In addition to the MEMs set in the ambient stations, pairs of collocated PM₁₀/PM_{2.5} MEM were set in the near-outdoor zone (just outside the homes, approximately 3–6 m above the sidewalk), and indoor environments (including the bedrooms, shops, and living rooms) of the households in each session. In some households, both PM_{2.5} and PM₁₀ measurements were taken; whereas in others, only PM₁₀ was sampled (see Figure 1 for a sample household). For the nurses' sessions, the indoor environments refer to the dormitory living areas with one exception: in the N1

session, one set of PM₁₀ and PM_{2.5} MEMs was put in an air-conditioned emergency room of Chulalongkorn hospital to assess nurses' exposure levels during working hours.

The pumps were plugged into household electrical outlets and, to reduce noise, placed in insulated plastic boxes (coolers). The indoor MEMs faced away from the nearest surface at approximately adult breathing height, if possible. For the near-ambient samplers, the pumps were placed indoors and the impactor inlets were hung in front of the residence. Each pump was calibrated with an automatic flow meter (Gilibrator, Gilian) to 4 ± 0.05 lpm before sampling. The flow rate was checked again 24 h later before removal of the loaded filter.

For the shop sessions, the use of indoor PM sources such as charcoal stoves, incense sticks, and tobacco, and weather conditions (wind, rain, and sun) was recorded daily on the household questionnaire by the researchers. Indoor combustion sources are not allowed in the nurses' dorms; thus, only the weather conditions were recorded.

We tried to place the samplers in a way that would not interfere with residents' daily activities, but we occasionally found that the electric plugs were loosened or that the filters were missing for unknown reasons. These kinds of problems are expected to occur occasionally when monitoring equipment is left in residences.

Concentrations were calculated from sample weights net of mean laboratory and field blank filter changes. Duplicate samples represent about 9% of all samples, covering both sizes and all locations.² Collocated duplicates were averaged to obtain one concentration for the analyses.

Results

In any field study, it is necessary to exclude a portion of the data because of difficulties that arise due to such factors as power failures and pump faults. In this study, however, despite the fact that the same equipment and similar protocols had been used in previous studies (Clayton et al., 1991; Kamens et al., 1991; Smith et al., 1993, 1994; Thomas et al., 1993; Naeher et al., 1996), two separate major problems appeared in addition to expected losses: torn filters and bad batches of filter weighings. Thus, it was necessary to exclude an unusually large number of the samples from the final dataset.

For the first data screening, filters that had any one of the three characteristics were excluded — filters torn in the

²The precision of duplicates is calculated by the following formula:

$$\text{Relative standard deviation (RSD)} = \frac{|a_1 - a_2|}{(a_1 + a_2)} * \sqrt{2}$$

where a_1 and a_2 are measured concentrations of collocated duplicates. The average RSD is 0.30 for PM₁₀ (SD=0.31) and 0.06 for PM_{2.5} (SD=0.08).

Table 2. PCD Stationary ambient monitor data (unit: $\mu\text{g}/\text{m}^3$).

Sampler type	Size	S1			S2			S3			N1			N2		
		Number	Mean	CV	Number	Mean	CV	Number	Mean	CV	Number	Mean	CV	Number	Mean	CV
Dichotomous	PM _{2.5}	7	67	0.21	9	78	0.32	9	42	0.24	8	57	0.49	9	38	0.37
Dichotomous	PM ₁₀	7	130	0.23	9	144	0.13	9	84	0.18	8	104	0.22	9	81	0.20
High-volume	PM ₁₀	7	191	0.23	9	257	0.31	8	123	0.12	1	280	NA	9	121	0.30
Beta-gauge	PM ₁₀	8	116	0.30	9	132	0.19	9	69	0.07	9	71	0.28	9	77	0.38

middle, negative PM concentrations, and samples with pump faults (e.g., those with ending flowrates less than 3 lpm or greater than 5 lpm, or pumps that ran less than 70% of the programmed time). Other filters were torn at the edge when they were being separated from the back-up pads. Because there did not seem to be any loss of material with the edge-torn filters, however, they were retained in the dataset. About 16% of the original samples was eliminated in the first screening.

After the first screening, the ambient MEM data at Odean still showed large differences compared with the collocated PCD equipment (Table 2). The high MEM results existed mainly in the S3 and N1 sessions. The field notes and interviews with the research team showed that no special weather, holidays, or other conditions could be associated with those sessions. Further analysis indicated that post-sampling weighings for two filter batches were much higher than any of the others (when compared with stationary monitor data from the same days). Thus, the discrepancy seemed to result because these batches were handled such that they acquired incorrectly high post-sampling weights. Except for one isolated outlier, they represented several days' sequence of filters that, according to field notes, were weighed together. Thus, we deleted all of the data in the two

batches of filters that contained those ambient outliers. The eliminated filters included both ambient and indoor samples because the entire batch appeared to be suspect. The means of those excluded outliers were generally much higher than those of the remaining data. The number of samples, means, and coefficients of variance in each session after the second screening are listed in Table 3. The following analyses are based on the final screened dataset, containing 54% of the original raw data.

Correlation of Ambient PM₁₀ Over Time (Dichotomous, High-Volume, and Beta-Gauge Samplers Versus MEM Ambient and Near Measures)

The correlations among various ambient PM₁₀ measures in both locations are listed in Table 4. The results from any two of the four collocated PM₁₀ instruments, both stationary and MEM, were significantly correlated ($p < 0.05$), but the correlations were moderate. The beta-gauge measurements show good consistency over time between the Odean and Chulalongkorn ambient stations ($r = 0.96$), which are located about 5 km apart. The hourly PM₁₀ measurement of the beta-gauge in 3 randomly selected days of those two ambient stations is plotted in Figure 2. For these days, there was fairly good correlation of the hourly values at the two

Table 3. Descriptive statistics of MEM data retained after second screening (unit: $\mu\text{g}/\text{m}^3$).

Session	Location	Size	S1			S2			S3			N1			N2		
			Number	Mean	CV	Number	Mean	CV	Number	Mean	CV	Number	Mean	CV	Number	Mean	CV
Ambient	PM _{2.5}	8	140	1.00	3	62	0.21	1	153	NA	2	38	0.03	5	52	0.65	
	PM ₁₀	8	242	1.49	3	75	0.31	2	71	0.06	3	132	0.46	7	74	0.45	
Near outdoor	PM _{2.5}	9	124	0.39	2	191	0.08	3	69	0.23	1	59	NA	5	87	0.39	
	PM ₁₀	6	255	0.38	4	251	0.29	2	75	0.08	4	181	1.17	6	92	0.54	
Shop	PM _{2.5}	3	127	0.46	1	241	NA	2	115	0.98	NA	NA	NA	NA	NA	NA	
	PM ₁₀	16	257	0.34	13	235	0.37	9	132	0.78	NA	NA	NA	NA	NA	NA	
Living room	PM _{2.5}	13	137	0.21	4	184	0.28	2	64	0.70	NA	NA	NA	NA	NA	NA	
	PM ₁₀	29	180	0.37	5	245	0.18	8	154	0.87	NA	NA	NA	NA	NA	NA	
Bedrooms	PM _{2.5}	NA	NA	NA	5	91	0.36	3	91	1.04	1	44	NA	10	39	0.59	
	PM ₁₀	NA	NA	NA	5	143	0.29	2	220	0.85	12	97	0.64	32	66	0.39	
Hospital	PM _{2.5}	NA	NA	NA	NA	NA	NA	NA	NA	NA	4	55	0.85	NA	NA	NA	
	PM ₁₀	NA	NA	NA	NA	NA	NA	NA	NA	NA	4	73	0.26	NA	NA	NA	

Table 4. Correlation analysis among various PM₁₀ measures across five sessions (screened data).

Monitor location and type	N	Pearson's correlation coefficient	p-value
MEM ambient–MEM near	17	0.67	0.003
MEM ambient–stationary dichotomous	20	0.44	0.053
MEM ambient–stationary beta-gauge	22	0.51	0.016
MEM ambient–stationary high-volume	19	0.52	0.023
MEM near–stationary dichotomous	20	0.50	0.026
MEM near–stationary beta-gauge	21	0.40	0.072
MEM near–stationary high-volume	17	0.44	0.080
Stationary beta-gauge–stationary dichotomous	41	0.63	<0.001
Stationary beta-gauge–stationary high-volume	34	0.77	<0.001
Stationary dichotomous–stationary high-volume	32	0.74	<0.001

sites (r ranged from 0.72 to 0.90). The hourly average PM₁₀ concentrations over 3 months at the two stations (January to March, 1996) show two peaks as shown in Figure 3: one in the early morning (about 6–9 a.m.) and the other in the late evening (about 7–9 p.m.). During the sampling period, the Odean station had 35% higher PM₁₀ levels than the Chulalongkorn station (the 24-h averages: 105 $\mu\text{g}/\text{m}^3$ for Odean and 77 $\mu\text{g}/\text{m}^3$ for Chulalongkorn).

Overall, among the three collocated ambient stationary monitor types, there were significant but low correlations compared with other reported studies where r ranged from 0.89 to 0.99 (Jaklevic et al., 1981; Elzakker and Dermeulen, 1989; Mathai et al., 1990). The ambient samplers are designed for continuous operation over a long period of time with stable performance. Within ambient stationary measurements at the same site, the best correlation in this study was found between the high-volume sampler and the beta-gauge ($r=0.77$, Table 4). Moreover, the PM₁₀ concentrations obtained by high-volume samplers (cut-size=9 μm) were higher than the dichotomous samplers (cutsize=9.5 μm).

For calculation of the correlation reported in Table 4, each MEM measurement was matched to the stationary monitor data in the same study location, either Odean or Chulalongkorn. The near-MEM data were significantly correlated with the ambient MEM data ($r=0.67$, $p=0.003$). This suggests that day-to-day changes in ambient PM₁₀ concentrations throughout the study area neighbourhoods may be fairly well-represented by the measurements taken at the ambient sites. Correlation between the beta-gauge and the ambient-MEM ($r=0.51$, $p=0.016$) was better than that between the beta-gauge and the near-outdoor MEM data ($r=0.40$, $p=0.072$). This result is reasonable given that the ambient MEMs were located at the stationary

monitor sites, whereas the near-MEMs were placed in a different location for each of the five sessions at varying distances from the stationary sites. That the correlation between the stationary monitor data and the near-MEMs is only slightly lower than that with the ambient-MEM data is consistent with the conclusion that outdoor PM₁₀ concentrations fluctuate similarly day-to-day throughout the study area neighbourhoods.

Correlation Between PM_{2.5}-Ambient and PM_{2.5}-Near

The near sampling locations changed each session with different clustered households, but the ambient stations remained the same for all three shop sessions and two nurses sessions. Before excluding the aberrant filter batches, ambient PM_{2.5} was significantly correlated with the PM_{2.5} ($r=0.47$, $p=0.04$). Non-significant correlation was found between ambient MEM and dichotomous PM_{2.5}. For the screened data, no significant correlation was found among the ambient PM_{2.5}, the near PM_{2.5} and the dichotomous PM_{2.5}.

Correlation of Paired PM_{2.5}/PM₁₀ for the Near-Outdoor and Ambient

The average ratio of collocated PM_{2.5}/PM₁₀ pairs is listed in Table 5 for different microenvironments in each session. The averaged PM_{2.5}/PM₁₀ ranged from 0.4 to 0.9.³ The ratios are slightly lower in Odeon indoor microenvironments.

For the screened data, the correlations of PM_{2.5} and PM₁₀ across five sessions for the ambient and the near-outdoor pairs were 0.26 ($p=0.294$) and 0.50 ($p=0.056$), respectively (Table 6). The correlation for the stationary dichotomous PM_{2.5} and PM₁₀ ($r=0.81$, $p<0.001$) across five sessions was higher than the correlation of collocated MEM data.

Regression of Indoor PM₁₀ Against Ambient/Near PM₁₀, Weather, and Household Conditions

Regression analysis was used in an attempt to identify the factors that contribute to indoor PM. Outdoor and near PM concentrations, the weather (rain), indoor PM sources were considered as covariates. Indoor sources were modeled as dichotomous variables to explain the measured indoor PM concentrations, taking a value of 1 if the source was present or used that day and 0 if not present or used that day as reported in the daily questionnaire. Either the ambient PM (MEM ambient and beta-gauge) or the near-MEM was forced to be included in the model. Only S1 through S3 data were analyzed because no indoor sources were present in the nurses' dorms. Because the sample sizes for the bedroom PM measurements are too small, only the results

³These average values were determined after deleting five pairs with PM_{2.5}/PM₁₀ ratios greater than 2.

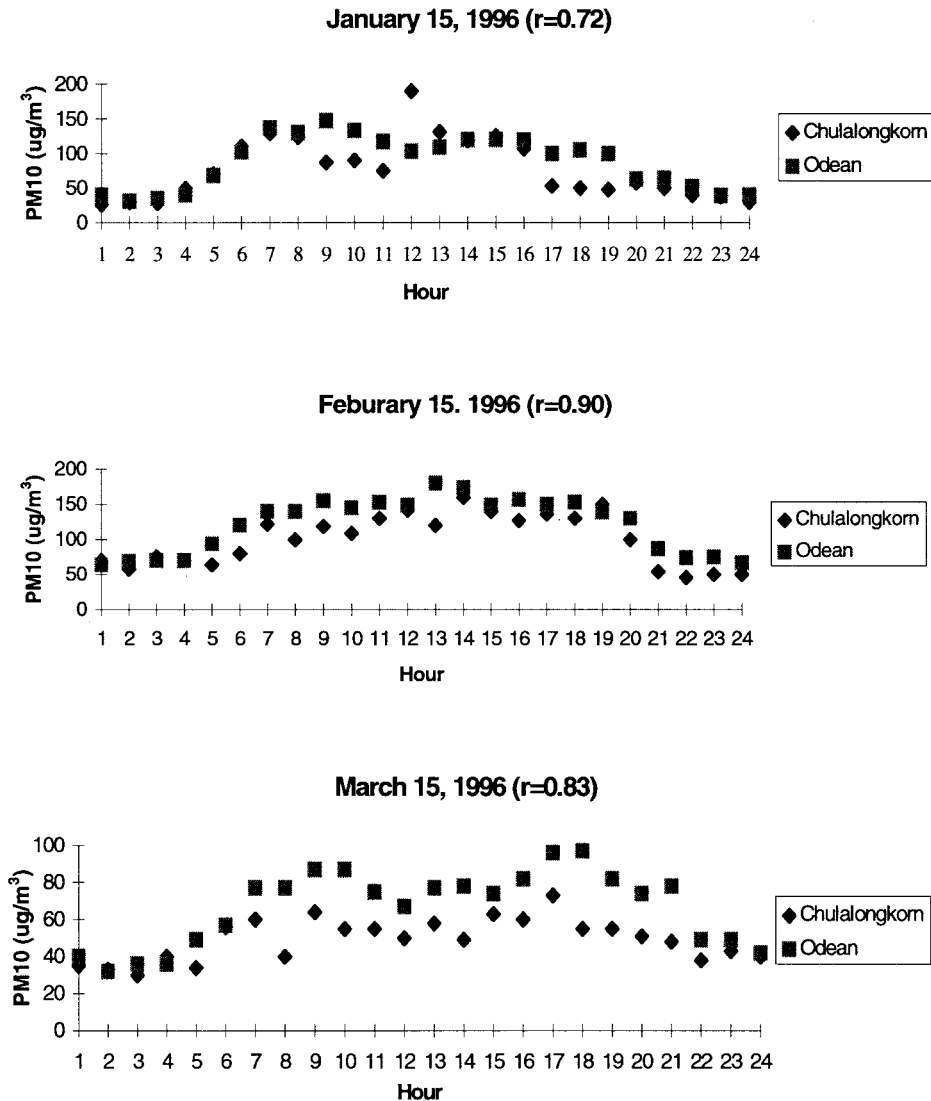


Figure 2. Correlation of two beta-gauge samplers in three randomly selected days between the Odean and Chulalongkorn ambient stations.

of the living room-PM and shop-PM are reported (Tables 7–10).

*PM*₁₀ Results of the regression model for the living room *PM*₁₀ are listed in Table 7. The *r* was highest (0.74) for the MEM-near model. The results from this model suggest a statistically significant relationship between near-*PM*₁₀ and living room *PM*₁₀. Cigarette smoking indoors⁴ and charcoal use contributed significantly to the 24-h average living room PM, increasing 60 $\mu\text{g}/\text{m}^3$ if smokers were present and by about 90 $\mu\text{g}/\text{m}^3$ if charcoal was used indoors. This is a high value for cigarette smoking, which has been shown to increase average indoor 24-h PM levels in U.S. homes at a

rate of about 1 $\mu\text{g}/\text{m}^3$ per cigarette smoked (Dockery and Spengler, 1981).

In the PM-near model, incense was found to be related to lower living room PM by 50 $\mu\text{g}/\text{m}^3$ ($p=0.04$). The relationship of incense use and cigarette smoking (both indoors and in the shops) was investigated as a possible explanation for this unexpected result. Through the three sessions, however, no significant relationships were found between incense use and smoking. This result remains inexplicable and may be related to other unknown activities in the home when incense is being used.

The results of shop-*PM*₁₀ regressions (Table 8) are similar to those for living room *PM*₁₀. The outdoor concentrations, however, were somewhat better predictors of the indoor concentration. The stationary beta-gauges and ambient-MEMs both had parameter values greater than 1,

⁴Cigarettes smoked indoors refer to all smoking in other indoor environments, such as upstairs or the living space behind the shop.

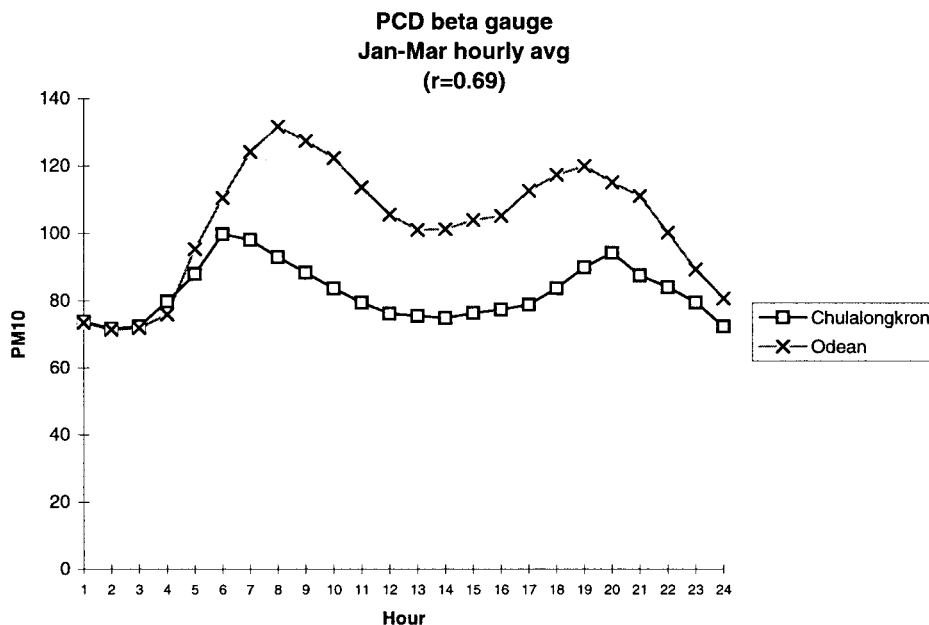


Figure 3. Correlation of hourly average PM₁₀ for three months between the Odean and Chulalongkorn ambient stations.

suggesting high penetration rates from outdoors to indoors. The shops are typically on the street level with open front doors and windows or, in some cases, with the entire front wall open to the sidewalk. Thus, indoor PM₁₀ may be more closely related to ambient concentrations than in living areas behind or above the shops. Cigarette smoking in the shop is statistically significant as an important source for indoor PM₁₀ in the shops under stationary beta-gauge model.

For the nurses' sessions, no regression analyses were performed because of lack of indoor sources. The indoor/outdoor relationships were explored by the correlation analyses of the bedroom PM₁₀ and ambient PM₁₀. The bedroom PM₁₀ was significantly associated with the near-PM₁₀ and with all ambient PM₁₀ monitors (r ranged from 0.7 to 0.9, $p < 0.01$) except the high-volume PM₁₀ ($r = 0.40$, $p = 0.33$).

Table 5. Average ratio of paired PM_{2.5}/PM₁₀ in various microenvironments of Odean and Chulalongkorn (screened data; number in the parenthesis: sample size).

	Odean shops	Chulalongkorn nurses
Stationary-dichotomous	0.53 (25)	0.48 (16)
Ambient-MEM	0.85 (10)	0.86 (5)
Near-MEM	0.55 (9)	0.76 (5)
Shop	0.45 (3)	NA
Living room	0.61 (15)	0.88 (4)
Bedroom	0.58 (7)	NA
Hospital	NA	0.40 (3)

PM_{2.5} For living room-PM_{2.5} (Table 9), charcoal use indoors shows effects similar to those seen with living room PM₁₀. The near-MEM PM_{2.5} was significantly associated with the living room PM_{2.5} concentration, as was the stationary dichotomous PM_{2.5}. The sample size for the shop PM_{2.5} is small, less than 10. No significant indoor source variables were found for the shop-PM_{2.5} (Table 10).

The average PM values in various microenvironments are listed in Table 11. The near-PM concentrations are higher than the ambient PM averages. This is surprising given that some of the near-monitors were located along less busy streets than were the ambient monitors, but may be due to indoor sources and/or pedestrian traffic on the sidewalk. Indoor concentrations in the Odean area are higher than the nurses' dormitories or the hospital.

Correlation of Average Daily Indoor PM And Daily Ambient PM

A single daily average indoor PM₁₀ concentration was calculated for each sampling day based on the screened

Table 6. Correlation analysis between ambient PM₁₀ and PM_{2.5} (screened data).

	N	Correlation coefficient	p-value
Ambient MEM PM ₁₀ vs. PM _{2.5}	18	0.26	0.294
Near MEM PM ₁₀ vs. PM _{2.5}	15	0.50	0.056
Stationary dichotomous PM ₁₀ vs. PM _{2.5}	41	0.81	<0.001

Table 7. Regression models for the living room PM₁₀ (screened data).

1st forced entered variable (parameter estimate/ <i>p</i> -value)	<i>R</i>	Additional significant variables (parameter estimate/ <i>p</i> -value)
Stationary beta-gauge (0.39/0.31)	0.26	None
MEM-ambient (0.10/0.79)	0.42	None
MEM-near (0.41/0.002)	0.74	cigarettes smoked indoor (56/0.04) charcoal (89/0.004) incense (−54/0.04)

LIVRM PM=stationary beta gauge/MEM-ambient/MEM-near+cigarettes smoked indoors (Y/N)+cigarettes smoked in the shop (Y/N)+use of charcoal (Y/N)+use of incense (Y/N)+rain (Y/N).

data. For S1 through S3, the indoor PM₁₀ is the average of all PM₁₀ measurements in the living rooms across households. For N1 and N2, the indoor PM₁₀ is the average of the bedroom PM₁₀. The indoor PM₁₀ is significantly associated with the ambient beta-gauge and the near-MEM measurements, but only marginally correlated with the ambient-MEM data (Table 12). This may imply that the ambient monitor is sufficient to characterize the day-to-day fluctuation of personal exposure over a long period of time. But the short-term variation and the absolute value of personal exposure are still unclear from the ambient monitoring.

Exposure Models for Local Residents in Bangkok

By combining time activity patterns and microenvironmental monitoring data, we can estimate the total PM exposure levels for the nurses and shop residents. The beta-gauge average is used as the “gold standard” for outdoor PM concentration. Various PM monitoring data obtained in the hospital, shops, living rooms, bedrooms, and dorm rooms are used as indoor concentrations. Times in each microenvironment were estimated by observing people’s behaviors. At Odean, the shops opened early at about 7–8

Table 8. Regression models for the shop PM₁₀ (screened data).

1st forced entered variable (parameter estimate/ <i>p</i> -value)	<i>R</i>	Additional significant variables (parameter estimate/ <i>p</i> -value)
Stationary beta-gauge (1.82/0.0002)	0.65	cigarettes smoked in shop (62/0.05)
MEM-ambient (1.16/0.03)	0.53	None
MEM-near (0.31/0.10)	0.57	charcoal (85/0.09)

SHOP PM=stationary beta-gauge/MEM-ambient/MEM-near+cigarettes smoked indoors (Y/N)+cigarettes smoked in the shop (Y/N)+use of charcoal (Y/N)+use of incense (Y/N)+rain (Y/N).

Table 9. Regression models for the living room PM_{2.5} (screened data).

1st forced entered variable (parameter estimate/ <i>p</i> -value)	<i>R</i>	Additional significant variables (parameter estimate/ <i>p</i> -value)
Stationary dichotomous (1.58/0.05)	0.65	charcoal (81/0.02)
MEM-ambient (−0.06/0.57)	0.45	NA
MEM-near (0.70/0.003)	0.75	NA

LIVRM PM=stationary dichotomous/MEM-ambient/MEM-near+cigarettes smoked indoors (Y/N)+cigarettes smoked in the shop (Y/N)+use of charcoal (Y/N)+use of incense (Y/N)+rain (Y/N).

a.m. and closed at about 5–6 p.m. The indoor PM of the Odean sessions was calculated as follows: sum of (one third of living room PM and two thirds of bedroom PM) to account for the time spent indoors.

Shop houses: (2 h×outdoor PM+10 h×shop PM+12 h×indoor PM)/24 h=24 h average exposure concentrations of 180 μg/m³ (PM₁₀) and 120 μg/m³ (PM_{2.5}).

Nurses: (2 h×outdoor PM+10 h×hospital PM+12 h×indoor PM)/24 h=24 h average exposure concentrations of 75 μg/m³ (PM₁₀) and 50 μg/m³ (PM_{2.5}).

The ranges of PM₁₀ and PM_{2.5} exposure levels are about 75–180 μg/m³ and 50–120 μg/m³, respectively, for these particular Bangkok residents. Although there was considerable variation in the ambient monitors, it would seem that, in general, the ambient monitoring data were quite good predictors for the nurses’ total exposure levels, but substantially underestimated the exposure levels of people living in the shophouses. We draw this conclusion by comparing the average daily exposure-level estimates with the ambient beta-gauge PM₁₀ and dichotomous PM_{2.5} data in Table 2, where over the appropriate sessions the Odean averages of PM₁₀ and PM_{2.5} were about 110 and 60 μg/m³ and those at the hospital were about 70 and 50 μg/m³. It might also be noted that the ambient PM₁₀/PM_{2.5} data

Table 10. Regression models for the shop PM_{2.5} (screened data).

1st forced entered variable (parameter estimate/ <i>p</i> -value)	<i>R</i>	Additional significant variables (parameter estimate/ <i>p</i> -value)
Stationary dichotomous (9.07/0.35)	0.84	NA
MEM-ambient (2.27/0.21)	0.98	NA
MEM-near (1.21/0.07)	0.77	NA

SHOP PM=stationary dichotomous/MEM-ambient/MEM-near+cigarettes smoked indoors (Y/N)+cigarettes smoked in the shop (Y/N)+use of charcoal (Y/N)+use of incense (Y/N)+rain (Y/N).

Table 11. Average PM concentrations (unit: $\mu\text{g}/\text{m}^3$) in various micro-environments of Odean and Chulalongkorn (note: number in the parenthesis is the sample size).

Microenvironments	Odean		Chulalongkorn	
	PM ₁₀	PM _{2.5}	PM ₁₀	PM _{2.5}
Ambient (beta-gauge)	103 (26)	NA	83 (18)	NA
Ambient (MEM)	95 (13)	121 (12)	92 (10)	48 (7)
Near (MEM)	223 (12)	127 (14)	127 (10)	82 (6)
Shop	220 (38)	142 (6)	NA	NA
Living room	183 (42)	139 (19)	NA	NA
Hospital	NA	NA	73 (4)	55 (4)
Bedroom	165 (7)	91 (8)	74 (44)	40 (11)

collected in this study are roughly consistent with the ambient TSP data taken in the 1980s (Table 1).

Discussion and conclusions

In spite of significant data loss, some useful findings emerge from analysis of the remaining data. Day-to-day fluctuations in indoor PM concentrations are generally correlated with PM concentrations at both near and ambient locations. For example, the near-MEM measurements are statistically significant predictors of indoor concentrations in the Odean sessions. This suggests that outdoor monitoring is probably sufficient to capture changes of personal exposure from day to day for use in epidemiological studies.

Although variation among monitoring types makes evaluation difficult, it seems that ambient monitors were only able to predict the average absolute total exposures of the residents (nurses) living with no indoor sources, but greatly underestimated the exposure levels of people (shop-house residents) living with indoor sources. Most indoor environments (including the shops, the living rooms and the bedrooms) in the shop sessions have higher concentrations than the ambient levels for both PM_{2.5} and PM₁₀. In contrast, the nurses' sessions usually have lower indoor PM concentrations than the ambient levels because no indoor combustion sources are present (Figure 4). Similar findings were reported in a study conducted in the Netherlands (Janssen, 1998), a totally different setting from Bangkok. In this work, personal exposure of both PM₁₀ and fine particle (PM_{3.0}) was well-correlated with outdoor monitor data, but personal PM exposure often exceeded the ambient concentrations, especially to those subjects exposed to ETS. Consistent findings, either in the developed or developing countries, support the use of ambient monitor data as a surrogate measure of personal exposure in the time-series epidemiological studies which link the day-to-day PM fluctuation to the change of health endpoint. Since true personal exposure may be substantially underestimated by

such monitoring, however, additional measurements to determine actual exposures are needed to determine population risks.

Consistent with previous studies, indoor smoking and charcoal use increase indoor PM levels. Based on the limited data obtained in the hospital emergency room, particle penetration into this air-conditioned indoor environment from high ambient PM levels is relatively low.

The data were not consistent among the ambient stationary monitors or between the MEMs and stationary monitors. These inconsistencies may be due to different designs of samplers or equipment failure. Generally, the reliability of beta-gauge samplers has been good (Wedding and Weigand, 1993). They are automatically operated and require no weighing. One study (Arnold et al., 1992) showed that the Wedding beta-gauge recorded 24-h average PM₁₀ that was approximately 19% lower than those recorded by Wedding PM₁₀ high-volume samplers. The beta-gauge concentrations measured in this study were always lower than any other ambient measures. This may imply some systematic error of beta-gauge operation that caused underestimation in PM₁₀ levels.

In the PTEAM study (Thomas et al., 1993), MEM measurements gave median PM₁₀ concentrations that were about 9% higher than the dichotomous samplers and 16% higher than the high-volume samplers due to different particle cutsize of the inlets (MEM: 11 μm ; Dichotomous: 9.5 μm ; High-volume: 9 μm). But the correlation among three measures was good ($r > 0.95$ for all types of samplers).

MEM samplers have been used extensively in previous studies (Clayton et al., 1991; Kamens et al., 1991; Thomas et al., 1993). The accuracy and precision of the samplers have been well-documented. The MEMs in this study did not seem to perform as well, however, at least based on comparing results with the ambient stationary monitoring equipment. This may be due to the following reasons:

(i) In this study, 30% of the filters (mostly Pallflex) were torn during sampling. As reported above, the same impactors and Pallflex filters were used in previous studies where there were no reports of torn filters. Since the manufacturer noted that there had been no change in the

Table 12. Correlation analysis for indoor PM₁₀ average (note: indoor average refers to the average living room PM for the Odean sessions and the averages bedroom PM in the nurse sessions; one number for a given sampling day).

	N	Correlation coefficient	p-value
Indoor average-MEM near	22	0.69	0.0004
Indoor average-MEM ambient	21	0.41	0.068
Indoor average-beta-gauge	27	0.63	0.0005

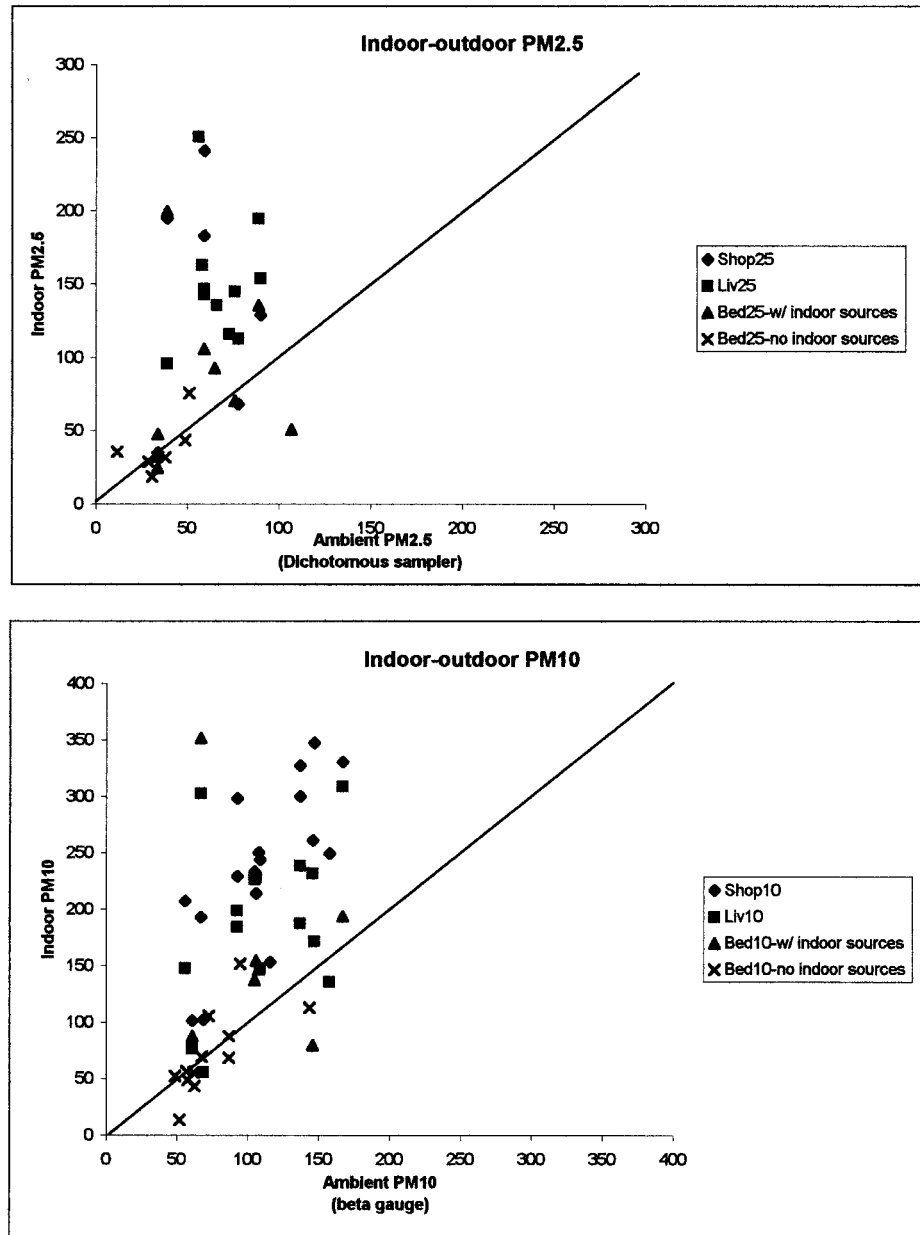


Figure 4. Plots of indoor–outdoor PM₁₀ and PM_{2.5}.

filter composition, we could not explain this phenomenon. Our recommendation for future research is to rely on the less-easily torn Teflon filters, in spite of their greater cost, although there may be problems of excessive pressure drop at high loadings.

(ii) Although the personal pumps used in this study are small and reasonably quiet for indoor sampling, they are designed for industrial hygiene applications of 40–60 h/week of operation. It is likely that they were overused by being operated nearly continuously for 7 weeks with breaks of only 2 days out of 11. At the end of the sampling

period, some pumps were not able to reliably maintain constant flow rates. More pumps and more frequent substitution may be needed for intensive long-term sampling.

The weighing procedure is a critical link in determining accurate PM concentrations. The loss of data from two batches of filters reduced the sample size so much that the ability to make statistically valid comparisons was severely compromised. Effort must be made to assure that the transport, handling, storage, and weighing of the filters are done as carefully as possible.

In retrospect, it is clear that the study should have planned to take more samples in fewer locations in order to be better able to sustain any loss of data and still obtain sufficient sample size for statistical analysis.

Acknowledgments

The authors thank Sudhir Shetty of the World Bank; Supat Wangwongwatana and Noppaporn Panich of the Royal Thai Government Pollution Control Department; and Jitsiri Thanapatra, for their support and assistance. The study was funded by a grant from the government of Japan to the Royal Thai Government, administered by the World Bank. This paper presents the views of the authors and does not necessarily reflect any official position of the World Bank, the Royal Thai Government, or the authors' employers. Errors and omissions are the responsibility of the authors. The authors are extremely grateful to the participating households in Bangkok for their patience and time.

References

ABT Associates and Sobotka. Ranking environmental health risks in Bangkok, Thailand (working paper). U.S. Agency for International Development Office of Housing and Urban Programs, Washington, DC, 1990.

Arnold S., Hague W., Pierce G., and Sheetz R. The use of beta-gauge monitors for PSI and every day SIP monitoring: an overview of the Denver experience. In: PM₁₀ standards and nontraditional particulate source controls: an A&WMA/EPA International Specialty Conference. Air and Waste Management Association, Pittsburgh, PA, 1992, pp. 13–23.

Chestnut L.G., Ostro B.D., Vichit-Vadkan N., Laixuthai A., Aekplakorn W., Smith K.R., and Tsai F.C. Health effects of particulate matter air pollution in Bangkok. Final report prepared for the World Bank and the Royal Thai Government, March, 1998.

Clayton C.A., Pelizzari E.D., and Wiener R.W. Use of a pilot study for designing a large-scale probability study of personal exposure to aerosols. *J. Expos. Anal. Environ. Epidemiol.* 1991; 1 (4): 407–421.

Dockery D.W., and Spengler J.D. Indoor-outdoor relationships of sulfates and particles. *Atmos. Environ.* 1981; 15: 335–343.

Elzakker B.G., and Dermeulen A. Performance characteristics of various beta-dust monitors: intercomparison. *J. Aerosol Sci.* 1989; 20 (8): 1549–1552.

Jaklevic J.M., Gatti R.C., Goulding F.S., and Loo B.W. A β -gauge method applied to aerosol samples. *Environ. Sci. Technol.* 1981; 15: 680–686.

Janssen N. Personal exposure to airborne particles: validity of outdoor concentrations as a measure of exposure in time series studies. PhD Dissertation, Wageningen Agricultural University, the Netherlands, 1998.

Kamens R., Lee C.T., Wiener R., and Leith D. A study to characterize indoor particles in three non-smoking homes. *Atmos. Environ.* 1991; 25: 939–948.

Mathai C.V., Watson J.G., Rogers C.F., Chow J.C., Tombach I., Zwicker J.O., Cahill T., Feeney P., Eldred R., Pitchford M., and Mueller P.K. Intercomparison of ambient aerosol samplers used in western visibility and air quality studies. *Environ. Sci. Technol.* 1990; 24: 1090–1099.

Naeher L.P., Smith K.R., Leaderer B.P., Grajeda R., Mage D., and Boleij J.S.M. Particulates and CO in Highland Guatemala. In: Yoshizawa S. et al. (Eds.), *Indoor Air '96, The 7th International Conference of Indoor Air Quality and Climate*, Institute of Public Health, Tokyo, Vol. 2, 1996, pp. 405–410.

Smith K.R., Liu Y., Rivera J., Boy E., Leaderer B., Johnston C.S., Yanagisawa Y., and Lee K. Indoor air quality and child exposures in highland Guatemala. In: Jaakkola et al. (Eds.), *Indoor Air '93* Proceeding, University of Technology, Helsinki, Vol. 1, 1993, pp. 441–446.

Smith K.R., Apte M.G., Ma Y.Q., Wongsekiartitrat W., and Kulkarni A. Air pollution and the energy ladder in Asian cities. *Energy* 1994; 19 (5): 587–600.

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

United Nations Environment Programme and World Health Organization (UNEP/WHO). *City Air Quality Trends (GEMS/AIR Data)*. Vol. I, 1992.

Wedding J.B., and Weigand M.A. (1993). An automatic particle samplers with beta gauging. *J. Air Waste Manage. Assoc.* 43: 475–479.