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PERSONAL EXPOSURE TO RESPIRABLE PARTICLES: A CASE STUDY IN WATERBURY, VERMONT

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Abstract—A study to assess personal exposure to respirable particles was conducted during January to March 1982 in Waterbury, Vermont. Forty-eight nonsmoking volunteers carried Harvard/EPRI personal samplers every other day for two weeks. Simultaneous measurements with similar monitors were made inside and outside each participant's home. Findings indicate that outdoor (ambient) particle levels were not an important determinant of personal exposure, while in-home concentrations accounted for 25–30% of the variation in personal values. A linear regression technique was used to estimate respirable particle concentrations in three micro-environments where measurements were not available. These values were combined with data on time activities and observed outdoor and in-home concentrations to construct a simple time-weighted exposure model. Predicted exposure using this approach agreed well with measured values, however, the validity and suitability of estimated coefficients for applications to other communities and different times of year has not been established.

Key word index: Personal exposure, exposure models, respirable particles, passive tobacco smoke, indoor air quality, personal monitoring, time-activity patterns, indoor/outdoor measurements.

INTRODUCTION

Accurate estimation of human exposures is a prerequisite for realistic evaluation of air pollution health risks. Traditionally, population exposure estimates have relied almost exclusively on ambient (outdoor) measurements. It is becoming increasingly apparent, however, that personal exposures are not characterized adequately by ambient air monitoring networks.

The ability of stationary outdoor monitors to define personal exposures is a function of the degree to which readings reflect concentrations experienced by individuals. The relationship between outdoor and personal values is complicated by the fact that people spend much of their time indoors or in areas distant from fixed monitors, where pollutant concentrations may be drastically different. For example, being indoors is likely to reduce one's exposure to photochemical oxidants, such as ozone, but may increase exposure to respirable particles, especially in the presence of smoking. Unless temporal and spatial variation in pollutant concentrations is taken into account, misclassification of exposures can lead to spurious conclusions concerning public health risks.

Although only a few personal monitoring studies for respirable suspended particles (RSP) have been conducted (Binder *et al.*, 1976; Ferris *et al.*, 1979; Spengler *et al.*, 1980; Spengler and Tosteson, 1981; Dockery and Spengler, 1981; Spengler *et al.*, 1981; Spengler *et al.*, 1983; Sega and Fugas, 1982), available evidence indicates that ambient measurements are not a strong predictor of individual exposures. Differences are due to the fact that a person experiences a spectrum of concentrations as he or she moves through various indoor and outdoor locations (e.g. walking along a busy street, working in a high-rise office building, commuting in an automobile, sleeping at home, eating in a restaurant). Currently, a paucity of data exists to evaluate the contribution of these different environments to personal exposures.

Efforts to reduce uncertainties in exposure estimation have focused on combining time-budget and activity-pattern data with information about pollutant levels. Models to predict personal RSP exposures are all based on the premise that the summation of pollutant values in important 'micro-environments' (e.g. home, work, outdoors, in-transit), weighted by fraction of time spent in each micro-environment, provide an adequate approximation of integrated individual exposures (Fugas, 1976; Moschandreas and Morse, 1979; Duan, 1980; Ott, 1980; Dockery and Spengler, 1981; Duan, 1982). Therefore, to characterize RSP levels experienced by specific persons or groups, it is necessary to obtain information about relevant time-activity patterns as well as concentrations in each type of micro-environment.

This paper reports results from an intensive personal monitoring study involving 48 nonsmokers in Waterbury, Vermont. During two separate monitoring periods conducted from January to March 1982, volunteers carried personal RSP samplers every other

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day for 2 weeks. Participants kept detailed activity logs documenting time spent in five major micro-environments (i.e. home, work, outdoors, other indoors, in-transit) and whether or not they experienced passive exposure to tobacco smoke. Simultaneous 24-h RSP samples were also collected inside and outside each participant's home. Findings are presented emphasizing the relative importance of indoor and outdoor measurements for estimating personal exposure to respirable particles.

EXPERIMENTAL

The Harvard wood-burning study was conducted from 29 January to 11 March, 1982, in Waterbury, Vermont. Descriptions of the community, the ambient monitoring program, and indoor/outdoor measurements have been published previously (Sexton *et al.*, 1984a, b).

Personal measurements

Information from the Vermont Agency of Environmental Conservation energy-use survey was used to develop a mailing list for Waterbury. Requests for volunteers to participate in the personal monitoring portion of the study were mailed to 312 families during December 1981. Forty-eight people (45 adults and 3 children) from 24 different homes were selected from among the respondents. No attempt was made to obtain a random sample. Instead, selection was based on willingness to participate and use of wood fuel as a primary or secondary heating source. Only nonsmokers were chosen in order to minimize the confounding effects of tobacco smoke on in-home RSP concentrations.

The age distribution of the volunteers is given in Table 1. Ages ranged from 10 to 82 years. The sample consisted of 22 adult men, 23 adult women and 3 children (⩽ 17 y). Seventeen of the men were employed fulltime, as were 16 of the women. The three children (ages 10, 15 and 17) were students.

Participants carried Harvard/EPRI personal sampling pumps with Bendix cyclone preseparators (Turner *et al.*, 1979) every other day for 2 weeks. Twenty-five people from 12 different homes participated from 29 January to 11 February and another 23 from 12 additional houses during 26 February to 11 March. Individuals maintained detailed activity logs, recording time spent in various micro-environments and documenting passive exposures to tobacco smoke.

The sampling schedule was designed so that all volunteers turned on their personal monitors at 0800 on sampling days and left them running for 24 h. When possible (e.g. during indoor sedentary activities), units were plugged into the nearest wall socket and placed in close proximity to the individual. Otherwise, pumps were powered by a 12-volt nickel–cadmium battery with a lifetime of approximately 8 h. Flow checks with a calibrated rotometer were performed before and after each 24-h sampling period.

Table 1. Age distribution of participants in the 1982 Harvard Personal Monitoring Study in Waterbury, Vermount

Number of persons	Age (years)
2	5–14
3	15–24
12	25–34
18	35–44
2	45–54
6	55–64
3	65–74
2	75–84
Total 48	

Indoor/outdoor measurements

The 48 participants in the personal exposure study resided in 24 homes (19 with wood-burning appliances). These 24 residences (all occupants were nonsmokers) made up the sample population for the indoor/outdoor portion of the study. Monitoring operations were divided into two sampling periods, with 12 homes studied from 29 January to 11 February and another 12 homes investigated from 26 February to 11 March. Twenty-four hour (i.e. 0800–0800) RSP samples were collected inside and outside each dwelling every other day for two weeks. Measurements were timed to coincide with occupants' personal samples.

Concentrations of RSP were measured with the same type of monitor (i.e. Bendix cyclone preseparators attached to Harvard/EPRI portable sampling pumps) used for personal sampling. Two RSP monitors were placed inside each residence and one was installed outside. The outdoor pump was encased in a heated box and connected to an external cyclone and filter. Flow checks with a calibrated rotometer were performed on all units before and after each run.

RESULTS

Mean personal, indoor and outdoor RSP concentrations for each participant in the study are summarized by monitoring period in Tables 2 and 3. Average personal exposure was always higher than outdoor values and exceeded mean at-home levels for 43 out of the 46 participants for which valid samples were available. Individual RSP values were greater than outdoor concentrations for 83% of the 280 24-h samples collected and higher than indoor levels for 78% of 278 samples. Sixty-five percent of daily in-home values ($N = 163$) were higher than matched outdoor levels.

Outdoor, indoor and personal respirable particle concentrations are compared graphically in Fig. 1. Outdoor values refer to the daily 'community average,' which is defined as the mean ambient RSP level calculated from measurements outside all 12 residences on each sampling day ($n = 14$). Indoor and personal concentrations include all valid 24-h samples in each category ($n = 163$ and $n = 280$, respectively). These data show that mean (arithmetic) personal exposure (36 $\mu g\,m^{-3}$) is 11 $\mu g\,m^{-3}$ (44%) higher than average indoor RSP (25 $\mu g\,m^{-3}$) and 19 $\mu g\,m^{-3}$ (112%) greater than average outdoor RSP (17 $\mu g\,m^{-3}$). Similarly, the mean particle concentration indoors exceeds that outside by 8 $\mu g\,m^{-3}$ (47%).

Percentage distributions and summary statistics for outdoor, indoor and personal RSP values are given in Fig. 2. Measured outdoor RSP concentrations exhibited relatively slight variation, with all values between 6 and 30 $\mu g\,m^{-3}$. Indoor levels ranged from 6 to 69 $\mu g\,m^{-3}$ and 24% exceeded 30 $\mu g\,m^{-3}$. Personal exposures were even higher, varying from 7 to 125 $\mu g\,m^{-3}$. Forty-seven per cent of observed personal values were higher than 30 $\mu g\,m^{-3}$.

Cumulative percentage plots for each distribution are shown in Fig. 3. These data highlight dissimilarities

Table 2. Average personal, indoor and outdoor RSP concentrations recorded during 29 January–10 February 1982, in Waterbury, Vermont

		RSP Concentrations ($\mu g\ m^{-3}$)											
		Personal				Indoor				Outdoor			
Home ID	Person type	N	$\overline{X}$	S.D.	S.E.	N	$\overline{X}$	S.D.	S.E.	N	$\overline{X}$	S.D.	S.E.
B	Adult male	6	34.5	16.5	6.7	7	22.6	4.8	1.8	7	16.7	6.0	2.3
	Adult female	4	23.0	5.1	"	"	"	"	"	"	"	"	"
C	Adult male	7	49.9	35.9	13.6	7	32.4	12.2	4.6	"	"	"	"
	Adult female	7	33.7	12.8	4.8	"	"	"	"	"	"	"	"
F	Adult male	5	36.2	14.6	6.5	7	21.4	12.6	4.8	"	"	"	"
	Adult female	7	38.1	31.7	12.0	"	"	"	"	"	"	"	"
G	Adult male	7	24.7	10.4	3.9	7	21.4	5.3	2.0	"	"	"	"
	Adult female	7	34.3	7.1	2.7	"	"	"	"	"	"	"	"
H	Adult male	7	22.0	10.2	3.9	7	20.7	9.0	3.4	"	"	"	"
J	Adult male	5	78.8	80.5	36.0	7	18.6	3.8	1.4	"	"	"	"
	Adult female	7	57.9	76.7	29.0	"	"	"	"	"	"	"	"
	School child	7	56.1	78.6	29.7	"	"	"	"	"	"	"	"
K	Adult male	7	41.9	16.5	6.3	7	12.9	3.6	1.4	"	"	"	"
	Adult female	7	25.1	21.0	7.9	"	"	"	"	"	"	"	"
	School child	7	27.7	21.4	8.1	"	"	"	"	"	"	"	"
L	Adult male	7	17.7	2.6	1.0	7	17.9	3.4	1.3	"	"	"	"
	Adult female	6	23.2	10.9	4.5	"	"	"	"	"	"	"	"
Q	Adult male	6	77.7	38.7	15.8	6	25.5	–	–	"	"	"	"
	Adult female	6	37.3	10.4	4.2	"	"	"	"	"	"	"	"
T	Adult male	7	56.9	19.1	7.2	7	30.2	17.1	6.5	"	"	"	"
	Adult female	7	45.3	21.3	8.0	"	"	"	"	"	"	"	"
U	Adult male	7	32.1	31.7	12.0	7	18.2	5.0	1.9	"	"	"	"
	Adult female	7	25.9	7.6	2.9	"	"	"	"	"	"	"	"
V	Adult male	5	27.8	20.3	9.1	7	20.4	6.4	2.4	"	"	"	"
	Adult female	5	23.4	7.6	3.4	"	"	"	"	"	"	"	"

S.D., Standard deviation.
S.E., Standard error.

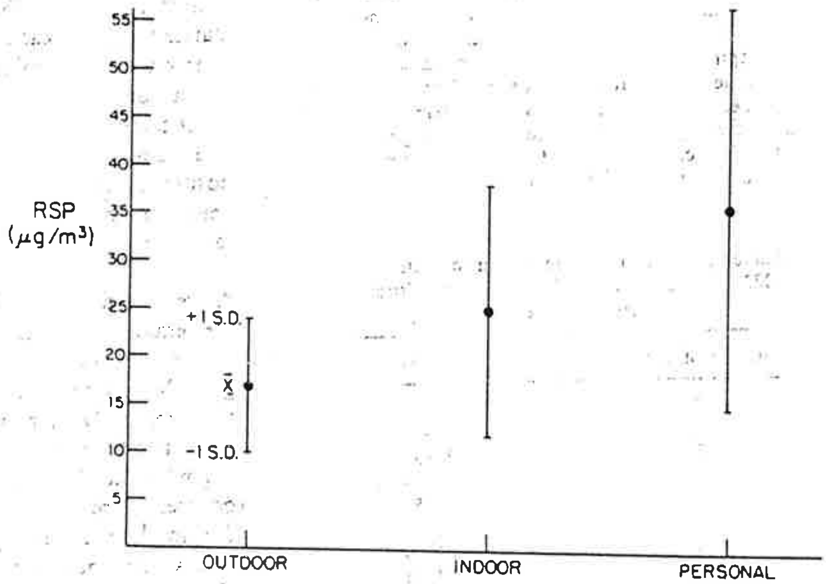

Fig. 1. Comparison of means and standard deviations for outdoor, indoor and personal RSP concentrations ($\mu g\ m^{-3}$).

Table 3. Average personal, indoor and outdoor RSP concentrations recorded during 26 February–11 March 1982, in Waterbury, Vermont

		RSP Concentrations ($\mu g\, m^{-3}$) Personal				Indoor				Outdoor			
Home ID	Person type	N	$\bar{X}$	S.D.	S.E.	N	$\bar{X}$	S.D.	S.E.	N	$\bar{X}$	S.D.	S.E.
A	Adult male	6	45.2	10.1	4.1	7	18.4	4.5	1.7	7	18.1	6.1	2.3
	Adult female	7	26.4	10.6	4.0	"	"	"	"	"	"	"	"
D	Adult male	2	30.0	–	–	7	13.1	4.3	1.6	"	"	"	"
E	Adult male	7	32.4	24.7	9.3	7	15.3	7.6	2.9	"	"	"	"
	Adult female	6	18.8	7.8	3.2	"	"	"	"	"	"	"	"
I	Adult male	7	45.3	12.9	5.3	7	24.3	17.8	6.7	"	"	"	"
	Adult female	6	29.1	9.6	3.6	"	"	"	"	"	"	"	"
M	Adult male	7	47.9	25.0	9.5	7	20.2	9.5	3.6	"	"	"	"
	Adult female	7	32.1	23.7	9.0	"	"	"	"	"	"	"	"
O	Adult male	7	37.9	16.0	6.0	7	28.6	11.1	4.2	"	"	"	"
	Adult female	7	31.7	10.4	3.9	"	"	"	"	"	"	"	"
P	Adult male	5	40.4	8.2	3.7	5	42.6	4.8	2.2	"	"	"	"
	Adult female	5	44.8	7.6	3.4	"	"	"	"	"	"	"	"
R	Adult male	7	52.3	14.4	5.4	7	49.3	16.7	6.3	"	"	"	"
	Adult female	7	66.1	30.4	11.5	"	"	"	"	"	"	"	"
S	Adult male	6	38.3	22.2	9.1	7	28.6	7.7	2.9	"	"	"	"
	Adult female	6	36.5	26.9	11.0	"	"	"	"	"	"	"	"
W	Adult male		No valid samples			7	49.0	11.5	4.4	"	"	"	"
	Adult female		No valid samples			"	"	"	"	"	"	"	"
X	Adult male	6	28.8	18.0	7.4	7	24.3	12.0	4.6	"	"	"	"
	Adult female	6	33.3	12.5	5.1	"	"	"	"	"	"	"	"
	School child	7	36.9	24.4	9.2	"	"	"	"	"	"	"	"
Y	Adult female	5	25.6	8.9	4.0	5	26.2	4.3	1.9	"	"	"	"

S.D., Standard deviation.
S.E., Standard error.

among outdoor, indoor, and personal particle levels. For example, approximately 70% of recorded ambient concentrations are below 20 $\mu g\, m^{-3}$, while 45% of indoor and only 25% of personal concentrations are less than this value. Similarly, although outdoor levels were all less than or equal to 30 $\mu g\, m^{-3}$, 75% of indoor values and just 53% of personal exposures were as low. Results of paired t-tests confirm that differences among the three sample types are statistically significant ($P < 0.05$).

Daily fluctuations in average outdoor, indoor, and personal RSP are displayed schematically in Fig. 4. Mean personal exposure was higher than both indoor and outdoor measurements in all cases. Average indoor levels exceeded ambient concentrations on 12 out of 14 sampling days. Mean personal values also tended to fluctuate more widely, often increasing or decreasing by 10 $\mu g\, m^{-3}$ from one 24-h sampling period to the next. Day-to-day indoor values varied by more than 5 $\mu g\, m^{-3}$ only once. Measured outdoor RSP concentrations were generally between 10 and 20 $\mu g\, m^{-3}$ and daily variations were less than 10 $\mu g\, m^{-3}$ on all but 2 sampling days. Neither personal nor indoor RSP were strongly correlated with outdoor values (personal vs outdoor: $n = 280$, $r = 0.06$, $P < 0.35$; indoor vs outdoor: $n = 163$, $r = 0.11$, $P < 0.17$). A significant relationship was observed, however, between personal exposure and in-home concentrations (personal vs indoor: $n = 278$, $r = 0.50$, $P < 0.0001$).

The general relationship observed among RSP samples in Waterbury, personal > indoor > outdoor, has been a consistent finding in all personal monitoring studies (Binder *et al.*, 1976; Ferris *et al.*, 1979; Spengler *et al.*, 1980; Spengler and Tosteson, 1981; Dockery and Spengler, 1981; Spengler *et al.*, 1981, 1983; Sega and Fugas, 1982). Because individuals move through a variety of micro-environments (and RSP concentrations) during their normal day-to-day activities, personal exposure and associated variability are likely to be greater than measured in-home or outdoor values (Repace and Lowry, 1980). Sources of elevated particle concentrations which a person might encounter in the course of a typical day include passive exposures to tobacco smoke (especially in enclosed, poorly ventilated spaces) and occupational and in-transit exposures.

A summary of time-activity data for the 48 volunteers (280 person-days) is presented in Table 4. On the average, participants spent approximately 74% of their time at home, which undoubtedly accounts for the stronger correlations between in-home and personal RSP measurements. People were indoors (i.e. home, work, public place, other) 94% of the time, in-

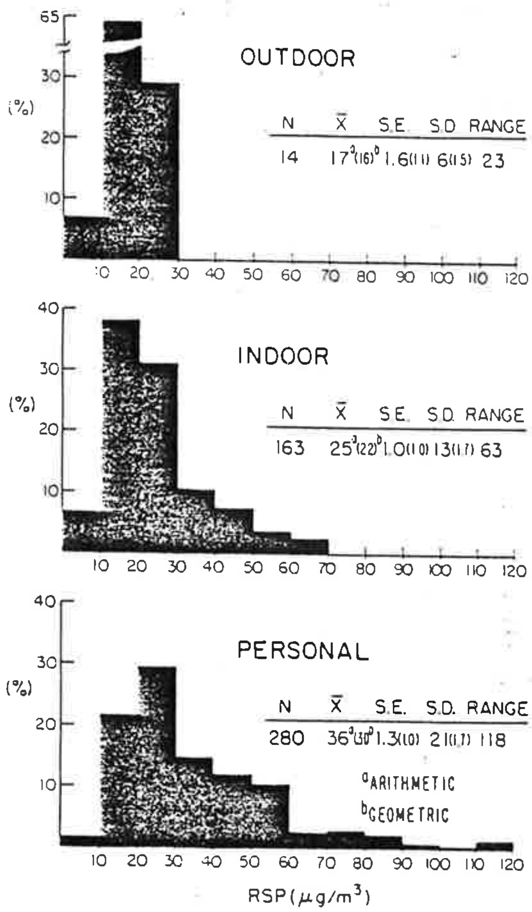

Fig. 2. Percentage distributions and summary statistics for outdoor, indoor and personal RSP concentrations ($\mu g\,m^{-3}$).

transit 4%, and outdoors only 1%. Women were at home a significantly ($P < 0.05$) greater amount of time than men (76.5% vs 71.6%). Similarly, men spent more time in-transit (5.2% vs 3.7%) and outdoors (2.1% vs 0.7%) than women. These values are in excellent agreement with figures presented by other investigators (Chapin, 1974; Szalai, 1972; Moschandreas and Morse, 1979).

Because women stayed at home a greater portion of the time, correlations between in-home RSP concentrations and personal exposure were higher for them ($r = 0.61$; $P < 0.0001$) than men ($r = 0.42$; $P < 0.0001$). Not surprisingly, mean personal exposure for men ($40\,\mu g\,m^{-3}$) exceeded that for women ($33\,\mu g\,m^{-3}$) by $7\,\mu g\,m^{-3}$ (21%). A significant correlation ($r = 0.43$, $P < 0.0001$) was observed between husbands' and wives' individual exposures.

A comparison of time-activity data for weekdays versus weekends is given in Table 5. As expected, on weekends significantly more time is spent at home (83.2% vs 70.5%) and outdoors (2.5% vs 0.9%) and less at work (2.5% vs 16.6%). Yet even though people were inside their homes a greater percentage of the time, weekend personal exposures were not as strongly correlated with in-home measurements ($r = 0.42$, $P < 0.0002$) as weekday values ($r = 0.53$, $P < 0.0001$). The reason for this apparent discrepancy is unclear, however, differences were slight and probably due in part to the small sample size.

Average personal exposure as a function of exposure category and time exposed is shown in Table 6. No differences in average personal exposure were apparent based on time spent at work, in-transit and outdoors. Cigarette smoke, however, was found to be

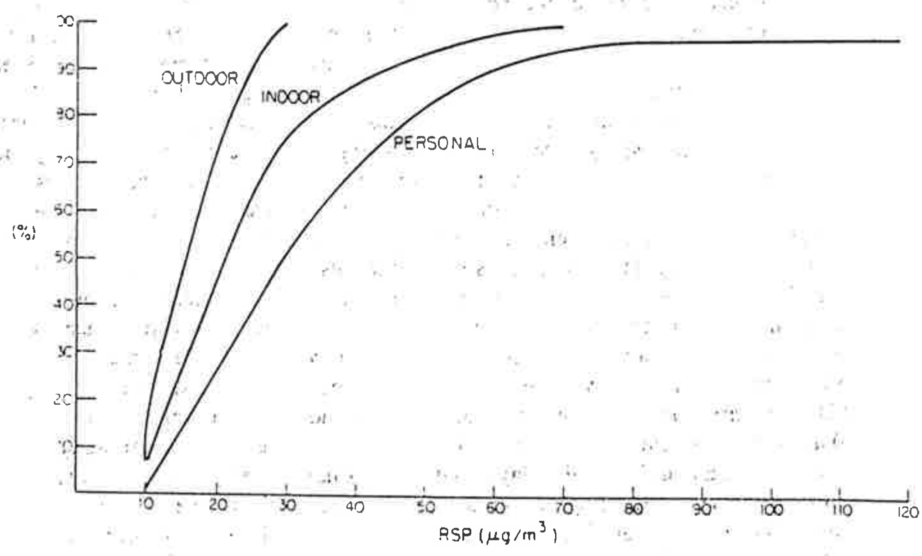

Fig. 3. Cumulative percentage distributions for outdoor, indoor and personal RSP concentrations ($\mu g\,m^{-3}$).

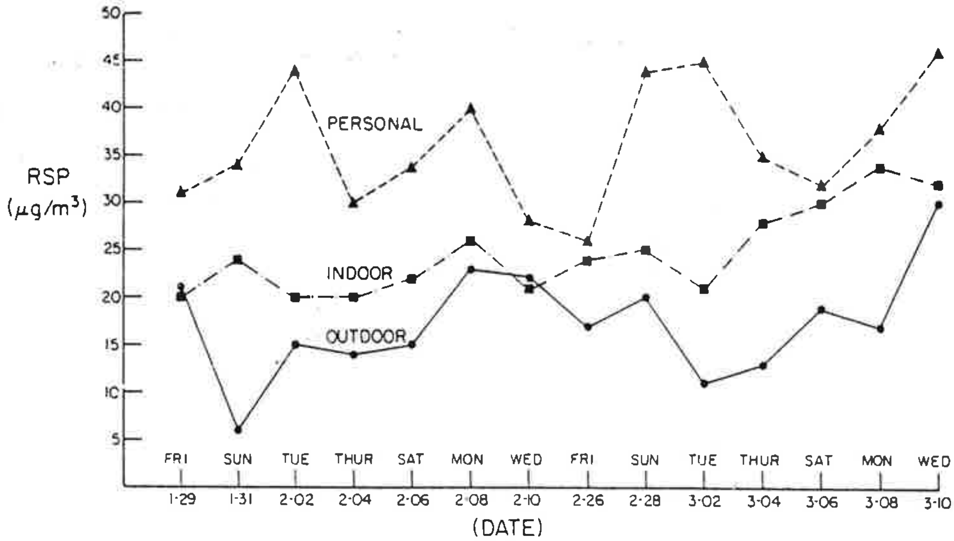

Fig. 4. Daily fluctuations in average outdoor, indoor and personal RSP concentrations ($\mu g\,m^{-3}$).

an important determinant. People experiencing passive exposure to tobacco smoke for more than 2 h day^{-1} had significantly greater RSP values. Their mean personal exposure (50.1 $\mu g\,m^{-3}$) was 18.4 $\mu g\,m^{-3}$ (58 %) higher than individuals who were not subjected to any tobacco smoke (31.7 $\mu g\,m^{-3}$). Similar findings have been reported by other investigators (Repace and Lowrey, 1980; Dockery and Spengler, 1981; Spengler *et al.*, 1980; Spengler and Tosteson, 1981; Spengler *et al.*, 1981, 1983).

Percentage distributions for personal RSP exposure in each smoke-exposed category are shown in Fig. 5. It is clear that exposure tended to be elevated for individuals in the 'high' smoke-exposed group

Table 4. Summary of time–activity data for participants in the 1982 Harvard Personal Monitoring Study in Waterbury, Vermont

		% Time			
Micro-environment	Person type	N*	$\bar{X}$	S.E.	S.D.
Home	All	280	73.9	1.0	17.1
	Adult males	123	71.6†	1.7	18.7
	Adult females	144	76.5†	1.3	15.6
Work	All	280	12.7	0.9	15.8
	Adult males	123	14.2	1.5	16.9
	Adult females	144	12.6	1.3	15.0
Public place	All	280	4.5	0.4	7.2
	Adult males	123	5.0	0.9	8.2
	Adult females	144	4.4	0.5	6.5
In-transit	All	280	4.3	0.3	5.7
	Adult males	123	5.2†	0.7	7.4
	Adult females	144	3.7†	0.3	3.7
Other indoors	All	280	3.2	0.6	9.5
	Adult males	123	2.0	0.9	9.6
	Adult females	144	2.2	0.5	5.8
Outdoors	All	280	1.3	0.3	4.1
	Adult males	123	2.1†	0.5	5.4
	Adult females	144	0.7†	0.2	2.5

* N, Number of person-days.

† Values for males and females are significantly different ($P < 0.05$) based on t-test results.

S.E., Standard error.

S.D., Standard deviation.

Table 5. Comparison of time–activity data for weekdays and weekends for participants in the 1982 Harvard Personal Monitoring Study in Waterbury, Vermont

Micro-environment	Day	% Time			
		N*	$\bar{X}$	S.E.	S.D.
Home	Weekday	204	70.5†	1.1	16.2
	Weekend	76	83.2†	1.9	16.3
Work	Weekday	204	16.6†	1.2	16.4
	Weekend	76	2.5†	0.9	7.5
Public place	Weekday	204	4.7	0.5	7.5
	Weekend	76	4.0	0.7	6.5
In-transit	Weekday	204	4.4	0.4	5.2
	Weekend	76	4.0	0.8	7.0
Other indoors	Weekday	204	3.0	0.6	8.1
	Weekend	76	3.8	1.4	12.6
Outdoors	Weekday	204	0.9†	0.2	3.3
	Weekend	76	2.5†	0.7	5.6

* N, Number of person-days.
† Significantly different ($P < 0.05$) based on t-test results.
S.E., Standard error.
S.D., Standard deviation.

Table 6. Personal RSP concentration as a function of exposure mode and time exposed

Exposure mode	Time exposed (min day^{-1})	Personal RSP concentration ($\mu g\,m^{-3}$)			
		N*	$\bar{X}$	S.E.	S.D.
Passive exposure to tobacco smoke	> 120	63	50.1	2.8	22.1
	1–120	33	32.9	2.5	14.1
	0	184	31.7	1.5	19.9
Work	> 120	116	38.6	2.2	23.1
	1–120	14	29.6	3.6	13.4
	0	150	34.5	1.6	20.0
In-transit	> 120	30	36.6	3.3	17.8
	1–120	183	35.8	1.5	20.5
	0	67	36.1	3.0	24.6
Outdoors	> 120	55	34.8	2.8	20.5
	1–120	169	26.1	1.6	20.4
	0	56	36.7	3.3	24.4

* N, Number of person-days.
S.E., Standard error.
S.D., Standard deviation.

(> 120 min day^{-1}). Mean values were similar for medium-exposed (1–120 min day^{-1}) and nonexposed classifications. Five personal samples (four different people) in the nonexposed group exceeded 80 $\mu g\,m^{-3}$, despite the apparent absence of tobacco smoke (based on activity-log data). Since corresponding in-home RSP levels for these five individuals varied from 2 to 58 % of measured personal exposure, it is likely that elevated personal values resulted from high RSP concentrations encountered away from home.

Because participants in the study were nonsmokers, as were all occupants of their respective residences, it is important to establish where passive-smoke exposure occurred. Thirty-four per cent (98 person-days) of the 280 personal RSP values were classified as smoke exposed from activity-log data, while 66 % (184 person-days) were considered to be free of tobacco smoke effects. Data presented in Table 7 show smoke exposure occurrences (time exposed per day) by micro-environment. None of the volunteers was exposed to tobacco smoke during travel (in-transit) and only 9 out of 280 24-h samples had passive smoke exposure at home. Similarly, just 13 24-h samples had exposure to passive cigarette smoke in 'other' indoor micro-

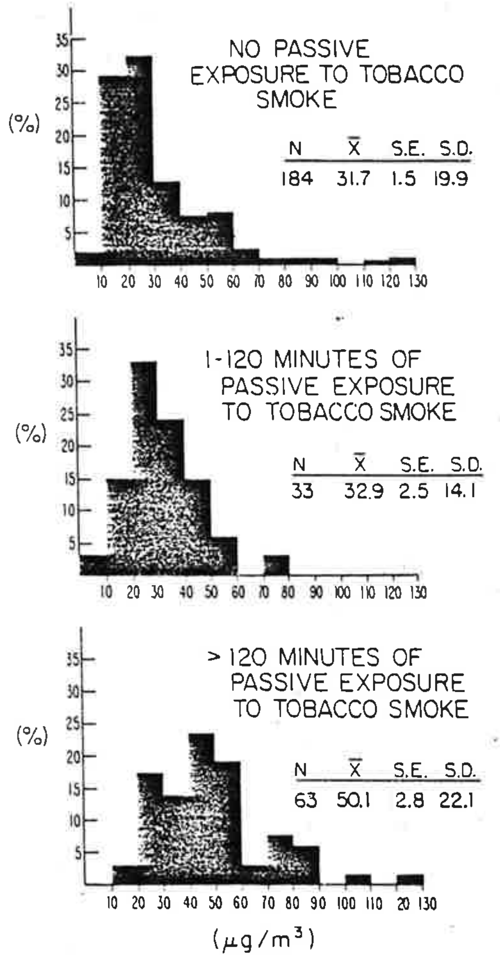

Fig. 5. Percentage distribution for personal RSP exposure by smoke-exposed category.

Table 7. Time exposed per day to tobacco smoke by micro-environment

Micro-environment	Time exposed to tobacco smoke (min)	N*
Home	> 120	5
	1–120	4
	0	271
Work	> 120	28
	1–120	10
	0	242
In-transit	> 120	0
	1–120	0
	0	280
Public place	> 120	30
	1–120	19
	0	231
Other	> 120	4
	1–120	9
	0	269

* N, Number of person-days with reported smoke exposure.

environments. Most smoke exposure was in public places (30 person-days with > 120 min) and at work (28 person-days with > 120 min).

Developing a model for personal exposure

It is becoming increasingly apparent that personal RSP exposure is not characterized adequately by outdoor measurements. This and other studies (Dockery and Spengler, 1981) have shown that in-home RSP concentration is the single most important determinant. However, even when information about time at home and associated particle levels is on hand, most of the variation in personal exposure remains unexplained. Because large-scale personal monitoring studies are not feasible currently, development of a method to estimate personal exposure from available data is a primary goal.

Assessment of integrated exposure to air pollution must take account of time spent in important micro-environments and associated pollutant concentrations. The basis for this approach has been described by Fugas (1976) and elaborated upon in subsequent papers by several investigators (Ott, 1980; Duan, 1980; Duan, 1982; Tosteson and Spengler, 1981). While the time-weighted exposure model provides a useful theoretical framework for analysis, its practical value is limited by a paucity of information about time-activity patterns and indoor pollution levels.

Data collected during the 1982 Harvard Personal Monitoring Study in Waterbury, Vermont, offer a rare opportunity to evaluate the predictive capability of a simple time-weighted exposure model. Measured parameters available for inclusion in the model are personal, in-home and outdoor RSP concentrations as well as time spent in various micro-environments. Average values were calculated for each of the 43 participants with 4 or more valid sampling days. Means, standard deviations, and minimum and maximum values for each parameter are given in Table 8. All time exposed to tobacco smoke, regardless of where it occurred, was treated as a separate micro-environment.

These data confirm that people were indoors most of the time (98.7%), primarily at home (73.7%). Despite the fact that all volunteers were nonsmokers, the average time exposed to tobacco smoke across all microenvironments was 5.7% (range 0–23%). The mean time-weighted outdoor RSP contribution ($t_{OUT} * C_{OUT}$) to personal exposure was just 0.2 $\mu g\,m^{-3}$, while the average time-weighted indoor RSP contribution ($t_{IN} * C_{IN}$) was 18.2 $\mu g\,m^{-3}$. Mean personal exposure ranged from 17.7 to 77.7 $\mu g\,m^{-3}$, with an arithmetic mean of 36.0 $\mu g\,m^{-3}$.

The correlation matrix for model parameters is displayed in Table 9. Personal exposure (C_{PERS}) was positively correlated with $t_{IN} * C_{IN}$ ($r = 0.40$; $P < 0.008$) and t_{EXPS} ($r = 0.30$; $P < 0.05$). Personal exposure was negatively correlated with time spent at home ($r = -0.28$; $P < 0.07$), suggesting that in-home RSP concentrations tended to be less than values

Table 8. Measures of central tendency and variability for model parameters

Parameters	$\bar{X}$	S.D.	Min.	Max.
Time outdoors (%)*	1.3	2.7	0	16.5
Time in public places (%)*	2.6	2.5	0	9.2
Time in 'other' micro-environments (%)*	2.9	5.7	0	24.9
Time in-transit (%)*	4.3	3.2	0	17.6
Time exposed to smoke (%)	5.7	6.4	0	23.0
Time at work (%)*	9.5	9.1	0	28.2
Time at home (%)*	73.7	10.7	49.6	98.1
$t_{OUT} \times C_{OUT}$ ($\mu g\, m^{-3}$)†	0.2	0.4	0	2.7
$t_{IN} \times C_{IN}$ ($\mu g\, m^{-3}$)‡	18.2	7.6	8.6	44.7
C_{PERS} ($\mu g\, m^{-3}$)§	36.0	12.2	17.7	77.7

* No smoke exposure.
† t_{OUT} = fraction of time outdoors, C_{OUT} = measured RSP concentration outdoors.
‡ t_{IN} = fraction of time indoors at home; C_{IN} = measured in-home RSP concentration.
§ C_{PERS} = measured personal RSP exposure.
S.D., Standard deviation.

Table 9. Correlation matrix for model parameters

	t_{PP}	t_{OTHER}	t_{TRAV}	t_{EXPS}	t_{WORK}	t_{IN}	$t_{OUT} \times C_{OUT}$	$t_{IN} \times C_{IN}$	C_{PERS}
t_{OUT}	−0.02* 0.90†	0.01 (0.93)	−0.06 (0.71)	−0.24 (0.13)	−0.20 (0.21)	0.07 (0.67)	0.98 (0.0001)	−0.06 (0.71)	−0.13 (0.40)
t_{PP}		−0.22 (0.16)	0.22 (0.16)	−0.20 (0.20)	−0.06 (0.70)	−0.01 (0.98)	−0.03 (0.87)	0.28 (0.07)	0.14 (0.36)
t_{OTHER}			−0.07 (0.64)	−0.20 (0.20)	−0.22 (0.16)	−0.15 (0.32)	−0.03 (0.84)	−0.22 (0.16)	−0.25 (0.11)
t_{TRAV}				0.23 (0.13)	0.10 (0.52)	−0.52 (0.004)	−0.07 (0.67)	−0.28 (0.07)	0.22 (0.15)
t_{EXPS}					−0.09 (0.59)	−0.39 (0.01)	−0.21 (0.18)	−0.22 (0.15)	0.30 (0.05)
t_{WORK}						−0.65 (0.0001)	−0.07 (0.67)	−0.28 (0.07)	0.22 (0.15)
t_{IN}							0.11 (0.49)	0.50 (0.0001)	−0.28 (0.07)
$t_{OUT} \times C_{OUT}$								0.09 (0.55)	−0.14 (0.36)
$t_{IN} \times C_{IN}$									0.40 (0.008)

t_{OUT} = time fraction outdoors.
t_{PP} = time fraction in public places (no smoke exposure).
t_{OTHER} = time fraction in 'other' micro-environments (no smoke exposure).
t_{TRAV} = time fraction in-transit (no smoke exposure).
t_{EXPS} = time fraction exposed to smoke.
t_{WORK} = time fraction at work (no smoke exposure).
t_{IN} = time fraction indoors at home (no smoke exposure).
$t_{OUT} \times C_{OUT}$ = time fraction outdoors times measured outdoor RSP concentration.
$t_{IN} \times C_{IN}$ = time fraction indoors at home times measured indoor RSP concentration.
C_{PERS} = measured personal RSP exposure.
* Pearson correlation coefficient.
† Probability.

encountered away from home. It is important to point out, however, that RSP emissions are likely to be greatest when people are at home. Therefore, use of a 24-h average to represent C_{IN} may under-represent the indoor contribution and over-represent other contributions.

To estimate exposure, data on RSP concentrations as well as time in relevant micro-environments are necessary. Although information about time-activities was available for each individual, RSP measurements were conducted in only two micro-environments; outdoors (C_{OUT}) and indoors at home (C_{IN}). As shown in Tables 8 and 9, $t_{IN} * C_{IN}$ is a major determinant of personal exposure, while $t_{OUT} * C_{OUT}$ makes a negligible contribution. Given that personal exposure tended to be negatively correlated with time spent at home (t_{IN}) and that $t_{IN} * C_{IN}$ by itself explained just 16% of the variance in personal exposure, it is likely that particle concentrations in other micro-environments had substantial impact on individual RSP values.

To investigate this issue further, a model was constructed to estimate RSP concentrations in micro-environments where measurements were not made (e.g. work, exposed to smoke, in-transit). Because fraction of time spent in all of the micro-environments sums to 1 for each individual, a modification of the conventional linear regression technique is needed (Spengler and Tosteston, 1981). To accomplish this, the time-weighted in-home concentration ($t_{IN} * C_{IN}$) is subtracted from measured personal exposure (C_{PERS}) and this value (excess RSP away from home) serves as the dependent variable. Explanatory variables are fraction of time spent in various micro-environments (i.e. work, exposed to smoke, in-transit, public place, other, outdoors).

Apart from taking covariance among time fractions into account, subtracting $t_{IN} * C_{IN}$ from personal RSP exposure is a logical step. Considering only 'excess RSP away from home' ($C_{PERS} - t_{IN} * C_{IN}$) reduces the amount of particle mass to be approtioned among remaining micro-environments. A linear regression approach relating $C_{PERS} - t_{IN} * C_{IN}$ to time in other locations was combined with a stepwise regression technique (SAS, 1982) to derive estimates of RSP concentrations in three micro-environments where no measurements were conducted; exposed to tobacco smoke (any place), work (no smoke eposure), and in-transit (no smoke exposure). Results are summarized in Table 10.

The fraction of time people experienced passive exposure to tobacco smoke was the single most important determinant of $C_{PERS} - t_{IN} * C_{IN}$. Adding time at work to the model decreased the root mean square (r.m.s.) difference from 9.2 to 8.2 $\mu g\ m^{-3}$ and increased the explained variance (r^2) from 27 to 44%. The best 3 variable model (i.e. exposed to smoke, work, in-transit) lowered the r.m.s. difference to 7.7 $\mu g\ m^{-3}$ while increasing the proportion of explained variance to 51%. Adding additional independent variables to the model (i.e. time fraction in public places, other indoor environments, outdoors) did not provide any significant improvement in predictive capability.

Regression coefficients derived for each micro-environment in the three variable model are statistically significant ($P < 0.05$) and furnish a means of estimating RSP concentrations in these locations. Respirable particle values were calculated to be 81 $\mu g\ m^{-3}$ ($\pm 19\ \mu g\ m^{-3}$) during exposure to tobacco smoke, 45 $\mu g\ m^{-3}$ ($\pm 13\ \mu g\ m^{-3}$) at work (no smoke exposure), and 92 $\mu g\ m^{-3}$ ($\pm 39\ \mu g\ m^{-3}$) in-transit (no smoke exposure). The intercept term implies that the combined RSP concentration outdoors, in public places, and in 'other' micro-environments was approximately 5 $\mu g\ m^{-3}$. While this estimate is probably low (e.g. average outdoor RSP concentration was

Table 10. Best-fitting least-squares regression models for personal RSP exposure ($\mu g\ m^{-3}$) minus time-weighted in-home concentration ($\mu g\ m^{-3}$)

Model	Terms	Coefficients ($\mu g\ m^{-3}$)	S.E.	F	$P > F$	r.m.s. Difference ($\mu g\ m^{-3}$)	r^2	Adjusted r^2
Best 1 variable model	intercept	13	—	—	—			
	exposed to smoke	87	22	15.31	0.0003	9.2	0.27	0.25
Best 2 variable model	intercept	8	—	—	—			
	exposed to smoke	92	20	22.11	0.0001	8.2	0.44	0.41
	work (no smoke exposure)	49	14	12.33	0.0011			
Best 3 variable model	intercept	5	—	—	—			
	exposed to smoke	81	19	17.98	0.0001			
	work (no smoke exposure)	45	13	11.44	0.0017	7.7	0.51	0.47
	in-transit (no smoke exposure)	92	39	5.62	0.0227			

17 $\mu g\ m^{-3}$), it is doubtful that actual levels were high enough to have a substantial impact on integrated personal exposure. For example, because so little time was spent in nonsmoke-exposed public places (average 2.6%). RSP concentrations would have to be about 175 $\mu g\ m^{-3}$ to have a time-weighted effect of the same magnitude as smoke exposure.

The RSP concentration estimates derived for smoke exposure, work and in-transit can be combined with measured parameters (e.g. in-home RSP concentration, outdoor RSP concentration, time-activity data) to specify a simple deterministic model for personal exposure. The equation describing personal RSP exposure for participants in the Waterbury study is given below

$$E = t_{IN} * C_{IN} + t_{OUT} * C_{OUT} + t_{EXPS} * 81\ \mu g\ m^{-3} + t_{WORK} * 45\ \mu g\ m^{-3} + t_{TRAV} * 92\ \mu g\ m^{-3},$$

where
E = personal RSP exposure ($\mu g\ m^{-3}$)
t_{IN} = fraction of time indoors at home (no smoke exposure)
C_{IN} = measured in-home RSP concentration ($\mu g\ m^{-3}$)
t_{OUT} = fraction of time outdoors
C_{OUT} = measured outdoor RSP concentration ($\mu g\ m^{-3}$)
t_{EXPS} = fraction of time exposed to tobacco smoke
t_{WORK} = fraction of time at work (no smoke exposure)
t_{TRAV} = fraction of time in-transit (no smoke exposure).

It is important to assess the predictive capability of the model and determine whether it offers a significant improvement in exposure estimation over its individual components. Data presented in Table 11 provide a direct comparison of three estimators: outdoor RSP concentration ($\mu g\ m^{-3}$); indoor RSP concentration ($\mu g\ m^{-3}$); and the time-weighted model. Predicted values for each method are compared to measured personal concentrations by proportion of explained variance (r^2), root mean square (r.m.s.) difference, and paired t-test.

Results of paired t-tests show that differences between predicted and observed values were significant in each case ($P < 0.001$). Outdoor RSP concentration is clearly not an important determinant, since it explains none of the variance in personal exposure and has a r.m.s. difference of 12.3 $\mu g\ m^{-3}$. Indoor RSP levels were a substantial improvement over outdoor values as evidenced by the better r^2 (0.29) and lowered r.m.s. difference (10.4 $\mu g\ m^{-3}$). Application of the time-weighted model provided an additional improvement over indoor values, raising the explained variance to 53% and reducing the r.m.s error to 8.4 $\mu g\ m^{-3}$.

An examination of observed RSP values vs those predicted from the time-weighted model show that estimates were reasonably close to measured concentrations for 42 of 43 people. However, the model seriously under-predicted (35 $\mu g\ m^{-3}$) personal exposure for the individual (adult male) with the highest average measured value (77.7 $\mu g\ m^{-3}$). In contrast, his wife's observed exposure (37.3 $\mu g\ m^{-3}$) was estimated closely and agreed well with measured in-home RSP (25.5 $\mu g\ m^{-3}$). Since he reported no passive exposure to tobacco smoke, it is likely that the discrepancy results from failure to record smoke exposure. Alternatively, it is possible that he consistently experienced elevated RSP levels in some other microenvironment. Removing this one person from the data set ($n = 43 - 1 = 42$) increased the proportion of variance explained by the model to 67% and lowered the r.m.s. error to 6.1 $\mu g\ m^{-3}$.

DISCUSSION

Previous studies

Personal monitoring studies are expensive, time consuming, and labor intensive. Available instrumentation is still relatively primitive compared to ambient monitors and real-time measurements are not feasible at the present time. Given these limitations, it is not surprising that few such investigations have been undertaken. Location, study design, and findings from previous personal monitoring studies which focus on particle concentrations are given in Table 12. A more thorough review of the state of the art in this field is available in a recent publication from the World Health Organization (WHO, 1982).

These data highlight the paucity of information on

Table 11. Comparison of three estimators of personal RSP exposure: outdoor RSP concentration; in-home RSP concentration and a time-weighted exposure model

Parameter	Estimators Outdoor*	In-home†	Model‡
Proportion of explained variance (r^2)	0.00	0.29	0.53
r.m.s. Difference§	12.3	10.4	8.4
Paired t-statistic (41 d.f.)	10.1	7.3	3.7

* Outdoor RSP concentration.
† In-home RSP concentration.
‡ Exposure = $t_{IN} * C_{IN} + t_{OUT} * C_{OUT} + t_{EXPS} * 81\ \mu g\ m^{-3} + t_{WORK} * 45\ \mu g\ m^{-3} + t_{TRAV} * 92\ \mu g\ m^{-3}$.
§ Root mean square difference.

Table 12. Summary of location, study design, and findings from previous personal monitoring studies

Location	Reference(s)	Study design	Findings
Ansonia, CT	Binder (1976)	20 school children carried personal RSP samplers for 1 day	Outdoor measurements do not reflect accurately the RSP concentrations experienced by individuals.
Zagreb, Yugoslavia	Fugas *et al.* (1981) Sega and Fugas (1982)	12 volunteers carried personal RSP samplers during winter and summer 1980/1981	Good correlation in winter between outdoor and personal RSP measurements, but none during the summer.
			The apparently good agreement between outdoor and personal exposure (winter) is not due to close association, but to the fact that both varied within relatively narrow limits at high concentrations.
			A considerable part of personal exposure comes from particles which are not related to outdoor sources.
Watertown, MA Steubenville, OH	Dockery and Spengler (1981)	37 volunteers carried personal RSP samplers during summer and winter 1975/1976	Mean personal exposure reflects city-wide outdoor concentrations.
			Measured in-home RSP concentrations explained about 50% of the variance in personal exposure.
			A time-weighted activity model did not provide significantly better predictions than just in-home concentrations alone.
Topeka, KS	Spengler *et al.* (1980), Spengler and Tosteson (1981), Tosteson and Spengler (1981)	46 volunteers carried personal RSP samplers during May and June 1979	Personal exposures were poorly correlated with ambient RSP concentration.
			Passive exposure to cigarette smoke stands out as the most common cause of high personal exposure.
			There was high variability in personal exposures across the population.
Kingston Harrison, TN	Spengler *et al.* (1981) Spengler *et al.* (1983)	88 volunteers carried personal RSP samplers during February and March 1980	Personal exposure is only weakly correlated with outdoor measurements at central sites.
			Ambient RSP values underestimate exposures for non-smoking and smoking subjects.
			The chemical composition of the average personal excess (personal-outdoor) may be different than that of outdoor RSP.
			The positive covariance between exposure and ventilation may enhance the difference between personal and outdoor exposures.

personal exposure which is currently available. Less than 250 people have carried personal RSP monitors and some studies lasted only one day. The limited data base is reflected in the conflicting nature of published results, with some investigators reporting a weak relationship between outdoor and personal RSP (Binder, 1976; Spengler *et al.*, 1980; Spengler and Tosteston, 1981; Tosteson and Spengler, 1981; Spengler *et al.*, 1981, 1983) and others finding a strong correlation (Fugas *et al.*, 1981; Sega and Fugas, 1982; Dockery and Spengler, 1981). One finding which has been consistent across all studies is the important contribution of in-home RSP concentration to individual exposure.

1982 *Harvard personal monitoring study*

It is important to put the Waterbury, Vermont, data into perspective before attempting to draw any conclusions. Measurements were conducted during two 2-week monitoring periods from January to March 1982. Indoor pollution levels are known to be higher in the winter due to reduced ventilation (NAS, 1981) and people are likely to spend more time indoors during cold weather. Furthermore, outdoor pollution levels also vary with season and could be higher during summer months depending on local sources, regional transport, and meteorological conditions.

It is interesting to note that studies reporting a strong correlation between personal and outdoor particle concentrations were done in relatively polluted areas (Fugas *et al.*, 1981; Sega and Fugas, 1982; Dockery and Spengler, 1981). The consistently low ambient RSP concentrations (and limited variability) in Waterbury precluded the possibility of finding a strong correlation with either indoor or personal values. As reported in an earlier paper (Sexton *et al.*, 1983a), RSP levels in residential sections of Waterbury exhibited dramatic diurnal variation, with night-time values frequently exceeding afternoon concentrations by 5- to 10-fold. If, as expected, people spend less time outdoors at night and air-exchange rates in homes tend to decrease in the evening, the impact of outdoor particle values on personal exposure is reduced even further.

No attempt was made to obtain a random sample from the Waterbury population. Only nonsmoking volunteers were accepted and preference was given to couples from the same household. Participants tended to be well-educated and conscious of environmental issues. Because it is obvious that the self-selection process and elimination of smokers from the study introduced biases, one must exercise caution when interpreting results and applying findings to other communities.

CONCLUSIONS

Results of a personal monitoring study in Waterbury, Vermont, during the winter of 1982 indicate that personal RSP exposure is not characterized well by outdoor (ambient) measurements. In-home particle concentrations provide a better estimator, but still account for only about 25% of the variance in individual values. A linear regression technique was used to estimate RSP concentrations in three microenvironments where measurements were not available (i.e. passive smoke exposure = 81 $\mu g\,m^{-3}$, work: no smoke exposure = 45 $\mu g\,m^{-3}$, in-transit: no smoke exposure = 92 $\mu g\,m^{-3}$). A simple time-weighted exposure model, constructed using these values along with time-activity data and observed indoor and outdoor RSP levels, explained more than 50% of the variance in personal exposures. These results are encouraging, yet it must be remembered that model coefficients were derived from these same data and therefore predictive capability may be artifically high. Furthermore, values may not be valid for other seasons and their applicability to other people in Waterbury (e.g. children, smokers) is uncertain. Estimates need to be improved and refined through subsequent personal monitoring studies.

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