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ORIGINAL RESEARCH

Exposure of infants to outdoor and indoor air pollution in low-income urban areas — a case study of Delhi

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Indoor air pollution is potentially a very serious environmental and public health problem in India. In poor communities, with the continuing trend in biofuel combustion coupled with deteriorating housing conditions, the problem will remain for some time to come. While to some extent the problem has been studied in rural areas, there is a dearth of reliable data and knowledge about the situation in urban slum areas. The microenvironmental model was used for assessing daily-integrated exposure of infants and women to respirable suspended particulates (RSP) in two slums of Delhi — one in an area of high outdoor pollution and the other in a less polluted area. The study confirmed that indoor concentrations of RSP during cooking in kerosene-using houses are lesser than that in wood-using houses. However, the exposure due to cooking was not significantly different across the two groups. This was because, perhaps due to socioeconomic reasons, kerosene-using women were found to cook for longer durations, cook inside more often, and that infants in such houses stayed in the kitchen for longer durations. It was observed that indoor background levels during the day and at nighttime can be exceedingly high. We speculate that this may have been due to resuspension of dust, infiltration, unknown sources, or a combination of these factors. The outdoor RSP levels measured just outside the houses (near ambient) were not correlated with indoor background levels and were higher than those reported by the ambient air quality monitoring network at the corresponding stations. More importantly, the outdoor levels measured in this study not only underestimated the daily-integrated exposure, but were also poorly correlated with it.
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Introduction

It is well known that rapid industrialization and urbanization have led to a deterioration of environmental conditions. In urban areas, poor sanitation, generation of solid wastes, inadequate housing, and water supply are acknowledged causes of ill health. What is less well known is that the traditional domestic practice of cooking in primitive stoves with low-grade fuels and in badly ventilated kitchens can have serious implications for the health of women and children (Bruce et al., 2000, Smith, 2000). In rural areas, women and children are mainly exposed only to pollutants from the combustion of cooking fuels, garbage and agricultural wastes; agricultural machines; small mills, tobacco smoking, and from natural dust sources. But their counterparts in urban slums are also exposed to pollution from industrial and vehicular sources because slums are commonly located near factories and highways. The dense clustering of houses, poor ventilation, and fugitive emissions compound the problem manifold. Thus it is likely that the urban slum community bears the largest air pollution exposure burden in developing countries. A number of studies have attempted to estimate the exposure from biomass combustion in rural areas of India, Nepal, and a few countries in Africa and South America (for example, Smith et al., 1983; Menon, 1988; Ramakrishna, 1988; Saksena et al., 1992; Albalak et al., 1999; Ezzati, 2001). However, the information related to the urban situation is meager (Ellgard and Egneus, 1993; Raiyani et al., 1994; Smith et al., 1994; Ellegard, 1996).

It has been postulated that household fuel switching from lower to higher quality fuels generally leads to substantially lower emissions of health damaging pollutants. However, the extent to which exposures are reduced is difficult to predict,

1. Abbreviations: AM, arithmetic mean; ANOVA, analysis of variance; CO, carbon monoxide; GM, geometric mean; GSD, geometric standard deviation; r^2, correlation coefficient; RSP, respirable suspended particles

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especially in urban areas, because of the presence of both indoor and outdoor sources. Across the world, biofuels are the most important fuels in terms of the number of people affected. In energy content, they are the most important fuels in many poor countries, although second to the fossil fuels on a global basis. They are used principally at the household level for cooking and space heating. Furthermore, they are likely to remain important for much of humanity for many decades. While at the household level the financial implications of shifting to cleaner energy systems may not be significant, but considering the large populations of countries in the developing world the macrolevel implications are indeed astronomical. Coupled with the limitations of availability of alternatives and associated infrastructural and institutional requirements, the policy issues are of serious concern to decision-makers and planners. Before embarking on new national policy or technical initiatives, there is a need to gather extensive scientific evidence. Some questions that are of interest here are:

- how clean are clean fuels and stoves?
- are clean fuels and stoves the sole guarantee to a better energy–environment situation?
- what would be the energy–environment implications of the rural–urban migration at the micro- and macro-levels?

The objective of this study was to assess the daily exposure of infants (and their mothers) to respirable suspended particles (RSP) ($d_{50} = 5\,\mu$m) and carbon monoxide and determine the factors that influence exposure. The exposure assessment exercise was part of a larger epidemiological study that tested the association between indoor air pollution and acute lower respiratory infection in infants (Sharma et al., 1998).

Study design

Zartarian et al. (1997) have defined exposure to be the contact between an agent and a target. They further define instantaneous point exposure as contact between an agent and a target at a single point in space and at a single instant in time. Duan (1982) introduced the term "micro-environment type" to compute exposure over any time period. He also suggested that a microenvironment should be defined with sufficient resolution to be homogeneous. On the other hand, a microenvironment type has to be somewhat broad so that the analyst does not have too many types to assess. The study attempts to estimate an individual's daily integrated exposure using Duan's definition. The following assessment procedure was used:

$$E_i = \sum_{j=1}^{m} C_{ij} t_{ij}$$

where E_i is the exposure of the ith individual, C_{ij} is the concentration of the pollutant measured in the jth microenvironment of the ith individual, t_{ij} is the time spent by the ith individual in the jth microenvironment. The total number of microenvironments is m such that:

$$\sum_{j=1}^{m} t_{ij} = 24h$$

Infants and their mothers were chosen as the target population group, because of the significant amount of time spent in the kitchen as well as their being a sensitive health group. Exploratory surveys helped in identifying the predominant microenvironments for these population groups (Malhotra et al., 2000). These turned out to be six in number: the three cooking sessions, the session between meals which could be spent indoors or outdoors, and the sleeping session. The other microenvironments (such as the time after rising till breakfast, from dinner till sleep, etc.) were found to be either comparatively too short or difficult to monitor.

The concentration levels were measured using portable samplers, while the time spent in each microenvironment was estimated through recall-based questionnaires. Two slums were chosen for the study: one in a highly polluted area and the other in a negligibly polluted area. This was done so as to facilitate comparisons and ensure variability in the sample. In each slum we chose 20 houses that used wood and the same number of houses using kerosene. Each house was monitored for two consecutive days, that is, all microenvironments were monitored twice. In a week two houses were monitored in each group of households.

Description of study region

The 1991 census put the total population of Delhi (National Capital Territory) at 9.37 million. Of this, the natural growth of population accounts for 35,000 families per year and rural–urban migration for 40,000 families per year. As a result, the density of population stands at 6319 persons/km^2. With a population of 4.7 million slum dwellers, half of Delhi's population lives in substandard areas.

More than three-quarters of the emissions of air pollutants are caused by vehicles in Delhi (Kandlikar and Ramachandran, 2000). The total number of vehicles in 1991 was 1.9 million (22 percent cars and 67 percent two-wheelers). Delhi has three big thermal power stations — all coal based. While two of these are located within the city, the third is on the outskirts. However, there is much uncertainty about the total number of sources and emission factors. Kandlikar and Ramachandran (2000) have shown, based on sensitivity analysis, that the emissions can have an error of $\pm 100\%$.

The Central Pollution Control Board monitors the quality of air at nine stations in Delhi. The latest data published before the field work commenced pertained to 1991 (CPCB, 1992). The range of mean annual concentrations across these nine stations were: total suspended particulates (TSP) = 255–

643 $\mu g/m^3$; nitrogen dioxide (NO_2) = 24.2–61.7 $\mu g/m^3$; sulphur dioxide (SO_2) = 8.4–51.2 $\mu g/m^3$.

Till the early 1980s the consumption of fuelwood was high in Delhi. Since then, however, the firewood supply has decreased drastically. A survey conducted in over 8000 slum households (TERI, 1993) indicated that kerosene is the predominant fuel, accounting for 60 percent of the total energy consumption.

Selection of Sites

The purpose of the site selection exercise was to identify slums with a large enough population of infants in households where wood is the predominant cooking fuel. After short-listing such slums, another criteria, viz. ambient pollution level, was applied to select sites for the study.

Ideally sites should be selected at random from a comprehensive list of slums. It was not possible to follow this approach because (a) there is no up-to-date list of all slums in Delhi, and (b) the only list of slums available does not include information on critical parameters such as: fuel use, housing type, and ambient pollution levels.

It would be too time consuming to survey all slums in Delhi to obtain extra information just for the purpose of random selection. The selection procedure adopted was more judgmental in nature, relying on secondary information (such as data published by government agencies, reports and papers published by other researchers, etc.) and slum-level surveys conducted in a few cases. The procedure was:

Step 1: Identify big slums in Delhi (more than 1000 households).

Step 2: Using secondary information identify those big slums where wood is likely to be used by a majority of the population.

Step 3: Visit the slums selected in Step 2 to validate secondary information regarding fuel use and obtain information related to other parameters.

Step 4: Draw-up a list of likely sites for the study. Revisit these sites to crosscheck data on critical parameters.

Step 5: Select slums based on whether cooperation is to be expected from dwellers.

During surveys conducted in earlier stages of the project it became apparent that a large fraction of fuelwood might be collected and not purchased. Based on this information an attempt was made to identify big slums near green belts, forests, and in less urbanized areas. It is also likely that wastes from timber markets and saw mills are purchased/collected by slum dwellers in the vicinity. Such slums were also visited.

In order to classify the ambient air quality of slums, it was assumed that a slum has air quality similar to that of the nearest monitoring station. If a particular slum was very far from a monitoring station then land-use information, anecdotal reports, and educated guesses were used to classify the slum. Cluster analysis was used to classify slums into high and low categories of ambient pollution (for details see Saksena, 1999).

After identifying big slums and those where wood is likely to be used 52 of these were visited to obtain information on key parameters based on observations and open-ended discussions with community leaders. These parameters are: total number of households; fraction of households using wood; ethnic distribution; and housing types. In all, 26 of the slums were discovered to be either too small to possibly offer the desired sample size, or had other logistical problems associated with them. Finally, we chose Kusumpur Pahari as the slum in the low polluted area and Kathputly Colony as the slum in the high pollution category.

Selection of Households

In the two selected slums a preliminary scoping survey was done to identify those houses which had an infant (533 in Kathputly colony — the highly polluted slum and 545 in Kusumpuri Pahari). Information about these households was gathered on the following parameters: predominant fuel usage; cooking location; mother's employment status; ethnic groups; kitchen walls and roof construction materials; number of rooms in the house; type of family (joint/single); and number of elder children. In each slum 320 households were chosen for the epidemiological survey by first applying certain rejection criteria and then randomly selecting the remaining ones. These rejection criteria were: household using fuels other than wood or kerosene, more than two rooms in the house, households whose response to the question on location of cooking was ambiguous, and houses situated far away from the main cluster of houses (for practical reasons).

Then, in each slum 40 houses were selected for the exposure assessment survey, out of the 320 houses chosen for the medical survey. A stratified random sampling design was used for this purpose. The sample was distributed in a proportional manner. The two stratifying criteria were: location of cooking, and mother's employment status. It was felt that these factors contribute most to the variance in exposure levels. Of the 40 houses, half use wood and half kerosene.

Methods

A personal air sampler, based on the gravimetric principle (of SKC make, models 224-PCXR7 and 224-XR7), was used along with an aluminum cyclone to measure levels of RSP. The cyclone has a 50 percent removal efficiency for particle diameters of 5 μm (d_{50}). The flow rate was maintained at 1.9 l/min ($\pm$10 percent) using the soap bubble technique. Teflon filters with pore size 1 μm were used after desiccating them with silica gel for

24 h. Filters were weighed in a balance having an accuracy of 10 μg. One in every 20 filters was kept as a "field control blank." Each weighing of the filter was repeated at least twice till a difference of 100 μg or less was achieved. Blank corrections were made batch wise. CO was measured using miniature samplers that work on the electrolytic principle (National Drager, model 190 Datalogger; 1 ppm accuracy and OLDHAM make, model MX21). The instruments were calibrated once a week with a span gas of known concentration (99 ppm) and zeroed before the start of each sampling session.

Table 1 shows the location of samplers and the duration of sampling prescribed for each microenvironment. Protocols were pretested in houses that were not part of the main study. The experience gained from this testing helped in modifying the final protocol. The sampling was conducted in the winter months (December 1994–February 1995).

A total of 80 houses were sampled. In each house the infant and its mother were the target individuals. Sampling in all six microenvironments was conducted on two consecutive days, except for the personal exposure of the mother during cooking, which was done only on the first day. In addition, 16 houses were monitored once continuously for 24 h stationarily. In this case samplers were placed in the room in which the infant spends the maximum amount of time, at the same height (0.61 m above the floor).

Table 1. Salient features of the monitoring protocol.

Microenvironment	Location of sampler	Duration
Cooking sessions (breakfast, lunch, dinner)	1 m from the stove	As long as cooking lasts
Indoor background (between meals)	Center of the room	4 h
Outdoor (between meals)	2 m from door	4 h
Sleeping session	Center of room	2 h

Notes

1. Height of sampler was 0.61 m above the floor/ground.
2. For assessing mother's exposure during cooking, the personal sampler was attached to her waist and the cyclone pinned to her shoulder, ensuring that the cyclone remains vertical, that the inlet is facing outward and never obstructed by the clothes.
3. CO was measured only during cooking sessions.
4. Indoor background and outdoor background were concurrently sampled. These sessions began after at least 30 min had elapsed after the last cooking session. On each day two samples were taken, typically once between 09:30 and 11:30 h, and once between 15:00 and 17:00 h. But, a single filter was used; preserved after the first session and then again used when the sampling resumed. In this form of intermittent sampling it was ensured that same pump and cyclone were used. In some cases where this was not possible due to the habits of the people of the house, a 4 h continuous sample was taken.
5. During cooking sessions samplers were switched on a minute before the fire was lit, and switched off a minute after the fire was extinguished.

A recall-based questionnaire was used to determine time spent in the six micro-environments (for details see Malhotra et al., 2000). In addition, during the cooking session a stopwatch was used to record total cooking time, and also to keep track of the infant's movements — whether it is near the stove, in another room, or outside.

Verbal consent was obtained from community leaders and each participating household for conducting the monitoring. It was explained to the participants that the survey was purely for research purposes.

Data Quality Analysis

The main sources of error in measuring RSP with the gravimetric principle are related to: (a) filter weighing procedures, and (b) flow rate changes during the sampling. Ideally, filters should be weighed in a clean room under climate-controlled conditions (especially low humidity). If these conditions are not met and coupled with human error, it is not uncommon to find, after exposing a filter, that the change in mass is either zero or negative. To a large extent this problem can be overcome by using blanks. In this study 51 blanks were used. The mean change in mass was -4.7 μg. In 41 percent of the cases the change in mass was negative. The distribution can be approximated by a normal curve ($\chi^2 = 15$, $P < 0.06$). The blank corrections were made batch-wise because of the degree of variance in the change in mass of the blanks.

Owing to sensitive nature of the microbalance, it is not possible to always get the same value of mass upon repeated weighings. The experimental protocol allowed for a maximum difference of 100 μg between consecutively measured values. It was observed that in 96 percent of the cases the difference in the mass readings between repeated measurements was less than or equal to 50 μg. The results also indicate that in the range of operation, the precision of measurement is not affected by the filter loading. Analysis of the final and initial flow rates of the sampling pump indicated a variation of 0.5–2.1 percent, while the maximum allowable variation was 10 percent.

Results

Cooking microenvironment

It is observed that while the area sampling values of CO and RSP are significantly higher in the wood group as compared to the kerosene group, the personal levels of RSP (cook) are not different. This may be because of a buoyant plume affect — the cook being located in the shadow of the plume. However, the plume effect is likely to be stronger in wood stoves than in kerosene stoves (Table 2). The variability of RSP (area) across different groups is shown in Figure 1. The pattern in this figure is supported by results of the analysis of variance (ANOVA). In the wood group, the levels of RSP (area and personal) and CO are always higher when cooking is done indoors in comparison to when cooking is done outdoors. In the kerosene group this is not always the case. But, since the sample of kerosene-using households that cook outdoors is small, the results are not conclusive.

The results of ANOVA also indicated that there were no significant variations of CO and RSP (area sampling) during cooking sessions across the two days of sampling. It was also indicated that there were no differences across the three cooking sessions in a day, that is, breakfast, lunch, and dinner. This justifies combining these three microenvironments as one, as was done while estimating the daily exposure. In woodstove-using houses it was observed that personal levels of RSP during cooking are statistically significantly less than (paired t-test) fixed area levels. As mentioned, before, this may be due to a plume effect from the stove. In kerosene-using houses, the reverse was found to be true.

It is of special interest to examine the correlation between the levels of RSP as measured through area and personal sampling. When the data across groups were pooled, the square of correlation coefficient was estimated to be 0.72 (r^2). The group-wise estimates of "r^2" are shown in Tables 3 and 4. We observed that the correlations between RSP and CO are stronger in the wood group and when cooking is done indoors, possibly because of little influence of other outdoor sources of pollution. As CO/RSP ratios vary between indoor sources and outdoor pollution, it is not surprising that correlations were not great.

Other Microenvironments

The indoor background microenvironment has been defined as the indoor environment when no cooking occurs. The overall mean level of RSP in this micro-environment was 390 $\mu g/m^3$. The group-wise results are shown in Table 5. The location of the slum had an affect on the indoor background levels, that is, in the slum with highly polluted ambient atmosphere, the indoor levels were also higher. This implies an association between outdoor and indoor environments. But this does not imply that indoor background levels can be fully accounted for by outdoor levels, as we shall see in a later section. This significant effect of site location on indoor levels was also suggested by ANOVA ($F = 45$, $P < 0.001$). Analysis of variance also indicated that there was no difference between RSP levels on the first and second day.

While sampling the indoor background microenvironment the outdoor micro-environment was concurrently sampled, just outside the house, and near breathing level heights. Such a location of sampling can also be referred to as near-ambient, to distinguish it from the traditional outdoor ambient location, which is typically much further away from residences and at much greater heights. The mean level of RSP in the slum classified as highly polluted was found to be 350 $\mu g/m^3$, and in the slum classified as low polluted this was found to be 180 $\mu g/m^3$. The group-wise results are shown in Table 5. Though levels of RSP are higher in the slum assumed to be highly polluted, the degree of variability and skewness is also more. The results of ANOVA ($F = 46$, $P < 0.001$) also prove that the outdoor levels are higher in this slum, thus validating our approach (through cluster

Table 2. Concentration (geometric mean) of RSP and CO during cooking sessions.

Fuel	Location of cooking	Slum	n	RSP ($\mu g/m^3$)		Area CO (ppm)
				Personal sampling (mother)	Area sampling (infant)	
Wood	In	High	15	1630	1680	16
				(2.0)	(2.3)	(2.0)
		Low	10	987	1210	9
				(1.5)	(1.7)	(1.7)
	Out	High	5	820	690	6
				(1.7)	(2.0)	(1.6)
		Low	10	650	830	8
				(1.7)	(1.6)	(2.2)
Kerosene	In	High	19	730	650	4
				(1.5)	(1.5)	(1.7)
		Low	19	590	610	1
				(1.7)	(1.5)	(3.4)
	Out	High	1	1650	1280	9
				(na)	(na)	(na)
		Low	1	450	830	0
				(na)	(na)	(na)

The values in parentheses are the geometric standard deviation; n = number of housholds; na = not applicable.

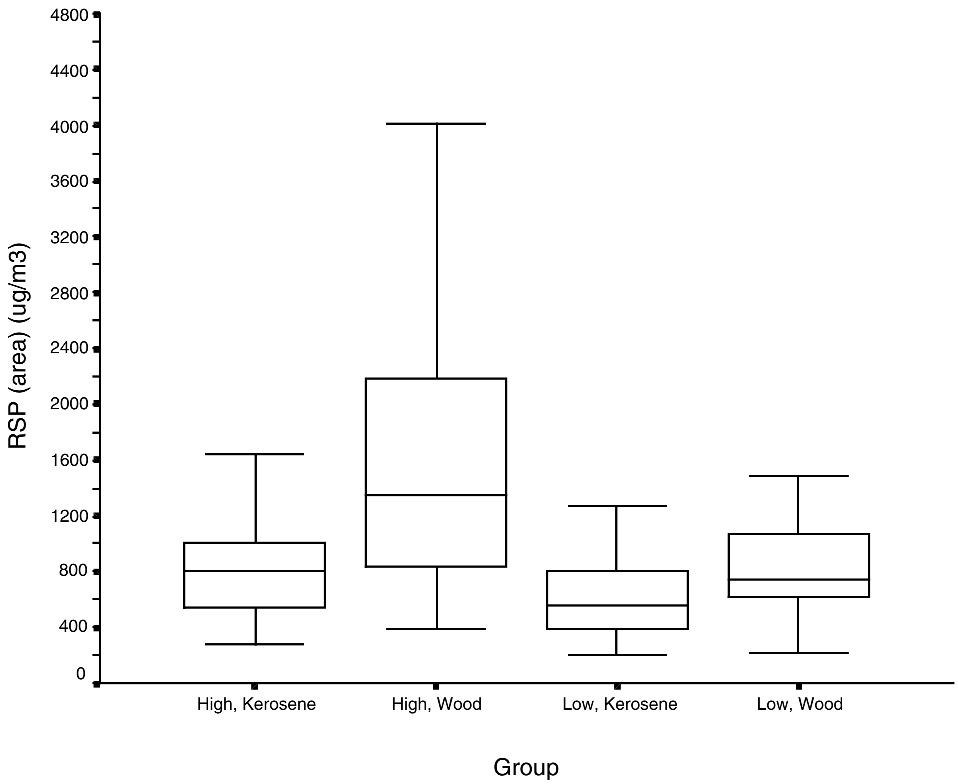

Figure 1. Box plot comparing RSP (area) concentrations across groups during cooking.

Table 3. Correlation between RSP and CO across fuel and slum location groups.

Slum	Fuel	Correlation coefficient (r^2)		
		RSP (area) vs. RSP (personal)	RSP (area) vs. CO (area)	RSP (personal) vs. CO (area)
High	Kerosene	0.50	0.15	0.13
	Wood	0.87*	0.92*	0.83*
Low	Kerosene	0.49	0.00	0.01
	Wood	0.27	0.34	0.04

*Significant at $P=0.05$.

analysis, described earlier). We found, that indoor background levels are far greater than outdoor (near ambient) levels. Analysis of variance also indicated no significant difference in the mean concentration of RSP across the days of sampling.

The average level of RSP as measured at nighttime indoors was found to be comparably very high — 900 μg/m^3. The group-wise results are shown in Table 5. These levels are higher in the slum where ambient levels are also high. These nighttime RSP levels indoors are far higher than the corresponding daytime indoor background levels and the daytime outdoor (near ambient) levels, for all four groups. As for the other environments, no difference was observed between values measured on the first and second days.

Table 4. Correlation between RSP and CO and their dependence on location of cooking.

Location of cooking	Correlation coefficient (r^2)		
	RSP (area) vs. RSP (personal)	RSP (area) vs. CO (area)	RSP (personal) vs. CO (area)
In	0.79*	0.72*	0.61*
Out	0.19	0.48*	0.07

*Significant at $P=0.05$.

Table 5. Levels of RSP (μg/m^3, geometric mean) in the other microenvironments.

Slum	Fuel	Indoor background	Outdoor background	Nighttime sleeping
High	Kerosene	330 (1.6)	250 (1.5)	860 (1.8)
	Wood	550 (1.9)	380 (1.6)	860 (1.6)
Low	Kerosene	260 (1.6)	190 (1.4)	660 (1.9)
	Wood	200 (1.5)	150 (1.4)	670 (2.0)

The values in parentheses are the geometric standard deviation. Sample size = 20 houses in each group.

It is necessary to examine the correlations between microenvironments for two reasons: (a) to understand the dynamic relationships between these environments and to locate possible sources of pollution, and (b) for practical reasons to identify surrogate predictors for any microenvironment. But in this study it was observed that the correlations are very poor, the only slightly strong associations are between the indoor background and outdoor microenvironments (in the low-wood and high-kerosene cases). These results imply that (a) the relationship between indoor and outdoor microenvironments is weak, and (b) in such situation it is very difficult to find a suitable surrogate for any of the microenvironments.

Daily Integrated Exposure

Daily integrated exposure estimates are based on pollutant concentration and time budget data. While the pollutant concentration data have been described above, for details on the time budget data refer to Malhotra et al. (2000). It was observed that the daily-integrated exposure to RSP was the highest for the wood group in the highly polluted slum, for both women and infants. The microenvironment-wise results are shown in Table 6 for infants and Table 7 for women.

It was observed that in the case of infants, the cooking microenvironment contributed 11 percent to the total daily exposure for kerosene users and for wood users this fraction was higher at 14 percent. The outdoor environment contributed 8 percent for kerosene and wood users. The indoor background environment contributed 21 percent for kerosene users and 26 percent for wood users. The maximum contribution for all groups came from the sleeping microenvironment. For the kerosene users this was about 60 percent and for wood users this was 52 percent.

It was observed that in the case of women, the cooking microenvironment contributed 15 percent to the total

Table 6. Daily integrated exposure of infants to RSP (mg h/m^3).

Group	Statistic	Cooking	Indoor	Outdoor	Sleeping	Daily integrated exposure
High,	AM	1.6	3.2	1.2	8.2	14.2
kerosene	GM	1.2	2.9	1.0	7.3	13.4
	GSD	1.3	1.7	1.7	1.8	1.4
High,	AM	2.5	7.1	1.9	7.6	19.0
wood	GM	1.4	5.3	1.6	6.9	16.8
	GSD	1.5	2.0	1.8	1.6	1.7
Low,	AM	1.4	2.4	1.0	7.6	12.3
kerosene	GM	1.1	2.1	0.9	5.9	10.7
	GSD	1.3	1.7	1.5	1.9	1.7
Low,	AM	1.7	1.9	0.8	7.7	12.0
wood	GM	1.2	1.7	0.7	6.1	10.7
	GSD	1.4	1.5	1.5	2.0	1.6

AM = arithmetic mean;
GM = geometric mean;
GSD = geometric standard deviation.

Table 7. Daily integrated exposure of women to RSP (mg h/m^3).

Group	Statistic	Cooking	Indoor	Outdoor	Sleeping	Daily integrated exposure
High,	AM	2.2	1.8	2.2	8.1	14.3
kerosene	GM	1.3	1.6	1.9	7.1	13.6
	GSD	1.3	1.7	1.8	1.8	1.4
High,	AM	3.8	4.0	3.0	8.3	19.1
wood	GM	1.6	2.7	2.8	7.5	17.3
	GSD	1.3	2.3	1.6	1.6	1.6
Low,	AM	1.8	1.5	1.5	7.4	12.2
kerosene	GM	1.2	1.2	1.4	5.8	10.8
	GSD	1.4	2.0	1.5	2.0	1.6
Low,	AM	2.4	1.1	1.3	6.9	11.6
wood	GM	1.4	1.0	1.2	5.6	10.6
	GSD	1.3	1.5	1.5	1.9	1.6

AM = arithmetic mean;
GM = geometric mean;
GSD = geometric standard deviation.

daily exposure for kerosene users and for wood users this fraction was higher at 21 percent. The outdoor environment contributed 14 percent for kerosene and wood users. The indoor background environment contributed 13 percent for kerosene user and 15 percent for wood users. The maximum contribution for all groups came from the sleeping microenvironment. For the kerosene users this was about 59 percent and for wood users this was 51 percent.

The variation of daily-integrated exposure across groups is shown in Figures 2 and 3 for infants and women, respectively. It was observed that the spread of the data is higher in wood groups, that is they are more heterogenous.

Analysis of variance indicated that the total daily-integrated exposure was significantly affected only by the location of the slum (high or low polluted area) (for infants, $F=3.7$, $P<0.05$; for women, $F=6$, $P<0.02$). The exposure just due to cooking was significantly higher in wood-user houses only for women ($F=9$, $P<0.01$) and not for infants.

The total exposure of women and infants to RSP was well correlated ($r^2=0.94$). But the exposure during cooking sessions of the women and the infant was not strongly correlated ($r^2=0.42$).

It was observed that exposure during cooking as estimated with the time recorded with a stopwatch was considerably less as compared to that estimated through the recall method (Table 8). It was also observed that daily-integrated exposure of infants and women to RSP was poorly correlated with the outdoor levels ($r^2=0.38$ for infants, and $r^2=0.42$ for women). Thus, the outdoor (near ambient) RSP levels not only underestimate the magnitude of daily exposure, but they are also not satisfactory in explaining or predicting the variance in the exposure.

In 16 houses (four in each group) in addition to the microenvironmental approach to exposure assessment, a 24-h continuous stationary sample was collected indoors. It was observed that these data poorly correlated with either the infant's or the mother's daily exposure estimate. In Table 9 the two sets of results are compared. It is observed that the 24-h continuous stationary sampling method, though very easy to manage, seriously underestimates the daily exposure.

Discussion

The levels of RSP and CO during cooking were found to be very high and comparable to the results of five similar studies in poor urban areas (Table 10). The major discrepancy being the exceedingly high levels of CO measured in the Ahmedabad study and the low levels of RSP in kerosene in the Bombay study.

An analysis of the coefficient of variation of the concentration distribution of RSP levels in the four

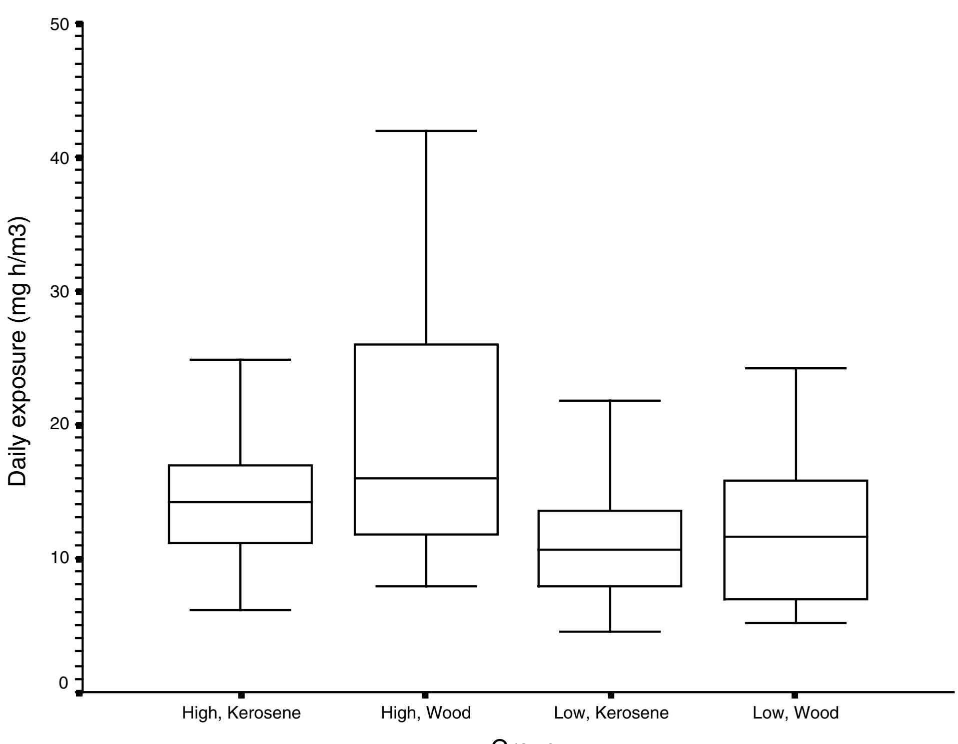

Figure 2. Comparison of the daily integrated exposure of infants to RSP.

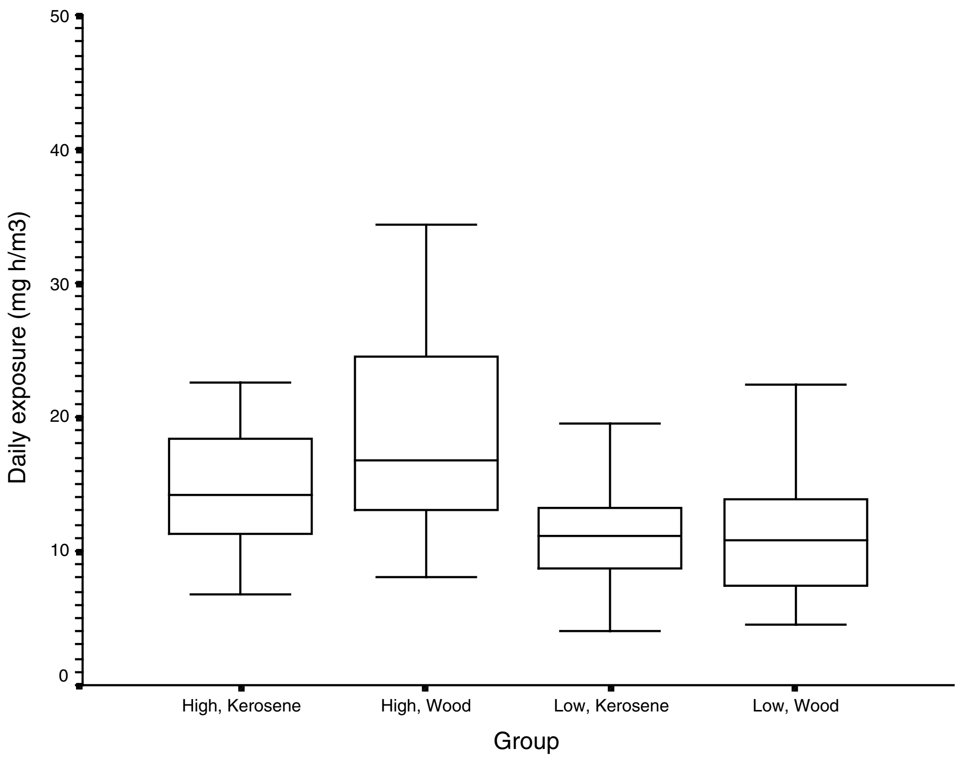

Figure 3. Comparison of the daily integrated exposure of women to RSP.

Table 8. Error in estimating the exposure during cooking through the recall method for time activity data.

Slum	Fuel	Exposure to RSP during the cooking microenvironment (mg h/m^3)			
		Infants		Women	
		Recall based	Actual measurement	Recall based	Actual measurement
High	Kerosene	1.63	1.00	2.15	1.62
High	Wood	2.47	0.87	3.79	2.40
Low	Kerosene	1.39	1.02	1.83	1.47
Low	Wood	1.68	1.24	2.39	2.07

$n = 20$ houses in each category.

Table 9. Comparison of two approaches to daily exposure assessment.

Slum	Fuel	RSP level (μg/m^3)	
		24-h continuous sample	Daily integrated exposure converted to concentration units
High	Kerosene	280	500
High	Wood	400	500
Low	Kerosene	260	390
Low	Wood	340	480

$n = 4$ houses in each category.

fuel-slum groups leads us to conclude that the quality of data is satisfactory. The higher variation in the wood category is because of the higher variation in parameters such as fuel type (different species are used), different stove designs, location of the stove, and type of kitchens.

In all groups we discovered that indoor noncooking RSP levels are higher than outdoor levels. It is difficult to compare our indoor background RSP levels with those of other studies because of the paucity of similar data. Most previous researchers have measured 24-h continuous indoor levels and there are very few studies from developing countries. Since indoor background levels are much higher than the concurrently measured near house outdoor levels, we cannot explain the high indoor background levels just by infiltration of outdoor air. In another study in Bombay (Sabapathy, 1998) five households spread over many areas were monitored for indoor and outdoor levels. It was again observed that indoor levels can be higher than outdoor levels, specially if the houses are far away form a road. The indoor

Table 10. Comparison of RSP and CO levels during cooking across studies in poor urban areas.

Type of sampling	Location	RSP ($\mu g/m^3$)		CO (ppm)		Reference
		Wood	Kerosene	Wood	Kerosene	
Area sampling	Bombay, India		140			WHO (1984)
	Ahmedabad, India	1110	380	165	120	Raiyani et al. (1993)
	Lusaka, Zambia	890		9		Ellegard and Egneus (1993)
	Accra, Ghana					Benneh et al. (1993)
	Delhi, India	1370	690	12	3	This study
Personal sampling	Pune, India	1100	530	9	7	Smith et al. (1994)
	Maputo, Mozambique	1200	760			Ellegard (1996)
	Delhi, India	1200	750			This study

These are arithmetic means.

levels of RSP ranged from 40–260 $\mu g/m^3$. A recent study in middle-income homes of Delhi found PM10 levels to be as high as 170–810 $\mu g/m^3$ even in homes where there was no cooking or smoking activity (Kumar, 2001). Even in houses in developed countries it has been observed that often indoor RSP levels can exceed outdoor levels based on 24-h sampling (Ju and Spengler, 1981; Spengler et al., 1981).

We observed that in the two slums, the near ambient outdoor (just outside the house) levels of RSP are higher than the RSP levels at the nearest ambient monitoring station (CPCB, 1997). We found no significant correlation between indoor background and outdoor (near-ambient) RSP levels, unlike a study in Bangkok that found a correlation (Tsai et al., 2000) for PM10.

The RSP levels in the sleeping (nighttime indoor) microenvironment were found to be very high, and also greater than the day time indoor background and outdoor levels, across all groups. Since the outdoor levels are much less than the sleeping time levels, it is not possible to account for these high levels just by attributing these to infiltration of outdoor air with 100 percent penetration. Nighttime outdoor levels of RSP were not measured in this study. If it is believed that in winter the atmospheric inversions would cause elevated levels, then the nighttime outdoor levels would have to be at least three to four times as high as day time outdoor levels, in order to ascribe the indoor sleeping levels entirely due to infiltration. Previous studies suggest that nighttime peak levels can only be twice as high as daytime peak levels (Sadasivan et al., 1984; Sharma and Patil, 1991; Singh et al., 1997; Varshney and Padhy, 1998).

It is very likely that the high levels of RSP during daytime indoor background and nighttime sleeping periods could be ascribed to a combination of: (a) infiltration of outdoor air (including smoke from neighboring stoves and outdoor open fires for space heating), (b) indoor space heating (though this is not widely prevalent), (c) tobacco smoking, (d) resuspension of house dust, and (e) unknown indoor sources. A review of major studies on indoor particles (Wallace, 1996) also highlighted the role of resuspension of dust. It also mentioned that in many studies, unknown sources could account for as much as 25 percent of the indoor RSP levels.

The daily-integrated exposure to RSP was the highest for the wood group in the highly polluted slum, for both women and infants. It was observed that in the case of infants, the cooking microenvironment contributes 11 percent to the total daily exposure for kerosene users and for wood users this fraction is higher at 14 percent.

It was observed that in the case of women, the cooking microenvironment contributes 15 percent to the total daily exposure for kerosene users and for wood users this fraction is higher at 21 percent. For infants and women the maximum contribution came from the sleeping (indoor nighttime) and indoor background microenvironments. The study design did not permit quantification of the contribution of tobacco smoking to exposure. We believe that the absolute level of exposure is most certainly influenced by the presence of smokers. However, the difference between the cooking fuel groups is not likely to be significant, because of the uniformity in smoking habits.

The exposure just due to cooking was significantly higher in wood-user houses only for women and not for infants. The total exposure of women and infants to RSP was well correlated. But the exposure during cooking sessions of the women and the infant was not strongly correlated. Daily-integrated exposure of infants and women to RSP was poorly correlated with the outdoor levels. Thus, the outdoor (near ambient) RSP levels not only underestimate the magnitude of daily exposure, but they are also not satisfactory in explaining or predicting the variance in the exposure.

The model for daily exposure to RSP used in this study predicts a range of 12–19 $mg\,h/m^3$ for infants in wood fuel houses, and a range of 12–14 $mg\,h/m^3$ for infants in kerosene fuel houses. These findings are not in the same range of that of Smith et al. (1994) in Pune. Their results were 17–27 $mg\,h/m^3$ for biomass users and 2.4–3.6 $mg\,h/m^3$ for kerosene users though they used different model for computing the exposure. The estimates of this study are higher than those observed in a rural hilly area by Saksena et al. (1992) (TSP was measured in that study. We assume for sake of comparison that the RSP/TSP ratio is 0.55). But our estimates are lesser than those observed by Ezzati et al. (2000) in rural Kenya. A study in Bombay of low-income workers indicated a daily-integrated exposure of about 8 mg h/m^3 (Kulkarni, 1998).

Though the concentration of RSP during cooking is less in kerosene-using house as compared to wood-using houses, the exposure during the same period is similar. This is because of three factors:

(a) daily cooking time is greater for kerosene-using houses as compared to wood-using houses (because the number of meals cooked in a day and the duration of each session are higher),

(b) the fraction of total cooking time actually spent near the fire by the infant is also higher in kerosene-using houses, and

(c) most kerosene users cook indoors, keeping their infants also indoors, while wood users cook outdoors, keping their infants outdoors or indoor depending on the season.

The study has improved upon previous exposure assessment techniques used in developing countries by:

- Carefully identifying the optimum number of microenvironments to be monitored.
- Adopting longer sampling durations for noncooking and sleeping microenvironments, as well as repeating measurements twice.
- Refining the survey tool used for time budget study.

In conclusion, this study has provided, for the first time, reliable estimates of daily exposure of infants, in low income groups of urban areas, to RSP, based on field measurements and surveys. Reliable estimates of the relative importance of various microenvironments to total exposure have also been obtained. However, the design and the scope of the study do not permit us to necessarily identify the actual sources of pollution and their relative contributions in each microenvironment.

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