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Exposure of Infants to Outdoor and Indoor Air Pollution in Low-Income Urban Areas: A Case Study of Delhi

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Exposure of Infants to Outdoor and Indoor Air Pollution in Low-Income Urban Areas—A Case Study of Delhi

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Abbreviations used:

AM	:	arithmetic mean
ANOVA	:	Analysis of Variance
CO	:	carbon monoxide
GM	:	geometric mean
GSD	:	geometric standard deviation
r	:	correlation coefficient
RSP	:	Respirable Suspended Particles

Abstract

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 dearth of reliable data and knowledge about the situation in urban slum areas. The micro-environmental 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 usually 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 socio-economic 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 re-suspension 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.

Introduction

It is well known that rapid industrialization and urbanization have lead 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 exposed only to pollutants from such combustion. But their counterparts in urban slums are additionally 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 would appear 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 few countries in Africa and South America (for example, Albalak et al. 1999, Ezzati 2001, Menon 1988, Ramakrishna 1988, Saksena et al. 1992, Smith et al. 1983). However, the information related to the urban situation is meager (Ellegard 1996, Ellgard and Egneus 1993, Raiyani et al. 1994, Smith et al. 1994).

It has been postulated that household fuel switching from lower to higher quality fuels, i.e., movement up the ‘energy ladder,’ generally leads to substantially lower emissions of health damaging pollutants. However, the extent to which exposures are reduced is difficult to predict, especially in urban areas, because of the presence of both indoor and outdoor sources.

Historically people will evidently generally move up the energy ladder when they have the opportunity to do so. While roughly half the world has moved upwards (with respect to wood), the other half is still at the same stage or has been forced to move down to inferior fuels. In summary, 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 better energy systems may not be significant, but considering the large populations of countries in the developing world the macro-level implications are indeed astronomical. Coupled with the limitations of availability of alternatives and associated infra structural 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-stoves?
- are clean fuels-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 study is of special interest because of the paucity of information regarding the urban slum situation and possible complex interactions between indoor and outdoor air quality and housing conditions in slums. We wished to study these questions using exposure analysis as a tool. The objective of this study was to assess the daily exposure of infants (and their mothers) to Respirable Suspended Particles 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

Recently 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. There are two possible methods for estimating exposure of a person (or a population) to air pollution: a) field studies, and b) mathematical models. Field studies involve monitoring pollution concentrations using portable equipments worn by the subjects to assess ‘personal’ exposure. Mathematical models, on the other hand, involve measurement of pollutant concentration at established sites/environments/locations and the time spent by the subject in these locations/environments to assess the ‘total’ exposure. The concept of integrated exposure incorporates the duration of the exposure by integrating the concentration with the duration of exposure. Duan (1982) introduced the term ‘micro-environment type’ to compute exposure over any time period. He also suggested that a micro-environment should be defined with sufficient resolution to be homogeneous, i.e. the concentration coefficients should not vary appreciably from one individual to another, in other words variance of individual exposures within a micro-environment should be smaller than the variance of exposures from one micro-environment to another. On the other hand, a micro-environment 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 cumulative exposure would then account for both indoor and outdoor exposures.

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 micro-environment of the ith individual, t_{ij} is the time spent by the ith individual in the jth micro-environment. The total number of micro-environments 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 the most sensitive health group. Exploratory surveys helped in identifying the predominant micro-environments 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 micro-environments (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 micro-environment was estimated through recall based questionnaires. Two slums were chosen for the study: one in a highly polluted are 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 twenty houses each were chosen that used wood and kerosene. Each house was monitored for two consecutive days, that is, all micro-environments 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 migration for 40,000 families per year. As a result, the density of population now stands at 6319 persons per square kilometer. With a population of 4.7 slum dwellers, evidently half of Delhi's population lives in sub-standard areas.

More than three quarters of the emissions of air pollutants are caused by vehicles in Delhi. The total number of vehicles in 1991 was 1.9 million (22 percent cars and 67 percent two-wheelers). This is a nine-fold increase over the total number of vehicles in 1971. 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.

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: Suspended particulate matter (SPM) = 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, firewood supply has decreased drastically. The reason for this is good supply of kerosene, coal and LPG. Delhi has the highest per capita consumption of kerosene. The percentage of households using soft coke is next only to Bihar and West Bengal. For the year 1978-79, the annual per capita energy consumption in Delhi was: coal—67.7 kg, kerosene—19 litres, LPG— 5.7 kg, firewood 6.7 kg, and other solid fuels—12.3 kg (NCAER, 1981). Another survey conducted in over 8000 slum households (TERI, 1993) also indicated that kerosene is the predominant fuel, accounting for 60 percent of the total energy consumption. The next most widely used fuel is fuelwood, accounting for 19 percent of total fuel consumption in the east zone and 26 percent in the west and south zones.

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.
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 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 cross-check 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. Delhi has nine monitoring stations: six operated by the Central Pollution Control Board (CPCB) and three by the zonal laboratory of the National Environmental Engineering Research Institute (NEERI) on behalf of the CPCB. Land-use patterns have changed significantly since CPCB adopted the land-based classification system for its monitoring stations. More importantly, heavy traffic—a ubiquitous phenomenon—would contribute to air pollution even in non-industrial areas. Therefore, it is not safe to assume that ambient levels in industrial areas would be higher than in commercial areas, with residential areas as the least polluted. The question to be answered through statistical analysis is: can the nine stations be classified into high, medium, and low polluted groups?

Evidently, there is a need to statistically classify the nine monitoring stations. The appropriate technique for this purpose is cluster analysis. Cluster analysis involves splitting a data set into a number of groups of observations which are distinct in terms of typical group values of the variables. The aim is to maximize between-group variance and to minimize within-group variance. Cluster analysis is a classification technique where any number of variables may be used to classify members of the sample.

Monthly means of 1991 at each station were used as input data (CPCB, 1992). Classification was done separately for each pollutant, viz., SPM, SO_2 and NO_2, though classification based on combinations of two or three pollutants at a time is also possible (CPCB has compiled data of the years 1992 and 1993, but they were not published before the field work began). Hierarchial agglomeration for clustering, based on average linkage between groups method and the Euclidean distance measure were used.

Results of cluster analysis showed that the nine monitoring stations could be be classified into two groups—high and low (for more details refer Saksena 1999). Based on this the air quality of each slum was classified. In cases where monitoring stations were far from the slums, secondary information was used.

After identifying big slums and those where wood is likely to be used fifty-two 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. Twenty-six 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. The only slums in the low polluted areas are those at Kusumpur Pahari and Bhatti mines. Kusumpur Pahari was chosen, because at Bhatti mines, men and women are employed as labourers in quarries. They are exposed to dust—an occupational hazard. Their time allocation patterns and child management practices are also very different from that of other slum populations. In the high pollution category, the slum at Kathputly Colony was chosen. Though the ambient levels at traffic junctions near Gautam Nagar and Nehru Place are likely to be high, the situation in the slum may be different because high-rise buildings may act as barriers.

Selection of households

In the two selected slums a census survey was done of only those houses which had an infant (533 in Kathputly colony—the highly polluted slum, and 545 in Kusumpuri Pahari—the less polluted slum). 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 the epidemiological survey by first applying the 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 forty 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 forty 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}), in accordance with the

Johannesburg convention. The flow rate was maintained at 1.9 l min^{-1} (±10 percent). Flow rate was adjusted using the soap bubble technique, before each experiment. The average of five replicates was used. After sampling, the flow rate was again measured in a similar manner. A dummy filter was used for this purpose and replaced each week, or earlier if its appearance (darkening) suggested so. But the actual cyclone to be used in the field was used for calibration. Teflon filters with pore size 1µm were used after desiccating them with silica gel for 24 hours (the hydrophobic property of Teflon filters was the chief reason for choosing it). A three-piece filter cassette was used. This was assembled and disassembled along with the cyclone only in the field office and not in the field. Filters were weighed in a balance having an accuracy of 10µg. 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 100µg 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). Levels of CO are displayed digitally and had to be recorded manually at intervals of one minute (least count = 1 ppm). 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.

Four sets of such instruments were employed to make the measurements in the four groups. An issue of concern, was whether the four CO monitors (of two different makes) do indeed perform similarly. To test this the four monitors were placed near each other at the center of a confined chamber and a fire lit to generate smoke. The display readings were simultaneously noted for a period of 45 minutes. This procedure was repeated using wood (high range of concentrations) and kerosene (low range). Statistical analysis of the data (correlation and two-tailed paired t-test) indicated that the instruments were comparable.

A protocol was designed to ensure 1) minimum disturbance to the normal habits of the household, and 2) an efficient and complete recording of all the variables of interest. The protocol was pre-tested in houses that were not part of the main study. The experience gained from this testing helped in modifying the final protocol.

Table 1 shows the location of samplers and the duration of sampling prescribed for each micro-environment. The sampling was conducted in the winter months (December 1994 to February 1995). The reason for choosing this season is that ambient levels of pollution are higher in winter, owing to inversions, and even indoor levels could be high due to space heating and prolonged cooking sessions. The natural incidence of respiratory diseases is also observed to be high in winter.

A total of eighty houses were sampled. In each house the infant and its mother were the target individuals. Sampling in all six micro-environments was conducted on two consecutive days, except for the personal exposure of the mother during cooking, which was done only on the first day. Thus exposure estimates were available for 160 individuals. In addition, 16 houses were monitored once continuously for 24 hours stationarily. In this case samplers were placed in the room in which the infant spends the maximum amount of time, at the same height.

A recall based questionnaire was used to determine time spent in the six micro-environments. 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 (Malhotra et al. 2000)

Results

Cooking micro-environment

As expected, the RSP and CO concentrations in kerosene using houses is less than that in wood using houses **(Table 2**). The variability of RSP and CO across different groups are shown in **Figures 1, 2, and 3**. It is observed that CO and area sampling values of RSP are significantly higher in the wood group. The personal levels of RSP (cook) are surprisingly (because the sampler is closer to the stove) not different across fuel groups. 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. The patterns in these figures are 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 clubbing of these three micro-environments as one, as was done while estimating the daily exposure. In wood stove 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 was pooled, the correlation coefficient was estimated to be 0.85 (r). The group wise estimates of ‘r’ 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. Overall, it seems that among these three variables, none can be used as a surrogate for the other to predict either the mean value or variability.

Other micro-environments

The indoor background micro-environment has been defined as the indoor environment when no cooking occurs. The overall mean level of RSP in this micro-environment was 390µg 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 high. 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 micro-environment 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 350µg m^{-3}, and in the slum classified as low polluted this was found to be 180µg 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 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—900μg 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.

It is necessary to examine the correlations between micro-environments 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 micro-environment. 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 micro-environments (in the Low-Wood and High-Kerosene cases). These results imply that a) the relationship between indoor and outdoor micro-environments is weak, and b) in such situation it is very difficult to find a suitable surrogate for any of the micro-environments.

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 -4.7μg. 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 micro balance, it is not possible to always get the same value of mass upon repeated weighings. The experimental protocol allowed for a maximum difference of 100μg 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 50μg. 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.

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 micro-environment 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 micro-environment 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 micro-environment. 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 micro-environment contributed 15 percent to the total 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 micro-environment. 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 **Figure 4 and 5** 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 ($r = 0.97$) as seen from **Figure 6**. But the exposure during cooking sessions of the women and the infant was not strongly correlated ($r = 0.65$).

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 = 0.62 for infants, and r = 0.65 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 micro-environmental approach to exposure assessment, a 24-hour 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-hour continuous stationary sampling method, though very easy to manage, grossly 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.

The concentrations of Respirable Suspended Particles (RSP) measured in this study in the kitchen micro-environment are in the same range as those measured by Smith et al. (1994). In another Indian city, Pune. Their results were: 1100μg/m^3 for wood fuel households, and 530μg/m^3 for kerosene fuel households. Significant differences in RSP levels during cooking between wood and kerosene using houses are a common observation of both studies. On the other hand, the mean outdoor levels encountered by them are much higher (340-920μg/m^3) than those measured in this study. It is known that Delhi has the world's third highest levels of particulate matter (UNEP 1992). Also, Pune is not an industrial city. Thus, we are led to conclude that perhaps the differences in i) location of samplers, and ii) the sampling protocol are the cause of the difference in these results.

An analysis of the coefficient of variation of the concentration distribution of RSP levels in the four 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 non-cooking 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-hour 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.

The indoor to outdoor ratio of RSP levels ranged from 1.39 (in houses of kerosene users) to 1.48 (in houses of wood users) in this study. In a study of not so poor households in Bombay, indoor to outdoor ratios of RSP (24 hour sample) were found to be 1.1 for houses away from as well as near roads (WHO 1984). Most of these houses used LPG for cooking. Hence the contribution of cooking to daily RSP levels may be very small in such houses. The indoor levels ranged from 40-150μg m^{-3}. 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 levels of RSP ranged from 40-260μg m^{-3}. A recent study in middle- income homes of Delhi found PM10 levels to be as high as 170-810μg 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 twenty four hour sampling (Ju and Spengler 1981, Spengler et al. 1981).

Indoor non-cooking levels (no cooking in the house) were significantly higher in houses of wood users compared to those in houses of kerosene users. This is so even given the fact that a large fraction of wood users cook outdoors.

As expected, the outdoor levels were significantly higher in the slum classified as highly polluted than those in the slum classified as low polluted. This validated the slum selection procedure and measurement method chosen for the outdoor micro-environment. An attempt is made to compare the outdoor levels of RSP measured in this study with the reported values from Central Pollution Control Board's monitoring network for the two stations closest to the two slums selected in this study for the same period of time (CPCB 1997). The network data reports TSP and not RSP. We assume a RSP to TSP ratio of 0.55 for urban air. Therefore, the estimate that we obtain from the network data for the RSP value at the less polluted site is 160μg m^{-3}, whereas what was measured by us just outside the houses in the corresponding slum was 190μg m^{-3}. For the other slum the network data reported about 200μg m^{-3}, whereas our measurements suggest 345μg m^{-3}. Thus, we observe that in slums, the near ambient outdoor (just outside the house) levels of RSP are higher than the RSP levels at the nearest ambient monitoring station. 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) micro-environment 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 3-4 times as high as day time outdoor levels, in order to ascribe the indoor sleeping levels entirely due to infiltration. There are few studies in the region that have reported the diurnal variation in pollutant levels in urban areas (Singh et al. 1997, Sadasivan et al. 1984, Sharma and Patil 1991, Varshney and Padhy 1998). Meteorological factors suggest that inversion conditions in Delhi in winter persist from 2100 to 0900 hours. Most of these studies have however measured volatile organic compounds, ozone, etc. There is therefore little data on diurnal variation of particulate levels. In any case these studies suggest that nighttime peak levels can only be twice as high as daytime peak levels. The study by Sharma and Patil (1991) in Bombay indicated that concentrations of size segregated particulates were mostly higher during night hours than day hours by a factor ranging from 1.8 to 2.3.

In the Bombay study by Sabapathy (1998) it was also observed that in houses away from roads, the indoor nighttime RSP levels can be higher than the outdoor night time levels. But in this case the indoor nighttime levels were always found to be less than the daytime indoor levels.

It is very likely that the high levels of RSP during day time indoor background and night time 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) re-suspension of house dust, and e) unknown indoor sources.

The factors mentioned above have been acknowledged by other studies as well, though mainly in developed countries. In a study that aimed at characterizing indoor air quality in wood burning homes in the United States, the authors concluded that even in houses with no smokers the high indoor to outdoor ratios could be due to re-suspended dust after taking into account wood burning (Sexton et al. 1986). In another such study (Daisey et al. 1989) it was observed that the indoor to outdoor ratio of RSP was greater than 1 during wood burning and non-wood burning periods (wood used for space heating). In fact, no significant difference was observed in the ratio between these periods. These authors also concluded that outdoor infiltration as well as re-suspension of indoor dust are possible sources of indoor pollution other than combustion. In the PTEAM study in the United States, based on the correlation analysis of indoor and outdoor levels it was observed that the degree of infiltration was lesser at night.

A recent review of major studies on indoor particles (Wallace 1996) also highlighted the role of re-suspension 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 micro-environment 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 micro-environment 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 night time) and indoor background micro-environments.

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 is 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 micro-environments to be monitored.
- Adopting longer sampling durations for non-cooking and sleeping micro-environments, 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 micro-environments 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 micro-environment.

Future Research

Based on the experiences gained in this study some suggestions can be made for future research:

Exposure assessment

Attempts should be made to measure the degree of correlation between continuous twenty-four hour personal sampling and the micro-environmental model, under various conditions and settings. More studies, in various settings, in all seasons, are needed to confirm our findings that indoor background (daytime and nighttime) levels can be exceedingly high, and whether this is true of other pollutants. In studying activity patterns in illiterate communities, more reliance should be placed on actual observation as opposed to recall methods. At the least, for all major micro-environments an estimate of the recall error should be made through smaller sample surveys.

Indoor-outdoor relationships and source apportionment

Perhaps the highest research priority must be assigned to studying indoor-outdoor relationships, in a small, manageable sample with intensive monitoring prior to any exposure survey. While sampling any type of indoor micro-environment, simultaneous outdoor sampling must be done just outside the indoor micro-environment. Continuous and simultaneous indoor-outdoor sampling over very long durations (such as 8 hours, or 24 hours) that span over many activities, fails to provide the kind of the information that is needed to understand the dynamics within each micro-environment. Study designs should also attempt to quantify the exfiltration effect of cooking related combustion pollutants. To what extent does the cooking activity deteriorate the outdoor (near ambient) air quality? The micro-environment modeling approach is very useful in estimating the daily exposure. However, on its own it cannot identify sources of pollution within each micro-environment. In future such exposure surveys should be accompanied by other techniques of source apportionment (either chemical mass balance or factor analysis) in indoor environments. The pollutants to measure in these surveys would be: Polycyclic Aromatic Hydrocarbons (PAH); Potassium (associated with wood combustion), Cadmium (associated with tobacco smoking); Lead, Bromine, Vanadium, Barium (associated with automobile pollution); and crustal elements (such as Iron, Silicon, Calcium, etc.). More sophisticated analysis of particle size distribution in indoor and outdoor environments would not only help in health related studies, but could also aid in understanding the sources of pollution and indoor-outdoor relationships.

Population exposure simulation

Large scale statistically designed surveys should be conducted to obtain frequency distribution of the following: activity patterns, housing characteristics (kitchen volume, ventilation, actual air exchange rate, etc.), fuel usage, emission factors (across various stove related parameters), etc. This will help in predicting population exposure through a combination of causal and probabilistic models.

Epidemiology

Epidemiological surveys that have attempted to test the association between biomass smoke and incidence of disease have rarely measured pollutant levels. The underlying assumption in many of these studies has been that just knowing the type of cooking device is an adequate indicator of environmental exposure. Our study shows that there is a considerable overlap between wood and kerosene using houses in terms of: concentration levels, time spent in cooking and the resultant cooking exposure, at least in urban and peri-urban areas. Therefore relying just on the type of cooking fuel may lead to exposure miss-classification. Future studies should therefore measure actual exposure levels. At the least, in a pilot phase such epidemiological studies should, in smaller samples, test the association between actual exposure levels and any surrogate indicator the researchers may wish to use.

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Table 1. Salient features of the monitoring protocol

Micro-environment	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 minutes had elapsed after the last cooking session. On each day two samples were taken, typically once between 0930 - 1130 h, and once between 1500 - 1700 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 hour 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.

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

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

The value in parenthesis is the geometric standard deviation.

n = Number of housholds
na = Not applicable

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

		Correlation coefficient (r)		
Slum	Fuel	RSP (area) vs. RSP (personal)	RSP (area) vs. CO	RSP (personal) vs. CO
High	Kerosene	0.71	0.39	0.36
	Wood	0.93	0.96	0.91
Low	Kerosene	0.70	0.07	0.12
	Wood	0.52	0.58	0.19

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

Location of cooking	Correlation coefficient (r)		
	RSP (area) vs. RSP (personal)	RSP (area) vs. CO	RSP (personal) vs. CO
In	0.89	0.85	0.78
Out	0.43	0.69	0.26

Table 5. Levels of RSP (μg m^{-3}, geometric mean) in the other micro-environments

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 value in parenthesis is the geometric standard deviation.

Sample size = 20 houses in each group

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

Group	Statistic	Cooking	Indoor	Outdoor	Sleeping	Daily integrated exposure
High,	AM	1.63	3.23	1.19	8.19	14.24
kerosene	GM	1.15	2.86	1.04	7.27	13.43
	GSD	1.3	1.7	1.7	1.8	1.4
High,	AM	2.47	7.07	1.87	7.55	18.96
wood	GM	1.35	5.33	1.63	6.87	16.77
	GSD	1.5	2.0	1.8	1.6	1.7
Low,	AM	1.39	2.40	0.94	7.59	12.32
kerosene	GM	1.09	2.13	0.87	5.88	10.73
	GSD	1.3	1.7	1.5	1.9	1.7
Low,	AM	1.68	1.85	0.75	7.70	11.98
wood	GM	1.22	1.70	0.70	6.10	10.72
	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	2.15	1.81	2.18	8.14	14.28
kerosene	GM	1.31	1.60	1.86	7.09	13.55
	GSD	1.3	1.7	1.8	1.8	1.4
High,	AM	3.79	3.98	3.03	8.27	19.07
wood	GM	1.62	2.73	2.76	7.45	17.25
	GSD	1.3	2.3	1.6	1.6	1.6
Low,	AM	1.83	1.51	1.50	7.34	12.18
kerosene	GM	1.16	1.24	1.37	5.75	10.80
	GSD	1.4	2.0	1.5	2.0	1.6
Low,	AM	2.39	1.09	1.28	6.84	11.60
wood	GM	1.36	1.00	1.17	5.61	10.51
	GSD	1.3	1.5	1.5	1.9	1.6

AM = Arithmetic mean
GM = Geometric mean
GSD = Geometric standard deviation

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

		Exposure to RSP during the cooking micro-environment (mg h m^{-3})			
		Infants		Women	
Slum	Fuel	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 ($\mu g\ m^{-3}$) 24-hour continuous sample	RSP level ($\mu g\ m^{-3}$) 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

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.
	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.

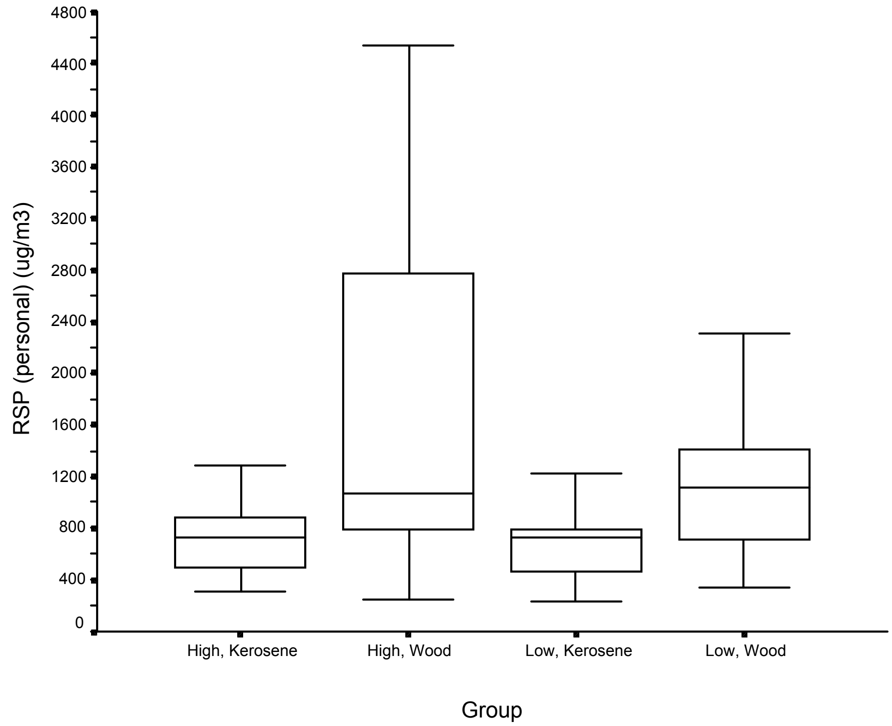

Figure 1 Box plot comparing RSP (personal) concentrations across groups during cooking

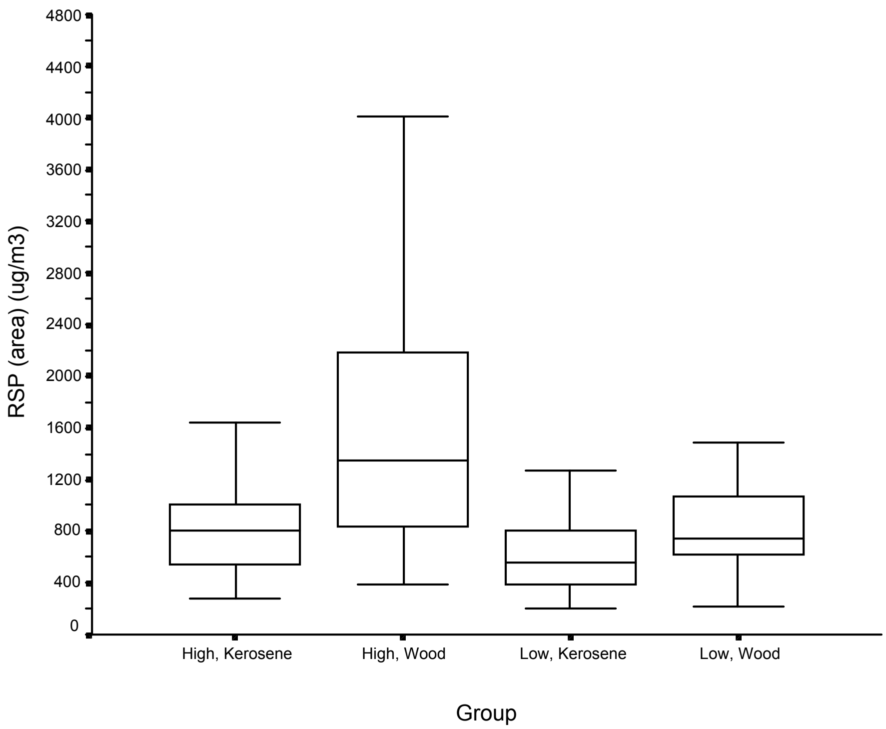

Figure 2 Box plot comparing RSP (area) concentrations across groups during cooking

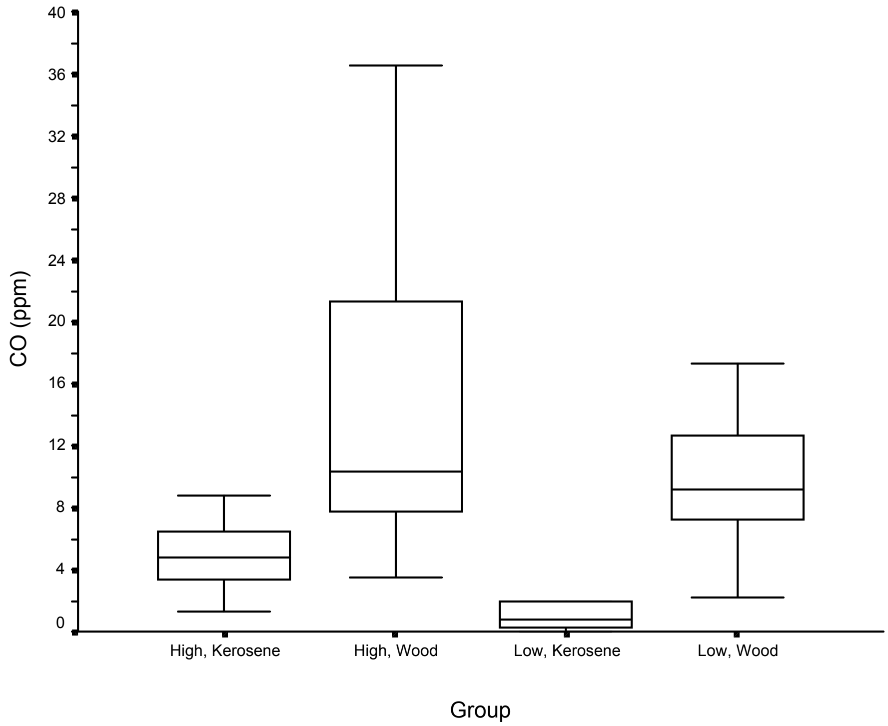

Figure 3 Box plot comparing CO concentrations across groups during cooking

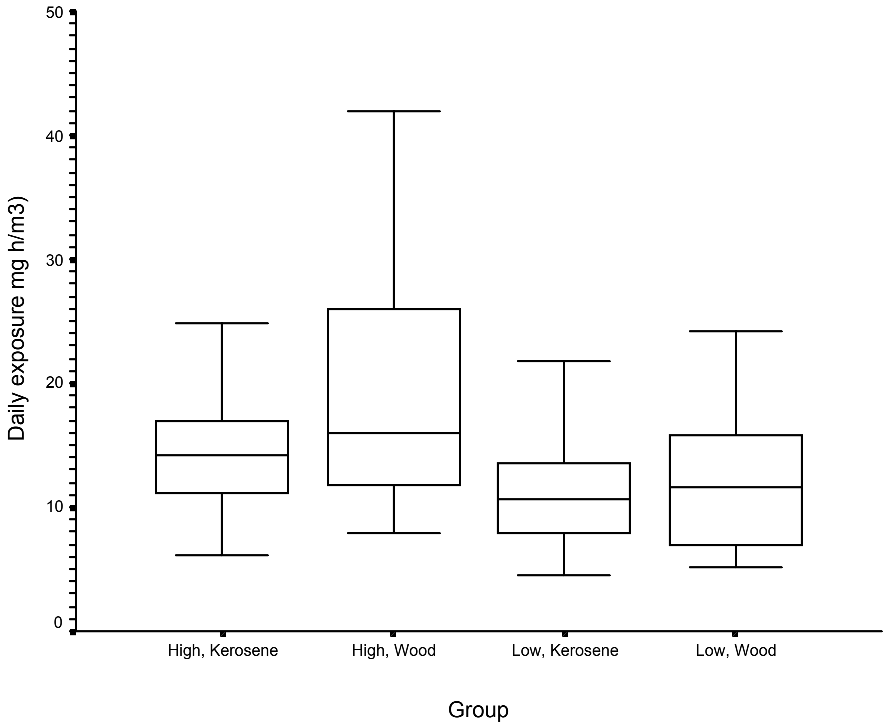

Figure 4 Comparison of the daily integrated exposure of infants to RSP

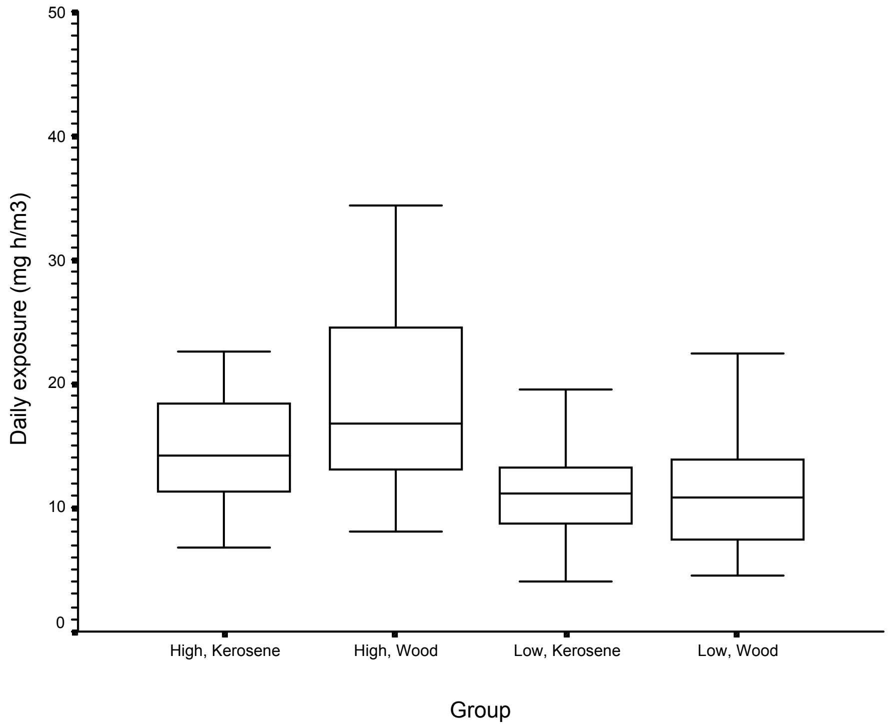

Figure 5 Comparison of the daily integrated exposure of women to RSP

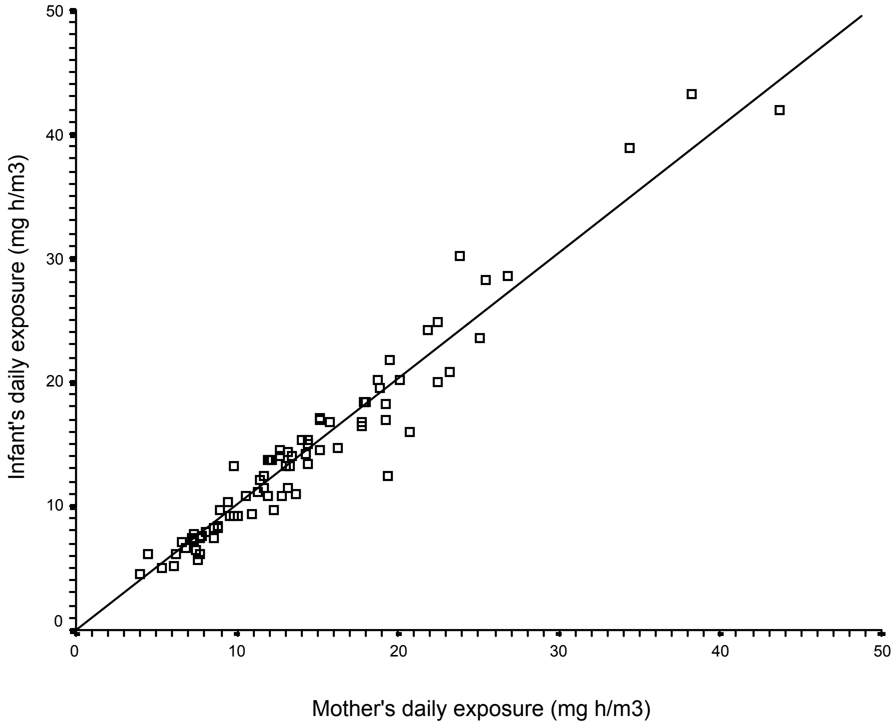

Figure 6 Relationship between the daily exposure of infants and their mothers to RSP