Daily Average Exposures to Respirable Particulate Matter from Combustion of Biomass Fuels in Rural Households of Southern India

Kalpana Balakrishnan,[1] Jyoti Parikh,[2] Sambandam Sankar,[1] Ramaswamy Padmavathi,[1] Kailasam Srividya,[1] Vidhya Venugopal,[1] Swarna Prasad,[1] and Vijay Laxmi Pandey[2]

[1]Sri Ramachandra Medical College and Research Institute (Deemed University), Porur, India; [2]Indira Gandhi Institute for Development Research, Mumbai, India

Indoor air pollution resulting from combustion of biomass fuels in rural households of developing countries is now recognized as a major contributor to the global burden of disease. Accurate estimation of health risks has been hampered by a paucity of quantitative exposure information. In this study we quantified exposures to respirable particulate matter from biomass-fuel combustion in 436 rural homes selected through stratified random sampling from four districts of Tamil Nadu, India. The study households are a subset of a larger sample of 5,028 households from the same districts in which socioeconomic and health information has been collected. Results of measurements for personal exposures to respirable particulate matter during cooking were reported earlier. This has been extended to calculation of 24-hr exposures with the aid of additional measurements during noncooking times and the collection of time-activity records. Concentrations of respirable particulate matter ranged from 500 to 2,000 μg/m^3 during cooking in biomass-using households, and average 24-hr exposures ranged from 90 ± 21 μg/m^3 for those not involved in cooking to 231 ± 109 μg/m^3 for those who cooked. The 24-hr exposures were around 82 ± 39 μg/m^3 for those in households using clean fuels (with similar exposures across household subgroups). Fuel type, type and location of the kitchen, and the time spent near the kitchen while cooking were the most important determinants of exposure across these households among other parameters examined, including stove type, cooking duration, and smoke from neighborhood cooking. These estimates could be used to build a regional exposure database and facilitate health risk assessments. ***Key words:*** **biomass fuels, developing countries, exposure assessment, indoor air pollution, rural health.** ***Environ Health Perspect*** **110:1069–1075 (2002). [Online 10 September 2002]**
http://ehpnet1.niehs.nih.gov/docs/2002/110p1069-1075balakrishnan/abstract.html

About half of the world's population relies on biomass fuels (wood, agricultural residues, and charcoal) as the primary source of domestic energy; nearly 2 billion kg of biomass are burned every day in developing countries (Barnes et al. 1994; Reddy et al. 1996). In rural India, nearly 90% of primary energy use is accounted for by biomass (wood, 56%; crop residues, 16%; dung, 21%) (TEDDY, 1998). Combustion of biomass fuels in poorly ventilated kitchens using poorly functioning stoves leads to high concentrations of respirable particulates; gases including carbon monoxide, sulfur dioxide, and nitrogen oxides; and toxic compounds such as benzene and formaldehyde (Albalak et al. 1999; Ezzati et al. 2000; Smith 1987, 1993; Smith et al. 1983). Exposure to these pollutants has been shown in many recent studies to be causally linked to several health effects, especially in women who cook with these fuels and in young children. Strong associations between biomass-fuel exposure and increased incidences of chronic bronchitis in women and acute respiratory infections in children have been documented (Armstrong and Campbell 1991; Bruce et al. 1998; Pandey 1984; Pandey et al. 1989; Robin et al. 1996; Smith and Liu 1994; Smith et al. 2000).

Several studies concerning biomass combustion, air pollution, and health have been conducted in rural Indian villages (Awasthi et al. 1996, Behera et al. 1991, Mishra and Rutherford 1997, Ramakrishna et al. 1989). The burden of disease attributable to use of biomass fuels in India is estimated as 5–6% of the national burden of disease (Smith 1996, 2000; Smith and Mehta 2000).

Although these estimates are reasonable for placing indoor air pollution as a major risk factor contributing to the national burden of disease, considerable uncertainty exists about the absolute magnitude of the health risks. Few quantitative exposure assessment studies have been conducted. Many studies have been conducted with small sample sizes that do not adequately capture the influence of multiple exposure variables such as the type of fuel, type and location of kitchen, and type of stove on actual exposures. Use of surrogate exposure indicators without quantitative measurements and poorly defined illness outcomes also results in considerable ambiguity in understanding the exposure–response relationship.

A recent study examined the exposure–response relationship between biomass combustion and acute respiratory infection in children of rural Kenyan households (Ezzati and Kammen 2000). This was preceded by rigorous quantitative exposure assessments in the same households (Ezzati et al. 2000). Quantitative exposure assessments are therefore crucial for the subsequent development of exposure–response relationships.

The few studies that have been carried out in India have all been done in northern Indian households. Little information on exposures in southern India is currently available. The climatic and cultural differences between the northern and southern Indian regions have the potential to influence exposures significantly. Biomass fuels are seldom used in the south for heating. Except for a brief period of monsoons, the weather remains fair almost throughout the year, making cooking outdoors fairly prevalent. Further, the restrictions on the movement of women are significantly fewer in the south. Unlike in northern India, women in the south do not cover their faces and usually have freedom to move outside the house even in the presence of men, factors that may substantially reduce exposures.

The present study was aimed at assessing exposures to respirable dusts in rural households selected using a stratified sampling design across four districts of Tamil Nadu, India. Through a combination of personal monitoring, area measurements, and records of time activity patterns, 24-hr average exposures of cooks and other members of the households were determined for members of > 400 households that covered all major sociocultural zones across the state. Several covariates of exposure were identified. The study is a part of a larger study conducted by The Indira Gandhi Institute of Development Research, Mumbai, involving 5,028 households in which additional data on socioeconomic and health parameters are being collected (Parikh and Pandey 2000). The data presented here

---

Address correspondence to K. Balakrishnan, Environmental Health Engineering, Sri Ramachandra Medical College & Research Institute, Porur, Chennai-600 116, India. Telephone: 91-44-476-5609. Fax: 91-44-476-7008. E-mail: kalpanasrmc@vsnl.com

We thank T.K. Partha Sarathy, K. Parikh, B.W.C. Satyasekharan, P. Venkatesan, and A.C. Nielson for valuable assistance in planning the study. We thank K. Smith, P. Breysse, P. Lees, and H. Hu for their invaluable support and guidance. Finally, we thank the women who participated in the study.

This work was supported in part through a subcontract to the Sri Ramachandra Medical College from the Indira Gandhi Institute for Development Research under the UNDP Cap21 project.

Received 10 August 2001; accepted 26 April 2002.

extend our earlier work reported for exposures during cooking times (Parikh et al. 2001). To our knowledge this has been one of the largest quantitative exposure assessment studies on biomass fuels undertaken in southern India thus far.

Methods

Research location. The study was executed in four districts of Tamil Nadu (Figure 1), a coastal state in southern India. During the study period the outside temperature varied between 24°C and 36°C. Agriculture and cattle herding were the prime occupations in these districts. All districts had similar socioeconomic backgrounds and were similar in dietary habits.

Selection of villages/households. We selected 30 villages through population proportional sampling from four districts representing four sociocultural zones of the state of Tamil Nadu. Villages were classified as small (population < 1,000), medium (1,000–3,000), and large (3,000–5,000). Around 450 rural households were then selected in these 30 villages through systematic random sampling. The number of households was decided on the basis of maximal field technical capacity available with the investigators for executing the project within a period of 20 weeks between July and December 1999.

Monitoring households within a village. Small villages were monitored within a day, medium villages within 2 days, and large villages within 3 days. A short questionnaire was administered to each household to assess prevalence of exposure covariants that included fuel type, kitchen location, stove type, cooking duration, number of meals cooked, time spent in or near the kitchen while cooking, and presence or absence of chimneys. We obtained consent from the cooks to attach the personal samplers while cooking. Cooking times were determined at the beginning of the day so as to facilitate scheduling of monitoring. Separate samples were taken during cooking and noncooking times. A high-volume respirable dust sampler was placed on the roof of the tallest available building within the village and run for 2–10 hr, depending on the availability of power. We made this measurement to assess contributions (if any) from other (e.g., industrial) point sources located near the households. The contributions from outdoor cooking were assessed through separate samplers placed outside the households.

Monitoring within a household. We placed samplers inside and outside the houses first, for area measurements during noncooking periods. Subsequently filters were changed for sample collection during cooking. One sampler in each household was attached to the cook, and area measurements inside as well as outside the house were taken to cover cooking times. A total of 450 households were monitored for respirable particulate levels during various time windows. We obtained valid measurements from 436 households. Exposure for the cook while cooking was always assessed with aid of battery-powered personal samplers attached to the cook. Because the availability of samplers did not permit attaching a sampler to every member of the household, we used area concentrations and time activity records to assess exposure for the others during all times and for cooks during noncooking times. The location of samplers for area measurements depended on the type of kitchen and time of measurement. The sampling locations for various household configurations are illustrated in Figure 2.

Reconstruction of 24-hr exposures. A total of 529 time–activity records were obtained from members of these households that included women cooks, women not involved in cooking, and men. We did not collect time–activity records for children. Records were obtained on the basis of a 24-hr recall that detailed the type, location, and duration of each activity carried out. The monitoring data provided area concentrations for two microenvironments (indoors and outdoors) during cooking and noncooking times as well as personal exposures of cooks while cooking for each household. Using area concentrations at each microenvironment together with the total duration spent at each location during cooking/noncooking times, we calculated the 24-hr exposures for all those not involved in cooking. The exposure for cooks was estimated similarly, except that exposure while cooking was assessed through personal samplers. Cooks are likely to be exposed the most, and small variations in where they are while cooking could make large changes in their exposures. The use of personal samplers during cooking times therefore allowed their exposure to be estimated with greater certainty. We thus performed the exposure calculations on a case-by-case basis, using individual time–activity records together with the particular microenvironmental concentration information collected in the household.

Respirable dust measurements. We collected and analyzed area and personal samples for respirable dusts according to U.S. National Institute of Occupational Safety and Health protocol 0600 (NIOSH 1984). Briefly, samples were collected by drawing air through battery-operated, constant-flow pumps supplied by SKC Inc. (Eighty Four, PA, USA); pumps were equipped with a 10-mm nylon cyclone with a 50% cut-off of 4 µm at 1.7 L/min using 37-mm PVC filters (5 µm pore size). All pumps were calibrated using an electronic flow meter on the field before and after sampling; electronic flow meter was in turn calibrated using a Mini Buck (A.P. Buck Inc., Orlando, FL, USA) soap bubble meter in the laboratory. We subjected 10% of all samples to analysis as field blanks.

Gravimetric analyses were conducted at the Sri Ramachandra Medical College and Research Institute laboratory using a Mettler balance (Mettler of Toledo, Inc., Greifensee,

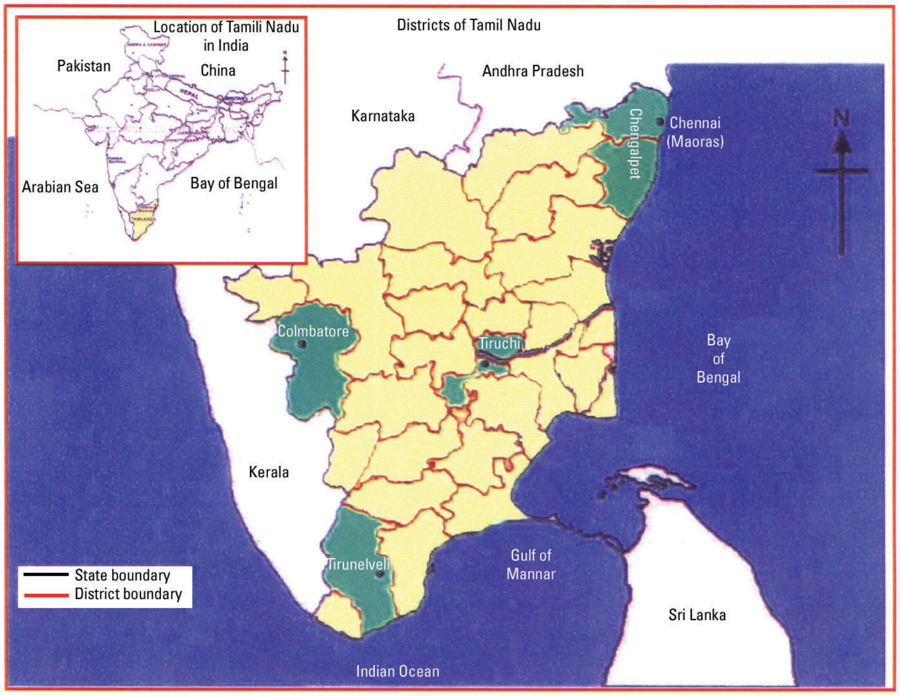

Figure 1. Map of the study area showing locations of districts (green) within the state of Tamil Nadu. Villages monitored were chosen within a 100 km^2 radius of the district headquarters.

Switzerland; calibrated against standards provided by The National Physical Laboratory, New Delhi, India). The room was maintained at 20 ± 1°C and 50% ± 5% relative humidity. All filters were conditioned for 24 hr before weighing. Respirable dust concentrations expressed in terms of micrograms per cubic meter were calculated by dividing the blank corrected filter mass increase by the total volume sampled. All blank-corrected filter mass values below the limit of detection (LOD; 0.005 mg) were replaced with LOD/$\sqrt{2}$.

Data analysis. We analyzed results of concentration measurements and 24-hr exposure calculations across households to examine relationships between various potential exposure covariates (as obtained from the questionnaire). Parameters examined included fuel type, type and location of kitchen, stove type, cooking duration, number of meals cooked, time spent in or near the kitchen while cooking, presence or absence of chimneys, and smoke from neighborhood cooking (as assessed by sampler placed outside the house). Because concentrations and exposures were log normally distributed, all comparisons were made using log-transformed data. Analyses were carried out using the SPSS package (version 8.0) (SPSS, Inc., Chicago IL, USA).

Results

Profile of study population. About 90% of the households used only biomass fuels. Firewood was the most common fuel used (75% of households), followed by agricultural produce (12% of households) and wood chips (4% of households). Of the biomass-fuel users, 36% used the fuels in indoor kitchens without partitions, 30% in separate kitchens inside the house, 19% in separate kitchens outside the house, and 16% in outdoor kitchens. Less than 10% of households in the study used clean fuels such as kerosene, liquified petroleum gas, and biogas. Even among the households that used clean fuels, nearly 95% of them used biomass fuels to cook at least one meal. The frequency of biomass-fuel use in households with access to clean fuels varied depending upon availability of clean fuels, the economic situation of the household, and occasional social considerations. But for the most part these households used biomass fuels, as there was no direct cost involved in procuring the fuels locally.

Respirable particulate measurements. The distribution of personal exposures, living area, and outdoor concentrations during cooking times across fuel types is shown in Figure 3 and described in Table 1. One-way analysis of variance (ANOVA) (Table 1) showed that both personal exposures of cooks and living area concentrations were significantly different across fuel types ($p < 0.01$). Use of agricultural produce resulted in highest levels of respirable particles, followed by wood chips, wood, kerosene, and gas, respectively. Outdoor area

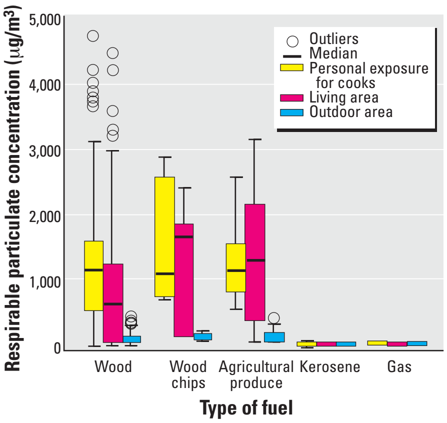

Figure 3. Distribution of personal exposures, living area concentrations, and outdoor area concentrations of respirable particulates during cooking times across households using various fuels. The ends of the box (hinges) are at quartiles, so that the length of the box is the interquartile range (IQR). The median is marked by a line within the box. The two whiskers ouside the box extend to the smallest and largest observations within 1.5 × IQR.

Table 1. Description and results of one-way ANOVA for personal exposures of cooks and indoor and outdoor area concentrations during cooking times across study households using various fuels.

	Concentrations (μg/m³)		
Type of fuel	Personal exposure	Living area	Outdoor
Solid fuels			
Wood			
Mean	1,307*	847*	190
n	308	248	162
SEM	50	50	10
GM	1,043	498	159
Wood chips			
Mean	1,359	1,343	269
n	13	6	9
SEM	211	376	40
GM	1,189	901	246
Agricultural produce			
Mean	1,535	1,327	245
n	51	21	24
SEM	115	207	23
GM	1,346	913	221
Clean fuels			
Kerosene			
Mean	132	80[a]	79
n	42	36	33
SEM	41	4	2
GM	91	77	78
Gas			
Mean	83	78	79
n	7	5	4
SEM	6	3	2
GM	81	78	79

GM, geometric mean; all comparisons were made using log-transformed values.

[a] Not significantly different from gas. *F statistic significant at $p < 0.01$ as compared to other fuel types.

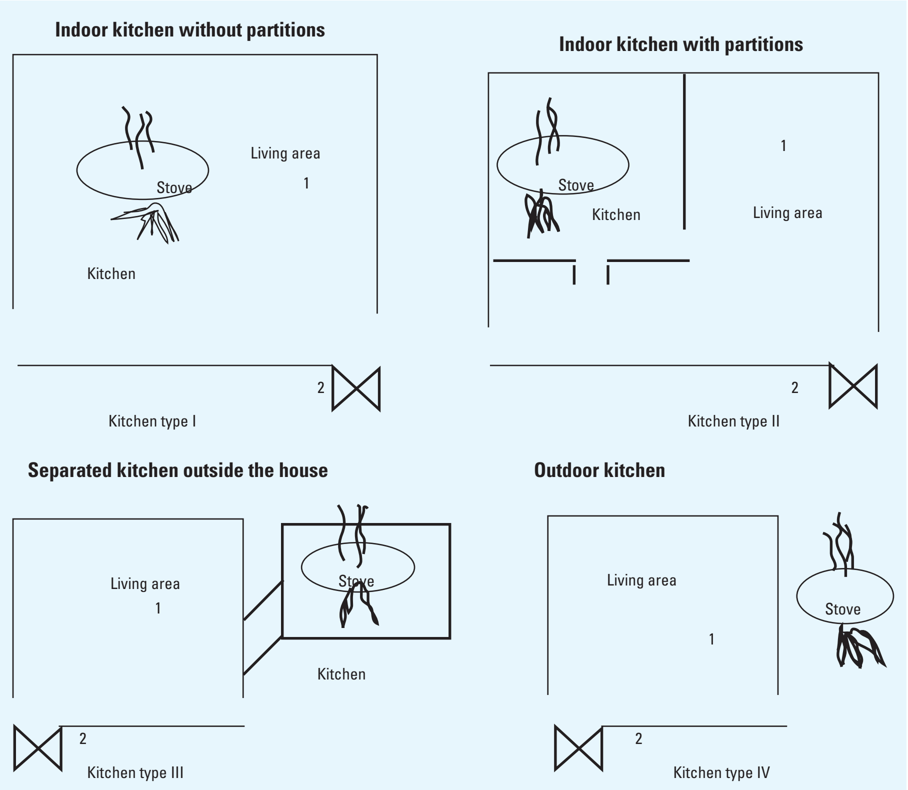

Figure 2. Floor layout of various kitchen types with sampling points for respirable particulates. In addition, one sampler was attached to the cook for personal sampling, and one high-volume sampler (not shown) was placed in the village to record emissions of significant point sources near the village (if any). The typical location of the sampler for area measurements inside the house is indicated by "1," and the typical location of the sampler for area measurements outside the house indicated by "2."

concentrations during cooking with solid fuels was similar across categories of solid-fuel users but higher than kerosene or gas users.

The distribution of personal exposures, living area, and outdoor concentrations during cooking times in solid-fuel users across kitchen types is shown in Figure 4 and described in Table 2. One way ANOVA (Table 2) showed that personal exposure of cooks was not significantly different across enclosed kitchen types (i.e., between indoor kitchens with or without partitions and separate kitchens outside the house) but was significantly different ($p < 0.05$) from exposures of cooks using open outdoor kitchens. This is not surprising because kitchen dimensions are similar across enclosed kitchens, and because cooks are likely to be close to the stove while cooking, dispersion of emissions indoors contributes little to their exposures. In general, dispersion is greater outdoors and, therefore, cooks cooking in the open outdoors experience lower exposures compared to those in enclosed kitchens. Living area concentrations, however, were significantly different ($p < 0.05$) across all kitchen types. Households with kitchens without partitions experienced the highest levels, followed by kitchens with well-defined partitions and outdoor kitchens. This is presumably the result of greater potential for dispersion with increasing distances from the stove. Outdoor measurements were not significantly different across kitchen types among solid-fuel users. In houses using clean fuels, there were no significant differences in personal exposures, living area, and outdoor area measurements during cooking times across various types of kitchens.

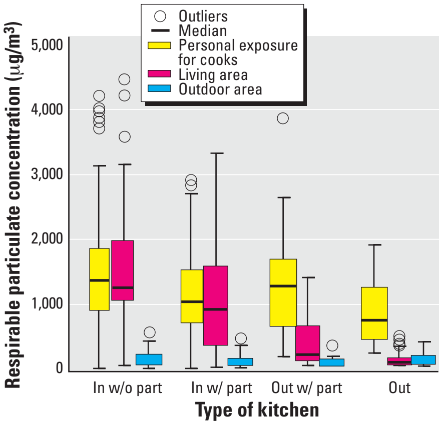

Figure 4. Distribution of personal exposures, living area concentrations, and outdoor area concentrations of respirable particulates during cooking times across households using solid fuels and having various kitchen configurations. Abbreviations: In w/ part, indoor kitchen with partitions; In w/o part, indoor kitchen without partitions; Out w/ part, outdoor kitchen with partitions; Out, outdoor cooking. The ends of the box (hinges) are at quartiles, so that the length of the box is the interquartile range (IQR). The median is marked by a line within the box. The two whiskers ouside the box extend to the smallest and largest observations within 1.5 × IQR.

Table 2. Descriptives and results of one-way ANOVA for personal exposure concentrations and indoor and outdoor area concentrations during cooking windows in solid-fuel users across kitchen types.

	Concentration ($\mu g/m^3$)	
Type of kitchen	Personal exposure	Living area
Enclosed		
Indoor kitchen without partitions		
Mean	1,578	1,442[a]
n	129	105
SE	87	79
GM	1,256	1,181
Indoor kitchens with partitions		
Mean	1,474	970
n	104	68
SE	88	91
GM	1,204	690
Separate enclosed kitchen outside the house		
Mean	1,269	460
n	49	32
SE	102	74
GM	1,086	316
Outdoor		
Mean	884**	199**
n	90	70
SE	46	22
GM	779	154

GM, geometric mean; all comparisons were made using log-transformed values.
[a]Significantly different from other types of enclosed kitchens. ***F* statistic significant at $p < 0.05$ as compared to other types of kitchens.

Also, there were no significant differences between indoor and outdoor area concentrations during noncooking times across various types of kitchens and fuels. Smoke generation from combustion of biomass fuels, therefore, was the single most important source of respirable particulates in the study households.

Personal exposures, living area concentrations, and outdoor area concentrations during cooking times were significantly correlated with fuel type ($r = 0.67$, 0.45, and 0.38, $p < 0.01$, respectively), whereas only the living area concentrations were correlated with kitchen type ($r = 0.53$, $p < 0.01$). None of the concentrations was significantly correlated with cooking duration, number of meals cooked, or presence or absence of chimneys (although only about 1% of study households reported having chimneys). Stove type was dependent on the fuel type and therefore could not be examined independently.

Finally, ambient concentrations as measured through roof-top sampling using a high-volume sampler ranged from 45 to 65 $\mu g/m^3$, indicating that there were no other point sources in the villages monitored.

Exposure profile. The reconstruction of the 24-hr exposure profile relied on personal monitoring data, measurements of area concentrations, and the collection of time–activity records. The individual time–activity records allowed the computation of total time spent by members of the household at the indoor or outdoor locations differentially during cooking/noncooking times. Study household members were divided into five subgroups: women who cook, women not involved in cooking, women noncooks involved in assisting the cook, men staying home, and men with outdoor jobs. The mean durations spent at each location by various household subgroups are summarized in Table 3.

The distribution of 24-hr exposures for cooks and noncooks across fuel types is shown in Figure 5 and described in Tables 4 and 5. One-way ANOVA (Table 4) shows that the average 24-hr exposure for women cooks when using biomass fuels (231 ± 109 $\mu g/m^3$) is significantly higher ($p < 0.01$) than for those using clean fuels (82 ± 39 $\mu g/m^3$) and for noncooks in homes using solid fuel (179 ± 108 $\mu g/m^3$). Among noncooks in households using solid fuel, women not involved in cooking and men with outdoor jobs had the lowest exposures, while women involved in assisting the cook and men staying home had the highest exposures. Men staying home were either older men or infirm and therefore spent a significant fraction of

Table 3. Mean duration of time spent in household microenvironments by various subgroups of study household members.

	Time spent during cooking times (hr)			Time spent during noncooking times (hr)		
Subgroup	Kitchen	Living	Outdoors	Kitchen	Living	Outdoors
Women who cook (*n* = 339)						
Mean	2.74	0.30	0.30	4.02	12.64	4.00
SD	1.05	0.60	0.21	3.70	3.13	3.26
Women not involved in cooking (*n* = 29)						
Mean	0.21	0.87	1.25	0.55	15.62	5.50
SD	0.63	1.21	0.91	1.71	5.38	4.39
Women involved in assisting the cook (*n* = 46)						
Mean	1.40	1.50	0.25	2.55	12.80	5.50
SD	0.61	1.43	0.76	1.32	2.38	5.39
Men staying home (*n* = 76)						
Mean	0.18	1.97	1.2	1.30	15.21	5.14
SD	0.39	1.22	0.81	3.23	4.61	2.13
Men with outdoor jobs (*n* = 39)						
Mean	0.15	0.92	0.54	1.64	9.65	11.10
SD	0.41	0.54	0.36	1.06	3.78	2.34

their time indoors, resulting in greater potential for exposures. Exposures were not significantly different between cooks and noncooks in clean-fuel users.

The distribution of 24-hr average exposures in solid-fuel users across kitchen types is shown in Figure 6 and described in Table 6. The 24-hr average exposures for women cooks using biomass fuels in enclosed kitchens (248 ± 117 μg/m^3) was significantly ($p < 0.05$) higher than for those that used biomass fuels in outdoor kitchens (171 ± 55 μg/m^3). Exposures were not significantly different across women cooks using biomass fuels in various types of indoor kitchens. This parallels the trend in personal exposures of cooks during cooking windows. Further, in households using biomass fuels, exposures for men and women who were not involved in cooking and stayed far from the stove during cooking were not different across kitchen types, but for women and men who were indoors during cooking times, exposures decreased as one moved from a kitchen with no partitions to separately enclosed kitchens and outdoor kitchens. This parallels the trend in living room concentrations during cooking times in solid-fuel users. Proximity to the stove during cooking times is thus a good indicator of exposures for both men and women noncooks.

Correlation among 24-hr exposures, personal exposures while cooking, and area concentrations. The 24-hr exposures for women cooks were significantly ($r = 0.94$; $p < 0.01$) correlated with personal exposures while cooking, and exposures for other women and men staying indoors during cooking times correlated well with living area measurements taken during cooking times ($r = 0.97$ and 0.87, respectively; $p < 0.01$). All correlations significantly improved if comparisons were made within fuel and kitchen subtypes.

The 24-hr exposures were not significantly associated with outdoor area concentrations while cooking and other area concentrations during noncooking windows for all subgroups of household members. The 24-hr exposures for cooks were not significantly correlated with number of meals cooked and cooking duration, presumably because of extreme homogeneity among study households in both number of meals cooked and cooking duration. Finally, exposures for members of houses using clean fuels were calculated for the hypothetical situation in which all households with access to clean fuels are assumed to use them exclusively. Actual exposures for these members are likely to be much higher because of their frequent intermittent use of biomass fuels.

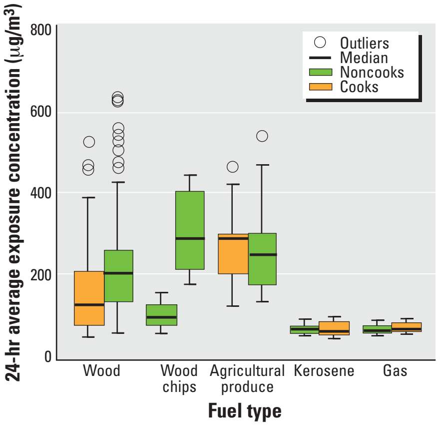

Figure 5. Distribution of 24-hr average exposure concentrations of respirable particulates for cooking and noncooking household members across households using various fuels. The ends of the box (hinges) are at quartiles, so that the length of the box is the interquartile range (IQR). The median is marked by a line within the box. The two whiskers ouside the box extend to the smallest and largest observations within 1.5 × IQR.

Discussion

This study has provided for the first time quantitative exposure assessment data for individual exposures to indoor air pollutants for a wide cross-section of rural homes using biomass fuels under a variety of exposure conditions in southern India. These estimates may be used to build a regional database and used in other similar studies in Tamil Nadu, as such monitoring may not always be feasible. Although several parameters were examined for possible correlations with concentrations and exposures, fuel type, kitchen type, and proximity to the stove during cooking times were the only parameters that showed significant association. Future expansion of this database to include other determinants such as room/window dimensions, fuel quantity, and ventilation levels may perhaps allow an assessment of the most important determinants of indoor air pollution exposure in households of this region.

Although exposures and health impacts in cooks have been known from many earlier studies, few studies have quantified exposures for others residents. The results of the present study have shown that living area concentration in households with kitchens without partitions are often greater than kitchen concentrations. This would put

Table 4. Description and results of one-way ANOVA for 24-hr average exposure concentrations (μg/m^3) in study households using various fuels.

Fuel type	Mean	n	SE	GM
Cooks				
Solid-fuel users				
Wood	226*	256	7	204
Wood chips	285	7	42	266
Agricultural produce	262	34	16	246
Clean-fuel users				
Kerosene	83	34	7	78
Gas	79	8	4	78
Noncooks				
Solid-fuel users				
Wood	172*	159	8	147
Wood chips	103	6	2	103
Agricultural produce	262	14	28	238
Clean-fuel users				
Kerosene	76	13	3	75
Gas	76	3	10	74

GM, geometric mean; all comparisons were made using log-transformed values.
*F statistic significant at $p < 0.01$ as compared to other fuel types.

Table 5. Description and results of one-way ANOVA for 24-hr average exposure concentrations (μg/m^3) for various subgroups of household members in study households.

Subgroup	Mean	n	SE	GM
Solid-fuel users				
Cooks				
Women cooks	231**	297	6	210
Noncooks				
Women noncooks not involved in cooking	86	22	1	86
Women noncooks involved in assisting the cook	195	46	12	179
Men staying home	202	76	11	180
Men with outdoor jobs	94	25	6	91
Clean-fuel users				
Women cooks	82[a]	42	6	78
Women noncooks not involved in cooking	97	2	2	97
Men with outdoor jobs	73	14	3	72

GM, geometric mean; all comparisons were made using log-ransformed values.
[a]Not significantly different from other categories of clean fuel users. **F statistic significant at $p < 0.05$ as compared to other categories of household members.

young children and the elderly, in addition to the cooks, at high risk of suffering adverse consequences, as they are most likely to be indoors during cooking times.

Most studies concerning particulate measurements in homes using biomass fuels have been done using total suspended particulates or PM_{10} (particulate matter < 10 µm in diameter) as an indicator. Few studies have reported results using the NIOSH protocol for respirable particulates. This standard is more reflective of the particulate fractions likely to be associated with deposition in the lower airways. It also allows comparisons to be made with studies in other occupational settings where similar short, intense exposures are likely to occur. Table 7 compares results of some recent studies.

The levels reported in this study are much lower than levels reported in households using biomass fuels in several other studies. However, other studies (Albalak et al. 2001; Robin et al. 1996) reported levels similar to those observed in this study. Studies are not similar in their choice of particle size cut-offs for monitoring and have been done across a wide range of populations in different geographic and sociocultural zones. Lower levels obtained in the study may thus be reflective of both lower cut-offs chosen for measurement as well as lower exposures for this population. Further, in a study in Navajo Indian homes reporting results similar to those obtained in this study, Robin et al. (1996) documented a significant association between acute respiratory infection in children and respirable suspended particulate matter levels for concentrations as low as 30 µg/m^3. Finally, much of the work in India reported earlier has addressed the populations in northern India. This is one of the largest assessments in southern India. Northern parts of the country remain cold for several months a year, and the types of food eaten also tend to differ markedly between the north and south. The state of Tamil Nadu where the study was carried out has moderate to hot temperatures most of the year. The mean duration of cooking is longer in the north because of both cooler temperatures and the type of food prepared (typical breads prepared by women in north are toasted on the stove individually for each family member, and this consumes more time; women in south usually cook a batch of rice for all members of the household together). Although no quantitative assessment for kitchen ventilation was made, houses in the south are likely to be better ventilated as it is possible to keep the doors open; in addition, it is possible in the south to cook outdoors during most parts of the year. Sociocultural and housing design differences may thus contribute to regional differences in exposure in addition to type of fuel and stove combinations.

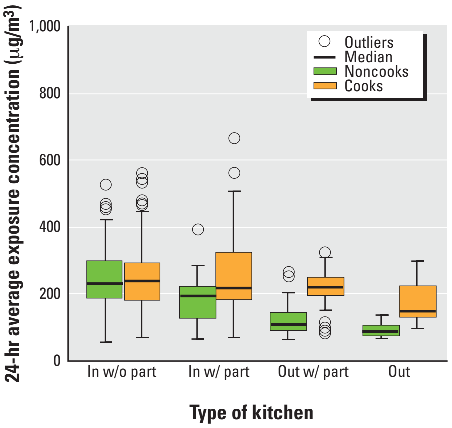

Figure 6. Distribution of 24-hr average exposure concentrations of cooking and noncooking household members in households using solid fuel and having various kitchen configurations. Abbreviations: In w/ part, indoor kitchen with partitions; In w/o part, indoor kitchen without partitions; Out w/ part, outdoor kitchen with partitions; Out, outdoor cooking. The ends of the box (hinges) are at quartiles, so that the length of the box is the interquartile range (IQR). The median is marked by a line within the box. The two whiskers ouside the box extend to the smallest and largest observations within 1.5 × IQR.

The exposure estimates derived in the study are currently being used for deriving exposure–response relationships between respirable particulates and lung function in women cooks of the same households in an independent study (Sankar et al. 2001). Exposure–response relationships for PM_{10} and acute respiratory infection in biomass in Kenyan households has been recently reported (Ezzati et al. 2001). Further, given the high degree of variability in exposures across populations using biomass fuels, quantitative exposure estimates offer the potential to better calculate health risks as opposed to assessing on the basis of reported biomass use. These newly emerging relationships will allow considerable refinements to earlier calculations of the burden of disease attributable to indoor air pollution (Smith 2000).

Conclusion

The burden of environmentally associated diseases is just beginning to catch the atten-

Table 6. Description and results of one-way ANOVA for 24-hr average exposure concentration (µg/m^3) in solid-fuel users across kitchen types.

Kitchen type	Mean	*n*	SE	GM
Cooks				
Enclosed kitchen				
Indoor kitchen without partitions	253	113	11	229
Indoor kitchen with partitions	253	86	13	228
Separate enclosed kitchen outside the house	216	34	13	203
Outdoor kitchen				
Outdoor cooking	171**	64	6	163
Noncooks				
Enclosed kitchen				
Indoor kitchen without partitions	250^a	60	16	220
Indoor kitchen with partitions	200	44	13	182
Separate enclosed kitchen outside the house	122	29	9	114
Outdoor kitchen				
Outdoor cooking	94**	41	3	91

GM, geometric mean; all comparisons were made using log-transformed values.
^{a}Significantly different as compared to noncooks in other types of enclosed kitchens. ***F* statistic significant at $p < 0.05$.

Table 7. Comparison of particulate levels as determined in some recent studies in developing countries.

Location	Averaging time, size fraction/range	Type of fuel	Mean levels (µg/m^3)
Gujrat, India (Smith et al. 1983)	Cooking period/TSP	Wood	6,800
Garhwal, India (Saxena et al. 1992)	Cooking period/TSP; 24-hr exposures/TSP	Wood/shrubs	4,500 (GM); 710–1,960 (winter); 250–1,130 (summer)
Pune,India (Smith et al. 1994)	12–24 hr/PM_{10}	Wood	2,000 (area); 1,100 (personal)
Mozambique (Ellegard 1996)^4	Cooking period/PM_{10}	Wood	1,200
Rural Bolivia (Albalak et al. 1999)	6 hr/PM_{10}	Dung	1,830 (GM-indoor kitchens); 280 (GM-outdoor kitchens)
Kenya (Ezzati et al. 2000)	Daily average exposures/PM_{10}	Wood/charcoal	1,000–4,800
Guatemala (Albalak et al. 2001)	24 hr/ $PM_{3.5}$	Wood	1,560 (GM, traditional stove); 250 (GM, improved stove); 850 (GM, LPG /open fire combination)

GM, geometric mean; LPG, liquified petroleum gas; PM_{10}, particulate matter < 10 µm; $PM_{3.5}$, median particle size 3.5 µm; TSP, total suspended particulates.

tion of health policy makers in developing countries. The morbidity and mortality associated with such smoke exposures and the associated economic costs are now recognized as significant, but in order to devise various measures for risk reduction, it is imperative that more attention be focused on quantitative exposure assessments.

The biggest strengths of the present study have been quantifying exposures and laying the framework for the creation of a regional exposure database. It is hoped that integration of the results of this study with other exposure assessment studies will strengthen the preliminary exposure–response relationships emerging specifically for indoor air pollutants in developing countries. This would also allow the generation of a composite exposure index that can be used as a simple surrogate indicator for large-scale health studies. The study has provided substantial baseline exposure information on rural homes in southern India. This information may thus be useful for making comparisons in future studies concerned with implementing interventions and assessing the efficacy of interventions.

REFERENCES

Albalak R, Bruce N, McCraken J, Smith KR, Gallardo T. 2001. Indoor respirable particulate matter concentrations from an open fire, improved cook stove and LPG/open fire combination in a rural Guatemalan community. Environ Sci Technol 35:2650–2655.

Albalak R, Keeler G J, Frisancho AR, Haber M. 1999. Assessment of PM_{10} concentrations from domestic biomass fuel combustion in rural Bolivian highland villages. Environ Sci Technol 33:2505–2509.

Armstrong JR, Campbell H. 1991. Indoor air pollution and lower respiratory infections in young Gambian children. Int J Epidemiol 20(2):424–429.

Awasthi S, Glick H, Fletcher R. 1996. Effect of cooking fuels on respiratory diseases in preschool children in Lucknow, India. Am J Trop Med Hyg 55(1):48–51.

Barnes DF, Openshaw K, Smith KR, van der Plas R. 1994. What Makes People Cook with Improved Biomass Stoves? A Comparative International Review of Stove Programs. Washington, DC:The World Bank.

Behera D, Jindal SK, Malhotra HS. 1991. Ventilatory function in non-smoking rural Indian women using different cooking fuels. Thorax 46(5):344–346.

Bruce N, Neufeld L, Boy E, West C. 1998. Indoor biomass fuel air pollution and respiratory health: the role of confounding factors among women in highland Gautemala. Int J Epidemiol 27:454–458.

Ellegard A. 1996. Cooking fuel smoke and respiratory symptoms among women of low income areas of Maputo. Environ Health Perspect 104:980–985.

Ezzati M, Kammen DM. 2001. Quantifying the effects of exposure to indoor air pollution from biomass combustion on acute respiratory infections in developing countries. Environ Health Perspect 109:481–489.

Ezzati M, Saleh H, Kammen DM. 2000. The contributions of emissions and spatial microenvironments to exposure to indoor air pollution from biomass combustion in Kenya. Environ Health Perspect 108:833–839.

Mishra V, Rutherford R. 1997. Cooking smoke increases the risk of acute respiratory infections in children. National Family Heath Survey Bulletin. Mumbai, International Institute for Population Sciences, and Hawaii, East-West Center.

NIOSH. 1984. Nuisance dust, respirable (Method 0600). In: NIOSH Manual of Analytical Methods (Eller PM, ed). 3rd ed. Cincinnati,OH:National Institute for Occupational Safety and Health.

Pandey MR. 1984. Prevalence of chronic bronchitis in a rural community of the Hill Region of Nepal. Thorax 39:331–336.

Pandey MR, Boleij JS, Smith KR, Wafula EM. 1989. Indoor air pollution in developing countries and acute respiratory infection in children. Lancet 1:427–429.

Parikh J, Balakrishnan K, Pandey V, Biswas H. 2001. Exposure from cooking with biofuels; pollution monitoring and analysis for rural Tamil Nadu, India. Energy 26:949–962.

Parikh J, Pandey V. 2000. Biofuels, pollution and health linkages. Econ Polit Weekly 35(47):4125–4137.

Ramakrishna J, Durgaprasad MB, Smith KR. 1989. Cooking in India: the impact of improved stoves on indoor air quality. Environ Int 15:341–352.

Reddy AKN, Williams RH, Johansson TB. 1996. Energy after Rio: Prospects and Challenges. New York:United Nations Publications.

Robin LF, Lees PSJ, Winget M, Steinhoff M, Moulton LH, Santhosham M, et al. 1996. Wood burning stoves and lower respiratory illness in Navajo children. Pediatr Infect Dis J 15:859–865.

Saksena S, Prasad R, Pal RC, Joshi V. 1992. Patterns of daily exposure to TSP and CO in the Garhwal Himalaya. Atmos Environ 26A(11):2125–2134.

Smith KR. 1987. Biomass Fuels, Air Pollution and Health: A Global Review. New York:Plenum Press.

Smith KR. 1993. Fuel combustion, air pollution and health: the situation in developing countries. Annu Rev Energy Environ 18:529–566.

Smith KR. 1996. Indoor air pollution in developing countries: growing evidence of its role in the global disease burden. In: Indoor Air ‘96: Proceedings of the 7th International Conference on Indoor Air Quality and Climate, Vol 3. Tokyo:Indoor Air ‘96; 33–44.

Smith KR. 2000. The national burden of disease in India from indoor air pollution. Proc Natl Acad Sci USA 97:13286–13293.

Smith KR, Aggarwal AL, Dave RM. 1983. Air pollution and rural biomass fuels in developing countries: a pilot village study in India and implications for research and policy. Atmos Environ 17:2343–2362.

Smith KR, Apte MG, Yoqing M, Wongsekiarttirat W, Kulkarni A. 1994. Air pollution and the energy ladder in Asian Cities. Energy 19(5):587–600.

Smith KR, Liu Y. 1994. Indoor air pollution in developing countries. In: Epidemiology of Lung Cancer (Samet JM, ed.). New York:Marcel Dekker, 151–183.

Smith KR, Mehta S. 2000. The burden of disease from indoor air pollution in developing countries. Comparison of estimates. Presented at the USAID/WHO Global Technical Consultation on the Health Impacts of Indoor Air Pollution and Household Energy in Developing Countries, 3–4 May, Washington, DC.

Smith KR, Samet JM, Romieu I, Bruce N. 2000. Indoor air pollution in developing countries and acute lower respiratory infections in children. Thorax 55:518–532.

TEDDY: Tata Energy Data Directory Yearbook 1998–1999. New Delhi:Tata Energy Research Institute.