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The Contributions of Emissions and Spatial Microenvironments to Exposure to Indoor Air Pollution from Biomass Combustion in Kenya

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Acute and chronic respiratory diseases, which are causally linked to exposure to indoor air pollution in developing countries, are the leading cause of global burden of disease. Efforts to develop effective intervention strategies and detailed quantification of the exposure–response relationship for indoor particulate matter require accurate estimates of exposure. We used continuous monitoring of indoor air pollution and individual time–activity budget data to construct detailed profiles of exposure for 345 individuals in 55 households in rural Kenya. Data for analysis were from two hundred ten 14-hour days of continuous real-time monitoring of concentrations of particulate matter ≤ 10 μm in aerodynamic diameter and the location and activities of household members. These data were supplemented by data on the spatial dispersion of pollution and from interviews. Young and adult women had not only the highest absolute exposure to particulate matter (2,795 and 4,898 $\mu g/m^3$ average daily exposure concentrations, respectively) but also the largest exposure relative to that of males in the same age group (2.5 and 4.8 times, respectively). Exposure during brief high-intensity emission episodes accounts for 31–61% of the total exposure of household members who take part in cooking and 0–11% for those who do not. Simple models that neglect the spatial distribution of pollution within the home, intense emission episodes, and activity patterns underestimate exposure by 3–71% for different demographic subgroups, resulting in inaccurate and biased estimations. Health and intervention impact studies should therefore consider in detail the critical role of exposure patterns, including the short periods of intense emission, to avoid spurious assessments of risks and benefits. *Key words*: Africa, biomass combustion, exposure assessment, field study, household energy, indoor air pollution, particulate matter, public health. *Environ Health Perspect* 108:833–839 (2000). [Online 27 July 2000]
http://ehpnet1.niehs.nih.gov/docs/2000/108p833-839ezzati/abstract.html

Acute respiratory infections and chronic respiratory diseases (obstructive pulmonary disease in particular) together account for > 10% of the global burden of disease (*1–3*). In 1997 and 1998, acute lower respiratory infections were the leading causes of death from infectious diseases, with an estimated 3.7 and 3.5 million deaths worldwide for the 2 years, respectively (*3,4*). Exposure to indoor air pollution, especially to particulates, resulting from the combustion of biomass (wood, crop residues, dung, and charcoal) has been implicated as a causal agent of respiratory and eye diseases (including cataracts, blindness, and possibly conjunctivitis) (*5–12*). This association, coupled with the fact that globally more than two billion people rely on biomass as their primary source of domestic energy, has put preventive measures to reduce exposure to indoor air pollution high on the agenda of international development and public health organizations (*1,13–15*).

For efficient and successful design of measures to reduce exposure to indoor air pollution, it is necessary to determine the factors that influence the level of exposure and the relative contributions of each. These factors include household energy technology (the fuel–stove combination), housing characteristics, and behavioral determinants of exposure such as the amount of time spent inside the house or near the cooking area. Accurate measurement or estimation of exposure is also essential for quantifying the exposure–response relationship for indoor particulate matter. Numerous epidemiologic studies on the health impacts of indoor air pollution have used indirect measures, such as fuel or housing type, as proxies for personal exposure (*16*). Given the nearly universal use of biomass fuels in rural areas, this indirect approach to exposure estimation artificially clusters numerous people into a single exposure category. However, recent findings on large variations in emissions of individual stove types (*15,17*) or in exposure within individual households (*18,19*) illustrate that aggregate analysis and grouping of individuals artificially reduces the variability of the explanatory variable in the exposure–response relationship and therefore decreases the reliability of the estimation of its parameters. From a public health policy perspective, ignoring the variability of individual technologies and intrahousehold variation in exposure may dramatically change the relative importance of various strategies for reducing exposure to indoor air pollution.

The use of personal monitors has been an alternative to the indirect exposure measures (*7,20*). Although personal monitors resolve the issue of exposure estimation, with most personal monitors exposure is aggregated over time and space. This limits predictive assessment of various intervention strategies and prevents incorporation of the high-intensity emission episodes that commonly occur during the combustion of biomass fuels.

In this paper, we integrate extensive quantitative and qualitative data on individual time–activity budgets, household demographic characteristics, and continuous real-time monitoring of indoor air pollution to construct personal profiles of exposure to particulate matter resulting from biofuel combustion. Data used in this paper were collected between 1996 and 1999 as part of an ongoing study of the relationship among energy technology, indoor air pollution, and public health. We conducted continuous real-time monitoring of indoor air pollution (particulate matter and carbon monoxide) in 55 houses for 14–15 hr/day for > 200 days. During this time we also recorded the location and activities of household members, with emphasis on energy and exposure related variables. We complemented these data with extensive interviews with household members and local extension workers.

The exposure profiles in this analysis are uniquely constructed from fundamental components—emission concentrations and the location, time budget, and activities of household members. As a result we were able

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to determine the contribution of each factor to exposure. In this manner our study is similar to the thorough work of Saksena et al. (*19*), which used a microenvironment-based analysis in the Indian Himalayas. Moreover, with continuous data on instantaneous pollution levels, we were able to go beyond the single measure of average daily pollution and develop exposure profiles using other descriptive statistics of emission data that better characterize human exposure and therefore extend the current literature on exposure assessment.

Research Location

The study took place at Mpala Ranch/Research Centre in Laikipia District, central Kenya (0°20´ N, 36°50´ E). Mpala Ranch, located on semiarid land, is approximately 2,000 m above sea level. The average monthly temperature varies between 17 and 23°C. Cattle herding and domestic labor are the primary occupations of most of the inhabitants of the 80–100 households on the ranch; members of the remaining households are employed as maintenance staff. The residents have similar tribal backgrounds (Turkana and Samburu), economic status, and diet. The houses in both cattle-herding and maintenance villages are cylindrical with conic straw roofs. Table 1 provides details of housing characteristics in the two villages.

The stoves used by almost all of the households in the study group burn firewood or charcoal as fuel (three households use kerosene). The most common source of fuelwood in the area is species from the *Acacia* genera. The stove–fuel combinations in the study group are presented in Table 2. Field research at Mpala Ranch began in 1996. During the first 6–8 months of field research we collected background data, including detailed demographic data for all of the households residing on the ranch, and surveys of energy use, energy technology, and related characteristics.

Methods and Data

We used the *personal* DataRAM (PDR) monitor (MIE, Inc., Bedford, MA) to measure particulate matter. The PDR monitor uses nephelometric (photometric) monitoring technology with passive sampling, which minimizes interference with normal activities of the household. The maximum response particle size is 0.1–10 µm. Because of this response range, only a fraction of the measured concentration is due to particles ≤ 2.5 µm, which are believed to have the most important health impacts. Studies of particle pollution in both industrialized and developing countries have demonstrated correlations between concentrations of particulate matter ≤ 10 and ≤ 2.5 µm in aerodynamic diameter (PM_{10} and $PM_{2.5}$, respectively) (*21*,*22*), but further research on this relationship in the case of biomass smoke is needed. We measured carbon monoxide concentration using the Enerac Pocket 100 monitor (Energy Efficiency Systems, Inc., Westbury, NY). The instruments were sent to the factory approximately once a year for recalibration of measurement range (span), and replacement of PDR measurement chamber and Enerac Pocket 100 sensors. The instruments were zeroed in clean air outside the village compound every day and the PDR measurement chamber was cleaned using pressured air after every 2 days of measurement. Ezzati et al. (*15*) discussed the relationship between the concentrations of PM_{10} and CO concentrations.

Data on Temporal Variation of Suspended Particulate Emission and Time–Activity Budgets

The concentration of PM_{10} was recorded at a distance of approximately 0.5 m from the center of the stove. We placed the monitor on a flat surface at a height of 0.5 m. Because cooking some of the common foods in the area and the lighting and tending of fire are done with the user's head near the stove, we chose sampling distance as close to the user's breathing area as was possible under such circumstances. Other criteria for choosing the sampling point were avoiding interference with household activities, ensuring that the instruments could be placed in a stable position and not be damaged because of heat, and ensuring ready standardization of measurement point. PM_{10} concentration was averaged over and recorded in 1-min intervals between the hours of 0630 and 2030 and also during the night when we could ensure that the equipment could be left in the house safely and without disturbance to the household members. In every day of sampling, we also recorded the status of fire (whether it was off, starting, burning, or smoldering), the type of food prepared, and other energy or cooking-related behavior such as adding or moving fuel or the cooking pot, stirring food, etc., during the whole day. The fire status was recorded once every 5–10 min depending on how stable the fire was. Finally, we recorded the location and activities of all of the household members who were present at home during the day. Location data were recorded as whether the person was inside or outside, and whether he or she was near fire (defined as within approximately 1 m of the stove) or far from the fire. Activities and location were recorded as they occurred throughout the day.

Data collection was performed by two field research assistants (one female and one male). The assistants were accompanied by a principal researcher for the first 6 months of data gathering. The data-recording protocol was regularly examined after the first 6 months. Each person was assigned well-defined tasks, especially in the first few minutes of each day when the pollution monitoring equipment was placed in the house. Information such as names and ages of household members was collected independently in the first few months of field research so that on the monitoring days, data sheets for activities for each individual could be prepared before arrival in the house. Test sessions were conducted and the protocols were adjusted to ensure minimal interference with household activities. PM_{10} concentration data, which were logged automatically by the PDR, were downloaded into a personal computer after every day of monitoring. The dates and memory locations of PDR were checked against the other data sheets.

We conducted 210 days of sampling in 55 randomly selected houses in both cattle-herding and maintenance villages. The visits were made on random days of the week. We visited approximately 20% of the households,

Table 1. Housing characteristics in the cattle-herding and maintenance villages in the study area.

	Village	
Characteristic	Cattle-herding	Maintenance
Diameter	3–3.5 m	4–5 m
Wall material	Mud, dung, and wood	Stones and mud
Wall height	1.5 m	2 m
Roof material	Wood and grass	Wood and grass
Roof height	1.5 m	2 m
Internal divisions	Yes (mud, dung, and wood)	Yes (plastic)
Windows	No	Yes

Table 2. Stove–fuel combinations in the study group.

	Material				
Stove name	Body	Liner	Fuel	Price (U.S. $) equivalent	Number in use[a]
Three-stone	NA	NA	Firewood	$0	50
Kuni Mbili	Metal	Ceramic	Firewood	$4–6	26
Upesi	Metal	Ceramic	Firewood	$4–6	5
Lira	Metal	Ceramic	Firewood	$4–6	1
Metal Jiko	Metal	NA	Charcoal	$1.5–2	1
Kenya ceramic Jiko	Metal	Ceramic	Charcoal	$4–6	24
Loketto	Metal	Metal	Charcoal	$4–6	4

NA, not applicable.
[a]Number in use refers to the number of each stove type owned by the households in the sample of 55 households.

randomly selected in both village types, between 6 and 15 times to monitor the intrahousehold variation in emission concentrations as well as variations in time–activity budgets. We visited another 25% of households once, and the remainder between 2 and 5 times. Included in these days were four nights of activity monitoring of cattle guards and the emissions from the fire that they use for warmth. The demographic characteristics of the individuals in the study households are given in Table 3.

We also conducted extensive interviews with household members and local extension workers on energy technology, cooking practices, and time–activity budgets. In each household, an adult member responsible for cooking was asked in detail about the stove and fuel used by the household, location and times of cooking, and the types of meals prepared. An adult member was also asked about the location and activities of each household member during five time periods in the day (morning, midday, early afternoon, late afternoon, evening, and night), with additional questions about location and activities during cooking. Extension workers were asked the same questions separately.

Data on spatial variation of indoor air pollution. We also collected data on the spatial distribution of indoor air pollution. These measurements were all conducted in two houses (one in each size group) while the residents were away. We ensured that the fire remained stable for a 15-min period, during which we measured PM_{10} concentration sequentially at 10 points inside the house. Eight of the points were at distances of 0.4, 0.8, 1.2, and 1.9 m from the center of the stove at heights of 0.5 and 1.0 m. Points 9 and 10 were directly above the fire at a height of 1.0 m and in the sleeping area, respectively. These points cover those parts of the house where household activities take place; because of the the low roof heights, adults do not commonly stand in the house. Sampling took place once every second for 1 min at each point. We repeated this experiment under different conditions with doors and windows open and closed and with and without a cooking pot on the stove. Seventy-eight repetitions of this experiment were conducted in the two houses. Any measurement during which the status of fire changed (such as transition to smoldering phase) was discarded, which resulted in 68 sets of measurements that were used in analysis.

Table 3. Demographic characteristics of the study group.

Age group	Individuals in group (*n*)	Fraction female	Age (mean ± SD)
0–5 years	93	0.56	3.0 ± 1.4
6–15 years	109	0.56	9.7 ± 2.7
16–50 years	120	0.54	29.4 ± 10
> 50 years	23	0.65	63.8 ± 9.4
Total	345	0.56	18.3 ± 17.6

The age divisions were chosen because children ≤ 5 years of age have additional susceptibility to acute respiratory infections and at higher ages chronic conditions begin to show. For those between 6 and 50 years of age, we made a division at 15 years of age, the age at which it is common for people to enter the workforce or get married.

Data Analysis, Results, and Discussion

In our day-long home monitoring sessions, we collected data on pollution level at a single point [at a distance (x) of 0.4–0.5 m from the center of the stove and a height (z) of 0.5 m]. First, the data on spatial distribution of pollution were used to predict PM_{10} concentration at other points inside the house, which in turn could be combined with data on the location of household members to provide a complete spatial and temporal profile of exposure concentration.

Individual exposure: the role of spatial distribution of pollution. Figure 1 plots the concentration of particulate matter against horizontal distance from the stove (x) for measurements at heights (z) of 0.5 and 1.0 m for various measurement conditions corresponding to door or window being open and/or closed or a cooking pot present and/or absent.

Figure 1 shows that PM_{10} concentration initially drops rapidly with increasing distance from the stove, a pattern that can also be observed for visible smoke in actual conditions of use in Figure 2. Concentration then increases at a low rate after a distance of approximately 0.5 m. Further, points at a height of 1.0 m have slightly higher concentration than those at 0.5 m. This pattern indicates that individual exposure to smoke is dependent on the location of the individual relative to the fire, even in houses as small as those described here.

There are few models for characterizing the indoor dispersion of particulate matter. Smith (*23*) describes a steady-state model of pollutant dynamics that is based on the assumption of instant mixing, resulting in uniform concentration in the room. However, Dresher et al. (*24*) and Baughman et al. (*25*) illustrated that the instantaneous mixing assumption is not applicable to a closed room with limited air flow, as also seen in Figures 1 and 2. We divided the indoor area of the houses in the study group into six exposure microenvironments. The six microenvironments included the area immediately around the stove (where smoke rises and has the highest concentration), the sleeping area, and four additional areas. The four additional areas were formed by dividing the remainder of the house along a horizontal plane at a height of 0.5–1.0 m and a vertical plane at approximately 1.0–1.5 m (Figure 3). These divisions were based on incremental distances from the stove where activities take place. Assuming that each of these microenvironments is well mixed internally, a pairwise relationship among them can be expressed as the ratios of pollutant concentrations. The exact relationship between the microenvironment concentrations depends on the instantaneous air flow. However, detailed measurements of this variable are not possible in field data collection. We therefore used the average of the ratios obtained empirically under the different conditions of stove use to represent the relationship between the exposure microenvironments. Using this method, the ratios of PM_{10} concentration in the microenvironments of Figure 3 relative to the point ($x = 0.5$, $z = 0.5$) where daily monitoring took place were 7.0–7.5 for 1, 1.0–1.1 for 2, 1.7–1.8 for 3, 1.4–1.5 for 4, 2.0–2.2 for 5, and 1.2–1.3 for 6.

Individual exposure: the role of time–activity patterns. We showed elsewhere (*15*) that stove emissions exhibit large temporal variability throughout the day, including intense peaks of short duration. For instance, in a 137-day subsample of the

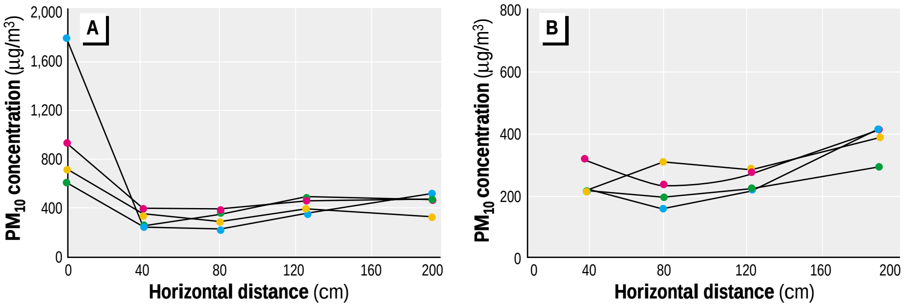

Figure 1. Spatial distribution of PM_{10} concentration. Each pair of curves at heights (*A*) 100 cm and (*B*) 50 cm shows the average of 10–15 sets of measurements for a measurement condition with combinations of window and/or door open/closed and cooking pot present/absent in the same house. Measurements took place for 1 min each at distances of 0, 0.4, 0.8, 1.25, and 1.9 m from a stable fire in two houses in the two size groups. The *y*-axis scales are different in *A* and *B* so that the curves in *B* can be distinguished from one another.

above data, emission concentrations in burning and smoldering periods of the day have average coefficients of variation of 3.2 and 4.0, respectively, indicating large daily variability around the mean (a low background level of combustion takes place throughout the whole day. For the purpose of this analysis we defined burning as the periods when the stove is used for cooking and/or it is in flame. Smoldering refers to periods that the stove is neither in active use nor in flame) (*15*). Our quantitative and qualitative data on time–activity budgets also indicate that some household members are consistently closest to the fire when pollution level is the highest. These episodes typically occur when fuel is added or moved, the stove is lit, the cooking pot is placed on or removed from the fire, or food is stirred (Figures 2 and 4). One of the most common foods in East Africa, particularly in rural areas, is ugali. Ugali is a porridge made from maize or sorghum flour thickened into a cake. After adding flour to boiling water, the cook continuously stirs the mixture. As water evaporates and the mixture hardens, stirring becomes increasingly vigorous and finally turns into folding the hardened dough. Throughout the process heat is controlled by increasing the burning rate or decreasing it into a smoldering (and hence very smoky) phase as stirring continues. After the water comes to boil and flour is added, the process takes 15–40 min, during which the cook is very close to the fire, actively controlling the heat or mixing of the flour and stirring.

Other individuals may be systematically outside or away from the house during some of these episodes, especially during the hours when the fire is lit or extinguished. This observation indicates that average daily concentration alone is not a sufficient measure of exposure. Therefore in addition to mean concentration (m), we used two descriptive statistics for the burning and smoldering phases:

- Mean above the 75th percentile ($m_{>75}$): we used this statistic for the household members who are closest to the stove during high-pollution episodes caused by cooking activities
- Mean below the 95th percentile ($m_{<95}$): we used this statistic to eliminate the effect of large instantaneous peaks that occur, especially when lighting or extinguishing the fire or when fuel is added.

Individual exposure: day-to-day variability. In addition to daily variations, we can expect day-to-day variability in exposure to indoor smoke as a result of variation in both emissions and time–activity budget. Emissions in a single household can vary from day to day because of fuel characteristics such as moisture content or density, air flow, type of food cooked, or whether the household uses multiple stoves or fuels. In the above data, for example, the fraction of variance of average burning-period emission concentrations (m) explained by interhousehold variation is 6.5 times the fraction explained by day-to-day variability (R^2 = 0.79). (The ratio, obtained by sequential analysis of variance, is for the fraction of variances explained by each variable alone.) The corresponding ratio for $m_{<95}$ equals 9.0 ($m_{<95}$ is less sensitive to instantaneous peaks; R^2 = 0.77). This comparison illustrates that, although considerably smaller than interhousehold variation, emissions in individual households vary from day to day. We found no indication of systematic seasonal variation in emissions in our study area, which we attribute to the fact that drying wood before use is a common practice among the households in the study group (in all of measurements the firewood used was dry). Activity patterns can also vary because of the seasonal nature of work and school, illness, market days, and so on. Therefore, in addition to use of multiple descriptive statistics for characterizing daily exposure, we constructed measures of exposure that are not solely based on measurements from a single day.

Specifically, rather than using measurements of emission concentration directly, we assigned households to pollution concentration categories. We performed this categorization for the three descriptive statistics (m, $m_{<95}$, and $m_{>75}$) for both the burning and

Figure 2. There is considerably higher smoke directly above the fire before dispersion in the room.

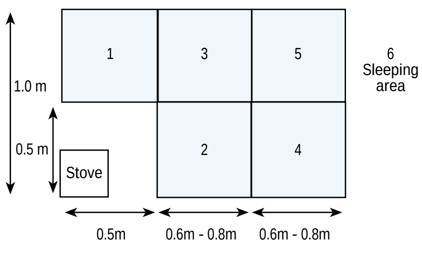

Figure 3. Schematic representation of indoor exposure microenvironments in the study houses. The divisions are based on incremental distances from the stove, where various activities take place. A division of mud or plastic separates the sleeping area (no. 6) from the rest of the house but the division is not complete (there is an open entrance).

Figure 4. Household members involved in cooking are exposed to episodes of high pollution level when they work directly above the fire. See Figure 2 for another example.

smoldering phases. We grouped time and activity budgets in a similar manner (including time spent inside near the fire and inside during cooking and whether the person cooks regularly/sometimes/never and whether the person performs noncooking household tasks regularly/sometimes/never) using the data from the 210 days of direct observation as well as the supplemental interviews.

The width of the concentration and time categories (i.e., bin size) were smaller in lower ranges to account for larger variability at higher values. Adjacent concentration and time categories were also overlapping to account for gradual transitions. For example, concentration categories for mean PM_{10} (m) during the burning period were < 200; 200–1,000; 500–2,000; 1,000–3,000; 2,000–5,000; 3,000–7,000; and 4,000–10,000 µg/m^3. The concentration categories for $m_{<95}$ were < 150; 100–300; 250–1,000; and 500–2,000 µg/m^3; the remaining categories were the same as those for m. The concentration categories for $m_{>75}$ were < 500; 300–1,000; 500–2,000; 1,000–5,000; 2,000–10,000; 4,000–20,000; 6,000–30,000; and 10,000–50,000 µg/m^3. The categories for smoldering period were only slightly different. The groups for time inside the house, as a fraction of the day, were < 0.2, 0.2–0.35, 0.3–0.45, 0.45–0.65, and > 0.6; these groups for time spent near fire were < 0.05, 0.05 – 0.1, 0.1 – 0.2, 0.2 – 0.4, and > 0.4.

Households that use multiple stoves or fuels span multiple categories. Further, those households that sometimes cook outside were assigned to two distinct categories, one for each cooking location. The time budget of individuals in the latter group of households is also divided between the two locations accordingly. Table 4 provides a summary of the time spent inside the house and near the fire in demographic groups divided by sex and age, which is similar to the findings of Saksena et al. (*19*) on male and female time budgets.

Exposure profiles as the basis of analysis. We constructed profiles of exposure for each individual in the monitored households based on the combination of time–activity budgets, spatial dispersion, and daily and day-to-day exposure variability. We divided the time budget of household members into the following activities: cooking, noncooking household tasks, warming around the stove, playing, resting and eating, and sleeping. We also considered the set of potential locations where each activity takes place. For example, playing or resting may take place inside the house or outside, cooking activities directly above the fire or slightly farther away, and so on. The activity groups and their related parameters are described in Table 5. We then obtained daily exposure using the following relationship:

$$E = \sum_{i=1}^{n} \sum_{j=1}^{6} w_j t_{ij} c_i \qquad [1]$$

where c_i is the emission concentration in the i^{th} period of the day, t_{ij} is the time spent in the j^{th} microenvironment in the i^{th} period, and w_j is the conversion (or dilution) factor for the j^{th} microenvironment, which converts the emission concentration measurements (at point $x = 0.5$, $z = 0.5$) to concentration at the j^{th} microenvironment using the spatial dispersion analysis described above.

Figure 5 illustrates the average exposure concentration (defined as the PM_{10} concentration that if sustained for the whole day would result in exposure equal to the total daily exposure of the individual) for total daily exposure for various demographic groups. We obtained these values by using Equation 1 and dividing time budgets among the possible location–activity pairs during both burning and smoldering periods (defined in Table 5) based on interviews, direct observation, and demographic characteristics of the household. In Figure 6 we decompose these values into exposure during high-intensity (i.e., when pollution is described by $m_{>75}$) and low-intensity episodes, respectively. Finally, in Figure 7 we compare these values with the average exposure concentration values obtained using only average emissions at a single point and time spent inside (i.e., without taking into account either the spatial distribution of pollution or the role of activity patterns on exposure).

The results in Figures 5–7 illustrate several points. First, in the exposure profile approach, the ratio of female to male total exposure is 0.91, 2.5, 4.8, and 1.2 for the four age groups. Therefore, young and adult women not only have the highest absolute exposure to particulate matter from biomass combustion (2,795 and 4,898 µg/m^3 average exposure concentrations, respectively), but

Table 4. Time–activity budget for demographic subgroups after assignment to time categories.

	Fraction of time inside[a]		Fraction of time near fire[b]		Probability of cooking[c]	
Age group	Female	Male	Female	Male	Female	Male
0–5 years	0.43	0.44	0.20	0.20	0	0
6–15 years	0.40*	0.26*	0.23*	0.13*	0.39*	0.02*
16–50 years	0.54*	0.24*	0.38*	0.06*	0.98*	0.11*
> 50 years	0.39	0.30	0.24	0.13	0.27	0.19
Total	0.45*	0.30*	0.27*	0.13*	0.48*	0.06*

The results are based on the midvalues for each category. In practice, the amount of time spent inside on different days is from a distribution around this midvalue.
[a]Fraction of time is based on a 14-hr day from 0630 to 2030. [b]Fraction of time is based on a 14-hr day from 0630 to 2030. Near fire refers to areas within a radius of approximately 1 m of the stove. [c]Average within the group, with a probability of 1 assigned to those who cook regularly, 0.5 to those who sometimes cook or look after the fire, and 0 to those who do not perform cooking and energy related tasks. *Difference between male and female rates significant with $p < 0.0001$.

Table 5. Activity groups inside the house, their location described by the microenvironments in Figure 3, and the descriptive statistics used to characterize emissions concentration while they occur.

Activity group	Examples	Location (microenvironment)	Emissions concentration[a]
Cooking 1	Lighting and tending fire; stirring food	1	Burning: $m_{>75}$
Cooking 2	Cutting and cleaning food items	3	Burning: m
Noncooking work	Cleaning utensils; serving food; cleaning the house	3 and 5	Burning: m Smoldering: $m_{>75}$[b]
Warming	Not applicable	2 and 3	Burning: m
Resting/eating 1 (females and children)	Not applicable	4 and 5	Burning: m Smoldering: m
Resting/eating 2 (adult males)	Not applicable	5	Burning: m[c] Smoldering: m
Playing (children)	Not applicable	3 and 5	Burning: m Smoldering: m
Playing (infants)	Not applicable	6	Burning: m Smoldering: m
Sleeping	Not applicable	6	Smoldering: $m_{<95}$[d]

Dilution factors for the microenvironments are given in "Individual Exposure: The Role of Spatial Distribution of Pollution." NA, not applicable.
[a]Cooking and warming over fire can take place only during burning. Other activities can in principle take place in both burning and smoldering, although the stove does not remain on at night while residents are sleeping. [b]Noncooking household tasks that take place during the smoldering phase often occur immediately before the fire is lit or after it is extinguished, during the upper end of emission concentrations. [c]For adult males, an alternative exposure profile would consider that they are systematically away when pollution is highest, especially during lighting and extinguishing. With this characterization, their exposure concentrations would be based on $m_{<95}$ instead of m. This choice has little effect on the outcome because adult males spend only a small fraction of the day indoors and because they are consistently away from the fire, where dilution reduces concentration the most. [d]Because wood is rarely added or moved during the night but background combustion continues, pollution is described by the smoldering period concentration without its most polluted moments.

also the largest exposure relative to that of males in the same age group. Second, the ratios of high-intensity exposure to total exposure for the four age groups are 0, 0.40, 0.61, and 0.31 for females and 0, 0.02, 0.11, and 0.08 for males. The larger value for young and adult women illustrates that high-intensity episodes account for a considerably larger fraction of exposure of those household members who are closest to fire at such times (and also much larger in absolute values because female exposure has larger base values). In terms of the relative contributions of cooking and living microenvironments, these results are consistent with those of Saksena et al. (*19*), who used direct monitoring of concentration in different microenvironments in the Indian Himalayas rather than a spatial model. The differences between the two studies include different housing characteristics, potentially different activity patterns for some demographic subgroups, and the use of average concentration versus multiple descriptive statistics for characterizing pollution. The combined effect of these factors seems not to influence the overall exposure distributions. However, each is important and should be considered in any study of exposure to indoor smoke. Third, the ratios of exposure estimates using average emissions at a single point (i.e., Figure 7) to those using the exposure profile approach (i.e., Figure 5) for the four age groups are 0.97, 0.44, 0.29, and 0.51 for females and 0.97, 0.91, 0.83, and 0.79 for males. The large variation of this ratio among the demographic groups indicates that ignoring the spatial distribution of pollution and the role of activity patterns on exposure could not only result in inaccurate estimates of exposure but also—and possibly more importantly—could bias the relative exposure levels for different demographic groups. The exposure of women who cook, and who therefore are most affected by high-intensity pollution episodes, would be underestimated most severely by using average pollution alone. This would in turn result in systematic bias in assessment of the health impacts of exposure and benefits from any intervention strategy.

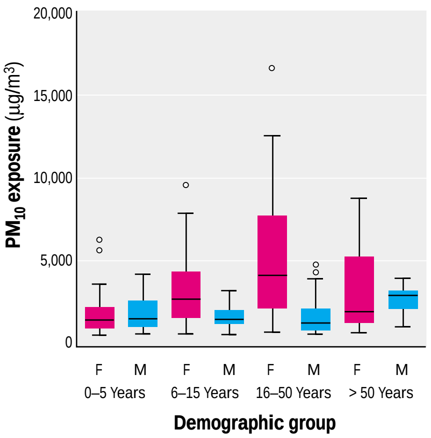

Figure 5. Average exposure concentration for total daily exposure to PM_{10} obtained using the exposure profile approach. Abbreviations: f, female; m, male; *n*, the number of individuals in the demographic subgroup; µ, the sample mean; σ, SD. The average exposure concentration is the PM_{10} concentration that, if sustained for the whole (24-hr) day, would result in exposure equal to total daily exposure of the individual. Exposure concentrations are obtained using the midpoint values of emission concentration and time categories. Lower and upper bounds on the exposure range for each individual can be found by using the lower and upper values of emissions and time budget simultaneously (estimates not reported). Statistics by demographic group are as follows: for 0–5 years of age $n = 52$, µ = 1,317, σ = 1,188 (female) and $n = 41$, µ = 1,449, σ = 1,067 (male); for 6–15 years of age $n = 61$, µ = 2,795*, σ = 2,069 (female) and $n = 48$, µ = 1,128*, σ = 638 (male); for 16–50 years of age $n = 65$, µ = 4,898*, σ = 3,663 (female) and $n = 55$, µ = 1,018*, σ = 984 (male); for > 50 years of age $n = 15$, µ = 2,639, σ = 2,501 (female) and $n = 8$, µ = 2,169, σ = 977 (male).

*The difference between male and female values is significant with $p < 0.0001$.

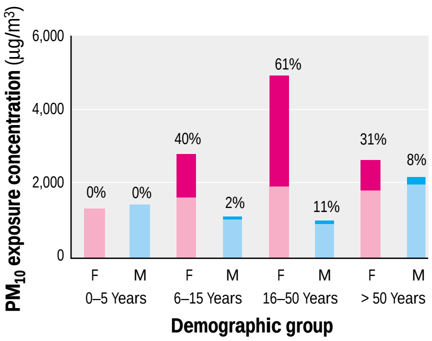

Figure 6. Breakdown of total daily exposure to PM_{10} (i.e., Figure 5) into high-intensity (darker shade) and low-intensity (lighter shade) exposure. For each demographic group the total height of the column is the group average from Figure 5 divided into group average for high- and low-intensity components. The percentages indicate the share of total exposure from high-intensity exposure. The high-intensity component of exposure occurs in less than 1 hr, emphasizing the intensity of exposure in these episodes.

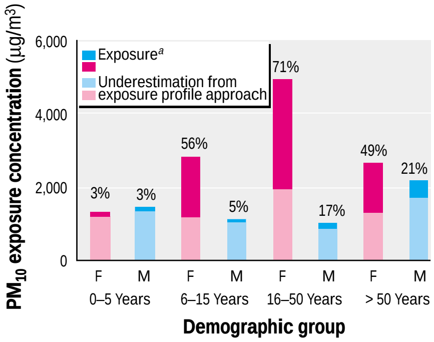

Figure 7. Comparison of exposure values using the exposure profile approach (i.e., Figure 5) to those using average emissions at a single point and time spent inside (without accounting for spatial dispersion and activity). For each demographic group the height of the column is the group average from Figure 5. The lighter shade is exposure calculated using average emissions at a single point. Therefore, the darker shade is the underestimation of exposure using this method relative to the exposure profile approach, also shown as a percentage.

[a]Calculated using average emissions at one point.

Conclusions

We used continuous PM_{10} monitoring, data on spatial dispersion of indoor smoke, and detailed quantitative and qualitative data on time–activity budget to construct measures of exposure to indoor particulate matter that take into consideration individual patterns of exposure, including daily and day-to-day variability. The inclusion of these factors beyond the commonly used single measure of average pollution level illustrates that average pollution concentration alone is not a sufficient measure of human exposure in situations where a large fraction of exposure occurs during high-intensity emission episodes, such as the case for individuals responsible for cooking using biomass stoves. Therefore, in designing intervention schemes such as new stove technology, worst-scenario emissions—such as emissions during lighting, extinguishing, or moving of fuel—should receive as much attention as average emission levels (*15*). Further, our results indicate the importance of detailed exposure assessment in quantifying the exposure–response relationship for indoor particulate matter that exhibits such episodic characteristics. Finally, the role of high-intensity exposure raises a research question about inhalation and pulmonary deposition of particulate matter under different exposure circumstances. Important recent work has shed new light on the dispersion of aerosol bolus in human airways (*26*). New research that integrates modeling, laboratory testing, and field trials is needed to consider dispersion, deposition, and health impacts as a function of pollution intensity.

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