Estimating personal PM2.5 exposures using CO measurements in Guatemalan households cooking with wood fuel

Amanda Northcross, a Zohir Chowdhury, b John McCracken, a,c Eduardo Canuz c and Kirk R. Smith * d

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As a part of a longitudinal study in the highlands of Guatemala to elicit the chronic health effects of wood smoke from cooking, mean area and personal 48 h concentrations of 2.5 µm particulate matter (PM2.5) and carbon monoxide (CO) were measured every 3 months over 19 months. Monitoring was conducted in 63 households, 28 using traditional open wood fires and 35 using wood cookstoves with chimneys. The goal of this paper is to estimate personal exposure concentrations to PM2.5 using the measurements from CO diffusion tubes as a proxy. CO tubes are cheaper and easier to use than PM-monitoring devices, and can be worn by all family members, even infants. The relationship of PM2.5 and CO was determined by comparing measurements from both co-located instruments. CO measurements in ppm were corrected for temperature and pressure to mass concentrations. PM2.5 exposure was modeled with the following linear regression created using measured concentrations:

$$\text{PM2.5 (mg m}^{-3}) = 0.10 \ (0.093, 0.12) \times \text{CO (mg m}^{-3}) + 0.067 \ (0.0069, 0.13), \ R^2 = 0.76.$$  

No significant difference was found between the separate regressions for open fires and cookstoves. No significant improvement was obtained by applying a mixed statistical model. The equation was used to estimate personal exposures of PM2.5 using personal CO measurements from CO tubes worn by women, infants under 18 months, and children 48–72 months. Estimated 48 h mean personal PM2.5 concentrations for mother, infants, and children in open-fire homes were 0.27 ± 0.02, 0.20 ± 0.02, and 0.16 ± 0.02 mg m^{-3} respectively. In chimney-stove homes, mothers and children experienced PM2.5 personal concentrations of 0.22 ± 0.03 and 0.14 ± 0.03 mg m^{-3}, respectively.

Introduction

In the developing world, open fires and inefficient stoves using biomass fuels are the primary methods of cooking. Large numbers of people are exposed to high concentrations of smoke containing primarily incomplete combustion products dominated by carbon monoxide (CO) as well as a wide range of toxic organic compounds, which are present in both the gas and particle phases.\textsuperscript{1–3} The particle phase is primarily less than 2.5 µm in aerodynamic diameter (PM2.5).\textsuperscript{4,5} The health implications of such large daily exposures to toxic gases and particulates have been estimated to be responsible for as many as 1.6 million premature deaths per year worldwide.\textsuperscript{9}

Although PM2.5 is likely to be the pollutant in biomass smoke most closely associated with many respiratory effects, PM2.5 exposures are not easily measured in these settings. The traditional methods to have a person carry pump and filter sampling equipment or a small continuous aerosol measuring device are expensive, intrusive, and logistically complicated, as well as impossible to use with infants or small children. CO, the main constituent of biomass smoke by mass, on the other hand, is relatively easy to measure using inexpensive electro-chemical monitors and small passive diffusion tubes, which are fairly simple to deploy and reasonably inexpensive.\textsuperscript{10}

Environmental impact

Biomass smoke from indoor cooking in the developing world is a major public health concern and an environmental pollutant. Worldwide NGOs and governments are challenged to reduce exposures to smoke from indoor cooking. Exposure assessment to support population based sampling for epidemiological health studies is imperative to clarify the magnitude of the problem and to quantify intervention effectiveness. Presently assessing personal exposure to PM2.5 associated with wood smoke is labor intensive, expensive and not currently possible for babies and small children. The use of CO as a proxy for PM2.5 in wood smoke is verified here. CO is cheaper, and easier to measure than PM2.5 making population based personal exposure assessment feasible for children and babies, and broadening the ability it assess stove intervention projects.
Being an important health-damaging pollutant for non-respiratory outcomes, CO measurements are important in their own right, but here we examine their use as an indicator of PM in settings using wood fuels. Using one pollutant as an indicator has a long tradition in exposure and health studies of complex mixtures. For example nitrogen oxides are commonly measured as a proxy for traffic pollution,\textsuperscript{11,12} and nicotine has been used as a tracer for cigarette smoke.\textsuperscript{13}

The data for this study were collected during the Chronic Respiratory Effects of early Childhood Exposure to Respirable particulate matter (CRECER) study, which is following a cohort of children in highland Guatemala to document the development of chronic respiratory diseases and associated physiological effects. Most of these children were part of earlier RESPIRE (Randomized Exposure Study of Pollution Indoors and Respiratory Effects), the first randomized controlled trial of air pollution.\textsuperscript{14–16} RESPIRE randomly introduced wood-burning chimney cookstoves into communities using open wood fires for cooking. All homes involved in the CRECER study now have a chimney cookstove, although 158 newly recruited open-fire homes were recruited into the cohort to increase the sample size.

Pilot measurements made before RESPIRE showed that CO can be used as an indicator for PM\textsubscript{2.5} emitted from wood smoke when wood is the primary fuel used, as is the case in our study homes.\textsuperscript{17} The study reported here presents a refined version of the Naeher model, which predicts PM\textsubscript{2.5} concentrations as a function of measured CO. This new model benefits from a much larger sample size and greater concentration range and includes corrections for temperature and elevation (pressure) differences. The improved model can be used to more accurately estimate PM\textsubscript{2.5} personal exposures from personal CO concentrations in settings where a single fuel and combustion situation dominates smoke emissions.

Although the CO : PM ratio varies substantially during the burn cycle of wood fires, the use of 48 h averaging times, which normally contain 6 or more burn cycles (cooking periods), seems to provide a reasonably stable ratio that then can be confidently combined with personal CO measurements to estimate personal exposures to PM\textsubscript{2.5}. Importantly, however, this is likely to work best only in settings like ours in which there is essentially only one local source of air pollution as other combustion sources would have different CO : PM ratios. Similarly, the mass ratio we found, 10 to 1, may vary in settings with different fuel and combustion conditions.

**Materials and methods**

All measurements presented in this paper were made between May 2006 and December 2007 in households in 23 indigenous communities in the highlands (2200–3000 m) of San Marcos, Guatemala, who speak Mam as their primary language. The exposure data are from a random subset of 63 of the total 533 homes in the CRECER study. The measurements were made in rural kitchens using either traditional open wood fires, or chimney woodstoves for cooking (Fig. 1A and B).

The chimney stoves had an enclosed combustion chamber connected to chimney that directed smoke outside of the home. The open-fire kitchens were newly added homes to the study and were awaiting the construction of their chimney stove for participation in the CRECER study. 35 homes had chimney cookstoves and 28 used open fires. These homes underwent “intensive” indoor air pollution (IAP) monitoring as well as personal CO monitoring. Intensive monitoring required continuous and cumulative measurements of CO and PM\textsubscript{2.5}, for 48 h every 3 months. A detailed oral survey was administered to the mothers in their native Mam language. Protocols for the inclusion of human subjects and informed consent procedures were approved by the Committees for Protection of Human Subjects at the University of California, Berkeley and Universidad del Valle, Guatemala.

**Household information**

A preliminary assessment of each home was performed to measure, inter alia, components of the kitchen including windows, the stove or open fire, doors, roof type, and any major holes in the structure. In addition a short survey was administered each time a home was monitored to determine whether sources of pollution other than the stove were in use such as tobacco smoking, problems and changes to monitoring equipment, and out of the ordinary behavior. The survey allowed us to remove outliers from the dataset when issues arose. The survey also included questions concerning the number of people living and eating in the home. Global positioning system (GPS) coordinates including elevation were also collected for each home.

**PM\textsubscript{2.5} measurements**

Integrated PM\textsubscript{2.5} measurements were taken with gravimetric methods using an SKC Universal PCXR8 Air Sampling Pump with 2.0 μm pore Teflon 37 mm filters (Pall) backed with cellulose support pads. The filter and pad were housed in an acrylic filter cassette (Sure Seal) and were connected in series with a BGI personal cyclone. The flow rate was 1.5 L min\textsuperscript{−1} providing a particle cut point of PM\textsubscript{2.5}. The pump sampled intermittently one out of every 5 min to extend the battery life for the full 48 h. Duplicate samples, as well as field and laboratory blanks were used for quality control. The pump flow rate was measured at 0, 24 and 48 h using a calibrated Matheson Tri Gas (Parsippany, New Jersey) rotometer. Only samples taken for 48 (±1) h are presented. Pre- and post-filter weights were measured at the UC Berkeley indoor air pollution research facility on a Mettler Toledo Microbalance (MT-5, SN 1118413759) in a temperature (65 ± 5 °C) and humidity (40 ± 3%) controlled room.

Continuous PM measurements were made using the University of California Berkeley (UCB) particle monitor.\textsuperscript{18,19} The UCB PATS (particle and temperature monitoring system) is a data...
logging optical particle monitor based on commercial smoke alarm technology, which passively measures PM2.5 concentration calculated based on Mie scattering theory. In addition to the aerosol concentration, the UCB PATS records relative humidity (\%RH) and temperature (T) at a 1 min time resolution. The PM data are not presented here, but the mean 48 h temperatures were used in the calculations. The UCB PATS along with the other monitoring equipment was placed on the wall of the kitchen at 100 cm from the combustion zone of the stove or open fire, 145 cm above the floor, and 150 cm from any open door or windows when possible.

**Carbon monoxide measurements**

**Continuous.** Continuous CO measurements were taken using the HOBO (Onset, Pocasset, MA), a data logging monitor with an electro-chemical sensor. The manufacturer reports an accuracy of ±6 ppm in the ranges measured, but we achieved greater accuracy through regular comparison with a calibration gas.\(^{16}\) Each HOBO was tested monthly at the field office using a 49.8 ± 2% ppm calibration gas (AIRGAS, Theodore, AL). A two-point (0 ppm and 49.8 ppm) calibration curve was used to correct the reported data. The HOBOs were deployed to sample for 48 h with samples taken every 30 s. The IAP engineer returned to the study homes after 24 h (mid-point in monitoring period) to ensure the HOBO and all other equipment were operating properly. HOBOs were placed in kitchens and also carried by mothers in a small cloth bag to measure CO concentrations.

**Integrated.** Integrated CO measurements were taken using Dräger Safety (Luebeck, Germany) passive diffusion tubes. Care was taken to ensure the tubes were produced from only 3 manufacturing lots to reduce variability in the sensitivities across lots. The tubes were collocated with the HOBO, UCB, and gravimetric monitoring equipment in the kitchens. Mothers wore tubes in the small loosely woven bag that also held a HOBO. Children and infants wore a CO tube placed in a small bag that was pinned to their upper back and shoulder. The small cloth bags were tested to ensure they did not impede CO diffusion and reduce reported concentrations.\(^{16}\) Children were 4–5 years of age and lived in both open fire and plancha homes. The infants were the younger sibling of the children in the open-fire homes and less than 18 months of age. The passive diffusion tubes operate by changing color as CO diffused through the tube. The length of the color stain and the amount of time the tube is exposed to the air are used to determine the cumulative CO concentration and the 48 h mean personal CO concentrations. At the end of each sampling period an air tight plastic cap was placed over the open end of the tube. The times when the tube was opened and capped were recorded and used to convert ppm hours to mean ppm. The tubes were stored in airtight containers in a refrigerator in the field office until the CO stain in the tube was recorded.

A consistent and unbiased reading of each tube was essential for an accurate CO concentration. Tubes were read within 2 days of sampling. Two independent readers read each tube under standard conditions using a sunlight spectra lamp. Both readers re-read tubes when the reported values were more than 10% apart from each other. A third reader was used if the second reading reported a value of more than 10% apart. CO tube data used were corrected using the HOBOs as these instruments were regularly compared with a calibration gas. A correction factor was determined as the ratio of the kitchen HOBO and kitchen CO tube measurements and then applied to all the tube measurements made in the same home. The methods used are similar to those reported in ref. 10.

Both PM2.5 and CO concentrations are reported in values of mg m\(^{-3}\). The CO values reported in ppm from other studies referenced in this paper were converted from ppm to mg m\(^{-3}\) using a value of 1.15 (mg m\(^{-3}\)) per ppm, assuming a temperature of 25 °C, pressure of 1 atm and a molecular weight of 28.01 g mol\(^{-1}\) for CO.

**Results**

Table 1 contains the 48 h averages of each stove type from concentrations measured in kitchens and on study participants. The personal concentrations include CO measured for mothers, infants, and children. Carbon monoxide values were measured in terms of ppm, and converted to mass concentration. The unit conversion from ppm to mg m\(^{-3}\) accounted for the lower than sea-level ambient air pressure due to the high altitude of the study site.\(^{20}\) Temperature was corrected using mean 48 h temperature measured from the UCB PATS in each home during each study period.

**PM : CO linear regression**

The relationship between the kitchen concentrations of CO and PM2.5 is quantified using linear regression. The resulting regression equation is then used to estimate personal PM2.5 concentrations using personal CO measurements. The approach requires two key assumptions: (1) sampling over a 48 h period averages out the variations in the ratio of PM2.5 to CO that result because of changes in emission over the burn cycle of a fire and (2) wood smoke accounts for the overwhelming majority of the PM2.5 and CO concentrations locally and personally. The use of additional fuels was investigated in the monitoring surveys and it was reported that other fuels are used sparingly in the area.

The difference between the 48 h mean concentrations of CO and PM2.5 in open-fire and chimney-stove kitchens is attributed mainly to the chimney venting the smoke from the fire to the outdoors. In addition, however, the combustion properties of the

| Table 1 | Median 48 h IAP measurements averaged by stove type. PM2.5 measured using gravimetric methods. CO tube measured with passive diffusion tubes. CO HOBO measured using continuous passive electro-chemical sensor. The reduction of CO and PM2.5 concentrations from open-fire to chimney-stove homes is reported as % improvement |
| --- | --- | --- | --- |
| Measurement location | Open fire | Chimney stove | Improvement (%) |
| N | Mean \(\mu\)g m\(^{-3}\) SD | N | Mean \(\mu\)g m\(^{-3}\) SD |
| Kitchen PM2.5 | 138 0.90 | 0.70 138 0.34 | 0.49 62 |
| Kitchen CO tube | 130 7.24 | 6.16 123 2.50 | 4.41 66 |
| Kitchen CO HOBO | 145 7.73 | 5.83 163 2.81 | 4.65 64 |
| Mother CO tube | 130 2.08 | 1.52 123 1.35 | 1.45 35 |
| Mother CO HOBO | 128 2.19 | 1.58 118 1.25 | 1.69 38 |
| Child CO tube | 128 0.93 | 0.57 124 0.73 | 0.58 22 |
| Infant CO tube | 98 1.31 | 0.65 | |
two types of fires may cause different ratios of PM2.5 and CO to be emitted. Naeher et al.\textsuperscript{17} reported differences in the Spearman correlation coefficient ($R$) for CO and PM in open-fire and chimney-stove homes. We thus investigated the regression coefficients of each cooking type individually to determine if separate equations are appropriate to estimate personal exposures for people living in homes with each type of stove.

Linear regression of the open-fire data ($n = 122$) produced eqn (1), with the 95% confidence interval of the regression coefficient and intercept expressed in parentheses. The regression coefficient and the intercept were both statistically significant with $p$ values of $<0.001$. The measured concentrations from kitchens with the chimney stove ($n = 110$) produced eqn (2), which is not significantly different from eqn (1). Eqn (3) includes data from both open-fire and chimney-stove homes as shown in Fig. 2.

\[
\text{PM2.5}_{OF} \text{ (mg m}^{-3}\text{)} = 0.10(0.093, 0.12) \times \text{CO}_{OF} \text{ (mg m}^{-3}\text{)} + 0.057(-0.068, 0.13), \quad R^2 = 0.73 \tag{1}
\]

\[
\text{PM2.5}_{STV} \text{ (mg m}^{-3}\text{)} = 0.94(0.084, 0.10) \times \text{CO}_{STV} \text{ (mg m}^{-3}\text{)} + 0.075(0.021, 0.20), \quad R^2 = 0.78 \tag{2}
\]

\[
\text{PM2.5} \text{ (mg m}^{-3}\text{)} = 0.10(0.093, 0.12) \times \text{CO} \text{ (mg m}^{-3}\text{)} + 0.067(0.0069, 0.13), \quad R^2 = 0.76 \tag{3}
\]

Using eqn (3), personal exposures of mothers, children, and infants were estimated from the personal CO tube exposures. Separating the data by stove type does not produce statistically significant differences in the regression equation, suggesting that stove type does not affect the regression equation, thus eqn (3) is used in the remainder of this study.

Beyond a simple linear regression model we also investigated the use of mixed models to evaluate the variables with significant effects on the ratio of CO : PM. The mixed effect statistical model estimated the fixed effects of carbon monoxide and other covariates on the prediction of PM. It also included the random effects and the covariance between and within households in the estimation of PM. We found no major change in the ratio or improvement in the regression coefficients. We also found that the concentration differences of CO and PM2.5 in the kitchens with different types of stoves made it difficult to determine whether the ratio of PM2.5 to CO differs by stove type.

**Personal PM2.5 estimates.** The mean 48 h estimated personal PM2.5 concentration estimates for mothers, children, and infants and the 95% confidence intervals in parentheses are listed in Table 2. As expected, Table 2 shows that the mothers are exposed to the highest concentrations of PM2.5, followed by the infants and then the children.

The mothers are responsible for cooking, exposing them more directly to the emissions of the fire. The Spearman correlation coefficients of mothers and their infants ($R = 0.73$) or their child ($R = 0.69$) in the open-fire homes and $R = 0.89$ for children in chimney-stove homes all with $p$ values of $<0.001$, show the intensity of association observed between the mother and her children for exposure to PM2.5. The exposure of children in homes with chimney stoves is more strongly associated to the mother’s exposure than children in homes with open fires. This could be a behavioral difference, where children in homes with stoves are more likely to be in the kitchen when the mother is cooking than children in homes with open fires. This reveals a possibly interesting change in behavior as a result of the stove intervention which should be further investigated.

Fig. 3 shows the estimated PM2.5 personal concentrations for the mothers using eqn (3) plotted against the 48 h mean kitchen concentration measured using the gravimetric pump and filter method. The solid black line represents the 1 : 1 line, or the line at which the personal and kitchen concentrations are the same. Data points which fall above the black line are estimated PM2.5 concentrations.

![Fig. 2](image1.png) **Fig. 2** Mean 48 h gravimetric concentrations versus mean 48 h CO concentrations measured with CO diffusion tubes for open-fire and chimney-stove kitchens. $N = 220$.

![Fig. 3](image2.png) **Fig. 3** Mean PM2.5 gravimetric 48 h kitchen concentrations versus estimated 48 h mean mother PM2.5 concentrations.

<table>
<thead>
<tr>
<th></th>
<th>Mean 48 h estimated PM2.5/mg m$^{-3}$ (95% CL)</th>
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<tbody>
<tr>
<td></td>
<td>Open fire</td>
</tr>
<tr>
<td>Mother</td>
<td>0.27 (0.25, 0.29)</td>
</tr>
<tr>
<td>Child</td>
<td>0.16 (0.15, 0.17)</td>
</tr>
<tr>
<td>Infant</td>
<td>0.20 (0.19, 0.21)</td>
</tr>
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Table 2 Personal PM2.5 estimated concentrations (eqn (3)) for mothers, children and infants grouped by stove type
mother concentrations that are smaller than the measured kitchen concentrations.

Discussion

As expected, the personal CO exposures measured in the open-fire homes in Table 1 are significantly higher than chimney-stove homes for the mothers (p < 0.001) and children (p = 0.0032). Personal CO exposures for infants were only measured in open-fire homes. The means from the CO tubes for the mothers in open-fire and chimney-stove homes respectively [2.08, SD 1.52; 1.35, SD 1.45] are the highest, followed by the infants [1.31 ± 0.65] and then the children [0.93, SD 0.57, 0.73 SD 0.58]. The mothers are expected to spend the most time in the kitchen cooking when PM and CO concentrations are the highest. The infants are often but not always carried on their mother’s back also exposing them to high concentrations. The children are able to run and play, do chores and possibly even attend school, keeping them out of the kitchens at times when CO and PM concentrations are the highest.

The reported kitchen concentrations of both CO and PM2.5 are lower and statistically significant (p < 0.001) in the homes with chimney cookstoves compared to the open-fire homes, similar to what was found in the RESPIRE study.\(^\text{16}\) However, the level of improvement of area concentrations is not as great as found in RESPIRE which achieved a 90% reduction in CO and PM concentrations. The difference in the level of smoke reduction can be explained by differences in the designs and timings of the two studies. The goal of RESPIRE, an efficacy study, was to create two distinctly different exposure groups, thus great care was taken to ensure the chimney stove was properly and continually used throughout the study. Weekly home visits were conducted compared to quarterly visits in CRECER. The measured reduction to smoke exposures was not as great during the follow-on non-randomized study (CRECER), nevertheless the chimney reduced exposures to PM2.5 and CO in both studies. The lower mean concentrations of pollutants in the kitchens with chimney stoves support the findings that exposure to biomass smoke is reduced with the installation of an chimney cookstove, and may also indicate some deterioration in effect after several years of stove use.

### PM : CO linear regression

The major difference between the open-fire and chimney-stove regression models is the intercept. If the intercept is assumed to represent the concentration of PM2.5 when CO is less than the limit of detection for CO, then the minimum PM2.5 concentration would be 0.057 mg m\(^{-3}\) using the linear regression for the open-fire homes. The confidence intervals of the intercept estimate a range of −0.068 mg m\(^{-3}\) to 0.130 mg m\(^{-3}\), exposing the error present in the estimate. The error in the intercept estimation is the most likely caused by range of the measured data. The first through third quartiles for the PM2.5 and CO\(_{\text{kitchen}}\) were 1.33–0.40 mg m\(^{-3}\) and 9.84–3.34 mg m\(^{-3}\) for the open-fire data respectively, none of the reported concentrations was at or less than the limit of detection, and the majority of the measurements were much larger than the limits of detection. In the chimney-stove homes the range of the confidence limits of the intercept is almost half of the value for the open-fire homes and the range of the PM2.5 and CO data from the first through the third quartile is 0.37–0.085 mg m\(^{-3}\) and 3.60–0.27 mg m\(^{-3}\) respectively. These values are much lower than the values for open-fire kitchens. The open-fire homes have high concentrations of smoke due to lack of adequate ventilation or a chimney. This makes it difficult to model low concentrations using data from open-fire kitchens, as this situation does not occur.

The difference between the ratio of CO and PM2.5 in the emissions from open fire and chimney stoves is negligible and the difference in the regression equations represents two different mean concentrations. Thus merging the data into one equation is appropriate (eqn (3)). Comparing eqn (3) to the regression equations published by Naeher et al.\(^\text{17}\) (eqn (4)) shows the slope and intercept are both smaller. However, the equation by Bruce et al.\(^\text{21}\) is quite similar to eqn (3).

\[
\text{PM2.5 (mg m}^{-3}\text{)} = 0.0667 \times \text{CO (mg m}^{-3}\text{)} + 0.0175
\]

Although the Bruce et al. equation was sampled in a similar Guatemalan community using wood fuel about 10 miles distant from our population, 3.5 μm particulates (PM3.5) were measured with \(n = 16\) chimney stove = 5, open fire = 11, where this study measured PM2.5 in 63 kitchens. The difference due to the size cuts between PM3.5 and PM2.5 is probably minimal as most wood smoke particles are smaller than PM2.5.\(^\text{5}\) The consistency of the values from eqn (3) and (5) provides some validation for this method presented. The difference in the reported slopes of eqn (3) and (4) can be attributed to particulate sampling method. Naeher et al.\(^\text{17}\) used pumps which sampled continuously for 24 h. This study and the Bruce study both used pumps set to sample 1 out of every 5 min to save battery power in the pumps. We have tested both sampling methods and found that intermittent sampling produces concentrations which are consistently larger than continuous samples taken simultaneously. This may help explain the similarity between eqn (3) and (5) and their difference from eqn (4).

### Estimation of personal PM2.5 concentrations

A comparison to personal PM2.5 exposures from indoor wood smoke in published studies confirms the estimated values in Table 2 are reasonable. Measurements made over 24 h in India\(^\text{22}\) on women cooking on open fires using wood fuel reported mean concentrations of 0.226 mg m\(^{-3}\). In Honduras 8 h mean PM2.5 concentrations for traditional stove users were 0.198 mg m\(^{-3}\) and 0.074 mg m\(^{-3}\) for chimney-stove users.\(^\text{21}\) In Guatemala at the same site as our current study, a previous study reported personal exposures of 0.264 mg m\(^{-3}\) for open-fire homes and 0.102 mg m\(^{-3}\) for chimney stoves in a group of grandmothers who were not the primary cooks.\(^\text{24}\) This study was conducted in a similar manner and supports our claim that mothers who are the cooks are exposed to the largest concentrations of wood smoke. The grandmother personal exposures are on par with the PM2.5 concentrations estimated for the children which are reasonable. Both spend more time out of the kitchens than the mother, who is usually the principal cook. Despite the differences the estimated Guatemalan measurements are close in the same order of
magnitude as measured PM2.5 concentrations made worldwide. Care should be taken when making direct comparison between measurements made in very different parts of the world as differences in home construction, wood types, and cooking practices exist. In addition difference in sampling methods may skew results.

The majority (67%) of the estimated personal PM2.5 concentrations are lower than the kitchen concentrations. The 33% of the personal concentrations that are larger than the kitchen concentrations could result because the mother was exposed to CO from a source other than the cooking fire, or being close to the fire during cooking may represent a larger portion of the personal CO concentrations. A questionnaire administered at each sampling visit attempted to determine when study participants were exposed to sources of CO other than wood smoke. One large source of exposure to CO is the chuj, a sauna like room used for bathing. Rocks are heated by an open fire on rocks in a small unvented room removed from the primary living and cooking space. The sampling protocol called for the personal monitors to be removed before entering the chuj for bathing; however, the tubes were worn during the fire building, when the exposures are the highest. Of the 33% the exposures where personal exposures were higher than kitchen concentrations, only 27% of homes used the chuj during the sampling period, and it was only slightly higher (24%) for the women with personal exposures less than the area concentrations. This suggests that CO exposure from the chuj is not responsible for personal exposure which is larger than the kitchen concentrations. CO exposures from a woman visiting an open fire in another home was also investigated, and found to have no correlation with estimated personal concentrations with values larger than measured area concentrations.

The ratio of CO to PM varies over the burn cycle of a fire. If a larger proportion of a woman’s CO exposure is represented by times when the ratio of PM : CO emitted by the fire is larger than the 48 h average PM : CO ratio, the resulting estimated PM2.5 will be larger than expected. The measurements made in this study do not allow us to test this hypothesis. This highlights one of the limitations of this measurement technique on the mothers. However, it reinforces the usefulness of monitoring CO as a proxy for PM2.5 for children and infants, who do not build or tend fires, ensuring a better average representative of PM : CO exposures.

Conclusions

The use of passive diffusion monitors to measure CO exposures in settings where the majority of CO and PM emissions is from single source is a reliable if not perfect proxy for PM2.5 exposure estimates. For large-scale epidemiology studies where measuring personal PM2.5 from wood smoke would be impossible, however, CO as a proxy is a good option. Eqn (3) can be used to estimate PM2.5 exposures using personal CO measurements in homes burning wood. Caution should be used when applying this model to CO measurements taken in other studies. At a minimum, area measurements should be compared to one of the equations presented in this paper to ensure the ratio of CO to PM2.5 is similar in other parts of the world. The models presented here do provide a good estimation of the relationship between the personal exposure of CO and PM2.5 in rural village homes in Guatemala using both traditional open-fire cooking and chimney cookstoves.

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