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Personal child and mother carbon monoxide exposures and kitchen levels: Methods and results from a randomized trial of woodfired chimney cookstoves in Guatemala (RESPIRE)

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Abstract

During the first randomized intervention trial (RESPIRE: Randomized Exposure Study of Pollution Indoors and Respiratory Effects) in air pollution epidemiology, we pioneered application of passive carbon monoxide (CO) diffusion tubes to measure long-term personal exposures to woodsmoke. Here we report on the protocols and validations of the method, trends in personal exposure for mothers and their young children, and the efficacy of the introduced improved chimney stove in reducing personal exposures and kitchen concentrations. Passive diffusion tubes originally developed for industrial hygiene applications were deployed on a quarterly basis to measure 48-hour integrated personal carbon monoxide exposures among 515 children 0–18 months of age and 532 mothers aged 15–55 years and area samples in a subsample of 77 kitchens, in households randomized into control and intervention groups. Instrument comparisons among types of passive diffusion tubes and against a continuous electrochemical CO monitor indicated that tubes responded nonlinearly to CO, and regression calibration was used to reduce this bias. Before stove introduction, the baseline arithmetic (geometric) mean 48-h child (*n*=270), mother (*n*=529) and kitchen (*n*=65) levels were, respectively, 3.4 (2.8), 3.4 (2.8) and 10.2 (8.4) p.p.m. The between-group analysis of the 3355 post-baseline measurements found CO levels to be significantly lower among the intervention group during the trial period: kitchen levels: −90%; mothers: −61%; and children: −52% in geometric means. No significant deterioration in stove effect was observed over the 18 months of surveillance. The reliability of these findings is strengthened by the large sample size made feasible by these unobtrusive and inexpensive tubes, measurement error reduction through instrument calibration, and a randomized, longitudinal study design. These results from the first randomized trial of improved household energy technology in

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Conflict of interest
The authors declare no conflict of interest.

a developing country and demonstrate that a simple chimney stove can substantially reduce chronic exposures to harmful indoor air pollutants among women and infants.

Keywords

improved stoves; biomass fuel; woodsmoke; longitudinal exposure reduction; indigenous population; color diffusion tubes

Introduction

About half of the world's population, and 90% of people residing in the rural areas of less-developed countries, cook with solid fuels (mainly wood and agricultural residues), many with unvented stoves that do not completely combust the fuel leading to high human exposures to the products of incomplete combustion (Mehta et al., 2006). Such exposures are responsible for an estimated 2.6% of the total global burden of disease, or about 1.6 million premature deaths each year (Smith et al., 2004). About two-thirds of this mortality is thought to be from child pneumonia, which itself is the largest single cause of child death globally. Associations between air pollution from household use of biomass fuels and acute lower respiratory infections (ALRIs), the majority of which are due to pneumonia among young children, have been reported in a number of observational studies (Smith et al., 2000, 2004; Dherani et al., 2008). To clarify whether biomass fuel smoke is a cause of ALRI in children under 18 months, a randomized controlled trial, RESPIRE (Randomized Exposure Study of Pollution Indoors and Respiratory Effects), was undertaken from October 2002 to December 2004 (Smith et al., 2006). This was the first randomized controlled trial of an intervention to reduce a population's everyday air pollution exposure and involved introduction of an improved chimney woodstove called the *plancha* in households using open woodfires for cooking in highland Guatemala.

Improved cookstoves with chimneys represent a major class of technical interventions for lowering household pollution exposures from solid cooking fuels, which also include kitchen ventilation improvements, promotion of advanced biomass combustion stoves that reduce emissions and introduction of cleaner burning fuels. Common among most such interventions is that they require change in household behavior, for example, in fuel handling and stove operation. The requirements for sustained change in behavior by the households tend to be major constraints on successful widespread adoption even when the availability and costs of the technologies are addressed. One of the criteria for choosing our Guatemalan site among the many considered for RESPIRE, therefore, was that there was a locally available chimney stove that had proven itself to be well accepted and used by the population and required no major change in household behavior, including using the same fuel, wood in this case, as the traditional open fire. We conducted pilot studies over the 1990s showing that the local population did indeed like and use the *plancha* and that pollution levels indoors reduced substantially as a result (McCracken and Smith 1998; McCracken *et al*., 1999; Naeher *et al*., 2000a, b, 2001; Albalak *et al*., 2001; Bruce *et al*., 2004). The only major constraint on its adoption by a larger population seemed to be its significant cost ~$100 at the start of our study. The exact degree of exposure reduction for mothers and children and how these might change over time, however, were not determined in our pilot study.

Although woodsmoke, such as tobacco smoke, contains thousands of chemicals, particulate matter (PM) in the inhalable or respirable ranges ($PM_{<10\ \mu m}$ or $PM_{<2.5\ \mu m}$) has been the principal pollutant category associated with exacerbations in respiratory illnesses such as pneumonia and asthma in children and COPD in women (Zanobetti et al., 2000; Hruba et al., 2001; Delfino et al., 2004). Currently, there is no feasible technology for personal exposure measurements of PM among young children or infants for any duration long enough to estimate typical daily exposures. Although such technology does exist for adults, it is expensive and difficult to implement. Furthermore, to be able to expand inferences beyond simple comparisons of group means at one point in time and evaluate sources of within- and between-person variability, sufficient numbers of repeated measures are required, furthering the need for an affordable, easy-to-use technology.

Carbon monoxide (CO), which is far easier to measure than PM, is also a health-damaging pollutant and the most abundant constituent of the products of incomplete combustion emitted from the fire (Smith, 1987). Previous studies in open woodfires and *plancha* kitchens in Guatemala have found that CO is a reliable surrogate for fine particles, particularly, over averaging times that include several entire burn cycles of the fire, that is, meals, and where there is little influence from combustion of other types of fuel (Naeher et al., 2000a, b). On the basis of these pilot studies, we used passive and relatively inexpensive color-stain diffusion tubes for measuring personal and kitchen area CO levels. Although designed for industrial hygiene applications, these diffusion tubes are sensitive to typical ranges of CO found in households using biomass for cooking and are sufficiently small, light, non-obtrusive and safe for use on infants.

As part of RESPIRE, therefore, we periodically fitted passive CO diffusion tubes on all study children and their mothers for personal exposure assessment (Figure 1). In a random subset of the households, we performed these same measurements in conjunction with more detailed personal and kitchen monitoring including PM (PM results reported separately). These data allow validation of several exposure assessment strategies, such as the use of repeated measures to estimate individual-level long-term average exposures (McCracken et al., 2009), the use of CO as a surrogate for woodsmoke particles, and indirect exposure assessment strategies that combine microenvironmental measures and time-activity patterns. Moreover, the randomized, longitudinal design affords a unique opportunity to assess the efficacy of the introduced stove for reducing personal CO levels using three different approaches: a between-groups comparison during the trial period, a before-and-after comparison among the intervention group, and a comparison of before-and-after changes between the control and intervention study groups. Other studies have either compared groups with different stove types or measured changes over time associated with stove adoption (Albalak et al., 2001; Saksena et al., 2003), but confounding bias remains an important concern in these studies.

In this paper, we (1) use continuous electrochemical CO monitors to assess the reliability of CO tubes in this field setting, and (2) report the effect of the *plancha* on personal exposures of children and their mothers and kitchen area concentrations on average and over time during the approximate 18 months post-intervention trial period.

Methods

The study sample consisted of women and children from 23 indigenous communities in the rural highlands area of San Marcos, Guatemala, who speak Mam as a primary language. On the basis of a rapid census survey of the area (5365 households), from ~700 eligible, 534 households were recruited if they had a child less than 4 months (n=268) or a pregnant woman (n=266) and if they used an open woodfire for cooking indoors. Half of the recruited households were randomly assigned to the intervention group, which received *plancha* stoves built in-place by a local stove/masonry company. The stove model, which had a 15-year history in Guatemala, was adopted by all intervention households, although occasional continued use of open fires was observed. Participant training sessions with stove use demonstrations were conducted initially and fieldworkers inspected the stoves weekly for proper use and maintenance and arranged for repairs if needed. The control households continued to exclusively use open fires, until they were offered *planchas* when they left the study. RESPIRE follow-up ended when the study child reached approximately 18 months, migrated, or died, the households voluntarily withdrew, or the scheduled end of the field work, December 2004. If a pregnant woman had a miscarriage or stillbirth, she was not followed during the trial period. Details of the RESPIRE project, including human participants approvals and informal consents, were reported previously (Smith et al., 2006; Bruce et al., 2007).

Characteristics of Study Homes

Randomization was achieved, with no significant difference between the two groups on baseline household and individual-level characteristics (Table 1). The typical study home was made of adobe mud walls, a dirt floor and a galvanized-iron roof. The vast majority of the participants self-identified as indigenous, while 6%self-identified as *ladino* (mixed Spanish-indigenous race). The *temascal*, a wood-fired sauna bath normally used weekly for bathing, may contribute significantly to total personal CO exposures in some households. Participants were asked not to wear the CO tubes inside the *temascal*, however, because the temperature and humidity in the *temascal* impede the tubes from measuring accurately. Although only three of the mothers in the study had smoked or currently smoked, 24% of the participating households reported other smokers in the house, usually the father of the study child. Motor vehicle traffic in the area is limited and all households are far from a main road.

Sampling Plan

The RESPIRE CO exposure assessment included both main (referred to as extensive) and validation (referred to as intensive) components. In the extensive portion of the study, personal monitoring was conducted in every house at baseline and approximately every 3 months thereafter until either the child reached 18 months or otherwise withdrew. As half of the study children were recruited *in utero*, baseline CO levels are not available for these children. We did measure the baseline CO exposures among all of the mothers, however.

Because of tube costs (approximately $8 each), mothers' exposures were measured in most, but not all, subsequent monitoring periods. To reduce the influence of wide daily variability on the uncertainty in our estimates of average exposures and kitchen levels (Bhangar et al., 2004), we sampled for 48 h rather than the typical 24-h periods used in previous studies in Guatemala (Naeher et al., 2000a; Albalak et al., 2001; Bruce et al., 2004).

We randomly selected 65 homes from the study population for intensive monitoring that included a range of simultaneous CO and PM measurements, both time integrated and continuous, at different fixed locations (e.g., personal, kitchen, bedroom, outside) and a detailed time-activity questionnaire. Over the trial period, we replaced households that dropped out of the intensive monitoring group, and have information on 77 unique households (45% with open fires). The intensive monitoring was repeated at approximately 3-month intervals.

Carbon Monoxide Measurement

Passive Diffusion Tubes—According to the material supplied by the manufacturer (Gastec Corp., 6431 Fukaya, Ayase-City, Kanagawa, 252–1195, Japan), a brownish-grey stain of length related to the cumulative CO dose (p.p.m.-h) appears on the Gastec tubes as a result of a chemical reaction in which CO reduces sodium palladosulfite to liberate metallic palladium. There are two types of Gastec CO tubes, 1D and 1DL, with nominal cumulative exposure ranges of 0–1000 p.p.m.-h and 0–200 p.p.m.-h, respectively, for sampling times between 0.5 and 24 h. During baseline, Gastec 1D tubes were used, as all households used open fires and we were concerned that a large fraction of the cumulative concentrations would be beyond the upper 200 p.p.m.-h limit of detection of the 1DL tubes. It was assumed, however, that the 1D tubes provided substantially less precision and sensitivity, due to the much larger p.p.m.-hr increments associated with each mm of stain. After completing our baseline measurements, we switched to the 1DL tubes. Although we did not collect duplicate measures with 1D tubes, we found that the inter-reader variation was about three times greater for 1D compared with 1DL tubes placed on children in open fire homes (unpublished data). Nevertheless, an important part of our analysis relates to the comparability of these tube types, as well as the linearity of the response within and beyond the manufacturer's stated cumulative dose ranges.

For the extensive assessment, tubes were deployed by locally recruited field workers who received training on tube use by the project air pollution team. Field supervisors visited a subsample of households on the first day of monitoring during each round, and again after approximately 24 h, to make sure the tubes were being worn correctly by the mother and child. CO tubes for intensive monitoring were deployed in the same manner by the project air pollution team, supervised by the project environmental engineer (Canuz). In both the extensive and intensive monitoring, measurements were reattempted in the households where tubes were lost or broken. If a second failure occurred during that monitoring period, the household measurements were lost for that period.

Duplicate identification labels were placed on the tubes at the field headquarters and one of these labels was transferred to the field monitoring form at the start of sampling. After the tube's end was broken off to start sampling, the field workers sanded off the glass tube with emery paper to make sure there were no sharp edges. Children wore the CO tubes pinned to the shoulder or upper back area to prevent them from handling or mouthing the tube. Tubes were protected from breakage by a strong plastic sleeve. The field workers emphasized the importance of keeping the tube on or near the child/mother at all times, and requested that the tube be kept near the child's bed during sleep, and outside the *temascal* when bathing. Babies in this area are generally kept with their mother or other adult caregiver during the day. Some women were reluctant to wear easily noticed devices when going out in public. Correspondingly, they were told that they could cover the tube with a sweater if preferred. Previous experiments showed that one or two layers of clothing had no effect on CO results (Bruce et al., 2004). At the end of sampling, the tubes were capped with a tight-fitting plastic cap and returned to the field station, where they were placed in a 4 °C refrigerator until read and then returned to the refrigerator for storage.

Each tube was read by the air pollution field worker and supervisor, usually the same day as tube collection. A lamp with a daylight (solar spectrum) bulb illuminated the tube reading area, which consisted of a standardized seating arrangement at a table covered with white paper. For the purposes of RESPIRE, we developed a new technique for reading the CO tubes. The protocol recommended by the tube manufacturer relies on a scale in p.p.m.-h etched on the tube. As this scale is not linear, it is difficult to interpolate between the scale markings. We thus first measured the length of the stain in millimeters. This measurement was subsequently converted to a cumulative exposure (p.p.m.-h) based on least-squares regression using the lengths from the starting point to each of the scale markings (mm) as the independent variable and the indicated cumulative exposure of that scale marking (p.p.m.-h) as the dependent variable. As these relationships varied by manufacturing lot, we developed a separate regression model for each of the nine tube lots used during the project. The cumulative exposure was then divided by the sampling duration to calculate the time-weighted average exposure or concentration. Anomalous marks found in the tubes, such as yellow stains and white gaps, were flagged in the database. Yellow staining, which was recorded on about 2% of the tubes and tended to cover the length of the scale, was reduced early in the study by taping tubes to reduce exposure to sunlight. We did not find any association between yellow staining and CO concentrations. White gaps, 9mm on average (SD=6mm), were recorded on less than 2% of the tubes, and we excluded them from the measurement of stain length, as their removal strengthened the correlation with collocated monitors.

Quality Assurance

Tube measurement validation included (1) an instrument precision substudy, where we compared 50 pairs of Gastec 1DL duplicate tube measures, (2) an exchangeability substudy, where we compared 50 pairs of 1D and 1DL tube measures, and (3) an external validation substudy, where both the 1D (n=45) and 1DL (n=232) tube types were collocated with a continuous electrochemical CO monitor in the household kitchens.

Continuous CO Monitors—In the 77 intensively monitored households, CO tubes were collocated in the kitchen with an inexpensive commercial electrochemical monitor, the HOBO/ Onset CO monitor (Onset Computer Corp, Pocasset MA, USA). These continuous datalogger monitors read CO concentration every second and logged means every 30 s simultaneously on two channels, one ranging from 0.2 to 125 p.p.m. with 0.5 p.p.m. resolution and the other with 2.0 p.p.m. resolution from 0.2 to 500 p.p.m. A main advantage of continuous monitors is that they can be quickly calibrated against standard CO span gas in the field laboratory.

The continuous CO monitors were calibrated against CO span gas at 10, 25 and 60 p.p.m., which span the range generally reached during fire use. Our calibrations indicated that the monitors responded linearly to increases in CO span gas concentration (data not shown). We performed 175 span gas calibrations on the 30 continuous CO monitors used in RESPIRE and used these data to calculate adjustment factors by which the concentrations in the field were multiplied. The adjustment factors on days between calibrations were calculated by assuming that the rate of change in adjustment factors was constant over time. Two continuous CO monitors without valid calibrations were assumed to require adjustment factors of 0.9, which was the mean of over all monitors calibrated.

Statistical Analysis

SAS version 9.1 (SAS Institute, NC, USA) and R software were used for all data analysis. CO measurement durations shorter than 42 h or longer than 54 h (*n*=25, 0.5% of total) were eliminated from the analysis data set. Owing to the right-skewed distributions, CO data were natural log-transformed for regression analyses.

Quality Assurance—To estimate the precision of the 1DL tubes and the validity of pooling 1D and 1DL measures, random effect models (SAS PROC MIXED) were used to estimate variance components and intraclass correlation coefficients for the collocations tests. We modeled the between-collocation variability using a random intercept for collocation test, and the within-collocation random instrument error was estimated by the residual variance. All variance component estimates are expressed in natural log units unless stated otherwise.

Regression calibration was used to reduce bias in the tube measurements and to make the 1D and 1DL tubes more comparable. Two alternative models were compared for calibrating the diffusion tubes against the continuous monitors: (1) a linear model of the form y=mx+b, where y is the monitor measure and x is the tube measure; and (2) using R software, a penalized spline model, which allows us to fit a nonlinear functional relationship between CO monitors without making strong parametric assumptions about the shape of that relationship (Eilers and Marx, 1996). The degrees of freedom for the penalized spline model were determined using generalized cross-validation. The models were fit separately by tube type. These regression calibrations of the CO tubes based on the monitor were validated by assessing the agreement between the 1D and 1DL tube measures from collocation experiments before and after calibration.

Intervention Effect—Following calculation of descriptive statistics from the baseline and post-intervention CO distributions in both groups, we used SAS PROC MIXED to fit linear mixed effect models with log CO as the dependent variable to estimate the effect of the stove intervention on exposures and kitchen concentrations. The data offer three distinct types of comparison for estimating the association between stove type and CO levels: (1) a between-groups comparison during the post-intervention trial period, (2) a before-and-after comparison among the intervention group, and (3) a comparison of before-and-after changes between the control and intervention study groups. In the between-groups comparison (1), we exclude data from the baseline period and the main parameter of interest becomes the fixed effect for study group. We consider this study design to be the main analysis for the effect of stove intervention on personal exposures. The before-and-after comparison (2), in which we exclude data from the control group and the main parameter of interest is the fixed effect for study period, has the strength of controlling for fixed subject characteristics by definition but is susceptible to confounding by determinants of exposure that vary over time. The comparison-of-changes approach (3), in which the main parameter of interest is a group-by-period interaction (main effects for group and period also included), has the advantage of using all the data (baseline and trial periods) and can also be viewed as a between-groups comparison adjusted for potential differences at baseline We do not consider this as our main estimate of the stove effect on personal exposures, however, because some children were not measured at baseline as they were recruited *in utero*. The comparison-of-changes approach (3) is of particular interest for kitchen area levels, as almost all intensive study kitchens were measured at baseline.

The models (1–3) were fit separately for women, children and kitchens, and a random intercept was included to account for correlation among repeated measures within individuals or kitchens. Selection among alternative models to account for covariance, including allowance of separate estimates of variance components by stove type, was made by comparing goodness-of-fit using Akaike's Information Criterion.

Given the longitudinal design of the study, we also assessed whether the CO exposures, or the effect of the *plancha* on CO exposures, changed throughout the trial period. We first examined this question by categorizing time (baseline, 0–6 months post-intervention, 6–12 months post-intervention and 12–18 months post-intervention) and testing for group-by-time-category interactions, as described in the comparison- of-changes approach (3). We also examined whether there was evidence of change over time in the exposure reduction effectiveness of the *plancha* stove by including time in the model as a continuous variable and testing for interactions with stove type. These continuous time-by-stove interactions were modeled using both linear regression and penalized regression spline models.

Results

Quality Assurance/Measurement Validity

The tube validation substudies are presented in Figures 2a–c. Based on 50 duplicate measures, we found that the 1DL CO diffusion tubes are precise relative to the variation observed between 48-h kitchen CO concentrations (error variance=0.017, intraclass r=0.99). This is illustrated in the percent difference *versus* mean plot in Figure 2a, in which distances along the vertical and horizontal axes represent equal increments on the log scale. Within the 50 pairs of collocated 1D and 1DL tubes, however, the error variance was almost 10 times greater (0.165) and the intraclass correlation coefficient was considerably lower (0.84). Figure 2b shows that the poorer agreement between the tube types is due to both greater random variability and differential bias by tube type. The solid line on this plot represents a penalized cubic spline, which models the relationship between the differences and the means. Departure from the horizontal line suggests that the ratio of the 1DL to 1D tube types depends on the concentration range.

Using scatterplots and penalized cubic spline models, we found evidence of nonlinear relationships between each of the tube types and the continuous CO monitors. The penalized spline model to predict 48-h average continuous CO datalogger measures from the 1D tube used 1.8 d.f. and had R^2=0.70 (n=45), and the model to predict continuous CO from the 1DL tubes used 4.4 d.f. and had R^2=0.81 (n=232). Therefore, we used the tube-specific penalized cubic spline fits to calibrate both tube types against the continuous CO monitor. As a validation of these regression calibrations, we repeated the comparison of 1D and 1DL tubes from the exchangeability substudy in a subset of the households after these adjustments. As shown in Figure 2c, we found that the adjusted tube measures agreed much better than the unadjusted measures. The spline model of the relationship between the difference and mean of adjusted 1D and 1DL measures follows closely to the horizontal line of equality. The error variance within collocated pairs of 1D and I DL tubes was reduced by half as compared with the unadjusted measures. The reliability of the interchangeable 1D/1DL measure as indicated by the intraclass correlation, however, remained lower than the measure based solely on 1DL.

Data Completeness—Accounting for both intermittent missing data and loss to follow-up, the tube measurements were 83% complete for both children and women, and there was no evidence of an association between intervention status and data loss. Among the 537 randomized children, we had at least one valid measure on 515 children, 270 of these at baseline and 500 children during the trial period. About half of the children were not measured at baseline by design because they had not been born, and 35 randomized children (20 control and 15 intervention) were not measured during the trial period due to miscarriage (*n*=5), stillbirth (*n*=4), dropout (*n*=11) or death (*n*=15). We obtained at least one exposure measure on 532 out of 534 randomized women, 529 of these at baseline and 488 women during the trial. During the trial period, 44 women had no follow-up measures (22 control and 22 intervention) due to miscarriage (*n*=4), stillbirth (*n*=3), dropout (*n*=21) or death of child (*n*=15), and one woman had no measures, as she was not home during tube collection.

Stove Effect on Personal Exposures and Kitchen Levels

Descriptive statistics for personal CO exposures and kitchen levels are listed in Table 2. Approximately half the children in both groups were monitored during the baseline period, before the families being informed of their randomized stove assignment. Although the original subsample for the intensive monitoring was selected randomly, dropout was more common among those participating in this more intensive research protocol. These dropouts were replaced by neighbors during the follow-up period, which explains why the overall number of kitchens monitored at least once was larger than the number in the intensive study at baseline. The numbers of children, mothers and kitchens monitored, as well as the numbers of repeated measures, are remarkably similar in the control and intervention groups during both the baseline and trial periods.

There were no significant differences in personal exposures or kitchen levels between the control and intervention groups at baseline, when all used the same stove type. Small differences in the arithmetic means are caused by few measures at the high end of these right-skewed distributions, whereas the geometric means are almost equal across study homes. Personal exposures were similar at baseline among children and mothers and much lower than kitchen concentrations. During the trial period, for children, women and kitchens, the means across all repeated measures are substantially lower among the intervention group. Whereas personal exposures remained lower than kitchen concentrations among the control group, this trend was reversed among the intervention group, and also unlike the baseline period, mothers' exposures were higher than children's in both groups during the trial period.

The estimated stove effects from our main analysis (between-groups comparison) indicated that the personal exposures and kitchen area levels were significantly reduced among the intervention group. As shown in Table 3, while the stove intervention removed approximately 90% of CO from kitchens, maternal and child exposures were reduced by ~60% and ~50%, respectively.

In Figure 3, we illustrate the results of the three distinct comparisons for estimating the association between stove type and CO level. The before-and-after comparison resulted in a greater estimated reduction in child exposure to CO than the between-groups and comparison-of -changes approaches. The strength of the association of the stove effect on maternal personal exposures, however, was not as strong in the before-and- after as in the other two approaches. All of the estimates from the comparison-of-changes approach were similar to the between-groups estimate, but the confidence intervals were wider, especially among child estimates of exposure. All three comparisons resulted in similar estimates of stove effect on kitchen levels.

Effect of Chimney Stove over Time

We examined whether the exposure reduction effectiveness of the *plancha* remained constant over the 18-month period. Proper use and maintenance of the stove is essential for continued, reduced exposures to indoor air pollution during a longitudinal study such as RESPIRE. Weekly surveillance of stove use and subsequent referral for repairs were made. Approximately 72% of the *plancha* households stated that they always used their *plancha*. At 10% of the visits, the fieldworker noticed that the *plancha* was in need of minor repair. There was no evidence of a change in the effect of the stove with time, as intervention, either evaluated as a continuous variable or as 6-month categories (all $P>0.3$).

The estimated geometric means and confidence intervals of personal CO exposures over time among children and women are plotted in Figures 4a and b, respectively. Whereas the groups had comparable exposures before randomization (at baseline), exposures were substantially lower among the intervention group during the trial period for both children and women. The groups' trajectories over time were roughly parallel during the trial.

Although declining more in intervention households, Figures 4a and b show exposure declines in control households as well, which may be due to behavior shifts during the early infancy. Only a small change is seen in kitchen levels, indicating that reductions in personal exposure over time were not the result of declining pollution levels in the kitchens (Figure 4c).

Discussion

We described a method to estimate the effect of a randomized chimney woodstove intervention on personal CO exposures and kitchen levels among a rural population of women and children using open woodfires for cooking. We first describe the application and validation of CO diffusion tubes for the field monitoring and then compare alternative approaches to estimating the effect of the stove intervention on CO levels.

Evaluation of the Tube Method

During RESPIRE we used innovative methods of reading, calibrating, and validating of passive diffusion CO tubes. The CO tubes were well accepted by the participants in the study and easily used by fieldworkers with minimal technical training. The extent of missing data due to noncompliance or tube loss or damage was limited and unlikely to result in substantial bias in stove effect estimates. On the basis of comparisons with electrochemical monitors calibrated with span gas, we found that at least one of the two tube types used did not respond linearly across the range of kitchen CO concentrations. Failure to adjust for such nonlinearity would have led to bias important to health studies and measuring the efficacy of stove programs.

The limitations of the method presented here include use of two tube types during baseline and intervention, and the need to work with different manufacturing lots during the longitudinal study. Although these issues posed challenges, we validated the analytic methods using an instrument precision substudy, an exchangeability substudy and an external validation substudy. Quality assurance analyses such as these are essential. As far as we know, no other inexpensive mass-produced device is available for CO personal exposure measurements and, taking into account the lessons learned here, we would recommend their use by others, although of course new technology is always coming onto the market – see Box 1.

Box 1

Recommendations for using commercial carbon monoxide (CO) diffusion tubes in personal exposure assessments based on best judgment of the authors

For all studies

- Best in situations where 24-h CO concentrations approaching 1 p.p.m., although depends on type of analysis to be done.
- Limit to one tube type and as few manufacturing lots as possible.

- Protect from exposure to sunlight before and after exposure.
- Read tubes under standard lighting conditions.
- Long duration is beneficial for reducing noise and intra-household variability but may stretch participant tolerance.
  - Must pilot to find proper balance between tube type and exposure time, in order to avoid readings that are either (i) too low to record precisely, or (ii) exceed the calibrated capacity of the tube.
  - Manufacturer does not guarantee long exposure times, but we were able to use for 48 h.
- Follow protocol for good quality control and protection of participants, including capping tightly in field and storing in a refrigerator until tubes can be read in standard conditions and housing tube in a protective sleeve to reduce risk of breakage when deployed.

For studies able to conduct calibration

- Read tubes by length in millimeters, i.e., not by etched marks on the tubes.
- Calibrate against standard CO span gas either directly or through intermediate instruments to obtain the relationship of stain length and true dose in p.p.m.-h.

Effect of Stove Intervention

The large sample size made possible by deploying a small, passive, inexpensive, robust and easily handled device, combined with the randomized design, allowed examination of relationships between stove type and personal exposure using three distinct types of comparison. The longitudinal nature of the data also allowed us to examine whether the stove effect changed over roughly an 18-month period.

At baseline before receiving the *plancha* chimney stove, there was no significant difference between the intervention and control households in 48-h kitchen CO levels or personal exposures in mothers and babies. As shown in Table 3, the most robust analysis (between-group) found all three metrics significantly lower after intervention: all methods produced tight confidence intervals and, in aggregate, provide strong evidence that the effect is not due to chance.

That personal exposures did not reduce as much as kitchen levels is consistent both with daily time-activity patterns, that is, neither mothers nor their babies spend the entire day in the kitchen, and the presence of other sources of CO exposure that were not affected by the intervention, particularly use of open fires for non-cooking purposes and preparation of the *temascal*. A simple chimney stove design, such as the *plancha*, does not appreciably improve combustion, and has limitations as an exposure-reducing intervention in that it does not actually reduce emissions, but rather at best just shifts them outside of the kitchen. Thus, concentrations around the rest of the household area, including the bedroom where much time is spent, are not nearly as strongly affected by the intervention as kitchen levels. In a

48-h total personal exposure evaluation, such as this, therefore, the exposure differences are less than the simple differences in kitchen air quality. Similar to our results, a Mexican study also found that differences in personal exposures were less than in kitchens (Amendariz-Arnez et al., 2008).

The longitudinal analysis revealed no significant difference over time in the effect of the intervention on any of the metrics evaluated, supporting the conclusion that the effectiveness of the stoves did not deteriorate or otherwise change over the approximately 18-month period. Although indicating the potential of a long-term effect for this intervention, this result should be viewed in context of RESPIRE as a measure of efficacy, not effectiveness. It thus is not fully reflective of performance in a community stove introduction that does not involve frequent checks of the condition and use of stoves in every household (weekly in the case of RESPIRE), followed up by advice on correct use as well as an offer of repairs where needed. Other studies have shown, for example, some deterioration in chimney performance and decline in stove use after introduction of improved stoves in before-and-after effectiveness studies in Mexico and India, where improvements in kitchen levels were much lower than those reported here (Chengappa et al., 2007; Dutta et al., 2007; Masera et al., 2007).

That personal child exposures fell in the control household as well as intervention households in a similar if less pronounced manner is undoubtedly due to the natural changes in mothers' behaviors in the first year after giving birth. This also probably explains the rise and fall seen in both groups of mothers. Evidence that the effect is due to behavior is supported by the lack of change in the kitchen levels themselves in both groups. The ability to separate out these effects illustrates another value of a randomized trial with a true comparison group in that analysis of a simple longitudinal before-and-after study would have had difficulty separating out the effect of the stove from the effect of behavior changes in the households following birth.

For many, but not all, of the main health effects thought to be associated with woodsmoke exposures, CO itself is not likely to be the primary causative agent. Nor are the mean, personal CO levels highly elevated as compared with air quality guidelines. Nevertheless, CO is formed by incomplete combustion in the fire in a way similar to the vast array of other toxic species in woodsmoke, including the primary indicator of hazard, small particles (Naeher et al., 2007). As noted earlier, pilot study in our area found a reliable ratio, roughly 1:9 in mass terms between particles and CO over averaging times covering several burn cycles in woodfires and when there were not multiple sources of combustion smoke (Naeher et al., 2001). Thus, 8 p.p.m. CO (approximately 9mg/m^3), would indicate roughly 1mg/m^3 of $PM_{2.5}$. Similar to the use of NO_2 as an indicator of traffic pollution in many outdoor air pollution studies (WHO, 2006) or sulfur as an indicator of particles (Sarnat et al., 2002), CO can be used as an indicator of woodsmoke exposure. The CO/PM relationships in different conditions in our study households and an estimation of particle exposures in the population will be discussed in future publications.

We close by noting that the *plancha* was chosen for the intervention trial largely because of its long successful history in Guatemala, local production, high acceptance in our study area and pilot studies confirming its ability to greatly reduce kitchen pollution levels over time. Although these characteristics remain important, there are new generations of improved woodstove technologies that seem to promise to substantially lower actual emissions through better combustion as well as decreased fuel use, perhaps at lower cost (Venkataraman et al., 2007). Should they also prove to be as robust and well accepted as the *plancha*, it would be important to know their exposure-reduction potential as well.

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Figure 1.

Mother and child by open cookfire. Child is wearing diffusion CO tube behind the left shoulder and mother on the left shoulder. Informed consent was obtained in writing for the photo.

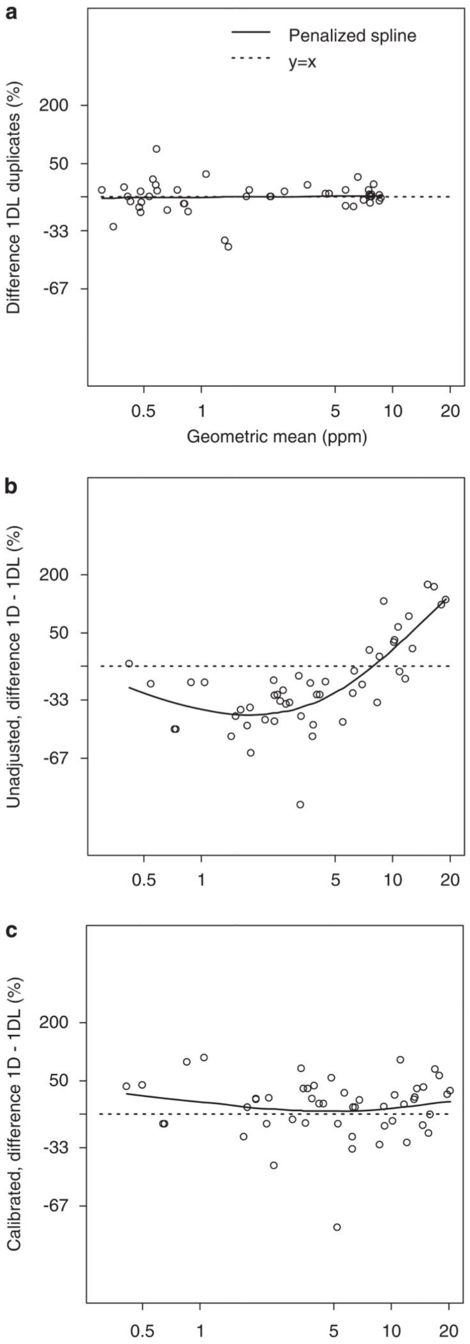

Figure 2.

(a–c) Comparisons of CO tubes between (a) duplicates; between (b) tube types; and by (c) tube type according to calibration against collocated electrochemical monitors.

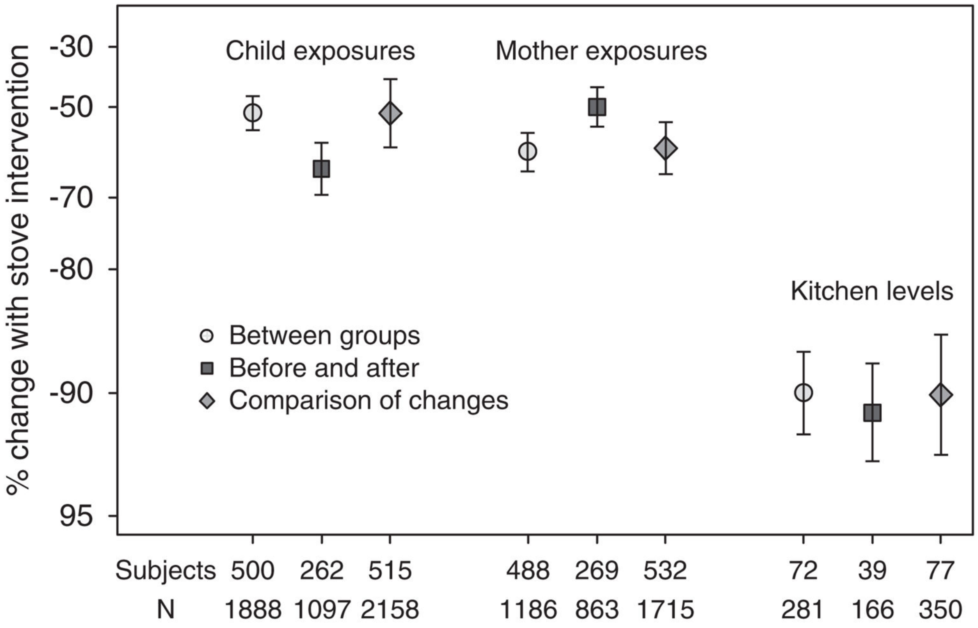

Figure 3.

Alternative estimates (95% confidence intervals) of the effects of the *plancha* chimney stove intervention on personal exposures and kitchen levels of carbon monoxide (CO). Repeated measures of 48-h CO were log-transformed and used as the dependent variable in linear mixed effects models. The models for between-groups comparisons are based on data from the trial period only and the intervention effect is estimated by including an indicator variable for randomized group. The models for the before-and-after comparisons use data from the intervention group only and the intervention effect is estimated by an indicator variable for the trial period in contrast to the baseline period. The comparison-of-change models uses data from both groups and from both the baseline and trial periods, and the main parameter of interest is the interaction between randomized group and study period, both of which are included as main effects.

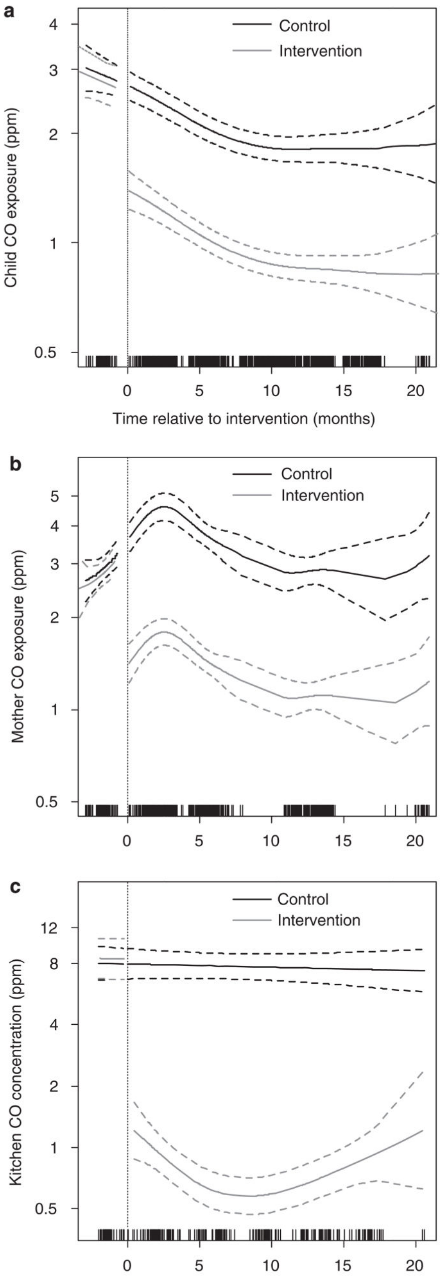

Figure 4.

(a–c) Trends of 48-h CO levels during RESPIRE for (a) child and (b) mother exposures and (c) kitchen concentrations by randomized group assignment. Estimated using penalized splines in generalized additive mixed models. Dashed lines represent point-wise 95% confidence intervals. Vertical dotted line represents time of stove intervention. Tick marks above x axis indicate individual measurements.

Table 1

Baseline characteristics among participating RESPIRE households, by randomized stove group.

	Control, N=265	Intervention, N=269
Household Characteristics		
Altitude in meters, mean (SD)	2613 (185)	2601 (179)
Dirt floor in main home, number (%)	245 (92.5)	239 (88.8)
No electricity in main home, number (%)	81 (30.6)	81 (30.1)
Number of rooms in house, mean (SD)	1.2 (0.4)	1.2 (0.4)
Number of people in house, mean (SD)	7.4 (2.8)	7.3 (2.9)
Cooking area in separate closed room, number (%)	200 (74.3)	202 (76.2)
Kitchen volume in cubic meters, mean (SD)	40.6 (22.8)	40.9 (22.2)
Kitchen roof type, number (%)		
Straw	69 (30.6)	64 (28.6)
Aluminum	104 (46.2)	101 (45.1)
Tile	52 (23.2)	59 (26.3)
Kitchen eave spaces, number (%)		
Completely closed	46 (16.5)	55 (19.4)
Partially closed	102 (37.1)	101 (35.7)
Completely open	117 (42.7)	113 (40.6)
Stove in same room as bed, number (%)	35 (13.2)	37 (13.8)
Smoker present in home, number (%)	71 (26.8)	55 (20.4)
Has *temazcal* wood-fired sauna bath, number (%)	224 (84.5)	234 (87.8)
Maternal Characteristics		
Recruited during pregnancy, number (%)	128 (48.3)	138 (51.3)
Maternal age, mean (SD)	27.0 (6.8)	28.9 (7.8)
Maternal education, number (%)		
None	98 (36.9)	83 (30.8)
Elementary school	157 (59.2)	162 (60.2)
Secondary school	4 (1.5)	13 (4.8)
Missing	6 (2.4)	11 (4.2)

Table 2

Child and mother 48-h CO exposures and kitchen levels in parts per million (p.p.m.) by randomized stove group and period.

Study period	Child		Mother		Kitchen	
	Control	**Intervention**	**Control**	**Intervention**	**Control**	**Intervention**
Baseline						
Households	138	132	263	266	34	35
Measures	138	132	263	266	34	35
p.p.m., mean±SD	3.6±3.1	3.2±2.3	3.5±2.8	3.2±2.2	11.0±6.7	10.0±5.9
GM (GSD)	2.8 (2.0)	2.8 (1.6)	2.8 (1.7)	2.8 (1.7)	8.8 (2.1)	8.4 (1.9)
Range	0.2, 20.9	0.6, 19.5	0.7, 20.5	0.7, 16.0	2.0, 24.8	1.8, 23.6
Trial						
Households	244	256	241	247	36[a]	36[a]
Measures	923	965	589	597	150	131
Repeats, median (range)	4 (1 to 6)	4 (1 to 6)	2 (1 to 4)	2 (1 to 4)	5 (1 to 6)	5 (1 to 6)
p.p.m., mean±SD	2.8±2.5	1.5±1.9	4.8±3.6	2.2±2.6	8.6±4.0	1.1±1.4
GM (GSD)	2.0 (2.3)	1.0 (2.4)	3.6 (2.2)	1.4 (2.5)	7.5 (1.8)	0.8 (2.3)
Range	0.2, 20.9	0.3, 15.7	0.3, 19.4	0.3, 17.5	1.0, 17.0	0.3, 11.8
Overall						
Households	253	262	263	269	38[a]	39[a]
Measures	1061	1097	852	863	184	166
Repeats, median (range)	5 (1 to 6)	4 (1 to 6)	3 (1 to 5)	3 (1 to 5)	5.5 (1 to 7)	5 (1 to 7)

GM=geometric mean; GSD=geometric standard deviation.

[a] Dropouts in the intensively measured household were replaced by neighbors during the follow-up period, which explains why the number of kitchens monitored at least once was larger than the number in the intensive study at baseline.

Table 3

Effects of the chimney stove on CO exposures and kitchen levels from between-groups models using data from the post-intervention trial period only, expressed as percent change in geometric means[a].

	N	Estimate	95% CI
Child exposure	1888	−52	−56, −47
Mother exposure	1186	−61	−65, −57
Kitchen levels	281	−90	−92, −87

[a] Estimates from linear mixed effects regression of natural-log CO on randomized stove type using an indicator variable for chimney stove and random intercepts for participant.