Carbon monoxide exposures and kitchen concentrations from cookstove-related woodsmoke in San Marcos, Peru

Adwoa A. Commodore[1], Stella M. Hartinger[2,3], Claudio F. Lanata[2], Daniel Mäusezahl[3], Ana I. Gil[2], Daniel B. Hall[4], Manuel Aguilar-Villalobos[5], Corey J. Butler[1], Luke P. Naeher[1]

[1]Environmental Health Science Department, College of Public Health, University of Georgia Athens, GA, USA, [2]Instituto de Investigación Nutricional, Lima, Peru, [3]Swiss Tropical and Public Health Institute, Basel, and University of Basel, Switzerland, [4]Department of Statistics, University of Georgia, Athens, GA, USA, [5]Asociacion del Aire Ambiental, Lima, Peru

Background: Nearly half of the world's population is exposed to household air pollution (HAP) due to long hours spent in close proximity to biomass-fueled fires.
Objective: We compare CO exposures and concentrations among study promoted intervention stove users and control stove users in San Marcos Province, Cajamarca region, Peru.
Methods: Passive CO diffusion tubes were deployed over a 48-hour sampling period to measure kitchen CO concentrations and personal mother and child CO exposures in 197 control and 182 intervention households.
Results: Geometric means (95% CI) for child, mother, and kitchen measurements were 1.1 (0.9–1.2), 1.4 (1.3–1.6), and 7.3 (6.4–8.3) ppm in control households, and 1.0 (0.9–1.1), 1.4 (1.3–1.6), and 7.3 (6.4–8.2) ppm among intervention households, respectively.
Conclusion: With no significant differences between control and intervention CO measurements, results suggest that intervention stove maintenance may be necessary for long-term reductions in CO exposures.

Keywords: Carbon monoxide, Children, Cookstove, Exposure assessment, Household air pollution, Peru, Women, Woodsmoke

Introduction

It is estimated that nearly half of the world's population burns biomass, mostly as fuel for cooking,[1,2] resulting in household air pollution (HAP). Women and young children bear the brunt of high HAP exposures due to the long hours spent in close proximity to cooking fires.[3,4] Household stoves typically used for cooking and heating in the developing world do not burn fuel cleanly leading to incomplete combustion in the domestic environment.[1,4,5] Smoke from incomplete biomass combustion contains health-damaging pollutants,[6,7] of which carbon monoxide (CO) and particulate matter with an aerodynamic diameter of ≤2.5 μm ($PM_{2.5}$) are major constituents.[5,8]

HAP exposure, from cooking with solid fuels, is responsible for approximately 3% of the global burden of disease.[2,9–11] HAP levels may vary depending on factors such as the time spent cooking, fuel type, cooking environment, and household ventilation.[12–14] Concentrations of CO and PM also vary over short (less than 1 day) time periods.[15] As such, it is essential to capture high-intensity exposures and emissions over an extended period of time. Adequate characterization of exposure to residential biomass combustion is crucial in vulnerable populations such as in rural communities in Peru where biomass fuels are used on a daily basis for cooking and heating.[16]

Personal exposures and kitchen concentrations of HAP can be estimated using questionnaires and exposure modeling, measured directly with air pollution monitors and to a limited extent, biomarkers can also be used to estimate internal dose from HAP exposures.[5,17–21] CO can be used as a proxy for $PM_{2.5}$ when both pollutants are from the same source and air pollution levels are high as observed in indoor cooking conditions.[22] A few studies in the past decade have successfully demonstrated the use of inexpensive passive diffusion tubes in quantifying exposure to HAP as well as ambient concentrations.[8,22–25]

Correspondence to: L P Naeher, Department of Environmental Health, College of Public Health, University of Georgia, Room 150, Environmental Health Science Building, Athens, GA 30602-2102, USA. Email: lnaeher@uga.edu

DOI 10.1179/2049396712Y.0000000014

We report a cross-sectional study conducted within the framework of a community-randomized controlled trial (c-RCT, parent study) by the Instituto de Investigación Nutricional (IIN) and the Swiss Tropical and Public Health Institute.[26,27] Our primary objective was to compare CO exposures and concentrations among study promoted intervention stove users and control stove users in San Marcos Province, Cajamarca region, Peru. We also investigated factors that are associated with CO exposures and kitchen concentrations among study subjects. Finally, we examined correlations in CO measurements between personal mothers' and children's exposures and between personal exposures and kitchen concentrations in this population.

Methods

Study design and study homes

Measurements presented in this paper occurred between June and August 2009. The May–August period in the study region is characterized by dry conditions and cold nights. All measurements were taken during this season, no follow-up measurements occurred during the rainy season. The altitude in the region ranges between 2200 and 3900 m above sea level. Mean altitudes $\pm$SD for intervention and control households are 2684$\pm$284 and 2727$\pm$438 m above sea level, respectively. For this cross-sectional study, control and intervention households were from participating households in the parent c-RCT (n=250 and 253 for intervention and control homes, respectively). The c-RCT involved 51 community clusters who used solid fuels in the Province of San Marcos, Cajamarca region, Peru.[26,27] The intervention was randomized at the community level, with the 51 community clusters allocated into the intervention arms by using covariate-based constrained randomization.[26] Field workers for the c-RCT visited all study homes during this 3-month period; however, subjects' availability, willingness to participate, as well as time and budget constraints, limited the total sample size of the present study.

The aim of the parent study was to evaluate an integrated home-based environmental intervention package against childhood diarrhea and respiratory infections. A pilot study was conducted in seven communities outside the study area, where several potential stove designs were tested, and subjects were consulted on cooking habits and preferences to provide a user-friendly stove design which met their household and cooking needs.[27] The final stove model for the c-RCT was called the OPTIMA-improved stove (hereafter OPTIMA stove). Kitchen performance tests of the OPTIMA stoves revealed a 15% reduction in daily fuel and energy use and a 16% reduction in fuel and energy use per capita compared with the traditional open fire stoves, although there was wide variability.[26,27] The OPTIMA stove was built with red burnt bricks plastered with a mixture of mud, straw, and donkey manure.[27] It has three pot holes for cooking, a closed combustion chamber, metal chimney with a regulatory valve, a hood, and metal rods for support.

OPTIMA stoves were installed between October 2008 and January 2009 in 250 households (hereafter intervention households). There were no emissions tests or HAP exposure assessment before installation of the intervention stoves. The current study reports the only exposure assessment conducted for these stoves 6–8 months after installation (median: 7.4; IQR=6.6–8.1 months).[28] OPTIMA stoves were later stratified (after exposure assessment had occurred) into two categories based on their levels of functionality (FL). FL-I stoves were in good running conditions at the time of the assessment (plastered stove and no visible leaks when in use) and FL-II stoves were in need of repairs (re-plastering, filling small cracks, cleaning the chimney, chimney valve replacement). Field workers, during monthly visits, instructed OPTIMA stove users in the correct use of the stoves including cleaning and removing ashes and wood residues. Although surveillance occurred in all study homes, stove repair and maintenance were not addressed during home visits until after air quality monitoring had occurred. Households with OPTIMA-improved stoves were re-visited 9 months (median: 9.3; IQR=9.0–9.7 months) after installation and repaired as needed by the original stove builders.[28]

The control arm of the c-RCT included households with a diversity of stove types.[27] As such control households in this study had a wide range of stove types including (1) chimney stoves whose raw materials were provided by non-governmental organizations (hereafter referred to as NGO; n=30); (2) chimney stoves built by the households themselves (hereafter referred to as self-improved by household; n=34); (3) gas stoves (n=4); and (4) non-vented stoves with pot holes for cooking including the common three-stone open fire stove (hereafter referred to as traditional; n=129). At the time of sampling, control households had stoves which had been in use between 4 months and over 10 years. Lastly, households in each arm of the intervention were classified according to the primary stove in use and it is possible that some chimney stoves were used together with traditional stoves in some households, particularly for cooking animal feed or other meals which required substantial cooking times.

Sample size

Mothers/primary caregivers (hereafter referred to as mothers) were sampled from 182 intervention households (final $n=161$) and 197 control households (final $n=154$) (Table 1). Some households were sampled two or three times during the study period (13 intervention households and 12 control households) and in eight control households, two tubes were used on the same day. In each case, the multiple measurements (pseudo-replicates) were averaged to get a single value for data analysis per subject. Losses in sample size were similar except for the number of broken tubes [$n=5/182$ (3%) among intervention and $n=18/197$ (9%) among control households]. We are unsure as to why there was a higher breakage rate among control households, but we do not expect this to influence our study findings. Measurements were not reattempted in households with lost or broken tubes.

During the first month of sampling, kitchen tubes were taped directly above stove openings in study kitchens at ~1.5 m. These tubes, representing 29% of the data, have been excluded from all analysis to avoid inflating the values of the kitchen measurements (Table 1). There were a total of 40 tubes [$n=11/182$ (6%) from intervention households and $n=29/197$ (14%) from control households] that had yellow and/or white stains. Like Smith *et al.* in 2010, these tubes were excluded from the final data set as the stains may be due to other gases that entered the tube along with CO during sampling. Duplicate same day measurements in a small subset of households were collected to check for reliability in tube measurement. All collocated tubes had stain length measurements within 1.5 mm of each other (10 ppm-hour). Owing to field workers monitoring previously sampled community clusters, certain households were sampled more than once during the 3-month exposure assessment.

Exposure assessment

Time integrated CO measurements were taken using Dräger Diffusion Tube for Carbon Monoxide, with a range of 6–600 ppm-hour (parts per million-hour). All tubes were from the same manufacturing lot. The sampler uses principles of diffusion and colorimetry where CO passively diffuses into the tube and causes the reduction of sodium palladosulfite to palladium metal.[29] The result is a grayish stain inside the tube, which corresponds to a cumulative dose of CO.

Three CO passive diffusion samplers were set up and left in place for 48 hours in each household to measure exposures to CO. Two tubes were for personal sampling: one worn in the breathing zone of the mother and one worn by a child under the age of 5 years who was enrolled in the parent c-RCT. The third tube was set up in the kitchen, at the breathing height (approximately 1.5 m) of the mother and close to where she stands during cooking. The times of tube breakage and capping, which marked the beginning and termination of sampling, respectively, were recorded on data sheets.

For all but 93 study subjects, tubes were placed in cloth coverings with an attached string for hanging around the neck, and pinned in the subject's breathing zones. The cloth covering was for comfort, protection of tubes from direct sunlight,[25] and has been shown to not affect CO measurements.[30] For 93 of the mothers (50 control and 43 intervention stove users) in this study, CO tubes were placed in vests worn in the breathing zones of subjects. These vests held real-time CO monitors and 48-hour time integrated $PM_{2.5}$ samplers for personal air sampling and the data for these measurements are presented elsewhere.[28] CO tubes from these 93 mothers are included in the final data set of this study. Subjects were instructed to keep the tubes on at all times and to place them by their bedside at night.

Upon return to the field station, tubes were stored in a $+4°C$ refrigerator before and after reading. Tubes were read by two of the authors (AAC and SMH) and an arithmetic mean was taken. Reading took place in a white, bright fluorescent tube lit laboratory room at a table with a white surface. The least squares regression technique developed by Smith *et al.*[25] for Randomized Exposure Study of Pollution Indoors and Respiratory Effects (RESPIRE) was employed. In brief, the length of stain was measured for each tube and converted to a cumulative exposure in ppm-hour. ppm-hour was subsequently divided by the total sampling time to

Table 1 Description of passive diffusion CO tubes deployed in intervention and control households during household air pollution exposure assessment in rural Peru

	Intervention homes			Control homes		
	Child	Mother	Kitchen	Child	Mother	Kitchen
Total number of tubes	172	182	182	173	197	197
Broken	9	5	0	10	18	2
Lost	5	14	1	11	17	0
Unavailable during pick-up	4	2	2	4	8	4
Sampling error	0	0	55	0	0	42
Tubes with stains	0	0	11	0	0	29
Final sample size	154	161	113	148	154	120

obtain CO personal exposures and kitchen levels. Questionnaires were administered on the second day of air sampling to obtain data on household air pollution, respiratory health-related symptoms, demographics, daily activities, and commuting habits.[28]

Human subjects and ethical issues statement

This study was approved by the Internal Review Boards at University of Georgia, the Centers for Disease Control and Prevention of the United States, and by the ethical committee of the IIN and the ethical review board at the Cayetano Heredia University in Peru. The demographic and socio-economic data had previously been collected in the parent study (ClinicalTrials.gov Identifier: NCT00731497) which had received clearance from the independent ethics committees of IIN and the ethical review board of University of Basel, Switzerland (Ethikkommission Beider Basel). Signed consent forms were obtained from all participating households. During May 2010, workshops were held to present study results and hold discussions with the communities.

Statistical Analysis

SAS version 9.1 (SAS Institute, Cary, NC, USA) was used for all data analysis. Sampling duration ranged from 2399 (40 hour) to 3442 (57 hour) minutes, with a mean of 2860 minutes (48 hours). All CO data were natural log transformed for regression analyses. SAS PROC GLM was used to fit general linear models which assess the impact of select variables on personal mother and child CO exposures as seen in equation (1):

$$y_{ij} = \mu_j + \beta_1 X_{1ij} + \ldots + \beta_p X_{pij} + \varepsilon_{ij} \quad (1)$$

Here y_{ij} is the log CO exposure/concentration measured on the *i*th subject/kitchen with the *j*th stove type; μ_j is the population mean log CO for the *j*th stove type at the average value of the covariate; β_p is the effect of X_p, the covariate under consideration and ε_{ij} is a mean zero, constant variance error term assumed to follow a normal distribution.

The passive CO tubes placed in kitchens were found to have reached the 600 ppm-hour upper limit after 48 hours for 46/113 intervention households and 59/120 control households. Hence for kitchen concentrations only, due to right censoring of approximately 47% of the data, PROC LIFEREG was used to fit linear models to the kitchen data. These models explain the linear relationship between kitchen CO concentrations and select variables in the form given in equation (1). The LIFEREG procedure implements maximum likelihood estimation and inference in the presence of censored data. Ignoring the censoring (e.g. by fitting the model via least squares as in PROC GLM) would result in biased parameter estimates, incorrect standard errors, and invalid statistical inference.

Information on covariates was obtained from the administered questionnaires on the second day of HAP sampling. Covariates were included in GLM models individually to test for significant associations with personal or kitchen CO. The final group of covariates considered for inclusion in the full models include mother's age, time spent playing with child, cooking time, number of people in household, presence of smokers in household, age of stove, wood type used in cooking, kitchen environment, mother's frequency of cleaning ashes from stove, distance of household to road, and stove type (Table 4). Backward elimination was the process used for model selection. Starting with all candidate variables, we removed non-significant variables other than stove type using a chosen model comparison criterion ($P=0.2$). Variables were deleted one at a time if the P values for their corresponding regression coefficients were higher than 0.2. This process was repeated until only variables that were statistically significant remained in the model. The effect of stove type was retained in all models to allow comparison of CO exposures and concentrations across stove type.

Kitchen environment refers to the nature of the cooking area which was categorized as enclosed (four full walls and a roof) or open (less than four walls, or open to the outside). Wood type refers to the most common wood type cooked with by the various wood stove users in this study. Cooking time refers to the estimated amount of time mothers spent cooking a meal on a typical day and it is a way to estimate proximity to the cooking fire. The time mothers spent in playing with their children during the day was also assessed to determine whether this affected their respective exposures. This variable was chosen as a proxy for how often the mother and child are together on any given day. This variable was considered to be potentially important because if playing time did not overlap with cooking time, it could impact personal exposures.

Stove type was retained in all models in order to compare personal exposures and kitchen log CO concentrations across stove types (first by control and intervention stoves and then by specific stove types). Comparisons were done with an F test for equal means across all stove types for all models. Then for personal mother and child exposures, Dunnett's test for pairwise comparisons of each stove type with OPTIMA FL-I as the reference stove was performed. Cooking time and time mothers spent playing with their children were centered at their respective means across households in all regression models. Finally, to examine how well the tubes predict personal and kitchen area measurements, Spearman correlation coefficients (*r*) between personal mother and child CO exposures and between personal (mother and child) and kitchen CO measurements were calculated separately by stove type.

Results

Household characteristics

Demographic and household information for households using various stove types are presented in Table 2. Except for differences in television ownership and the number of smokers present in households, the study population was comparable with respect to their socio-demographic and kitchen characteristics (Table 2). Households with NGO stoves and self-improved by household stoves owned fewer television sets: 5% and 6% respectively compared to 17%, 29%, and 30% for the OPTIMA FL-II, FL-I, and traditional stoves, respectively (Table 2). Households with self-improved stoves had 19% of family members who smoked, compared to 7–8% of smokers in households with other stove types (Table 2). All variables mentioned above are comparable among control and intervention households in the entire c-RCT population[26] and were not statistically significant during subsequent regression analysis. *Eucalypto* (eucalyptus) was the most common wood type used for cooking by 34% ($n=32$ OPTIMA FL-I stoves) to 65% ($n=13$ self-improved by household stoves) of the women in this study (Table 2).

CO Exposures and Concentrations

Summary statistics of unadjusted CO exposures and kitchen concentrations in intervention and control households and across stove type are presented in Table 3. It must be noted that our study population included mothers who used gas stoves ($n=4$), and these have been excluded from subsequent analysis.

Regression analysis: control and intervention households

There were no statistically significant differences between intervention and control households for any of personal CO exposures: mother ($F=0.02$; df=1, 288; $P=0.89$) and child ($F=0.49$; df=1, 287; $P=0.48$). Likewise, for kitchen concentrations, the model revealed no differences in kitchen CO concentrations in intervention and control households (Chi-square=0.28; df=1; $P=0.59$). Owing to the lack of statistical significant differences between control and intervention measurements, for the remainder of the results, we analyze data by stove type: OPTIMA FL-I, OPTIMA FL-II, NGO, and traditional and stoves which were self-improved by the households.

Table 2 Demographic and household information by stove type for study households in rural Peru

	Stove type*				
Characteristic	OPTIMA FL-I† ($n=92$)	OPTIMA FL-II† ($n=64$)	NGO‡ ($n=25$)	Self-improved by household ($n=21$)	Traditional ($n=96$)
Mothers' characteristics					
Mean age (SD), years	30 (7.1)	31 (9.3)	31 (8.0)	27 (7.4)	29 (6.6)
Mean time spent playing with child (SD), hours	0.9 (0.8)	0.8 (0.6)	0.7 (0.4)	0.7 (0.5)	0.8 (0.6)
Mean cooking time (SD), hours	3 (1.0)	3 (0.9)	3 (0.6)	3 (1.0)	3 (1.1)
Household characteristics					
Mean number of people in household (SD)	5 (1.5)	5 (1.8)	5 (1.4)	4 (1.3)	5 (1.5)
Number of households with smokers, *n* (%)	6 (7%)	4 (7%)	2 (8%)	4 (19%)	8 (8%)
Own a television set, *n* (%)	22 (29%)	7 (17%)	1 (5%)	1 (6%)	25 (30%)
Kitchen characteristics					
Length of stove use *n* (%)					
<1 year	92 (100%)	64 (100%)	9 (53%)	11 (69%)	16 (21%)
1–2 years	0	0	5 (29%)	1 (6%)	15 (20%)
3–5 years	0	0	2 (12%)	3 (19%)	16 (21%)
>5 years	0	0	1 (6%)	1 (6%)	29 (38%)
Most common wood type, *n* (%)					
Eucalypto	32 (34%)	24 (41%)	9 (39%)	13 (65%)	38 (40%)
Kitchen environment: number of kitchen walls, *n* (%)					
Four walls	69 (75%)	40 (63%)	18 (72%)	17 (85%)	77 (88%)

Note: *Total sample sizes for number of people in the household, mother's age, cooking time, and time spent playing with child for the various stove types are as follows: OPTIMA FL-I ($n=92$), OPTIMA FL-II ($n=64$), NGO ($n=25$), self-improved by household ($n=21$), and traditional ($n=96$). For all other variables, the sample sizes and percentages reflect the total number of responders for each stove category.

†Functionality level (FL) I refers to an OPTIMA-improved stove in good conditions, and FL-II refers to an OPTIMA-improved stove in need of repairs (e.g. re-plastering).

‡NGO: three main NGOs had improved stoves; JUNTOS-National cash transfer program. Part of the requirements is that families must build an improved stove with a chimney; SEMBRANDO and ADIAR are NGOs that work in nearby communities.

Table 3 Forty-eight-hour Unadjusted personal CO exposures and kitchen CO concentrations measured in all control and intervention homes

Stove type	Statistics	Child	Mother	Kitchen
Intervention	GM[§] (95% CI) ppm	1.0 (0.9–1.1)	1.4 (1.3–1.6)	7.3 (6.4–8.2)
	n	154	161	113
OPTIMA FL-I*	GM (95% CI) ppm	1.0 (0.6–1.4)	1.5 (1.1–1.9)	7.2 (6.6–7.8)
	n	93	97	67
OPTIMA FL-II*	GM (95% CI) ppm	1.1 (0.8–1.5)	1.5 (1.1–2.0)	7.4 (6.2–8.9)
	n	61	64	46
Control[†]	GM (95% CI) ppm	1.1 (0.9–1.2)	1.4 (1.3–1.6)	7.3 (6.4–8.3)
	n	148	154	120
NGO[‡]	GM (95% CI) ppm	1.1 (0.3–1.9)	1.5 (0.7–2.3)	6.3 (5.3–7.3)
	n	25	25	18
Gas	GM (95% CI) ppm	0.8 (0–3.5)	0.9 (0–3.8)	4.0 (0–9.4)
	n	4	4	4
Self-improved by household	GM (95% CI) ppm	0.7 (0–1.7)	1.2 (0.3–2.1)	7.0 (5.8–8.2)
	n	21	23	17
Traditional	GM (95% CI) ppm	1.1 (0.7–1.5)	1.5 (1.1–1.9)	7.6 (7.1–8.1)
	n	98	102	81

Note: *Functionality level (FL) I refers to an OPTIMA-improved stove in good conditions, and FL-II refers to an OPTIMA-improved stove in need of repairs (e.g. re-plastering).
[†]Geometric mean for all control stoves does not include gas stoves.
[‡]NGO: three main NGOs had improved stoves; JUNTOS-National cash transfer program. Part of the requirements is that families must build an improved stove with a chimney; SEMBRANDO and ADIAR are NGOs that work in nearby communities.
[§]GM refers to geometric mean.
Sample sizes represent the total number of subjects from whom CO measurements were taken. For mothers $n=154$ and 161, and for children, $n=148$ and 154 in control and intervention homes, respectively.

Regression analysis: specific stove types

Personal CO exposures: mothers

Summary statistics for covariates included in our models are presented according to stove type (Table 4). The regression model for mothers in this study revealed that personal CO exposures did not differ significantly across stove types (overall F test statistic=0.24, $P=0.92$, Table 5A). All other variables were found to be statistically insignificant using backward elimination. Dunnett's test revealed no significant difference between mean mother personal log CO exposures using the OPTIMA FL-I stove ($n=92$) and any other stove type [$P=1.00$, 1.00, 0.85, and 1.00 for OPTIMA FL-II ($n=59$), NGO ($n=23$), self-improved by household ($n=20$), and traditional ($n=96$) stoves, respectively, Table 5A].

Personal CO exposures: children

Although not found to be statistically significant, children's CO exposures were lower in households with self-improved stoves and higher for all other stove types (overall F test statistic=1.67, $P=0.16$, Table 5B). Dunnett's test revealed no significant differences in mean child personal CO exposures between OPTIMA FL-I ($n=92$) and other stove types [$P=1.00$, 0.79, 0.34, and 0.56 for OPTIMA FL-II ($n=59$), NGO ($n=22$), self-improved by household ($n=19$), and traditional ($n=95$) stoves, respectively, Table 5B].

For children in this study, the regression model showed that time mothers spent cooking during the sampling period was marginally associated ($P=0.0504$) with their CO exposures (Table 5B). The model estimated a decrease of 0.11 ppm (SE=0.056)

Table 4 Effects of all variables in the full model for each sample type. Test statistics and *P* values for modeled effects are provided for personal exposures and kitchen concentrations of log CO. All covariates listed in the table were included in an initial model and then backward elimination was used to arrive at the final model for each sample type

	Child		Mother		Kitchen	
Variable	*F* test statistic	*P* value	*F* test statistic	*P* value	Chi-square statistic	*P* value
Mother's age	0.70	0.41	1.22	0.27	0.05	0.82
Time spent playing with child	1.50	0.22	0.26	0.61	0.43	0.51
Cooking time	4.57	**0.03**	6.04	**0.02**	3.82	**0.05**
Number of people in household	0.22	0.64	0.84	0.36	1.39	0.24
Presence of smoker in household	0.02	0.90	0.07	0.80	0.10	0.75
Age of stove	0.06	0.81	2.06	0.15	0.03	0.86
Wood type	0.26	0.77	0.34	0.71	1.83	0.40
Kitchen environment	1.54	0.22	2.31	**0.04**	9.26	0.16
Mother's frequency of cleaning ashes from stove	0.55	0.70	0.76	0.55	1.82	0.77
Distance of household to road	0.33	0.92	1.26	0.28	1.91	0.93
Stove type	0.57	0.68	0.70	0.60	2.75	0.60

in children's personal CO exposures for every additional hour spent cooking by their mothers. Children's age in years was centered at its mean across households to investigate the effect of age, and possible interactions between child's age and mother's time spent cooking. However, neither of these effects were statistically significant (P=0.7363 and 0.1943), for the main and interaction effects, respectively. The interaction between cooking time and the time mothers spent playing with children also did not reach statistical significance (F test statistic=0.94, P=0.33).

Kitchen CO concentrations

Kitchen CO concentrations were marginally associated with the type of wood used for cooking (Chi-square=5.52, df=2, P=0.06, Table 5C). Study

Table 5 Model derived analysis of variance and geometric means (with 95% confidence intervals) for 48-hour time integrated personal CO exposures and kitchen concentrations

A		Mothers' personal CO exposures		
Variable		Num DF, Dem Df§	*F* test statistic	*P* value
Stove type		4, 285	0.24	0.92
Variable	*n*	Mean CO (ppm)	95% CI (ppm)	Ho: mean=OPTIMA FI-I¶
OPTIMA FL-I*	92	1.5	1.3, 1.7	–
OPTIMA FL-II*	59	1.5	1.2, 1.8	1.00
NGO†	23	1.5	1.1, 2.0	1.00
Self-improved by household	20	1.3	0.9, 1.7	0.85
Traditional	96	1.5	1.3, 1.7	1.00
B		**Children's personal CO exposures**		
Variable		Num DF, Dem Df	*F* test statistic	*P* value
Stove type		4, 281	1.67	0.16
Cooking time‡		1, 281	3.86	0.05
Variable	*n*	Mean CO (ppm)	95% CI (ppm)	Ho: mean=OPTIMA FL-I
OPTIMA FL-I*	92	1.0	0.9, 1.2	–
OPTIMA FL-II*	59	1.0	0.8, 1.2	1.00
NGO†	22	1.2	0.9, 1.6	0.79
Self-improved by household	19	0.7	0.5, 1.0	0.34
Traditional	95	1.2	1.0, 1.3	0.56
C		**Kitchen CO concentrations**		
Variable		Df§	Chi-square	*P* value
Stove type		4	1.68	0.79
Wood type		2	5.52	0.06
Variable	*n*	Mean CO (ppm)¶	95% CI (ppm)	*P* value
Stove (reference=OPTIMA FL-I*)	67	7.2	6.1, 8.5	–
OPTIMA FL-II*	46	7.4	6.2, 8.9	0.81
NGO†	18	6.3	4.7, 8.5	0.55
Self-improved by household	17	7.0	4.9, 10.2	0.53
Traditional	81	7.6	6.5, 8.9	0.43
Wood type (reference=other types of wood‡)	77	6.7	5.6, 7.8	–
Eucalypto (Eucalyptus sp)	82	7.4	6.4, 8.6	0.22
Hualango (Acacia sp)	68	8.4	7.2, 9.8	0.02

Note: *Functionality level (FL) I refers to an OPTIMA-improved stove in good conditions, and FL-II refers to an OPTIMA-improved stove in need of repairs (e.g. re-plastering).
†NGO: three main NGOs had improved stoves; JUNTOS-National cash transfer program. Part of the requirements is that families must build an improved stove with a chimney; SEMBRANDO and ADIAR are NGOs that work in nearby communities.
‡Cooking time refers to the estimated cooking time of mothers in study region that have been centered by subtracting the mean cooking time from individual cooking times.
§Num DF and Dem DF refer to numerator and denominator degrees of freedom, respectively. DF in part c refers to the degree of freedom for the model.
¶Ho: mean=OPTIMA FL-I refers to the probability of the mean personal CO exposure from other stove type=OPTIMA FL-I stove users mean CO exposure using Dunnett's test.
— denotes non-applicable results
Sample size represents subjects who had complete questionnaire information on wood type and stove type only rather than the total number of subjects from whom CO measurements were taken. For mothers, n=151 and 139, and for children, n=151 and 136 in control and intervention homes, respectively.

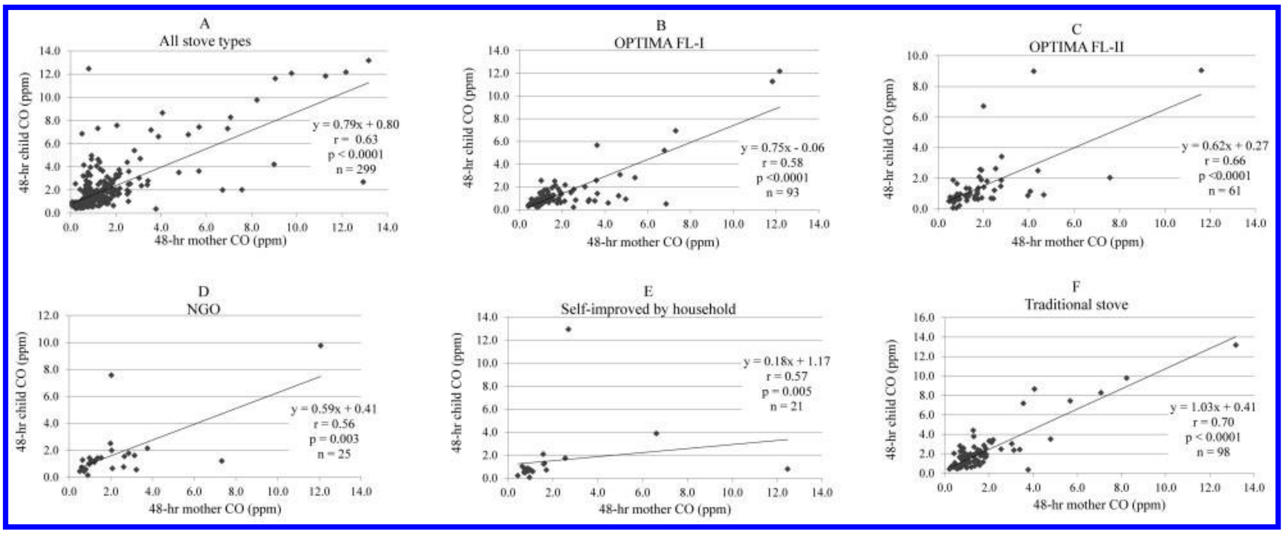

Figure 1 Spearman correlation coefficients (*r*) between personal mother and child CO exposures for all intervention and control households (A). Then separate plots are presented by stove type: OPTIMA FL-I (B), OPTIMA FL-II (C), NGO (D), self-improved by household (E), and traditional (F) stoves.

subjects used different types of wood as fuel including pine, *eucalypto* (eucalyptus), cypress, *talla*, *huayo*, and *hualango*. After preliminary analysis, firewood types were grouped into *eucalypto* ($n=82$), *hualango* ($n=68$) and other wood types ($n=77$). Households that used *hualango* had higher and statistically significant ($P=0.02$) kitchen CO, whereas households that used *eucalypto* did not ($P=0.22$) when compared to other wood types (Table 5C). There was no difference in kitchen CO between households that used *eucalypto* compared to *hualango* ($P=0.19$). Households using *hualango* had 8.4 (7.2–9.8) ppm (mean with 95% CI), those using *eucalypto* had 7.4 (6.4–8.6) ppm and those using other wood types had 6.7 (5.6–7.8) ppm of CO in the kitchen (Table 5C).

Passive tube correlations

Spearman correlation coefficients (r) between personal CO exposures and kitchen CO levels are presented by stove type used in households in Fig. 1. All mother and child measurements were correlated ($r=0.63$, $P<0.0001$, $n=299$; Fig. 1A). The correlation coefficient value between mother and child personal samples was larger for all control stoves when compared with all intervention stoves (control: $r=0.67$, $P<0.0001$, $n=145$; intervention: $r=0.60$, $P<0.0001$, $n=154$).

Among intervention households, correlations between personal mother and child CO exposures were moderate to low (Fig. 1B and C), with the strength of the correlation slightly increasing with decreasing stove quality ($r=0.58$, $P<0.0001$, $n=93$ for OPTIMA FL-I compared to $r=0.66$, $P<0.0001$, $n=61$ for OPTIMA FL-II). Personal mother and kitchen samples were moderately to weakly correlated ($r=0.23$, $P<0.03$, $n=67$ for OPTIMA FL-I compared to $r=0.29$, $P=0.02$, $n=46$ for OPTIMA FL-II). Child and kitchen samples had a weak correlation ($r=0.38$, $P=0.0002$, $n=67$) for households with OPTIMA FL-I and a marginal statistically significant correlation for OPTIMA FL-II households ($r=0.23$, $P=0.08$, $n=46$).

For personal mother and child's correlation in the control arm of the intervention, households using traditional stoves (Fig. 1F) had a larger correlation ($r=0.70$, $P<0.0001$, $n=98$) than households using NGO (Fig. 1D) and self-improved by household (Fig. 1E) stoves ($r=0.56$, $P=0.003$, $n=25$ and $r=0.57$, $P=0.005$, $n=21$, respectively). Kitchen CO levels were marginally correlated with mothers' personal exposures ($r=0.47$, $P=0.06$, $n=17$) and significantly correlated with children's exposures when stoves were self-improved by household ($r=0.51$, $P=0.04$, $n=17$).

Discussion

Carbon monoxide measurements in this study did not demonstrate statistically significant differences across the various stove types in both arms of the intervention. The lack of differences in CO exposures between control and intervention households seems contrary to results reported in other chimney stove intervention studies.[14,25,31–34] While some of the intervention studies mentioned above assessed HAP exposures before and soon after stove installation, other stoves were monitored frequently and stoves were routinely fixed. In this cross-sectional study, we present data on HAP measurements of chimney stoves referred to as OPTIMA stoves that had been in use, on average, for several months. Some of these stoves had not been maintained, and may have been improperly used. Our results have potential implications for intervention studies in the developing world aiming to answer the question of stove performance months after installation and use.

Findings from RESPIRE demonstrate that a well-maintained stove decreased CO exposures by 50%

and kitchen concentrations by 90% with a corresponding 22% decrease in physician diagnosed pneumonia in children.[35] It must be noted that these households had stoves that had been installed for on average of 18 months, with weekly visits where repairs and maintenance were provided as needed.[35] An ideal stove must be affordable and simultaneously have high heating efficiency and low, non-health-damaging emissions.[4,36] Lessons from current global stove intervention studies point to the fact that cookstove related woodsmoke exposures can be reduced; however, these reductions need to be larger and must be sustained for several years to yield greater public health benefits.[35,37]

One goal of the c-RCT was to determine impact of the OPTIMA stoves in reducing acute lower respiratory infections in children between the ages of 6 and 36 months. Children in homes with OPTIMA FL-II stoves had CO exposures of 1.0 (0.9–1.2) ppm. In the Gambia, a study of 1115 children reported a mean CO exposure of 1.04 ± 1.45 ppm ($\pm$SD).[23] Children in households using the plancha chimney stoves in the RESPIRE study had a geometric mean of 1.0 (2.4) ppm (SD).[25] These CO tube measurements from children in the above mentioned studies are similar to results in the current study; however, the levels of HAP experienced by OPTIMA stove users may not result in significant health improvements compared to control stove users due to two main reasons. First, there were no significant differences between control and intervention household measurements; hence, health impacts between the two groups are expected to be similar. Second, findings from an exposure-response analysis from the RESPIRE study suggest that larger HAP exposure reduction is needed to observe reductions in child mortality from acute lower respiratory infections.

Our results also suggest children's CO exposures decreased (marginally) with increasing time mothers' spent during cooking. This finding could be spurious although possible reasons could be due to decreased CO emissions from the fire presumably after cooking has occurred or after cooking, children were further away from the cookstoves. A third reason for decreased child exposure with increased cooking time could be due to maternal mis-reporting, that children were further away from cookstoves during cooking events. However, we do not have data from time activity diaries of subjects to corroborate these possible explanations.

All personal mother and child CO exposures were correlated amongst our study population. This agrees with the literature that suggests that when children data are unavailable, data from their mothers can be used to estimate exposures of the children especially in a high HAP setting.[22] As expected, kitchen CO measurements were higher compared to personal measurements; and mothers' personal exposures were higher compared to children's. Also as seen from our results, kitchen measurements need to be used with caution where personal measurements are unavailable, since kitchen levels can inform but can overestimate personal exposures.[8,13,25]

Aside from the significant correlation between personal exposures, our results showed an increase in the value of the correlation coefficient with a corresponding increase in stove deterioration. For example, among intervention stove users, the correlation between personal mother and child exposures among OPTIMA FL-II stove users had a slightly higher value compared to OPTIMA FL-I. Also among control stove users, the correlation among traditional stove users had a higher value compared to households with chimney stoves. This suggests stronger correlation between personal exposures with increasing HAP levels,[22] and is a finding which needs to be corroborated by other studies.

A number of reasons may have led to high HAP levels in intervention households in our study. Adequate stove design, manner of stove use (i.e. whether it is used continuously, properly and exclusively), as well as maintenance over time, are key factors in HAP mitigation. Design and construction of efficient cookstoves is also key to reducing and sustaining low exposure levels.[35] It must be noted that cookstoves, with use, are expected to degrade with time even with adequate maintenance.[38] Hence, there is the need to design and construct cookstoves where factor in the high temperatures and pressure factors will impact its degradation. Additionally, it is important to recognize the effect, if any, of altitude on the combustion efficiency of cookstoves.

Improper stove use is another important factor. If fitted pots are not placed in tightly sealed pot holes on the stove top during cooking, combustion emissions can leak into the indoor environment. The same is true for openings designed for fuel insertion. Any uncovered chimney stove opening may introduce into the household environment emissions akin to an open fire. Conversely, although OPTIMA stove users were not specifically asked whether they had used open fires during the sampling period, this is a possibility given that even gas stove users in this study reported the use of firewood during the sampling period. Findings from participatory observational surveys revealed a reported 90% (212/236) daily use of the OPTIMA-improved stove after about 7 months (median 7.4, IQR=6.6–8.1 month).[28] However, there is the possibility these households used open fire stoves throughout that period. Lack of exclusive and continuous stove usage can introduce more HAP into the kitchen environment and needs to be addressed if an intervention program is to be successful and sustained over time.

It has been documented that intervention stoves can improve health when properly used.[12,35,39] It is important then to determine the stove's performance at the time of installation[31] and also months and years after installation, as the intervention stove may possibly introduce greater HAP if improperly maintained and used. Also the importance of functionality levels within stove type is important in HAP exposure assessment. Clark *et al.*[40] suggest the utility of stove functionality levels to be more representative of HAP exposures and indoor levels. They note the importance of assessing the condition of the stoves rather than a mere comparison between traditional and improve stove type.[40] Our results indicate that after an average of 7 months of use, OPTIMA stoves (whether they were in need of repairs or not) did result in significantly lower personal CO exposures and kitchen levels when compared to control stoves. Hence, stove maintenance and functionality are both essential in understanding HAP exposures.[36]

Results from our study seem to suggest that stoves which were self-improved by households had lower HAP measurements, almost akin to gas stove measurements, although this was not statistically significant. We do not know the reason for this finding. However, we can surmise that these stoves may have had better durability, lower emissions or perhaps the subjects took more responsibility for the maintenance of these personally constructed stoves. The qualities of any control stove type must also be assessed in future studies as they could provide insight on potential stove designs in local communities.

Firewood type is another important factor in the quest to reduce HAP.[41] In our study, households using *hualango* (Acacia sp.) as firewood had higher mean kitchen CO compared to other wood types used. High biomass combustion by-products such as PM and CO are associated with biomass fuel use;[1,42] hence, this finding is expected. With the move to decrease HAP on the international horizon, the need for utilizing cleaner energy (from wood to eventually using gas and electricity) should be considered in conjunction with the design of cookstoves.

This study is timely even as The Global Alliance for Clean Cookstoves (GACC) continues to build momentum in the effort to reduce HAP and the adverse health effects associated with it. The GACC, led by the United Nations Foundation, has the goal of 100 million households adopting clean and efficient cookstoves by the year 2020.[43] The success of household air pollution mitigation programs will depend not just on the number of disseminated stoves, but on the number of stoves that are adequately designed, continually, exclusively and properly used, as well as maintained over time.[12–14]

Limitations

Although valuable lessons can be gleaned from our study, single 48-hour measurements limit our ability to detect the temporal and within household variability in exposure.[23,44,45] This is important for a site such as San Marcos, which is subject to considerable seasonal climate changes that may impact the combustion efficiency of cookstoves, and the types of available cooking fuel. Future studies should consider taking repeated measurements over time.[23,25] Also information from time activity diaries may help future studies to derive better estimates of exposure.

It is also essential to be able to make population inferences based on larger sample sizes for each stove type. Control groups in this study, by design of the parent study, consisted of a diverse range of stoves with varying air pollution levels. Future studies with the primary aim of assessing HAP exposure need to limit the number of control groups or ensure adequate sample sizes in each stove category.

Another limitation is the timing of the HAP exposure assessment. Study households were not sampled before and immediately after chimney stove installation and this prevented evaluation of the effectiveness of the OPTIMA stoves soon after installation. Additionally, a change in kitchen sampling procedure led to the loss of nearly 30% of kitchen samples and demonstrated the importance of accurately quantifying exposure.

Finally, air pollution levels in some study households may have contributed to some tubes reaching maximum stain length. Ideally, the tubes should be monitored after deployment to detect any high levels of exposure or other sampling problems[23] and replaced if the upper limit of detection is reached. However, this was a hard feat to accomplish given substantial traveling distances to study households in the 51 community clusters.

Conclusion

After installation of study promoted chimney stoves in San Marcos, Cajamarca region, Peru, personal CO exposures and kitchen levels measured with passive diffusion tubes did not differ significantly between intervention and control households. Personal mother CO exposures were correlated with children's exposures. These results point to the fact that where data are unavailable, mothers' exposures can be used to predict children's exposures especially in high-pollution settings. Results suggest that proper and exclusive chimney stove use, maintenance of stoves as well as changes to fuel types may be necessary in reducing CO and more generally, HAP exposures.

Acknowledgements

Sincere appreciation goes to: study subjects who allowed us to sample in their homes; the IIN staff in

Lima who helped with logistical issues of storing and transporting samples; Hector Verastegui for compiling the data set for the randomized control trial; field coordinator, Selenne Flores, the field workers and volunteers, who enabled the successful campaign of this study; Adam Gray who helped with pre- and post-field work data analysis and management and Christopher Fitzgerald who conducted field training; Regina Saavedra, Gayle Lennox, and Anna Hejl for their help with data compilation and Dr Jan Hattendorf and Dr Olorunfemi Adetona for their invaluable input during manuscript preparation.

This exposure assessment was made possible by NIH Research Grant #5-D43TW005746-04 funded by the Fogarty International Center, National Institutes on Environmental Health Services, National Institute for Occupational Safety and Health, and the Agency for Toxic Substances and Disease Registry. Additional funding was from the College of Public Health at the University of Georgia (UGA), the UGA Graduate School, and the Interdisciplinary Toxicology Program at UGA. This work was also supported by the UBS Optimus Foundation for the field work of the parent study (ISRCTN28191222) and grant #2T42OH008436 from NIOSH through the University of Alabama, Birmingham.

Disclosure

The authors declare no conflicts of interest.

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