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Chimney stoves modestly improved indoor air quality measurements compared with traditional open fire stoves: results from a small-scale intervention study in rural Peru

S.M. Hartinger[1,2,3], **A.A. Commodore**[5], **J. Hattendorf**[2,3], **C.F. Lanata**[1,4], **A.I. Gil**[1], **H. Verastegui**[1], **M. Aguilar-Villalobos**[6], **D. Mäusezahl**[2,3], and **L.P. Naeher**[5]

[1]Instituto de Investigación Nutricional, Av. La Molina 1885, Lima 12 - Perú [2]Swiss Tropical and Public Health Institute, P.O. Box, CH-4002 Basel, Switzerland [3]University of Basel, Petersplatz 1 CH-4003 Basel, Switzerland [4]Universidad Peruana de Ciencias Aplicadas, Prolongación Primavera 2390, Monterrico Lima 33 – Perú [5]University of Georgia, Athens, GA, USA [6]Asociación del Aire Ambiental, Lima, Perú

Abstract

Nearly half of the world's population depends on biomass fuels to meet domestic energy needs, producing high levels of pollutants responsible for substantial morbidity and mortality. We compare carbon monoxide (CO) and particulate matter ($PM_{2.5}$) exposures and kitchen concentrations in households with study promoted intervention (OPTIMA-improved) stoves and control stoves in San Marcos Province, Cajamarca Region, Peru.

We determined 48hr indoor air concentration levels of CO and $PM_{2.5}$ in 93 kitchen environments and personal exposure, after OPTIMA-improved stoves had been installed for an average of seven months. $PM_{2.5}$ and CO measurements did not differ significantly between OPTIMA-improved stoves and control stoves. Although not statistically significant, a post-hoc stratification of OPTIMA-improved stoves by level of performance revealed mean $PM_{2.5}$ and CO levels of fully functional OPTIMA-improved stoves were 28% lower (n=20, $PM_{2.5}$, 136μg/m^3 95%CI 54–217) and 45% lower (n=25, CO, 3.2ppm, 95%CI 1.5–4.9) in the kitchen environment compared to the control stoves (n=34, $PM_{2.5}$, 189μg/m^3, 95%CI 116–261; n=44, CO, 5.8ppm, 95%CI 3.3–8-2). Likewise, although not statistically significant, personal exposures for OPTIMA-improved stoves were 43% and 167% lower for $PM_{2.5}$ (n=23) and CO (n=25) respectively. Stove maintenance and functionality level are factors worthy of consideration for future evaluations of stove interventions.

Please address all correspondence to Luke P. Naeher, Ph.D, M.S, Department of Environmental Health, College of Public Health, University of Georgia, Room 150, Environmental Health Science Building, Athens, GA 30602–2102, USA. lnaeher@uga.edu.

Author Contributions:
The principal investigators: Hartinger, Naeher
Study concept and design: Hartinger, Naeher, Lanata, Mäusezahl
Obtained funding: Hartinger, Naeher
Acquisition of data: Hartinger, Commodore, Naeher, Aguilar-Villalobos
Data entry: Gil, Verastegui, Hartinger, Commodore
Analysis and interpretation of data: Hartinger, Hattendorf, Mäusezahl, Commodore, Naeher
Drafting of the manuscript: Hartinger, Hattendorf, Mäusezahl.
Statistical analysis: Hartinger, Hattendorf
Critical revision of the manuscript for intellectual content: Mäusezahl, Hattendorf, Naeher, Lanata, Aguilar-Villalobos

Keywords

household air pollution; carbon monoxide; particulate matter; improved chimney stoves; Peru

Introduction

Approximately half of the world's population continues to depend on biomass fuels in order to meet their basic energy needs for cooking, boiling water, lighting and heating (Rehfuess et al. 2006, Martin et al. 2011). Burning biomass fuels in un-vented stoves and closed rooms produces high levels of pollutants (Fullerton et al. 2008; Smith et al. 2000) beyond the USEPA National Ambient Air Quality Standards (EPA, 2005). According to the WHO, household air pollution (HAP) is responsible for about 1.6 million premature deaths per year due to incomplete biomass fuel combustion (Smith et al. 2004), representing nearly 3% of the overall disease burden in developing countries. This large burden affects mainly women and small children (Rehfuess et al. 2006; Díaz et al. 2007) due to their continuous indoor exposure to health damaging pollutants, including several carcinogenic compounds, hazardous gases (CO and NOx) and fine particles while cooking (Naeher et al. 2007). These pollutants increase the risk of acute lower respiratory infections, chronic obstructive pulmonary disease and may cause lung cancer (from coal stoves), asthma, low birth weight and other adverse birth outcomes (Po et al. 2011; Siddiqui et al. 2008; Tielsch et al. 2009), neurodevelopment impairments (Dix-Cooper et al. 2011), cardio-vascular and other inflammatory condition (Baumgartner et al. 2011; Clark et al. 2011; McCracken et al. 2011), eye diseases, such as cataract and blindness (Smith and Mehta 2003; Saha et al. 2005) and headaches (Díaz et al. 2007).

In Peru almost 93% of the rural population relies on biomass fuels for cooking and heating (INEI, 2007). Exposure-response analysis shows the relationship between combustion particles and respiratory illnesses and the need to reach low levels of HAP from biomass fuel use to successfully reduce adverse health effects including pneumonia (Smith and Peel 2010; Smith et al. 2011). One of the most cost-effective HAP control measures is the use of improved chimney stoves (Naeher, 2009), given that they are adequately designed, installed, maintained and continuously used. A recent randomized controlled trial found significant reductions in severe pneumonia cases for children under 18 months after receiving a woodstove with chimney (Smith et al. 2011).

The Global Alliance for Clean Cookstoves (GACC) initiative launched on September 2010 (GACC, 2011) has provided a platform where different entities can converge into a common goal of deploying 100 million clean and efficient cookstoves by 2020. The GACC is supported by private, public and non-profit partners which aim to overcome the market barriers and achieve the established goal. In Peru, two years prior to this initiative, several organizations aimed to install/deploy 500,000 certified biomass improved chimney stoves by 2011 (Bodereau, 2011); by the end of 2011 around 300,000 improved stoves were built. However, in many cases the success of these HAP mitigation programs, like the Peru national stove program, is often measured by the number of installed stoves rather than

adoption, continuous utilization and maintenance by the users over time (Armendáriz-Arnez et al. 2010, Bodereau, 2011).

As part of a community cluster randomized controlled field trial carried out in the Cajamarca region of Peru, we installed 250 improved chimney stoves (called OPTIMA-improved stoves), to determine their impact in reducing acute lower respiratory infections (ALRI) in children between the ages of six and 36 months when compared to 253 households with control stoves (Hartinger et al. 2011). The current study describes household air pollution levels of $PM_{2.5}$ and CO in 93 of the 503 kitchen environments and personal exposures of mothers at a median of seven months after the OPTIMA-improved stoves were installed. The effectiveness of the OPTIMA-improved stoves of improving air quality is compared to air pollution levels in control household using a number of stoves including traditional stoves.

Methods

Setting

The study was carried out in the northern highlands of Peru (Province of San Marcos, Cajamarca Region), between the months of June and August 2009 (dry season). The altitude ranges between 2200 and 3900 meters above sea level, with temperatures fluctuating between 7 to 25ºC and relative humidity between 59 to 73% as measured during the study period.

The population comprised mostly of farmers, typically living in small houses made out of earthen floors and adobe walls, with three or more people sleeping together in the same room. The majority of the population relied on firewood for cooking and heating. The wood was usually gathered from nearby shrubs, parcels of land or bought from the town or from local landowners. The cost of one load of wood (approx. 20kg) was about US$ 2.5 in local currency and usually lasted three to four days for cooking. Traditional stoves or open fires are usually located inside the house in an unventilated kitchen area (Hartinger et al. 2011). There were no relevant sources of outdoor or of indoor pollution (other than from open fire cooking) in study homes, and in the community.

Study Design and Enrolment

We conducted a cross-sectional HAP exposure assessment within the framework of a community-randomized controlled trial (c-RCT, parent study) of 51 communities in the San Marcos Province (Hartinger et al. 2011, Hartinger et al. 2012). The aim of the parent study was to evaluate an integrated home-based environmental intervention package (IHIP) against childhood diarrhea and respiratory infections. The interventions comprised of an improved chimney stove – called OPTIMA and a kitchen sink, complemented by the promotion of a solar disinfection method as a home-based water treatment (HWT), hand washing and kitchen hygiene. In an effort to increase the desire to use the stove and foster sustained user compliance for future users and recipients of the interventions during the trial, we conducted a pilot study in seven communities outside the study area. For this pilot study, we tested several potential designs and consulted on cooking habits and preferences to

provide a user-friendly stove design which met their household and cooking needs. The families thus commented on operation and maintenance issues, size of the mouth of the stove, number of furnaces and heat emission needs per furnace (Hartinger et al. 2012).

All OPTIMA-improved stoves were installed between October 2008 and January 2009 and evaluated for this study 6 and 8 months later (median 7.4 IQR = 6.6–8.1 month). All households from the parent study were eligible to participate, if they complied with the following criteria: (1) the stoves had to be located in a in-house kitchen environment (at least three full walls and a roof over the kitchen), (2) the households had to be within a half-hour walking distance from a road in order to transport the air sampling equipment and (3) the mother or caretaker had to agree to wear the equipment to measure air quality and comply with the project instructions for the duration of the study (48hr) and agree to sign the informed consent forms.

In the current study, households were conveniently selected from participating households of the parent study. Since we had a limited number of air quality equipment, we stopped the enrolment in each of the 51 communities after two households consented to participate. We enrolled a total of 93 households: 43 households had an OPTIMA-improved stove installed, 48 belonged to the control group of households using diverse cooking stoves (open fires N=35, self-improved stoves N=7, supplied by NGO N=6) and two household belonged to a neighboring community were the NGO *Sembrando* had implemented an improved stove program. We selected the two NGO household for comparison reasons and sampled them using the same selection criteria as described above. The selected households compared well to the general cohort (N=503). We found that 15% of our selected household and 9% of the non-selected households had a person who smoked; 45% of our selected household and 49% of the non-selected households has a completely closed kitchen environment. Cooking practices were similar among mothers in the study; our selected mother reported spending a mean of 189 minutes (SD +/− 73) and our non-selected households a mean of 169 (SD +/− 42) for cooking in a day.

Given that the control arm of the parent study included a diversity of stove types, the control households we selected for the current study also reflect this heterogeneity. This heterogeneity comprised the following stove types: ‘open fire’, ‘self-improved by household’ and ‘supplied by NGO’. The ‘open fires’ included the “Tulpia” stove, the most common traditional three-stone fire stove type in this area. The ‘self-improved by household’ type includes all households which constructed a stove without support or advice from any organizations or institution. The “supplied by NGO” type included stoves provided by the national program *JUNTOS* or independent NGOs such as *ADIAR*. These stoves were originally enrolled into the control arm of the RCT as control stoves which were improved by an NGO by the time enrolment for this study took place.

After the HAP exposure assessment (CO and $PM_{2.5}$ measurements), we decided to classify post-hoc all OPTIMA-improved stoves. The stoves were then stratified into two functionality levels: FL-I that were at the time of the assessment in good running conditions (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, etc).

Among all OPTIMA-improved stoves, 159/250 (64%) were classified as FL-I, and 91/250 (36%) as FL-II. Among household participating in this study, 28/43 (66%) were classified as FL-I, and 15/43 (35%) as FL-II. All OPTIMA-improved stoves were re-visited 9 months (median 9.3 IQR= 9.0–9.7 month) after installation and repaired as needed by the original stove builders.

Household Air Pollution Measurements

Personal exposure sampling—Personal air sampling equipment was placed in vests worn in the breathing zones of mother/caretakers (hereafter mothers) for 48hr. These vests held real time CO monitors and 48hr time integrated $PM_{2.5}$ samplers. The sampling inlets were placed on the chest halfway between the throat and the diaphragm. Subjects were instructed to keep the vests on at all times except when sleeping or washing clothes, in which case the equipment was placed next to them. They were instructed to place vests on a nightstand next to their bed during the night. To measure real-time CO exposure, each vest held a Draeger Pac III datalogger and a CO-specific sensor (Draeger Safety Inc., Pittsburgh, PA), set to record concentration levels at 30-second intervals. Forty-eight-hour time-integrated $PM_{2.5}$ samples were collected using particle-size-selective Triplex Cyclones (BGI Inc., Waltham, MA, Model SCC 1.062) and SKC universal sampling pumps (SKC Inc, Eighty Four, PA, Aircheck® XR5000), set to pull air at 1.5L per minute. Pre-flows and post flows were taken for each pump and all equipment was calibrated and cleaned per manufacturer protocol. After 48 hours, the vests were retrieved; starting and completion times (runtime) were recorded at the household for each piece of equipment, and air sampling calculated thereof. Filters for each sampling day were placed in individual cassettes and stored in Ziploc bags in a −20°C freezer at the study site.

Kitchen environment air pollutant sampling—A stationary sampling box was placed indoors and at approximate breathing height (1.5m) adjacent to were the mother/caretaker stands for cooking. Each box contained a sampling pump (SKC Inc, Eighty Four, PA, Aircheck® 2000), a 12V battery, a filter/cyclone sampling train attached to Tygon® tubing, and a Pac III CO monitor (Draeger Safety Inc., Pittsburgh, PA). The same protocol as for the personal filters was used. After 48 hours, the equipment and sampling box were retrieved; runtimes were recorded at the household for each piece of equipment, and sampled filters were transported in a cooler from the household and stored in the lab freezer at −20°C.

Community air pollutant sampling—A central outdoor location was selected in San Marcos town to serve as a fixed sampling site, providing background levels of both CO (real time) and $PM_{2.5}$ (48hr time integrated) concentrations. A sampling scheme similar to that used in the study homes was set up outside a window at this stationary outdoor site. To measure real-time CO, a Langan CO monitor (Langan Products Inc., Elmwood Park, NJ, model T15n) was used. Forty-eight-hour time-integrated $PM_{2.5}$ was measured using a SKC Air Check pump with a BGI Triplex Cyclone and Teflon-coated glass fibre filter.

Laboratory, field and open blanks—Two laboratory filter blanks were collected at the time of the pre- and post weighing. During each sampling week, field blanks were collected to adjust for background noise in the equipment, and the open blanks were collected to

account for noise in the filter media. There were a total of 44 field and open blanks (mean ± SE): 28 field blanks (0.013 ± 0.002mg) and 16 open blanks (0.004 ± 0.001mg). There was approximately one field blank for each sampling day and an open blank for every other sampling day. Final particulate mass values for study samples have been adjusted for field filter blank values by subtracting the average of the field blank (13μg) from the post weights. The difference of the pre and adjusted post weights, together with the average volume of air sampled over the 48hr period were used to calculate mass concentrations. All mass concentrations are presented in $\mu g/m^3$.

Analysis of pumps and filters

To better describe daily variability in our exposure measurements (Smith et al. 2004), the homes were sampled for a 48hr period. The $PM_{2.5}$ measurements were only considered valid if the equipment ran for at least 2160 minutes. Filters were collected, stored at the site lab and transported on cold packs to the University of Georgia for gravimetric analysis. The filters were desiccated in climate-controlled conditions (21 ± 0.1°C; 40.9 ± 1.5% relative humidity) for 48hr prior weighing. Following the EPA's Quality Assurance Guidance Document (2005) each filter was weighed twice before and after sampling using a Cahn C-35 microbalance with a sensitivity of ±1μg. $PM_{2.5}$ concentrations (weight/cubic meter air sampled) were derived by dividing the average mass of each filter weight by the intake volume of sampled air.

Compliance and observational data

We measured compliance and maternal cooking behaviour using questionnaires, conducting participatory observations and assessing compliance during monthly training visits as part of the c-RCT parent study. Questionnaires were administered on the second day of the indoor air sampling scheme. They were used to assess personal exposure to air pollution, behavioral habits (household chores, child care), mobility (including activities in- and around the home, attending the fields and commuting) cooking, cleaning, personal and household characteristics. We measured the kitchen volume and took window and door measurements (in cm).

Participatory observational data was collected as part of the c-RCT parent study in 236 (108 intervention and 128 controls) out of the 503 participating households. Such observational data were available for 18 out of 43 households with OPTIMA-improved stoves and 25 of the 48 control households in the present study. The mother's behavior was observed during the preparation of a lunch meal (9am–1pm) and recorded. Field workers remained at the household between three to four hours. This information provided input on the mother's cooking practices and usage of the stove. Additionally, we measured compliance in all OPTIMA-improved stove homes (N=43), routinely monitored actual usage, maintenance and problems with the stoves, with the aim of determining daily use and the mothers perception of the maintenance level of their stoves.

Statistical Analysis

Data were analyzed using STATA 10.0. Personal and kitchen $PM_{2.5}$ and CO means, standard deviations, confidence intervals and medians were calculated by stove type.

Skewed data was log-transformed where appropriate. Scheffe's multiple comparison tests were used to calculate significant levels between stove types. Results were considered to be statistically significant at $p<0.05$.

Spearman correlation coefficients were calculated for air quality measurements; between kitchen $PM_{2.5}$ and CO measurements and between kitchen and personal $PM_{2.5}$ and CO measurements. Linear regression models were created to determine potential covariates that could explain the variation in air quality measurements in the kitchen environment and personal exposure. CO and $PM_{2.5}$ measurements were log- transformed for the bivariate and multivariable regressions. The variables with P values less than 0.25 in the bivariate model were included in the multivariable model.

Ethics

The study was approved by the Nutrition Research Institute (IIN) ethical review board, the institutional review boards at the University of Georgia and Emory University and the ethical review board at the Cayetano Heredia University. Written informed consent for this study was obtained from each study participant. 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, EKBB). The participant information provided and the informed consent obtained for the current study included the information that previously collected data would be used and asked for the respective permission.

Results

We enrolled a total of 93 households. Forty three households had an OPTIMA-improved stove installed, 48 belonged to control stove households and two belonged to a neighbouring community with *Sembrando* stoves. The total "N" for the analysis of each group varies due to measurement errors and equipment failure. In total we exclude 27 $PM_{2.5}$ kitchen measurements (14 controls and 13 intervention), 14 personal $PM_{2.5}$ measurements, (6 intervention and 8 control), 8 CO kitchen measurements (4 intervention and 4 control), and 7 CO personal measurements (4 intervention and 3 control).

The study groups were comparable with respect to their socio-demographic and kitchen characteristics (table 1): 86% of the kitchens had four walls, and 43% had no windows in the kitchen area. Both groups used *Eucalyptus sp.* as the main source of firewood for cooking (table 1). Community air pollution sampling showed that the average background outdoor-$PM_{2.5}$ level during the study period was 13μg/m^3 for $PM_{2.5}$ and 0.6ppm for CO.

Arithmetic mean and median kitchen- and personal exposure to air pollutants are presented in figure 1 and table 2. Overall, $PM_{2.5}$ mean values for OPTIMA-improved stoves (148μg/m^3 95%CI 88–208, N=30) in the kitchen environment were 22% lower compared to control stoves (189μg/m^3 95%CI 116–261, N=34), however the differences were not statistically significant. Similarly, for CO in the kitchen environment, the overall difference was 19% (4.7ppm 95%CI 2.8–6.6ppm, N=39 *vs* 5.8ppm 95%CI 3.3–8.2ppm, N=44), which

was not statistically significant. At the personal level we did not observe a statistically significant difference in CO levels between users cooking with an OPTIMA-stove and in the control stove (35 open fires, 7 self-improved stoves, 6 supplied by NGO). However, $PM_{2.5}$ at personal levels were 20% lower among OPTIMA-stove users (table 2) compared to the control group, but this difference was also not statistically significant.

Larger differences in pollution concentrations were observed within the OPTIMA-improved stove functionality levels (figure 2 and table 2). FL-I stoves had 28% lower $PM_{2.5}$ (136μg/m^3 95%CI 54–216, N=20) and 45% lower CO (3.2ppm 95%CI 1.5–4.9, N=25) in the kitchen environment measurements compared to control stoves, however statistical significance was not reached (table 2). Similarly, personal exposure to PM and CO were 43% and 17% lower respectively, with no statistical significance observed compared to control stoves.

$PM_{2.5}$ and CO concentrations were moderately correlated in simultaneous measurements in the kitchen environments (Spearman's rank correlation coefficient $r_s = 0.63$, n = 61, p<0.0001). A significant correlation between $PM_{2.5}$ and CO was also found when we stratified the data by study group (OPTIMA-improved stove: $r_s = 0.70$, n=27, p<0.0001; Control: $r_s = 0.65$, n= 32, p<0.0001). Likewise, statistically significant correlations were found between kitchen and personal $PM_{2.5}$ ($PM_{2.5}$: $r_s = 0.52$, n=59, p<0.0001) and kitchen and personal CO concentrations (CO: $r_s = 0.64$, p<0.0001, n=84).

A bivariate analysis (table 3) showed that Acacia, a type of firewood (coefficient 1.0 95%CI 0.1; 1.9), was a significant determinant for predicting $PM_{2.5}$ concentrations in the kitchen environment. However, we did not observe any other predictor values for kitchen CO concentrations or for personal exposure levels of CO or $PM_{2.5}$. The multivariable analysis did not reveal any significant predictors for any of the personal or kitchen measurements of CO and $PM_{2.5}$. The R values were low, indicating that the predicting factors could only explain a low proportion of the overall variance.

Findings from the participatory observational surveys (n=236) revealed a reported 90% (212/236) daily use of the OPTIMA-improved stove and an observed lower lunch cooking times (50min *versus* 66min; p<0.0001) compared to those using other cooking stoves. Additionally, 96% of the mothers using the OPTIMA-improved stove (n=43) reported performing other activities while cooking, such as washing cloths, feeding the animals, cleaning, tending their children or visiting a neighbor. Finally, mothers' from the control households perceived stove-related smoke exposure more strongly as a nuisance than mothers using the OPTIMA-improved stove (table 4).

Discussion

We investigated the effectiveness of a beneficiary-designed improved stove in reducing exposure to household air pollution within the framework of a community-randomized trial. About seven months after initial introduction of the OPTIMA-improved stoves, $PM_{2.5}$ and CO concentrations were measured as household air pollution and compared to control stove

households which comprised of three-stone open fire stoves, self-improved by household stoves or supplied by NGOs

Overall $PM_{2.5}$ and CO arithmetic mean values for the kitchen environment and personal exposure were lower in the improved stoves group, but the difference lacked statistical significance. Also, despite a limited sample size and lack of statistical significance, when OPTIMA-improved stoves were stratified by functionality levels, fully functional improved stoves appeared to have lower $PM_{2.5}$ and CO values in both kitchen and personal measurements compared to OPTIMA-improved stoves in need of repair. On the other hand, faster cooking times and the possibility of performing other activities while cooking were much welcomed benefits derived from the improved stove confirming our findings from the exploratory pilot phase developing the parent trial (Hartinger et al. 2012).

Previous studies have yielded inconsistent evidence. In two randomized controlled field trials Smith and colleagues found in Guatemala up to 90% lower CO concentrations in the intervention group (Smith et al. 2011) whereas Burwen and Levine found no noteworthy reduction in rural Ghana (Burwen and Levine 2012). In two before and after stove installation studies, reductions between one third and two thirds were observed (Dutta et al. 2007, Masera et al. 2007, Fitzgerald et al. 2012)

We captured ambient air CO and $PM_{2.5}$ levels as a background against which to compare changes in indoor levels in control and intervention households. The purpose for community air pollution measures was to report the general ambient air levels in San Marcos in order to observe any changes throughout the study period which may have impacted our results. No such trends during the study period were observed.

In order to understand the variation in $PM_{2.5}$ and CO concentrations of our improved stove, we classified them post-hoc into FL-I and FL-II and observed a trend of increasing pollutant concentrations with declining stove performance due to structural damages from use. These included observed cracks or leaks of the general structure of the stove and around the potholders, the broken parts of the internal combustion chamber, or the chimney structure as well as the malfunction of the chimney valve. In categorizing the improved stoves the $PM_{2.5}$ and CO exposures at kitchen and personal levels could be better predicted compared to using a less sensitive dichotomous categorization of stove type (OPTIMA *vs* Control). This indicates the importance of presenting stove performance in terms of reduction of $PM_{2.5}$ and CO in relation to current stove conditions or levels of operation and maintenance needs.

Although the use of local materials and monthly training on the importance of repairs facilitated the self-maintenance of the stoves, OPTIMA-improved stoves were partly well-kept with post-hoc repairs revealing that 36% (91/250), of the stoves were not properly maintained. Further assessment of our compliance data revealed a gap between the mother's perception of appropriate maintenance and the actual repairs needed for the stove. The use of stove type to assign or determine exposure may be flawed given the varying HAP concentrations among households in our study which employed the same stove type. Clark et al. (2010) suggest the utility of stove levels may 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 (Clark et al. 2010).

Improved stove adherence could also prove to be a challenge. Our reported high daily use was due to the perceived convenience gains (shorter cooking times, reduced wood consumption and limited supervision) and matched traditional cooking practices (Hartinger et al. 2012). In Central Mexico, the Patsari wood cook stove reported a 50% adherence after 10 months (Romieu et al. 2009; Ruiz-Mercado et al. 2011). We expect adherence to OPTIMA-improved stove use to be higher given that after a median of 7.4 months (IQR: 6.6–8.1)OPTIMA-improved stove usage ranged at 90% although we cannot exclude dual use of open fire stoves during the study period.

In Bangladesh, of 105 biofuel-using households that had considered improved stoves, nine (8.5%) decided to use them, while the rest did not adopt improved stoves due to the large initial investment, inconvenience of the stoves or other reasons.(Dasgupta et al. 2006). Our results suggest that stove repair and maintenance are important in the success of any HAP mitigation program. Moreover, the metric of success needs to include the number of stoves that are adequately designed, as well as continually and exclusively used (Naeher, 2009, Smith et al. 2011, Clark et al. 2010, Dutta et al. 2007).

The type of wood used for cooking was associated with $PM_{2.5}$ concentrations in the kitchen in the bivariate analysis only. This nonetheless underscores the importance of combining clean energy use with new clean cookstove designs in the control of HAP. Mothers using improved stoves reported spending less time cooking a lunch meal while performing unrelated cooking activities, inside and outside the kitchen environment. Subjects performing other tasks in or around the kitchen may experience exposures which outweigh potential exposure risk reductions due to shorter cooking times (Künzli, 2011).

Our study experienced some equipment failure of the $PM_{2.5}$ pumps which were occasionally not recording measurements for the full 48hr battery lifetime due to insufficient charging of batteries caused by power fluctuations at the field site. Further, the study had no means to validate the correct and uninterrupted wearing of the mother’s equipment vest during the 48hr collection periods. Nonetheless, consistent with another study, we found moderate correlations between personal and kitchen $PM_{2.5}$ and CO measurements (Bruce et al. 2004). Finally, and since this study commenced after installing the OPTIMA-improved stoves, no data of baseline emissions of pollutants were available for before and after comparisons.

Consistent with findings from an HAP study in Mexico, the mothers in our study clearly identified perceptible smoke as a daily nuisance mentioning frequent eye irritations as a key sequel (Romieu et al. 2009). Mothers perceived smoke reduction from the OPTIMA-improved stove which ranged along a 45% reduction of $PM_{2.5}$ particles of the personal exposure for well maintained stoves after being in daily use for an average of seven months and a 17% reduction on CO, although these reductions were statistically insignificant. However, future impact evaluations of household air pollutions interventions should consider assessing both, outdoor and indoor determinants of air pollution risk exposures, since improved chimney stoves remove household air pollutants into the community

environment, which may cause significant human exposure outdoors particularly in densely populated areas (Künzli, 2011).

Overall, the reductions of indoor air $PM_{2.5}$ and CO concentrations from the OPTIMA-improved stove were lower than expected. At the overall mean concentrations measured in the intervention group ($PM_{2.5:}$ 148μg/m^3 and CO: 4.7ppm), the reduction in HAP is not expected to result in significant health improvements (Smith et al. 2011). In their analysis of outdoor air pollution, tobacco smoke, and active smoking studies Smith and Pillarisetti (2012) demonstrate that at about 150 ug/m^3 average annual $PM_{2.5}$ exposures for example, the CVD risk slowly increases to the level experienced by active smokers. In our study, kitchens with intervention stoves had overall mean $PM_{2.5}$ concentrations of 148μg/m^3 while control kitchens had a mean of 189μg/m^3. Hence the risk is essentially the same at these two mean $PM_{2.5}$ levels although the mean concentration measured in intervention kitchens appears to be lower compared to control kitchens. Given the large global population which experiences exposures between second-hand smoke and active tobacco smoke exposure levels, lower HAP levels must be achieved and sustained to yield greater public health benefits (Smith et al. 2011; Smith and Peel 2010).

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Practical Implications

The use of improved chimney stoves did not result in significantly lower levels of personal exposure to products of incomplete combustion from biomass fuels when compared to control stoves. However, stove performance may vary among stove types and it is usually linked to operation and maintenance, perception, user satisfaction and sustainability of these stoves. Thus, stove maintenance levels should be used as proper indicators of efficacy and performance and not only stove type. Additionally, long-term benefits and sustainability of programs are harnessed through education of all household members, focusing mainly on awareness, importance of household air quality and sustained stove functioning. Therefore stove program implementers and evaluators should not only need to look at achieving air pollution thresholds, but convenience gains and social impact on families.

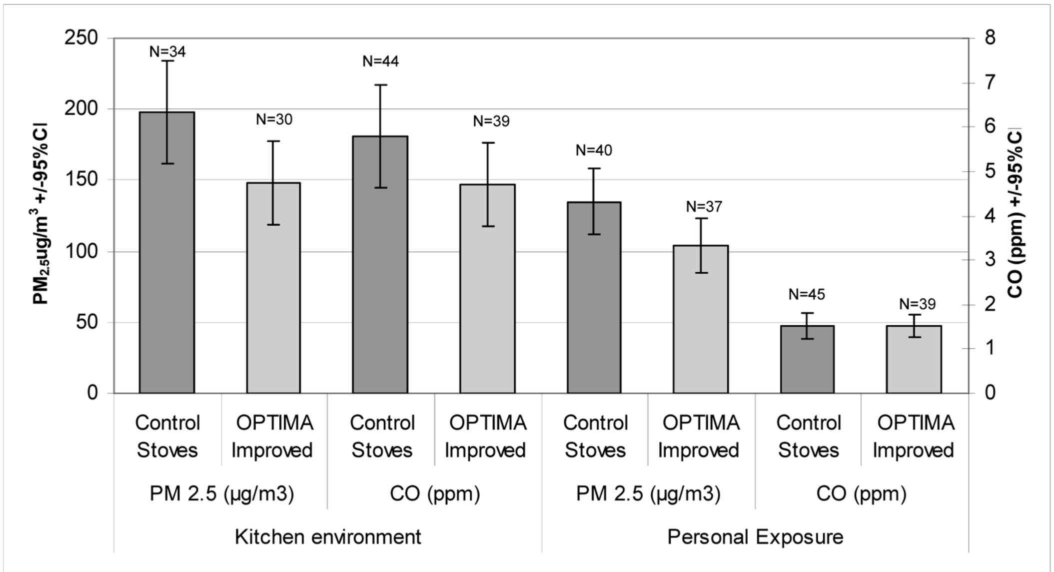

Figure 1.

48 hr PM2.5 and CO mean concentrations between traditional and OPTIMA-improved stove for kitchen environment and personal exposure

Control Stoves: include all control households, (open fires, Self-improved by household and NGO).

OPTIMA Improved: includes all OPTIMA-improved stoves functionality levels (FL-I and FL-II)

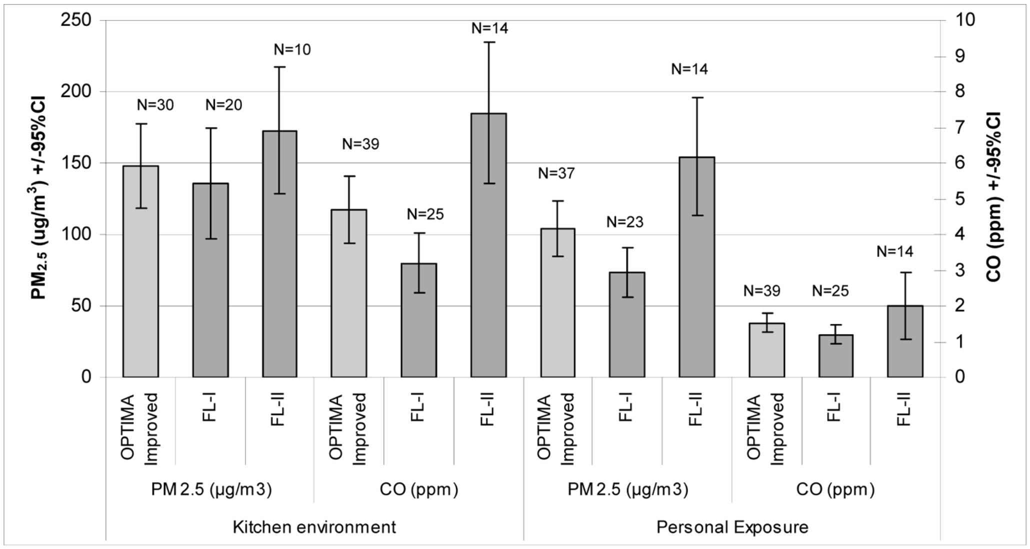

Figure 2.

48hr PM 2.5 and CO concentration in OPTIMA-improved households separated into functionality levels.

OPTIMA Improved: includes all OPTIMA-improved stoves functionality levels (FL-I and FL-II)

FL-I: stoves in good running conditions (plastered stove and no visible leaks when in use)

FL-II: stove in need of repairs (re-plastering, filling cracks)

Table 1

Basic socio-demographic and kitchen characteristics from the study participants of the San Marcos province. Data are means (SD) or numbers (%).

	Optima-Improved Stove (N=43)	Control stoves (N=48)
Socio demographic characteristics		
Number of family members¶	4.7 (1.2)	4.7 (1.3)
Housewife as main activity of mother	39 (91%)	45 (94 %)
Farming as main activity of the family head	34 (79%)	40 (83 %)
Family members that smoke cigarettes	4 (9%)	10 (21 %)
Kitchen characteristics		
Kitchen volume (m^3) †	29 (18.6)	37.2 (25.7)
Type of wood used for cooking §		
Eucalipto (*Eucalyptus sp.*)	18 (42 %)	21(45 %)
Acacia *(Acacia macrantha)*	8 (19 %)	9 (19 %)
Chamana (type of wood)	3 (7 %)	6 (13 %)
Other	14 (33%)	11 (23%)
Kitchen windows §		
Completely closed - No windows	20 (47 %)	20 (43 %)
One window	20 (47 %)	20 (43 %)
More than one window or door opening	3 (7 %)	7 (15 %)
Number of kitchen walls §		
Four walls	40 (93 %)	40 (85 %)

¶N = 42 for traditional stove arm.

†N = 42 for Optima stove arm.

§N = 47 for traditional stove arm

Table 2

Air quality measured for 48hr CO and PM_2 in the kitchen and at personal level in relation to stove type and functionality levels in rural Peru

Sampling Location	Measurement	Stove Type	N	Mean	95% CI	Median	% difference	p-values[¶]
Kitchen environment	PM 2.5 (μg/m^3)	**Control Stoves** [*]	**34**	**189**	**116 – 261**	**116**	**reference**	
		Open Fire	24	211	116 – 305	139		
		Self-improved by household	6	117	3.7 – 230	93		
		NGO	4	166	0 – 559	50		
		OPTIMA Improved Stove ([*])	**30**	**148**	**88 – 208**	**102**	**22%**	**0.87**
		FL-I	20	136	54 – 217	77	28%	0.36
		FL-II	10	173	72 – 273	123	8%	0.98
	CO (ppm)	**Control Stoves**	**44**	**5.8**	**3.3 – 8-2**	**2.4**	**reference**	
		Open Fire	32	5.2	2.8 – 7.5	2.4		
		Self-improved by household	7	7.2	0 – 17.8	3.1		
		NGO	5	7.5	0 – 23.1	2		
		OPTIMA Improved Stove	**39**	**4.7**	**2.8 – 6.6**	**2.9**	**19%**	**0.39**
		FL-I	25	3.2	1.5 – 4.9	2.1	45%	0.60
		FL-II	14	7.5	3.2 – 11.7	5.5	−28%	0.29
Personal Exposure	PM 2.5 (μg/m^3)	**Control Stoves**	**40**	**129**	**82 – 176**	**94**	**reference**	
		Open Fire	28	145	90 – 200	116		
		Self-improved by household	7	135	0 – 320	59		
		NGO	5	35	0 – 72	40		

Sampling Location	Measurement	Stove Type	N	Mean	95% CI	Median	% difference	p-values[¶]
		OPTIMA Improved Stove	**37**	**104**	**64 – 144**	**55**	**20%**	**0.55**
		FL-I	23	74	38 – 109	40	43%	0.12
		FL-II	14	154	65 – 244	76	−19%	0.99
	CO (ppm)	**Control Stoves**	**45**	**1.4**	**0.8 – 2.0**	**0.6**	**reference**	
		Open Fire	32	1.5	0.8 – 2.1	0.7		
		Self-improved by household	7	1.8	0.0 – 5.0	0.5		
		NGO	6	0.5	0.1 – 0.8	0.4		
		OPTIMA Improved Stove	**39**	**1.5**	**1 – 2**	**1**	**−6%**	**0.59**
		FL-I	25	1.2	0.7 – 1.7	0.8	17%	0.74
		FL-II	14	1.9	0.9 – 3.2	1.2	−39%	0.32

*Control Stoves: includes all control households (open fires, Self-improved by household and NGO). NGO: Stoves build by non-governmental organisation

*OPTIMA-improved stoves: includes all OPTIMA-improved stoves functionality levels (FL-I and FL-II). FL-I: stoves in good running conditions (plastered stove and no visible leaks when in use. FL-II: stove in need of repairs (re-plastering, filling cracks)

Mean refers to arithmetic mean

¶Scheffe's multiple comparison test was used

Table 3

Bivariate and multivariable regression analysis of covariates for 48hr log-transformed CO and $PM_{2.5}$ levels of kitchen and personal exposure.

	Carbon monoxide (CO)			Particulate matter ($PM_{2.5}$)		
		Bivariate	Multivariable[a]		Bivariate	Multivariable[b]
Variable	**n**	**Coef (95%CI)**	**Coef (95%CI)**	**n**	**Coef (95%CI)**	**Coef (95%CI)**
Kitchen						
Stove type	83			64		
Control (reference)						
FL-I		−0.3(−0.9; 0.3)	−0.3 (−0.9; 0.2)		−0.7 (−1.4; 0.1)	−0.7 (−1.4; 0.1)
FL-II		0.6 (−0.1; 1.3)	0.6 (−0.1; 1.3)		−0.0 (−1.1; 1.1)	−0.4 (−1.4; 0.6)
Kitchen volume ($100m^3$)	79	−0.2 (−1.4; 1.0)	-	61	−1.6 (−3.2; −0.0)	−1.5 (−3.2; 0.2)
Wood used for cooking	85			65		
Eucalipto (reference)						
Acacia		−0.4 (−1.1; 0.4)			**1.0 (0.1; 1.9)**[*]	0.6 (−0.5; 1.7)
Other wood types		−0.1 (−0.7; 0.4)	-		0.4 (−0.4; 1.1)	0.2 (−0.6; 1.0)
Kitchen windows	82			63		
No windows (reference)						
One or more windows		−0.3 (−0.9; 0.2)	−0.5 (−1.0; 0.1)		−0.2 (−0.9; 0.5)	-
Number of kitchen walls	82			63		
Four walls (reference)						
Less than four walls		−0.0 (−0.8; 0.8)	-		0.3 (−0.8; 1.4)	-
Personal exposure						
Stove type	85			77		
Control (reference)						
FL-I		−0.2 (−0.8; 0.3)	−0.2 (−0.8; 0.3)		−0.6 (−1.2; 0.1)	−0.4 (−1.1; 0.3)

	Carbon monoxide (CO)			Particulate matter ($PM_{2.5}$)		
		Bivariate	Multivariable[a]		Bivariate	Multivariable[b]
Variable	**n**	**Coef (95%CI)**	**Coef (95%CI)**	**n**	**Coef (95%CI)**	**Coef (95%CI)**
FL-II		0.5 (−0.2; 1.2)	0.6 (−0.1; 1.2)		0.3 (−0.6; 1.1)	0.4 (−0.5; 1.2)
Kitchen volume (100m^3)	79	0.3 (−0.9; 1.5)	-	74	−0.4 (−1.9; 1.1)	-
Time spent cooking (hrs)	81	−0.1 (−0.6; 0.4)		75	−0.4 (−1.1; 0.2)	−0.4 (−1.0; 0.3)
Does the mother perform other activities while cooking? (no = reference)	85	0.1 (−0.6; 0.7)		78	−0.1 (−0.9; 0.8)	-
Wood used for cooking	85			78		
Eucalipto (reference)						
Acacia		−0.5 (−1.2; 0.2)	−0.6 (−1.2; 0.08)		−0.1 (−1.0; 0.8)	-
Other wood types		−0.3 (−0.8; 0.3)	−0.4 (−0.9; 0.2)		0.1 (−0.6; 0.8)	-
Kitchen windows	82			76		
No windows (reference)						
One or more windows		0.1 (−0.4; 0.6)	-		0.3 (−0.4; 0.9)	-
Number of kitchen walls	82			74		
Four walls (reference)						
Less than four walls		−0.1 (−0.9; 0.7)	-		0.3 (−0.7; 1.3)	-

[a] Kitchen: n=82, R^2=0.09; Personal: n=82, R^2=0.09

[b] Kitchen: n=61, R^2=0.14; Personal: n=75, R^2=0.06

* Asterisks indicate statistically significance ($P < 0.05$)

- refers to variables not included in the multivariate models

Bivariate regression analysis refers to linear models which include the outcome variable and only one predictor variable. Multivariable regression analysis refers to linear models which include the outcome variable and all predictor variables listed in the table.

Table 4

Mothers' cooking behaviour and smoke exposure perceptions of 93 study participants in rural Peru. Data are means (SD) or numbers (%).

	Optima Improved Stove	Control Stoves
	N=43	**N=47**
Mothers' behaviour and perceptions		
Mother performs other activities while cooking[¶]	38 (96 %)	21 (56 %)
Hours the stove was lit[§]	9.1 (4.0)	9.2 (3.8)
Mother's self report of minutes spent cooking per day	187 (75)	201 (84)
Perceived exposure to smoke from motor vehicles		
Low	29 (67 %)	34 (72 %)
Medium	2 (5 %)	5 (11 %)
High	2 (5 %)	6 (13 %)
Does not know	10 (23%)	2 (4%)
Perceived exposure to smoke from kitchen stoves		
Low	26 (60 %)	11 (24 %)
Medium	7 (16 %)	15 (32 %)
High	5 (12 %)	19 (40 %)
Does not know	5 (12 %)	2 (4 %)

[¶]N = 38 for Optima stove and 37 for traditional stove arm.

[§]N = 38 for Optima stove arm and 45 for traditional stove