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Traditional and Improved Stove Use on Household Air Pollution and Personal Exposures in Rural Western Kenya

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Abstract

Background—Over 40% of the world's population rely on solid fuels for heating and cooking. Use of improved biomass cookstoves (ICS) has the potential to reduce household air pollution (HAP).

Objectives—As part of an evaluation to identify ICS for use in Kenya, we collected indoor air and personal air samples to assess differences between traditional cookstoves (TCS) and ICS.

Methods—We conducted a cross-over study in 2012 in two Kenyan villages; up to six different ICS were installed in 45 households during six two-week periods. Forty-eight hour kitchen measurements of fine particulate matter ($PM_{2.5}$) and carbon monoxide (CO) were collected for the TCS and ICS. Concurrent personal CO measurements were conducted on the mother and one child. We performed descriptive analysis and compared paired measurements between baseline (TCS only) and each ICS.

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Results—The geometric mean of 48-hour baseline $PM_{2.5}$ and CO concentrations in the kitchen was 586 μg/m^3 (95% CI: 460, 747) and 4.9 ppm (95% CI: 4.3, 5.5), respectively. For each ICS, the geometric mean kitchen air pollutant concentration was lower than the TCS: median reductions were 38.8% (95% CI: 29.5, 45.2) for $PM_{2.5}$ and 27.1% (95% CI: 17.4, 40.3) for CO, with statistically significant relationships for four ICS. We also observed a reduction in personal exposures with ICS use.

Conclusions—We observed a reduction in mean 48-hour $PM_{2.5}$ and CO concentrations compared to the TCS; however, concentrations for both pollutants were still consistently higher than WHO Guidelines. Our findings illustrate that ICS tested in real-world settings can reduce exposures to HAP, but implementation of cleaner fuels and related stove technologies may also be necessary to optimize public health benefits.

Keywords

Cookstove; household air pollution; particulate matter; carbon monoxide

Introduction

Nearly half of the world's population rely on solid fuels for household heating and cooking (Bonjour et al. 2013). These solid fuels are typically burned in inefficient and poorly vented devices (e.g., open fires, traditional stoves). As a result, incomplete combustion can contribute to high levels of household air pollution (HAP) including carbon monoxide (CO) and varying sizes of particulate matter (PM), as well as other air toxics (Naeher et al. 2007). The 2010 Global Burden of Disease (GBD) study reported evidence that these pollutants are a risk factor for a range of diseases. Based on those health outcomes with the most robust evidence (e.g., child pneumonia, ischemic heart disease, lung cancer), an estimated 3.5 million deaths annually and 110 million disability-adjusted life years were attributable to HAP in 2010 (Lim et al. 2012). Recently, the World Health Organization and Institute for Health Metrics and Evaluation (IHME) reported similar estimates (GBD 2013; IHME 2015).

Several strategies make up the global effort to reduce exposures to HAP including designing and implementing improved cookstoves (ICS), improving household ventilation, increasing efficient fuel use, and changing cooking behaviors (Muralidharan et al. 2015). ICS designs have been tested in different countries (Commodore et al. 2013; Ojo et al. 2015), and most did not see the same ICS performance as in a laboratory setting. Considerations in interpreting exposure measurements include housing characteristics, type of biomass fuel, other sources of HAP, and personal factors (e.g., daily activity patterns).

With considerations in mind, we conducted a study which aimed to measure personal and kitchen concentrations of particulate matter with an aerodynamic diameter ≤2.5 μm ($PM_{2.5}$) and carbon monoxide (CO) from different ICS among study participants in Kenya; assess changes in these measurements with everyday ICS use; and using mixed methods (e.g., Stove Use Monitoring, questionnaires, qualitative data from focus groups, etc.), help document actual use and the reasons for the choices made by households in carrying out their cooking tasks. Given the complexity and detail inherent in the different methodologies, we report key components of the work separately (Stanistreet et al., 2015; Loo et al., 2016;

Lozier et al., 2016) and then synthesize overall findings and explanations in the paper by Pilishvili et al. (2016). The overall goal of this exposure paper was to provide information to support the identification of stoves emitting the lowest concentrations of $PM_{2.5}$ and CO, based on kitchen and personal measurements. It also serves as an account of the exposures that these stove models have in everyday rural Kenya.

Methods

Stove selection

We selected six ICS to use in the study based upon several criteria: 1) the stove was centrally manufactured, 2) there was no assembly required, 3) the stove could be moved easily, 4) the stove was designed to burn wood, and 4) the stove performed well (≥50% reduction in $PM_{2.5}$ emissions compared to the TCS) in the Water Boiling Test protocol conducted in the US Environmental Protection Agency (USEPA) National Risk Management Laboratory. The laboratory-based performance testing monitored pollutant emissions and measured cooking power, energy efficiency, and fuel use (Jetter et al. 2012). Based on these criteria, six stoves were selected: a chimney stove (Prakti), two electric fan stoves (Eco Chula, Philips), two improved rocket stoves (EcoZoom, Envirofit) and a locally-made ceramic rocket stove with a thermoelelectric powered fan (RTI TECA) (Table 1, Figure S1) (Stokes et al. 2012).

All selected stoves had a metal or brick combustion chamber, or a ceramic liner, that were used to contain the fires and control air flow through the stove. However, the technologies differed in that the EcoZoom, Envirofit, Prakti, and RTI TECA burned the fuel in a single combustion stage, and the Philips and Eco Chula stoves had a two-stage burning process. The stoves also differed in the following characteristics: air flow features (e.g., fan, chimney), fuel size, and type of fuel feeding system.

Study design and study population

This study was conducted between July 2012 and February 2013 in two villages in the Nyando Division of Nyanza Province in rural Western Kenya. We evaluated the six ICS for acceptability and field performance by conducting a single arm pre- and post-intervention study in the home setting. A cross-over design was employed to limit the inter-household variability in indoor air pollution levels related to factors such as the size of the household, housing structure, and household practices. Information on household inclusion criteria and selection are described by Pilishvili et al. (2016). Briefly, women aged 15 – 49 years old, who had one or more children aged <5 years, were identified as eligible participants; 45 eligible homes from the two villages were selected for participation. For the first two-week intervention period (“round”), of the study, a baseline assessment was conducted and all participating homes used their TCS. In the subsequent rounds, one new ICS was installed for a two-week period; the order in which the stoves were installed in each home was randomized. For the last two days in each round, measurements in the kitchen were conducted for $PM_{2.5}$ and CO. Concurrent personal measurements of CO were also conducted on the mother and the participating child. Each two-week round was followed by a one-week “washout” period, where only the TCS remained in the home; after the washout period, a new ICS was installed in the home for another round. With the exception of the

RTI TECA, the TCS remained in the home with the new ICS. Households were requested to use only the ICS during the two-week intervention periods. The study was approved by the Institutional Review Boards of the Kenya Medical Research Institute and the Centers for Disease Control and Prevention.

Data collection

Ambient Air Pollution Sampling—Ambient air monitoring was conducted for a 48-hour period each week at a secure central site in the two villages; sampling alternated weekly between the two villages. Both gravimetric and real-time $PM_{2.5}$ measurements were conducted using an E-Sampler, a light-scattering aerosol monitor that measures particles from 0.1 to 100 μm at one-minute intervals (Met One Instruments, Grant Pass, OR, USA). Concomitant real-time CO measurements were conducted using a GasBadge Pro (Industrial Scientific, Oakdale, PA, USA), with detection limits between 0 -1,500 ppm, also set at one-minute intervals.

Kitchen Air Pollution Sampling—Concurrent 48-hour measurements of gravimetric $PM_{2.5}$, real-time $PM_{2.5}$, and real-time CO were conducted indoors in the kitchen. All instrumentation was placed on the kitchen wall at approximately 1.5 meters above the ground and 1 meter from the stove. For the gravimetric $PM_{2.5}$ sample, a time-integrated sample was collected using an active pump (Casella, Buffalo, NY, USA) with a BGI Triplex Cyclone (BGI Incorporated, Waltham, MA, USA), and 37 mm Teflon membranes (Pall, Port Washington, NY, USA). The target flow rate was 1.5 L/min. Pre- and post-calibrations were made by either a rotameter (AALBORG, Orangeburg, NY, USA) or a Dry Cal DC-Lite (Bios International, Butler, NJ, USA) in the field. Gravimetric analysis of the filters was conducted after conditioning in temperature- and humidity-controlled environments for 24 hours.

Real-time $PM_{2.5}$ concentrations were also measured in the kitchen using a portable, battery-operated UCB Particle and Temperature Sensor that can measure $PM_{2.5}$ concentrations between 0.030 mg/m^3 and 25.0 mg/m^3. (UCB-PATS, Berkeley Air Monitoring Group, CA, USA). Berkeley Air Monitoring Group performed quality assurance on all samples and calibration of real-time instruments (Supplemental Materials).

Personal Air Pollution Sampling—Mother's and children's personal CO measurements were collected during the 48-hour monitoring period. The mother's CO was assessed with a real-time device (GasBadge Pro, Industrial Scientific, Oakdale, PA, USA) and a passive colorimetric device, Draeger Color Diffusion Tube (Draeger, Pittsburgh, PA, USA) that provides a time-weighted average (TWA) concentration with detection limits between 6 and 600 ppm-hours. Both instruments were attached to a string and worn around the mother's neck. Participating children only wore the passive tube which was placed in a holder attached to back of their clothing. The mothers and children were instructed to keep the monitors on their body at all times except when sleeping or bathing. At the end of the sampling period, the colorimetric reaction was measured in triplicate. Concentration (ppm) was calculated using the colorimetric reaction measurement and sampling time.

Kitchen Performance Test—A modified kitchen performance test (KPT) was conducted to estimate fuel consumption and fuel moisture for each 48-hour sampling period. Prior to the sampling period, mothers were asked to collect enough fuel to last at least three days. On the first day, the mass of each type of fuel collected was weighed using the ElectroSamson digital scale (Salter Brecknell, Fairmont, MN, USA) with a 25 kg capacity and 20 g resolution; the scale was calibrated by the Berkeley Air Monitoring Group prior to use. The wood moisture in each type of fuel was measured using an Extech MO210 wood moisture meter (Waltham, MA, USA) before each sampling period. Each sample was measured nine times to calculate the average moisture value.

Stove Use Monitoring—Stove Use Monitors (SUMs), which are low-cost temperature logging sensors, were installed on the kitchen wall, TCS, and ICS to serve as objective monitors of stove use (iButton model DS1922T, Maxim Integrated, USA) during the two weeks of ICS use, including the 48-hour sampling period. The findings from the SUMs are described by Lozier et al. (2016).

Kerosene lamp tests—After data collection, a separate two-day pilot test measuring $PM_{2.5}$ and CO was conducted on the two most common types of kerosene lamps used in the villages—the simple wick and hurricane lamps—to more fully characterize their potential contribution to HAP. Tests are described in the Supplemental Materials.

Questionnaires and qualitative assessment—Questionnaires were administered prior to ICS installation to gather baseline data, and again after each two-week ICD intervention period. Qualitative findings on stove characteristics and functionality, fuel consumption, health effects, and user acceptability were collected through in-depth structured interviews and focus group discussions can be found at Loo et al. (2016) and Stanistreet et al. (2015).

Assessment of sampling methods—As part of the study design, co-located samples of gravimetric and real-time $PM_{2.5}$ as well as real-time CO were collected in the kitchen. We examined the relationships among all methods. Regression analysis between the mean 48-hour $PM_{2.5}$ mass measured by the UCB and 48-hour TWA $PM_{2.5}$ gravimetric samples generated an R^2 of 0.86, with a slope of 1.16 (N=256) (Table S1). Due to the strong agreement between the two samplers, and the fact that PM gravimetric measurements are often considered a gold standard, we used gravimetric data for all $PM_{2.5}$ analysis in this paper. For the 5.7% missing $PM_{2.5}$ gravimetric values, we applied the following regression equation to estimate $PM_{2.5}$ concentration in μg/m^3 (1):

$$\mathrm{PM}_{2.5} = [0.746 * (\text{mean 48h } \mathrm{PM}_{2.5} \text{ concentration from USB}) - 45.9] \ (1).$$

When examining the relationship between the two $PM_{2.5}$ instruments by the different stove types, we also found strong and statistically significant agreement for all stoves; the lowest R^2 was observed with the Envirofit (slope=0.71; R^2=0.69; n=35) and TCS (slope=1.32; R^2=0.79; n=44), and highest with Prakti (slope=1.25; R^2=0.94; n=38) (Table S1).

Statistical Analysis

Specific considerations were established to exclude samples from analysis that were deemed as non-valid; samples with missing information, samples that experienced equipment failure or did not maintain a flow rate within 10% of the target, and samples that had a sample duration of less than 90% (<2593 minutes) were excluded. We also excluded personal samples where the interviewer indicated that the GasBadge and/or CO tube were not worn by the mother or child, or if there was uncertainty about compliance. These exclusions represented <5% of all samples.

Instruments that collected continuous air pollutant measurements (i.e., GasBadge, UCB-PATS) captured indoor and outdoor concentrations in one minute intervals, over a 48-hour period. To summarize these concentrations, the mean of the measurements taken over the 48-hour sampling period was calculated. For all other measurements (i.e., $PM_{2.5}$ gravimetric measurement, Draeger Tubes), the cumulative 48-hour concentration represented the CO or $PM_{2.5}$ concentration. Percent change in air pollution concentration was calculated by taking the difference between the paired 48-hour pollutant concentrations from the ICS and baseline TCS, divided by the baseline TCS measurements; we reported the median percent change.

To determine if there was a difference in mean CO and PM2.5 concentrations in the kitchen between the baseline TCS and each type of ICS, we log-transformed the data to account for skewness and conducted a pairwise t-test.

SAS PROC GLM was used to fit general linear models to examine the relationship between co-located measurements of $PM_{2.5}$ and CO in the kitchen and the CO measurements in the mother's breathing zone. The linear comparisons also included the CO concentrations in the kitchen to the personal (mother and children) CO concentrations. Pearson correlation was also used and regression coefficients were calculated.

We conducted descriptive statistics for the weight of fuel burned (using the pre- and post-weight measurements) and average wood moisture. All statistical analyses were conducted using SAS v. 9.3 (SAS Institute, Cary, NC, USA). The design of our study, determined *a priori*, set α=0.05 and allowed comparison between multiple ICS to the TCS; no adjustments were made for multiple comparisons.

Results

Of the 45 households that participated in the study, seven used all six ICS, 30 used five ICS and eight households used two to four ICS each. Additional information on participant and household characteristics is summarized by Pilishvili et al. (2016). The data summarized in this paper represent pollutant measurements captured directly by the instrumentation in the kitchen and in the personal breathing zone. As the first objective is to describe the pollutant concentrations present in the microenvironments, no adjustments were made to account for other potential factors that may influence the pollutant concentrations such as concurrent stove use or use of kerosene lamps. Contributions from these additional factors are described more fully in Lozier et al. (2016) and Pilishvili et al. (2016).

Ambient air pollution concentrations

From August 2012 to January 2013, we collected seven ambient 48-hour $PM_{2.5}$ and CO samples in a central location in each village. The 48-hour arithmetic mean gravimetric $PM_{2.5}$ concentrations in the two villages were 9 μg/m^3 (SD: 7 μg/m^3; N=7) and 12 μg/m^3 (SD: 11 μg/m^3; N=7). For CO, the 48-hour mean concentrations were low and 79% (N=11) of concentrations were 0 ppm. For $PM_{2.5}$, there was a difference observed by village ($p<0.0001$) and by round ($p<0.05$).

Kitchen air pollution concentrations

The overall (across all rounds) geometric mean of all 48-hour $PM_{2.5}$ concentrations in the kitchen of the 45 participant homes was 435 μg/m^3 (95% CI: 391, 484; N=263) (Table S2). The geometric mean of the 48-hour $PM_{2.5}$ concentrations at baseline when only the TCS was present was 586 μg/m^3 (95% CI: 460, 747; n=45). In comparison, the overall geometric mean of the 48-hour $PM_{2.5}$ concentration when an ICS was present was 409 μg/m^3 (95% CI: 363, 460; n=218) (Table S2), representing a median reduction of 38.8% (95% CI: 29.5, 45.2) (Table 2).

When examined by stove type, the geometric mean of the 48-hour $PM_{2.5}$ concentrations ranged from 326 μg/m^3 (95% CI: 246, 432; n=36) for households with the Philips to 518 μg/m^3 (95% CI: 399, 674; n=36) for households with the Eco Chula (Figure 1a; Table S2). Households with Envirofit, Philips, Prakti, and RTI TECA had mean $PM_{2.5}$ concentrations that were significantly different from the TCS and had median reductions ranging from 35.6% (95% CI: 24.9, 61.9) to 48.1% (95% CI: 35.0, 60.7) (Table 2).

The geometric mean of all the 48-hour CO concentrations in the kitchens was 5.1 ppm (95% CI: 4.5, 5.7; N=257) and the distribution of CO concentrations by stove type are illustrated in Figure 1b and Table S2. The mean CO concentrations measured during the baseline period, when only the TCS was used, was 6.5 ppm (95% CI: 4.9, 8.5; n=44). The overall geometric mean of the 48-hour CO concentration when an ICS present was 4.9 ppm (95% CI: 4.3, 5.5; n=213), which represents a median reduction of 27.1% (95% CI: 17.4, 40.3) (Table 2). The highest mean CO kitchen concentration was observed when the EcoZoom was installed (mean=6.7 ppm; 95% CI: 4.9, 9.0; n=37) (Table S2). When the Envirofit, Philips, Pratki, and RTI TECA stoves were installed, mean CO kitchen concentrations were significantly different than baseline levels ($p<0.05$; Figure 1b); median reductions ranged from 22.0% (95% CI: 9.4, 57.5) to 53.1% (95% CI: 5.5, 62.2) in comparison to the TCS (Table 2).

We also examined the relationship between the co-located 48 hour mean CO and $PM_{2.5}$ measurements conducted in the kitchen. Regression analysis of the two instruments yielded an R^2 of 0.72 and a slope of 69.6 (N=257) (Table S1). When stratifying by stove type, the slopes ranged from 43.0 for the EcoZoom (R^2=0.48) and Philips (R^2=0.78), to 146.8 for the TCS (R^2=0.76).

Personal air pollution levels

Geometric mean 48-hour CO concentration among all the women was 1.3 ppm (95% CI: 1.3, 1.4; N=237) when using the GasBadge (Table S3) and 0.8 ppm (95% CI: 0.8, 0.9; N=248, data not shown) using the Draeger Tube. The personal measurements were 76% lower than the mean CO kitchen concentrations (measured by the GasBadge). The children's mean exposures to CO using the Dreager Tube was also 0.8 ppm (95% CI: 0.7, 0.8; N=239) (Table S3).

When examining the women's CO by stove type, levels were highest while using the TCS, regardless of sampling device (Figure 2; Table S3). Their GasBadge geometric mean personal CO exposures when using an ICS ranged from 0.9 ppm (95% CI: 0.6, 1.5; n=34) for the Prakti to 1.4 ppm (95% CI: 1.0, 2.1; n=33) for the RTI TECA (Figure 2; Table S3). The children's geometric mean personal CO concentration (Draeger Tube) was highest with the EcoZoom at 0.8 ppm (95% CI: 0.7, 1.0; n=33) and the TCS (0.8 ppm [95% CI: 0.1, 0.9]; n=39). Because 82% of the mother's and 90% of the children's Draeger tube results were below the instrument's limit of detection of 0.7 ppm, we aggregated the ICS data (Figure 2; Table S3).

For the mother's GasBadge measurements, a 44.9% (95% CI: 37.5, 57.1; N=180) median reduction was observed between the TCS and all ICS (Table 3). All median percent reductions were significant when comparing individual ICS to the TCS at baseline, with Eco Chula showing the greatest reduction of 56.3% (95% CI: 42.9, 74.3; n=30).

The kitchen CO concentrations (GasBadge) described a small part of the mother's overall personal exposure (R^2=0.07, p<0.0001; N=242) (Table S4). When stratified by stove type, kitchen CO concentrations weakly predicted corresponding variance in the mothers' personal CO exposures (all R^2<0.23) with the exception of the Philips stove (R^2=0.67, p<0.01). A similar trend between the personal and kitchen CO concentrations was also observed among children (Table S4). We also wanted to understand the relationship between the children's and their mother's personal exposures to CO; Pearson correlation coefficients (R) between their exposures were moderate (R=0.45, 95% CI: 0.33, 0.54; N=236).

As we were able to collect co-located samples from the mothers, we also examined the relationship between the two personal CO instruments and found that the mean 48-hour concentrations were strongly and significantly correlated (R=0.84; 95% CI: 0.79, 0.87; N=238). And when stratified by stove type, the correlation coefficients ranged from 0.24 – 0.99 (Table S1).

Fuel consumption and wood moisture

The most common fuel used by the households was wood (66%; n=170) and sisal, a plant that is often a component in twine and rope (13%; n=32); 16% (n=40) of samples were a combination of wood and sisal. Charcoal, crop residue, and other biomass represented the remaining 6% of samples. Here, we present data on fuel use (i.e., raw weight of fuel including water) and moisture on samples that included wood (N=212). On average, households used 7.80 kg (SD: 5.15; N=212) (Table 4) of wood during each 48-hour sampling period. For the TCS, the average amount of wood used was 11.28 kg (SD: 5.50;

n=39), which was significantly greater (p<0.0001) than wood consumed when using the ICS. On average, Prakti consumed the most wood among the ICS (8.59 kg; SD: 7.21 kg; n=28) and Philips the least (4.79 kg, SD: 2.72; n=25) (Table 4). The mean moisture level was 22.3% (SD: 8.8; N=228) for all samples and did not vary for each stove type when compared with the TCS (Table 4).

We examined the effect of wood consumption on kitchen pollutant levels using univariate regression analysis. We modeled wood consumption (kg consumed) as independent predictors of corresponding pollutant concentrations. For each kilogram of wood consumed, the $PM_{2.5}$ concentrations increased 34 μg/m^3 (R^2=0.05; p=0.0005; N=212). For CO, wood consumption also explained a small yet statistically significant portion of the variance (R^2=0.02; p=0.04; N=206), with a 0.26 ppm increase in CO concentration for each kilogram of wood consumed. Wood moisture also played a role in the observed kitchen concentrations; a weak but statistically significant correlation was observed for $PM_{2.5}$ (R=0.24, 95% CI: 12, 0.36; N=228) and for CO (R=0.19, 95% CI: 0.06, 0.31; N=222). For each percent of moisture increase, there was a 24 μg/m^3 and 0.19 ppm increase in $PM_{2.5}$ and CO concentration, respectively.

Kerosene

The 90-minute average $PM_{2.5}$ concentrations measured for the two tin lamps in the far-field test were 3466 μg/m^3 (SD: 1208) and 3224 μg/m^3 (SD: 1075). $PM_{2.5}$ concentrations from the near-field test were 906 μg/m^3 (SD: 329) and 3163 μg/m^3 (SD: 1225). For the hurricane lamp, the 90-minute average $PM_{2.5}$ concentrations from the far-field test was 180 μg/m^3 (SD: 0.014) and 123 μg/m^3 (SD: 0.010) for the two UCB samplers. The 90-minute near-field $PM_{2.5}$ measurements were 38 μg/m^3 (SD: 4) and 205 μg/m^3 (SD: 14). None of the $PM_{2.5}$ concentrations for the kerosene lamp study were gravimetrically adjusted. Concomitant measurements of CO were conducted for all tests and consistently, the concentrations were measured at 0 ppm.

Discussion

We assessed the performance of six ICS during daily stove use in 45 Kenyan households and conducted multiple ICS comparisons with the TCS, in the kitchen and personal breathing zone, providing insight on differences in exposures. For all six ICS tested in this study, we observed a reduction in mean 48-hour $PM_{2.5}$ and CO concentrations compared to the TCS, and four stoves—the Envirofit, Philips, Prakti, and RTI TECA—demonstrated modest and significant reductions. Our findings illustrate that the cleaner-burning stove designs tested in a real-world setting reduced exposures to air pollution. In a laboratory setting, Jetter et al. (2012) also found that, in comparison to other newer technology wood burning stoves, the Envirofit and Philips stoves emitted less CO and $PM_{2.5}$ per unit energy delivered, but for low moisture fuel. Previous studies also observed reductions in kitchen concentrations of $PM_{2.5}$ and CO under real-world conditions for 48-hour measurements (Chengappa et al. 2007; Masera et al. 2007).

Some studies observed greater HAP reductions in the forced draft stoves, which include a fan that helps to deliver air to the fire (Muralidharan et al. 2015). Other studies tested stoves with chimneys and observed significant reductions in exposures as well as specific health outcomes (Smith et al, 2011). In our study, we did not observe greater median reductions in all of the forced draft stoves that were tested (e.g., Eco Chula) and the performance of the Prakti stove (chimney) was consistent with the other stoves in showing significant mean reductions.

Despite the overall observed reductions, the geometric mean 48-hour $PM_{2.5}$ kitchen measurement for all ICSs was far greater than the interim 24-hour WHO $PM_{2.5}$ air quality guideline value of 35 μg/m^3. The mean CO kitchen concentrations for all ICSs, however, was near the WHO 24 hour CO Indoor Air Quality Guideline of 7 mg/m^3 (6.1 ppm based on standard conditions at 25°C and 1 atmosphere). Many previous ICS intervention studies were also not able to achieve air pollution levels that are considered safe (Northcross et al, 2010; Pennise et al. 2009; Sambandam et al. 2014). Johnson et al. (2015) examined different displacement scenarios of traditional stoves with higher performing technologies and found that, in order to meet the WHO $PM_{2.5}$ guidance levels, the TCS needs to be nearly eliminated. For CO, the TCS would also have to be “substantially limited”. In our study, a similar scenario may be needed based on findings by Lozier et al. (2016). Lozier et al. (2016) collected stove use information from the ICS and TCS in each participating household and observed that stove stacking occurred on 40% of the study days, and exclusive use of the ICS only occurred on 25% of study days. It was also observed that continued use of the TCS was associated with higher concentrations of $PM_{2.5}$ and CO. Accordingly, the removal of the TCS—and the potential for stove stacking—could lead to even greater reductions in HAP among our study population. Our study measurements, however, also reflect other real-world contributions including, kerosene use, and fuel type and moisture content.

Studies have shown that kerosene lamps can generate a considerable amount of $PM_{2.5}$ exceeding the WHO and USEPA air quality guidelines (Apple et al. 2010). Type of fuel and moisture content can also impact the variability observed in the measurements. Previous studies found that burning rates can be inversely proportional to the moisture content in the fuel (Chomanee et al. 2009; Yang et al., 2003); in our study, we observed a 24 μg/m^3 and 0.19 ppm increase in $PM_{2.5}$ and CO, respectively, for each percent of moisture increase.

The mother's preferences for specific ICS could also contribute to the heterogeneity in our results. In their qualitative assessment, Loo et al. (2016) found that there was a clear preference for the Philips stove among the mothers in our study population based on factors such as ease of use and cooking speed. Furthermore, they reported often using another stove in conjunction with, or in lieu of, the ICS under evaluation because of the need to cook for large groups, the inability to cook local dishes with the ICS, or unfamiliarity with the ICS. The information they shared were consistent with the SUMs data. These stove preferences and stacking practices can, notably, influence the personal exposure measurements that we collected.

To more clearly quantify the potential impacts that these factors may have on the observed exposures, Pilishvili et al. (2016) conducted a multivariate analysis examining stove type, stove stacking, fuel consumption, specific behaviors (e.g., average time spent cooking), and several measures of acceptability. The analysis showed that stove type, exclusive ICS use, and the amount of fuel used were independently associated with the $PM_{2.5}$ and CO concentrations measured in the kitchen.

While the measured kitchen concentrations were consistently higher than WHO air quality guidelines, the mother and child 48-hour average personal exposure concentrations to CO were consistently lower than the kitchen concentrations and the WHO 24-hr CO Indoor Air Quality Guideline. These findings are similar to other studies where personal exposures, especially children's, were lower than the kitchen concentrations (Baumgartner et al. 2011; Dionisio et al. 2012). While kitchen sources are a major contribution to personal exposures, they do not fully represent exposures throughout the day due to movements around and away from the home. In our study, the kitchen CO measurements (all stoves) explained approximately 7% and 5% of the variability in the individual mother's and children's exposures, respectively. On average, the mothers reported spending 61 to 82 minutes cooking each day, depending on the type of stove (Pilishvili et al. 2016). One important consideration that also needs to be carefully examined when interpreting these values is the participant's compliance in wearing the personal monitor. The urinary biomarker measurements of PAH collected in our study will assist us in understanding the personal exposures to the stoves and the level of compliance in wearing the personal monitor.

These observations support previous discussions (Clark et al. 2013; Smith et al. 2010) on the importance of conducting personal exposures to ensure better characterization of exposure-response relationships in studies examining disease risk. Based on our findings and those from previous studies, it is important that future investigations include personal exposure measurements, where feasible, as our results confirm that kitchen measurements alone would overestimate personal exposures. More accurate measures of personal exposure are needed to help quantify the level of air pollution reduction required to meet the health targets, although the goal of achieving indoor air quality that meets WHO guidelines remains a priority.

Another consideration in assessing exposures is the ability to capture accurate measurements with instrumentation that is appropriate for a field study. Traditional measurements of PM can be more difficult to conduct in field settings as it often requires use of a sampling pump and filter. Carbon monoxide, a key component of biomass smoke by mass (Northcross et al. 2010), is easier to measure using less expensive and less intrusive equipment such as passive diffusion tubes. Our study design enabled us to compare the co-located CO measurements from the GasBadge and Draeger Tube in the mothers' personal breathing zones. Overall, both instruments were strongly and significantly correlated; however, the strength of this relationship, as well as the slopes, varied by stove type. The inability of the passive tube to assess very low CO exposures (<0.7 ppm) could also have affected the observed relationships. In the kitchen, CO from the GasBadge and $PM_{2.5}$ gravimetric measurements were strongly correlated, yet this relationship also changed depending on the stove type. It has been found that stoves that are more efficient with higher combustion temperatures may have lower $PM_{2.5}$ emissions (L'Orange et al. 2012). Additional work will need to be done to more clearly understand the contributions of specific pollutants from biomass combustion.

The strengths of this study include our ability to conduct multiple ICS comparisons with the TCS, for both $PM_{2.5}$ and CO, in the kitchen and personal breathing zone. We were also able to adjust for differences related to housing characteristics by conducting the study within the same set of households. There were, however, several important limitations to our study design. Specifically, we can only estimate the contribution of indoor kerosene use based on our pilot study results. The results suggest that kerosene lamps can be a significant contribution to the $PM_{2.5}$ measured indoors. Also, consistently, the fuel used by all households was >20% in moisture, suggesting that this factor may have contributed to higher levels of pollution observed with the ICS. Last, with respect to the personal exposure data, some data were difficult to interpret, thereby highlighting the need for more information regarding compliance in the wearing the personal monitoring equipment. Additionally, the opportunity to conduct personal exposure measurements of $PM_{2.5,}$ as well as serial measurements of both pollutants, would have provided useful insight on the variability in, as well as the impact of, the different stove types on personal exposures.

Based on the exposure findings, we identified four stoves which resulted in statistically significant reductions in the levels of $PM_{2.5}$ and CO, yet these levels were still far greater than the WHO air quality guidelines and may have suboptimal benefits for health. This suggests that, while cleaner and more efficient biomass stoves may have the potential to reduce exposures to HAP, implementation of cleaner fuels and related stove technologies may be necessary to achieve greater health benefits. In fact, a number of African countries are now moving forward to scale up implementation of liquid petroleum gas (LPG) use among those currently relying on solid fuels, including Kenya, Senegal, and Ghana (WLPGA, 2015). However, as countries move towards developing infrastructure for clean fuels, improved stoves are still important considerations. The question of what levels could be achieved with the biomass stoves used in isolation–that is, what is the best performance that can be expected from these six ICS in everyday use–remains important, and continues to require careful assessment of the multiple technological and behavioral factors that have contributed to the post-intervention levels observed in the current study. These other factors, and the extent to which these could be modified, are analyzed and discussed in other publications from the study.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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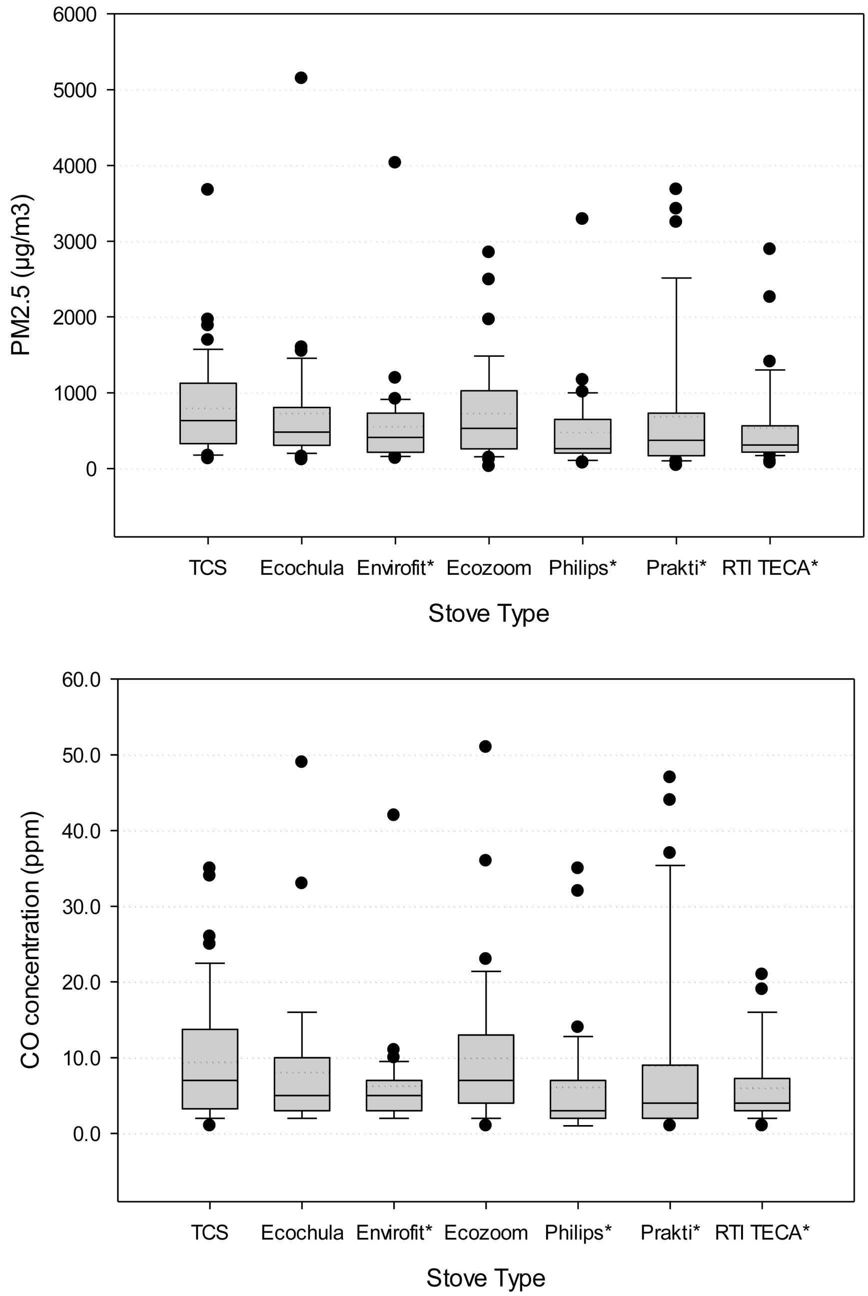

Figure 1.

Distribution of 48-hour a) gravimetric $PM_{2.5}$ ($\mu g/m^3$) and b) mean CO concentrations (ppm) in the kitchen, by stove type for (a) $PM_{2.5}$ and (b) CO.

*$p<0.05$ compared with TCS

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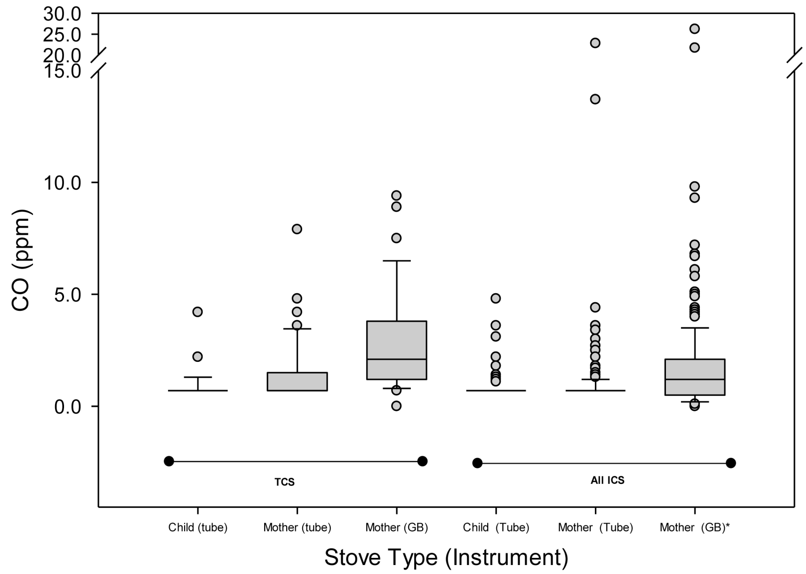

Figure 2.

Distribution of 48-hour personal exposures to CO (ppm) by TCS and all ICS for the mothers and children.

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Table 1

Description of stoves selected for the study.

Stove	Design	Combustion Chamber	Model number	Manufacturer
Eco Chula	Electric fan-assisted gasifier	Ceramic	XXL	Alpha Renewable Energy Pvt. Ltd. Atlanta, Georgia, USA
EcoZoom	Improved rocket	Ceramic	Dura	EcoZoom, Portland, Oregon, USA
Envirofit	Improved rocket	Metal alloy	G-3300	Envirofit International Fort Collins, Colorado, USA
Philips	Electric fan-assisted gasifier	Ceramic	HD4012	Philips African Clean Energy, Lesotho, South Africa
Prakti	Double pot rocket with chimney	Steel alloy	Leo	Prakti Pondicherry, India
RTI TECA	Built-in rocket stove with Thermoelectric- Enhanced Cookstove Add-on (TECA)	Brick/clay	Kenyan Jiko Kisasa stove	Local artisans RTI International, Research Triangle Park, North Carolina, USA
3 stone fire (TCS)	Stones	None		

Table 2

Median percent reductions between TCS and ICS: mean 48-hour $PM_{2.5}$ and CO concentrations in the kitchen, by stove type.

Stove	**$PM_{2.5}$**		**CO**	
	N	***Median reduction (%) (95% CI)***	***N***	***Median reduction (%) (95% CI)***
TCS		Ref.		Ref.
All ICS	218	38.8 (29.5, 45.2)	211	27.1 (17.4, 40.3)
Eco Chula	36	25.5 (-7.0, 42.2)	34	18.8 (-5.4, 54.8)
EcoZoom	37	24.4 (-1.7, 46.4)	37	12.6 (-10.9, 30.7)
Envirofit	35	43.2* (16.6, 55.1)	34	34.6* (14.3, 52.9)
Prakti	39	35.6* (24.9, 61.9)	37	37.3* (0.6, 55.7)
Philips	36	48.1** (35.0, 60.7)	35	53.1* (5.5, 62.2)
RTI TECA	35	44.8* (8.1, 53.8)	34	22.0* (9.4, 57.5)

* $p<0.05$

** $p=0.0001$

Table 3

Median percent reductions in personal exposures between TCS and ICS: mean 48-hour personal CO concentrations (GasBadge) for the mothers, by stove type.

Stove	**CO**	
	N	***Median reduction (%) (95% CI)***
TCS		Ref.
All ICS	180	44.9 * (37.5, 57.1)
Eco Chula	30	56.3 ** (42.9, 74.3)
EcoZoom	30	36.9 * (25.0, 57.9)
Envirofit	30	44.2 * (0.0, 63.6)
Prakti	32	40.9 ** (23.1, 77.1)
Philips	28	59.2 ** (28.6, 71.4)
RTI TECA	30	43.7 * (10.5, 75.5)

* $p<0.05$

** $p<0.0001$

Table 4

Arithmetic mean weight of fuel consumed, by stove type.

Stove	Mean fuel consumed		Mean fuel moisture	
	N	***kg (SD)***	***N***	***% (SD)***
All ICS	212	7.80 (5.15)	228	22.32 (8.81)
TCS	39	11.28 (5.50)	43	21.81 (8.74)
Eco Chula	33	8.95 (4.01) *	34	22.71 (8.14)
EcoZoom	31	6.44 (3.40) *	31	23.49 (6.81)
Envirofit	26	8.24 (4.94) *	29	23.90 (11.28)
Prakti	28	8.59 (7.21) *	31	21.95 (8.78)
Philips	25	4.79 (2.72) *	28	21.17 (9.54)
RTI TECA	30	6.99 (4.44) *	32	21.38 (8.74)

*p<0.001 when compared to the TCS