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Short Communication

Particulate Matter and Carbon Monoxide in Highland Guatemala: Indoor and Outdoor Levels from Traditional and Improved Wood Stoves and Gas Stoves

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Abstract Area 22-h average carbon monoxide (CO), total suspended particulates (TSP), particles less than 10 μm in diameter (PM_{10}), and particles less than 2.5 μm in diameter ($PM_{2.5}$) measurements were made in three test homes of highland rural Guatemala in kitchens, bedrooms, and outdoors on a longitudinal basis, i.e. before and after introduction of potential exposure-reducing interventions. Four cookstove conditions were studied sequentially: background (no stove in use); traditional open woodstove, improved woodstove with flue (*plancha*), and bottled-gas (LPG) stove. With nine observations each, kitchen $PM_{2.5}$ levels were 56 μg/m^3 under background conditions, 528 μg/m^3 for open fire conditions, 96 μg/m^3 for *plancha* conditions, and 57 μg/m^3 for gas stove conditions. Corresponding PM_{10}/TSP levels were 173/174, 717/836, 210/276, 186/218 μg/m^3. Corresponding CO levels were 0.2, 5.9, 1.4, 1.2 ppm. Comparisons with other studies in the area indicate that the reductions in indoor concentrations achieved by improved wood-burning stoves deteriorate with stove age. Mother and child personal CO and $PM_{2.5}$ measurements for each stove condition demonstrate the same trend as area measurements, but with less differentiation.

Key words Air pollution; Biomass fuel; Developing world; Respiratory health.

Practical Implications
Extraordinary exposures to indoor pollutants associated with biomass-fuel cooking in developing countries are well documented. This study demonstrates the importance of careful pilot study measurements before moving to substantial intervention programs that will change these cooking exposures. Naeher and co-authors demonstrate in extended measurements in a small sample of representative kitchens in Guatemala that improved wood stoves with flues and bottle gas stoves reduce exposures to 10 to 20% of those seen in kitchens using open fires for cooking.

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Introduction

It is estimated that around 50% of the world's population, some 75% of those living in developing countries, rely on biomass fuels (wood, dung and crop residues), which are typically burnt in simple open fire stoves, for household cooking and sometimes heating (Reddy et al., 1997; WHO, 1997). Such widespread use of biomass fuels results in indoor pollution levels, including particulate pollution, among the highest ever measured; thus, on a worldwide basis, it is these populations that probably have the greatest exposures (Smith, 1993).

Numerous urban studies in industrialized countries have shown associations between ambient particulate air pollution and acute and chronic respiratory morbidity and mortality in children and adults (Dockery and Pope, 1994). Although exposure characteristics vary tremendously from the developed world to rural areas in the developing world (e.g. particulate composition, exposure circumstances, demographics, and underlying health status), it is hypothesized that high exposure to contaminants from biomass fuel combustion is a risk factor for low birth weight (Astrup, 1972) and acute respiratory infection (ARI) (Smith, 1987) among other disease outcomes in the developing world. In its 1993 report, "Investing in Health", the World Bank estimates that indoor air pollution is responsible for almost 50% of the burden of total disease resulting from poor household environments in developing countries (World Bank, 1993).

Further studies from rural areas in developing countries are necessary to clarify the associations, including exposure-response relationships, between particulate

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pollution from biomass fuel and health. In 1992, the World Health Organization (WHO) began to examine the feasibility of carrying out controlled intervention studies designed to assess the effects on key child and adult respiratory health outcomes of a measured reduction in exposure. Pursuant to a set of epidemiological studies to determine the risk-reduction potentials of various interventions (e.g. including fuel substitution, stove alteration, ventilation provision, and behavioral modification), the WHO sponsored several pilot studies in the western highlands of Guatemala. (Bruce et al., 1998; McCracken and Smith, 1998; Neufeld, 1995; Smith et al., 1993).

Building on the work of Smith and colleagues (1993), we contributed to this pilot work through three exposure assessment studies in the western highlands of Guatemala in 1993–94. The first study, reported elsewhere (Naeher et al., 1999), provided a picture of the pollution levels coming from a range of cooking stoves in various levels of disrepair, a representation of how outdoor particle mass and CO vary from high- versus low-density villages, and demonstrated that the region has adequate exposure to be a good site for an intervention study. The objective of the second study, presented herein, was to determine the effectiveness of a range of indigenous intervention stoves in reducing indoor exposures to air pollution. The results from the third study, reported elsewhere (Naeher et al., 1996), which sought an efficient and effective $PM_{2.5}$ exposure measurement and explored the efficacy of CO as a proxy for $PM_{2.5}$, generally support the use of CO staintubes as a proxy for $PM_{2.5}$ in such cases where a single type of emission source is the predominant source for CO and $PM_{2.5}$.

Material and Methods

This study was done in the fall of 1993, during the cool, rainy season which runs from May to November. It was conducted in villages in the Quetzaltenango (Xela) region of the western highlands of Guatemala (altitude range 2500–2800 m). In this region, most families burn wood on open fires, with around 10–20% using woodburning stoves with chimneys like the *plancha* and the *lorena* and a few using gas stoves. The *planchas* are roughly 3 feet high, 4 feet long, 2.5 feet wide, with a brick and mortar base, and a top with three steel burners surrounded by tile. The *lorenas* are taller and more massive than the *planchas,* and typically have three burners in a circle atop a mud-based unit with no brick, steel or tile components like the *plancha*. Most of the *lorenas* were constructed over a decade ago, are in poor condition (e.g. cracked stove body and top), and function more or less as an open fire stove as opposed to a functional wood stove with chimney like the newer *planchas*. The houses are generally made of adobe and wood, sometimes with only one room but with a separate sleeping area in many. In the primarily Mayan population of this region, the women typically carry children under two years of age on their backs during much of the day, which results in high exposure for these children when the mother is cooking.

Kitchen, bedroom, and outdoor measurements were made in the same three homes using, first, no stove (background), then, sequentially, the three cookstoves – open woodfire, bottled gas (LPG), and *plancha*. The three homes were representative of the study region. Two of the homes were chosen from the village of Concepcion Chiquirichapa, which has a high-density semiurban (approximately 17 houses/hectare) (Naeher et al., 1999). In this village, one home (H1) was selected with the kitchen and the sleeping quarters in the same room and one (H2) with the kitchen and the sleeping quarters in separate rooms. The third test house (L2) was selected from Buena Vista, which has a low-density rural environment (approximately 0.2 houses/hectare) (Naeher et al., 1999) and had a separate kitchen and sleeping quarters. The householders were trained in the use of the improved stoves.

The test homes were selected under the following criteria: i) no smokers lived in the home; ii) a mother lived in the home; iii) a child under the age of 15 months lived in the home; iv) the homeowners used an open fire as their only means of cooking; v) the home met the specified urban vs. rural and one room or multiple room dwelling criteria; vi) the homeowners were willing to cooperate with all the components of the study (i.e. area and personal air monitoring, temporary use of a gas stove, and installation and use of a *plancha*); and vii) the home had electricity.

Essentially all monitoring was done on a near 22-h basis, since the overall purpose was to understand changes in total exposure, which could then be related to health effects. Each cooking condition in each test home was monitored for three separate 22-h periods at two (H1; kitchen/bedroom and outside) or three (L2, H2; kitchen, bedroom, and outside) locations. At each location there was placed a sampling pack containing: i) an SKC Universal Flow Sample Pump running at 2.0 l/min attached to a filter cassette for integrated total suspended particulates (TSP); ii) a similar pump running at 4.0 l/min attached to a PEM impactor for integrated particles less than 10 µm in diameter (PM_{10}); iii) another pump running at 3.5 l/min attached to a cyclone and filter cassette for integrated particles less than 2.5 µm in diameter ($PM_{2.5}$); iv) an infrared-scattering

Table 1 Summary of kitchen and personal (mother and child) carbon monoxide and particulate measurements

Background or stove condition	Statistic	Kitchen area monitoring (22 h)								Personal monitoring (10–12 h)			
		CO* (ppm)		$PM_{2.5}$** (μg/m³)		PM_{10}** (μg/m³)		TSP** (μg/m³)		CO* (ppm)		$PM_{2.5}$** (μg(m³)	
		All***	H1****	All***	H1****	All***	H1****	All***	H1****	Mother***	Child***	Mother***	Child***
Background	Average	0.4	0.5	56.2	77.7	183.9	214.5	174.1	211.4				
	Standard deviation	0.3	0.5	17.6	10.4	134.6	107.3	113.0	79.7				
	Sample size	9	3	9	3	8	3	9	3				
Gas stove	Average	1.3	1.3	56.8	73.9	210.2	284.5	217.7	267.6	1.5	2.0	135.6	148.5
	Standard deviation	0.6	0.4	19.0	27.7	100.3	108.0	88.1	120.5	0.4	1.8	117.0	68.5
	Sample size	9	3	9	3	9	3	9	3	2	3	3	3
Plancha	Average	1.3	2.0	96.5	173.8	186.3	273.4	275.5	525.1	2.4	1.9	257.2	169.7
	Standard deviation	0.7	0.2	66.5	52.1	89.5	107.0	199.1	105.7	1.3	1.8	75.4	153.6
	Sample size	9	3	9	3	9	3	9	3	3	3	3	3
Open fire	Average	5.9	5.7	527.9	635.6	717.1	918.8	835.8	1023.2	6.7	2.7	481.2	279.1
	Standard deviation	2.1	3.4	248.5	340.1	284.6	449.4	310.2	438.2	3.1	1.4	194.4	19.5
	Sample size	9	3	9	3	9	3	8	3	3	2	3	2

* Carbon monoxide (CO) measured by Draeger passive diffusion tube
** Particles less than 2.5 μm in diameter ($PM_{2.5}$), particles less than 10 μm in diameter (PM_{10}), total suspended particulates (TSP)
*** Measurements from all three test houses: H1, H2, and L2
**** Measurements from test house H1 only

Miniram with Langan datalogger (limit of detection= 0.06–13.8 mg/m³) for continuous $PM_{2.5}$ inserted between the cyclone and filter of iii); v) a battery-operated Draeger CO electrochemical sensor with datalogger for continuous CO, and; vi) a Draeger CO passive diffusion (color stain) tube for integrated CO. The continuous $PM_{2.5}$ data are not presented herein. All particle collection was on 37-mm Teflon®-coated glass fiber Pallflex filters. The air sampling packs were suspended from the ceiling at roughly 1 m from the nearest wall and 1.3 m off the ground, and were attached to 110 V household current.

In homes L2 and H2, a pack was placed in the bedroom, kitchen, and outside of the house; in home H1, a pack was placed in the bedroom/kitchen (same room) and outside of the house. For all of the houses, the packs in the kitchen were placed near the stove close to where the woman of the home would typically spend most of her cooking time, while the packs placed outside of the home were located roughly 10 m away from the room containing the cooking stove.

Personal monitoring for $PM_{2.5}$ and CO was collected for one 10–12-h sampling period for the mother and child of each test house under each stove condition. The sampling equipment used was the same described for the area monitoring. The mother was monitored with the equipment attached to a belt that she was asked to wear for the sampling period and the sampling inlet was clipped near her breathing zone. The child was monitored with the equipment contained in a bag that a technician looked after and moved as necessary tracking the baby's movements throughout the day. The sampling inlet was attached to the breathing zone of the child.

Equipment Handling and Quality Control

Standard methods were used to determine air pollution concentrations from the measurements made and to maintain quality control. Pre- and post-weighing occurred in climate-controlled laboratory facilities at the Harvard School of Public Health. The filters were conditioned for 48 h before both weighings. Two lab filter blanks were collected at the time of the pre-weighing. Twelve field filter blanks were collected, one per week for the duration of the study. Filters were placed in individually labeled cassettes immediately following the pre-weighing. They were removed from the cassettes at the time of the post-weighing. All pumps were calibrated every two to four days using a 'bubble flow meter'. The Draeger tubes were read on site immediately following the sampling period or covered with an air tight cap and read the same day upon return to the field base. The Draeger continuous CO monitors were calibrated every two weeks at the field base using 100 and 250 ppm CO calibration gas.

Results

As reported in Table 1, over 22 h, open-fire kitchens were clearly more polluted than background (no stove), gas, or *plancha* kitchens for all four pollutants ($PM_{2.5}$, PM_{10}, TSP, and CO). Scheffe means tests show that all these comparisons are highly significant except for some comparisons from H1 where open fire CO was not different from gas stove or *plancha* levels and open fire TSP was not different from *plancha* levels. Conversely, significant differences did not exist for any of the pollutants among background, gas, and *plancha* kitchens. Neither did significant differences exist at outdoor sites among different stove types. Similarly, with the exception of H1 where the kitchen and bedroom were the same room, significant differences did not exist at bedroom sites among the different stove types. These results are similar to those a 60-home cross-sectional study in the same region conducted by Smith and colleagues (1993).

Like the time-averaged data presented above, the continuous CO area monitoring data also demonstrate the tremendous difference between open fire and all other stove conditions. In L2, for example, the open-fire kitchen had CO peaks of about 40 ppm, while gas and *plancha* stove kitchens only reached 3–5 ppm. Outdoor CO peaks were not so different, however. For example, during L2 *plancha* use, outdoor peaks of 2–5 ppm were only just exceeded by the 3–7 ppm from open-fire use.

Personal $PM_{2.5}$ and CO measurements for the mothers and the children were lowest under gas stove conditions and highest under open fire conditions (Table 1), although the increasing trend is more evident for the mothers' measurements. Mothers' open fire $PM_{2.5}$ and CO exposures were significantly higher than exposures measured under gas stove or *plancha* stove conditions. However, mothers' personal $PM_{2.5}$ and CO exposures collected under *plancha* stove conditions were not significantly different than those collected under gas stove conditions. No significant differences were observed for the children's personal $PM_{2.5}$ or CO measurements between the three stove conditions.

Table 2 Summary of 24–24 h mean particulate matter ($PM_{2.5}$: particles less than 2.5 μm in diameters; PM_{10}: particles less than 10 μm in diameter) kitchen concentrations across studies

	Open fire	*Plancha**	Gas stove
PM_{10} (μg/m^3)	1210	520	140
Smith et al. (1993)	*0.6*	*1.1*	*0.4*
	[23]	[25]	[12]
	100%	43%	12%
PM_{10} (μg/m^3)	716	186	223
Current study	*0.4*	*0.4*	*0.4*
	[3×3]	[3×3]	[3×3]
	100%	26%	31%
$PM_{2.5}$ (μg/m^3)	520	88	45
Current study	*0.5*	*0.7*	*0.5*
	[3×3]	[3×3]	[3×3]
	100%	16%	10%
$PM_{2.5}$ (μg/m^3)	868	152	–
Naeher et al. (1996)	*0.6*	*0.8*	–
	[17]	[26]	–
	100%	18%	–

* A *plancha* is a wood-burning stove with a chimney
(Coefficient of variation in italics)
[Number of households in brackets]
Percent (%) of open fire shown for planche and gas stove (percentages done on a household basis for Smith et al. (1993), on basis of means for the other studies)

Discussion

In two homes, H2 and L2, open-fire levels were consistently and significantly higher than those during other stove situations. In H1, however, the variability during open-fire use and the elevated pollutant levels observed during *plancha* use makes the drawing of statistical conclusions difficult. Background, gas-stove, and *plancha* conditions were indistinguishable at the 0.05 level for all pollutants, as in H2 and L2. Also as in H2 and L2, open-fire levels were significantly different than background for all four contaminants, CO, TSP, PM_{10}, and $PM_{2.5}$. Unlike for test houses L2 and H2, however, H1 *plancha* levels in the kitchen were not significantly different from the levels during open-fire use for CO or TSP.

There would seem to be three possible explanations for the H1 variability: i) the homeowner may not have complied with the instructions to use the *plancha* only and may have used a small open fire for convenience; ii) contaminants may have been introduced by the frequent use of the *temescal**, which was just outside the front door of this home (this may have biased data from both gas stove and *plancha* measuring days); or iii) the *plancha* may have been installed or used less effectively in this house as compared to the other two.

The third explanation is consistent with two other pilot studies of the same series (Smith et al., 1993; Naeher et al., 1996), which demonstrate that some

* A "*temescal*" is a sauna-like structure in which a (wood) fire is first lit to heat water and rocks. When the fire is out, the people enter the steamy environment to bathe. The interior dimensions are about 1.5 m long by 1 m wide by 1 m high. Bathing in the *temescal* is typically done once per week.

planchas have fairly high indoor emissions, in spite of having flues. As shown in Table 2, 22-h kitchen PM levels for some *planchas* were intermediate between open fires and gas stoves. The last study (Naeher et al., 1996), which was a cross-sectional study of 43 households, found that some *plancha* $PM_{2.5}$ and CO levels overlapped the lower end of the range of open-fire values, although the means were significantly different. Using 76 μg/m^3, the maximum $PM_{2.5}$ background level in the present study as a cutoff, 17 of 26 *plancha* kitchens in the cross-sectional study (Naeher et al., 1996) were above what is likely true background. The mean kitchen level for *planchas* in the cross-sectional study (Naeher et al., 1996) was 152 μg/m^3, compared to 88 μg/m^3 in the current study, a disagreement that can be explained by the difference in *plancha* ages and the small sample size of the current study. The three *planchas* in the current study were all brand new, while the 26 in the cross-sectional study had been built months to years previously and were thus in widely varying condition. This is further illustrated by Figure 1, which shows that current study results can be explained as having two well-functioning *planchas* with kitchen levels of less than 80 μg/m^3 $PM_{2.5}$ and one moderately poor *plancha*, with kitchen levels of 120–220 μg/m^3, all fitting within the cross-sectional study distribution.

These results imply that if *planchas* are introduced carefully as an exposure-reduction intervention, they can be expected to initially reduce indoor exposures to roughly the same extent as gas stoves. Under normal conditions, however, the indoor emissions and exposures of a population of *planchas* can be expected to deteriorate with age resulting in an effective mean exposure between those due to the open fire and gas stove. The range of values within the population will

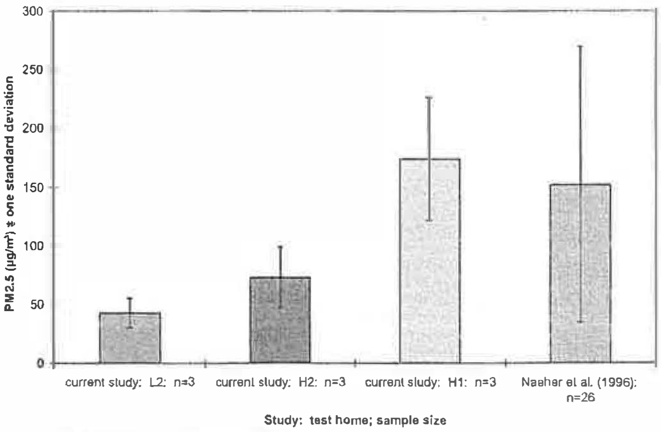

Fig. 1 Kitchen $PM_{2.5}$ (particles less than 2.5 μm in diameter) levels during plancha (wood-burning stove with chimney) use. Data from current study and Naeher et al. (1996)

greatly increase, however, since some *planchas* will remain in good condition and others will deteriorate even to the extent of reaching the lowest levels produced by open fires. Remaining to be demonstrated, therefore, is whether concerted efforts by the staff of an intervention program could retard or stop this deterioration by regular visits and offers of repair and maintenance services to the households in which *planchas* show signs of worsening with age.

It is important to point out that not all of the air pollution variation in *plancha*-using homes can be attributed to stove age and condition. Relevant to intervention epidemiological studies in these types of households, issues of subject compliance (i.e., subject is supposed to use only the *plancha* but uses multiple stoves during the study), as well as mode of stove use, length of cooking period, type of food cooked, and type of fuel used are other likely determinants of emissions that need to be considered. Further, correlation may also exist between age of stove and some of these variables resulting in a confounding effect (Bruce et al., 1998).

One primary limitation of the area monitoring data in this study is the small sample size. Building on the cross-sectional work of Smith et al. (1993), where 60 homes in this region were sampled, and complementing the work of Naeher et al. (1999), where 98 homes in this region were sampled, our objective here was to determine the effectiveness of a range of indigenous intervention stoves in reducing indoor exposures to air pollution. To accomplish this objective, we narrowed our scope to three test homes that were representative of the region, and conducted intensive sampling under controlled conditions within these three test homes on a longitudinal basis, i.e., before and after introduction of the inverventions. Despite the small sample size, the sampling scheme used in this study was sufficient to achieve its primary objective. As detailed in the methods section, we selected homes according to criteria (e.g., presence/absence of smokers, housing density, etc.) aimed at identifying homes representative of the region. Considering the home selection criteria used combined with the homogenous nature of the homes in this region, as observed by Smith et al. (1993) and Naeher et al. (1999), we are confident that the three homes selected were sufficiently representative of the region to achieve the objectives of this study.

In general, the personal exposure measurements reflect the ambient measurements discussed above. The personal $PM_{2.5}$ and CO measurements observed demonstrate a trend of increasing exposure as one moves from gas stove, to *plancha*, to open fire conditions. These data, however, have many limitations. First, considering all of the complicating factors involved with personal monitoring in this setting, the sample size (one 10–12-h measurement per mother and child, per home, per stove condition) is too small to draw meaningful conclusions. Second, it is likely that the behavior of the mothers and, even more, the children, was altered by the presence of the likely intriguing personal monitoring apparatus. Thus, the personal exposure data reported is limited in power due to the small sample size and may not accurately reflect true real-life exposure conditions because of the potential that the presence of the monitoring equipment altered personal behavior.

In summary, this pilot study demonstrates that reductions in indoor levels achieved by gas stoves and well-operating *planchas* are apparently to 15–30% of open-fire PM_{10} and 10–20% of open-fire $PM_{2.5}$. Although over the day there are contributions from other microenvironments where concentration differences may not be as great, the importance of the kitchen levels in daily child exposures would seem to imply that a reliable and significant difference in total particulate exposure can be achieved with these interventions.

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