

ORIGINAL RESEARCH

Household Air Pollution Exposures of Pregnant Women Receiving Advanced Combustion Cookstoves in India: Implications for Intervention

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Abstract

BACKGROUND Household air pollution (HAP) resulting from the use of solid cooking fuels is a leading contributor to the burden of disease in India. Advanced combustion cookstoves that reduce emissions from biomass fuels have been considered potential interventions to reduce this burden. Relatively little effort has been directed, however, to assessing the concentration and exposure changes associated with the introduction of such devices in households.

OBJECTIVES The aim of this study was to describe HAP exposure patterns in pregnant women receiving a forced-draft advanced combustion cookstove (Philips model HD 4012) in the SOMAARTH Demographic Development & Environmental Surveillance Site (DDESS) Palwal District, Haryana, India. The monitoring was performed as part of a feasibility study to inform a potential large-scale HAP intervention (Newborn Stove trial) directed at pregnant women and newborns.

METHODS This was a paired comparison exercise study with measurements of 24-hour personal exposures and kitchen area concentrations of carbon monoxide (CO) and particulate matter less than 2.5 μm in aerodynamic diameter ($\text{PM}_{2.5}$), before and after the cookstove intervention. Women ($N = 65$) were recruited from 4 villages of SOMAARTH DDESS. Measurements were performed between December 2011 and March 2013. Ambient measurements of $\text{PM}_{2.5}$ were also performed throughout the study period.

FINDINGS Measurements showed modest improvements in 24-hour average concentrations and exposures for $\text{PM}_{2.5}$ and CO (ranging from 16% to 57%) with the use of the new stoves. Only those for CO showed statistically significant reductions.

CONCLUSION Results from the present study did not support the widespread use of this type of stove in this population as a means to reliably provide health-relevant reductions in HAP exposures for pregnant women compared with open biomass cookstoves. The feasibility assessment identified multiple factors related to user requirements and scale of adoption within communities that affect the field efficacy of advanced combustion cookstoves as well as their potential performance in HAP intervention studies.

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The authors declare they have no conflicts of interest.

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KEY WORDS biomass fuel, carbon monoxide, Haryana, indoor air pollution, Newborn Stove Trial, Philips gasifier stove, PM_{2.5}

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INTRODUCTION

Household air pollution (HAP) resulting from the use of solid cooking fuels is a leading contributor to the burden of disease in India, accounting for about 1 million premature deaths and approximately 31 million disability-adjusted life years annually, approximately 6% of the national burden of disease.^{1,2} Nearly 74% of India's population continues to rely on solid fuels (such as biomass, dung, and coal) for their everyday household energy needs³, experiencing HAP exposures greatly in excess of the current World Health Organization air quality guideline (WHO-AQG) values.^{4,5} Additional environmental effects from biomass fuel use include black carbon emissions,^{6,7} unsustainable harvesting of fuelwood,⁸ and regional air pollution.⁹ The emissions, exposures, and disease burden estimates together argue for strenuous and targeted intervention efforts to address HAP in India.

The launch of the National Biomass Cookstove Initiative by the Ministry of New and Renewable Energy, Government of India represents an important step in this direction.^{10,11} The initiative has catalyzed the availability of a newer generation of "advanced combustion" biomass cookstoves (ACS) that meet the more stringent cookstove emission standards developed in 2013 by the Bureau of Indian Standards. Results from laboratory emissions testing for the newer ACS have been reported and have shown reductions ranging from 50% to 90% in emissions of particulate matter less than 2.5 μm in aerodynamic diameter (PM_{2.5}) and carbon monoxide (CO).¹²⁻¹⁵ More recent studies also are beginning to provide an understanding of the determinants of community-level uptake and adoption of ACS.¹⁶⁻¹⁸

However, relatively little effort has been directed at assessing the concentration and exposure changes associated with the introduction of a new ACS. Results from field measurements in households using commercially available ACS models recently were reported from the states of Uttar Pradesh, Tamil Nadu, and Maharashtra.^{19,20} Reported reductions in 24-hour kitchen concentrations of PM_{2.5} and CO ranged from 2% to 71% and 10% to 66%, respectively

compared with traditional cookstoves. Even with these reductions, however, resulting exposures and concentrations exceeded values recommended by the WHO-AQGs. Continued use of traditional stoves, infiltration of ambient air pollution, and perhaps other factors, appear to attenuate the reductions that are achieved by the ACSs within households, even when they perform as measured in the laboratory.

Laboratory testing of the Philips (Model HD 4012) forced-draft gasifier stoves consistently shows them to be among the best from an emissions standpoint.²¹ User acceptance and sustained adoption, however, has been less consistent.^{19,20,22-24} Additional field evaluations of the Philips stove, including personal and ambient monitoring are needed. Evidence from these evaluations could both improve the design of community-based intervention trials as well as inform the potential for intervention effectiveness in programs deploying ACS.

In this study, we describe the results of personal exposure and household and ambient monitoring after the dissemination of Philips ACS within the International Clinical Epidemiological Network (INCLIN) SOMAARTH Demographic Development & Environmental Surveillance Site (DDESS) located in Palwal, Haryana. These HAP monitoring results are part of a feasibility study to inform a potential large-scale HAP intervention (the NBS [National Newborn Stove] trial) directed at pregnant women and newborns. The details of the feasibility study and results from stove-use monitoring were published previously.^{23,24} We also discuss the broader implications of study results for intervention effectiveness in the context of national and global initiatives to address HAP.

The study described here was jointly undertaken by teams from Sri Ramachandra University (SRU), Chennai, the INCLIN Trust International, University of California, Berkeley, and Columbia University.

METHODS

Study protocols were jointly developed by investigators from collaborating institutions and approved by

the Health Ministry Screening Committee of the government of India and the Institutional Ethics committee of SRU and the INCLEN Trust International.

Study Location and Participant Recruitment. The study was conducted between December 2011 and March 2013 in 4 villages (Manpur, Gahlab, Banchari, Rahrana) that are within the INCLEN SOMAARTH DDESS. The surveillance site had a population of approximately 200,000 in 51 villages across 3 administrative blocks of Palwal district, encompassing 308 km². The site is supported by an extensive field infrastructure for research and surveillance activities pertaining to assessment of environmental and nutritional risk factors for children's health and noncommunicable diseases in adults.

As part of the feasibility study for the NBS trial, the INCLEN team recruited 200 pregnant women who each received the Philips HD 4012 ACS after pilot testing the stove for user acceptability.²³ Subsequently, the INCLEN team distributed the Philips stove through the network of trained female community accredited social health activists working at the SOMAARTH site. Eligibility for recruitment was based on the use of biomass as the primary household fuel and being less than 15 weeks pregnant at the time of recruitment into the study. Air pollution monitoring was planned in a subset (~25%; n = 50) of these households. Participants were enrolled after securing additional informed consents for air sampling.

The study was designed as a paired before–after comparison for detecting a desired level of improvement in HAP (ie, percent reduction between groups). Sample-size calculations were based on estimates of the expected differences between mean concentrations and the paired coefficient of variation for sample-size calculations as found in previous studies conducted.^{20,25} Because some monitoring protocols (ie, personal sampling for PM) could not be performed on pregnant women due to local cultural preferences, the INCLEN team identified additional households from the same villages from which nonpregnant women in similar households were recruited for air sampling. Fifty pregnant women and 15 nonpregnant women were enrolled for air sampling after securing additional informed consents for household and personal monitoring. Training on use and maintenance of the stove was provided to each study participant by the field staff of the INCLEN team. Although participants were asked not to use the traditional stove during the intervention-phase

monitoring days, many households followed their usual cooking routines. Households were not specifically requested to ensure similar cooking behavior or meal type between phases.

Air Pollution Measurements. Sampling plan. We designed a sampling strategy to both assess the exposure reductions accompanying the use of the Philips ACS for pregnant women and to inform the feasibility of performing such exposure measurements in a larger cluster-randomized intervention trial. Because standard sampling instrumentation for PM_{2.5} is bulky, noisy, and inconvenient to wear, personal exposures for pregnant women were limited to CO measurements. Correlations between personal PM_{2.5} and CO exposures were assessed through personal exposure measurements on nonpregnant women together with area and ambient measurements to estimate the correlations with personal exposures.

Exposure was assessed over a single 24-hour period at baseline and then after the stove was installed. Paired baseline and postintervention phase measurements of personal CO exposures and ambient measurements of PM_{2.5} were performed in both winter (December–February) and summer (June–July) seasons, whereas other paired measurements were performed in one or both seasons depending on equipment availability and field logistics. Winter measurements were performed within 1 to 3 months of stove distribution; summer measurements were performed 9 to 12 months after stove distribution.

Air sampling methods. Area concentrations and personal exposures for PM_{2.5} were measured as integrated 24-hour samples, collected using low-volume air sampling pumps (supplied by SKC Inc., or Casella Measurement Inc.). Pumps were operated at a flow rate of 1.5 L/minute. PM_{2.5} was collected on 37-mm TeflonTM filters (Pall Corporation, Port Washington, NY, USA), backed with cellulose support pads placed in a filter cassette connected to a BGI cyclone (BGI Inc., Waltham, MA, USA). Using a laboratory-calibrated rotameter, flow rates were measured before and after initiation of the sampling in the field. Filters were weighed before and after sampling, using an electronic microbalance with a sensitivity of ±1 µg (supplied by Sartorius Inc.) in a temperature- and humidity-controlled room at SRU. Filters were conditioned for 24 hours before to weighing. Twenty percent of the gravimetric samples were paired with field blanks (n = 13); none of the pre- and post-field blank weights differed by more than 0.003 mg.

Kitchen area $PM_{2.5}$ concentrations also were assessed continuously using the UCB-PATS (University of California Berkeley Particle and Temperature Sensor, Berkeley Air Monitoring Group; Berkeley, CA, USA) as described previously.^{20,26,27} Briefly, monitors were calibrated with combustion aerosols (eg, wood and charcoal) and against temperature in the laboratory before being used in the field. Particle coefficients were derived for each instrument in the field through collocation of UCB-PATs monitors and gravimetric samplers. All UCB-PATs were zeroed in a Ziploc bag for a period of 30 to 60 minutes before and after deployment. Particle and temperature coefficients, along with the results from zeroing, were subsequently used in the data-processing algorithm. After monitoring, all data files were batch-processed using a customized software package developed for this device. UCB measurements were performed primarily to allow estimation of the ratio of cooking to noncooking period concentrations of $PM_{2.5}$.

CO concentrations and exposures were measured using the portable, battery-operated, data-logging Drager Pac 7000 (SKC, Inc; Eighty Four, PA, USA) instrument, that was calibrated with span gas as per manufacturer specifications. The Pac 7000 recorded and logged the peak concentration that occurred within each minute during the monitoring period.

For kitchen area measurements, $PM_{2.5}$ and CO monitors were placed 1.5 m above the ground and 1 m from the primary stove. For personal exposure measurements, CO and PM monitors were attached to the participant's clothing with the inlets close to her breathing zone. Women were asked to place the personal monitor next to them when sleeping and bathing.

Ambient measurements for $PM_{2.5}$ were made using a MiniVolTM sampler placed in the center of a cluster of households, usually on a household roof top, at about 8 to 10 m height from the ground. Samplers were operated at a flow rate of 5 L/minute. Air was drawn through size selective $PM_{2.5}$ impactors. $PM_{2.5}$ was collected on 47-mm TeflonTM filters (Pall Corporation) and weighed in a microbalance following the same procedures used for area and personal samples. Six (20%) samples were paired with field blanks.

The full range of measurements thus included the following:

1. Paired 24-hour personal exposure measurements of CO for 50 pregnant women;

2. Paired 24-hour personal exposure measurements of $PM_{2.5}$ in 15 nonpregnant women;
3. Paired 24-hour kitchen area measurements of $PM_{2.5}$ and CO in 22 and 3 households, respectively; and
4. 28 measurements of 24- to 72-hour ambient $PM_{2.5}$ in 4 villages.

Questionnaire Administration. A postmonitoring questionnaire was administered to all participants by the research field staff immediately after completion of 24-hour monitoring. The questionnaire was printed in Hindi and English, but administered in Hindi. Time-activity recalls and information related to cooking activities (such as quantity and types of food prepared; quantity and types of fuel used; number of meals prepared in a day; cooking duration and ventilation) were collected. Information on other sources of HAP such as use of kerosene lamps, cigarettes, and incense was also recorded.

Statistical Analysis. All data analysis was performed using R (Version 3.02). Baseline and postintervention measurements were compared using 2-tailed nonparametric tests (Wilcoxon signed-rank test) to accommodate both positive and negative percent changes.

RESULTS

Household Characteristics. General characteristics of study households are summarized in [Table 1](#). Biomass (a mixture of dung and wood) was the primary fuel used on account of the inclusion criteria specified. Except for 2 households that reported using liquid petroleum gas or electricity, virtually no other additional fuels were reported as used (during times that monitoring was performed). Of the households in the study, 96% cooked in outdoor kitchens (open on 3 sides, often with a short wall or a sheet of insulating material shielding the stove on the back). This feature had important implications for the exposure measurement results as explained later. Households typically cooked a meal that included breads (roti), vegetables (sabzi), lentils (dal), and rice. On average, households (median size >4) cooked 2 meals daily, spending around 3.5 hours daily on cooking per day. Fieldworkers observed that women spend much of this time near the stove, preparing rotis. Animal fodder and milk were simmered on “haroo” stoves that burned only dung cakes and were usually operational outdoors throughout the day (generally within 5 to 10 m of the kitchen).

Table 1. General characteristics of participant households*

Variable	Description	N (%)
Kitchen type	Indoor kitchen with partition	1 (2)
	Separate outdoor kitchen	1 (2)
	Open-air kitchen	48 (96)
Fuel type	Biomass (dung + wood)	49 (98)
	Biomass + LPG/electricity	1 (2)
Doors in living room	1	21 (42)
	>1	29 (68)
Windows in living room	0	16 (32)
	1	20 (40)
	>1ne	14 (28)
Ventilator/open eve in living room	Yes	17 (34)
	No	33 (66)
Wall material of living room	Pucca	44 (88)
	Kutchha	6 (12)
Roof material of living room	Concrete	14 (28)
	Nonconcrete	36 (72)
Floor material of living room	Concrete	34 (68)
	Clay	16 (32)
Number of family members	≤4	8 (16.3)
	>4	41 (83.7)
Quantity of fuel used kg/d	≤2	39 (78)
	>2	11 (22)

LPG, liquefied petroleum gas.
 * Collected from enrolled pregnant women during the baseline phase of the study. Pucca houses are defined as those built using bricks, stones (packed with lime or cement), cement concrete, timber as wall materials and tiles, sheets (galvanized corrugated iron, asbestos cement, reinforced brick concrete and reinforced cement concrete). Kutchha houses have walls and/or roof made of material other than those just mentioned, such as unburnt bricks, bamboo, mud, grass, reeds, thatch, and loosely packed stones.

Comparison of Personal Exposures and Area Concentrations in Baseline and Intervention Phases. Table 2 and Figures 1 and 2 present results from personal exposure and area measurements for CO and PM_{2.5} recorded during the baseline and postintervention phases. As personal sampling for PM_{2.5} was not feasible on pregnant women, these measurements were performed only on nonpregnant women residing in nearby households from the same villages. The small sample sizes for other measurements on nonpregnant women, however, precluded reliable differential comparisons between

household measurements for pregnant and non-pregnant women and hence the results are reported together. Valid paired measurements for personal CO exposures were obtained from 51 women; from 8 women for personal PM_{2.5} exposures, from 3 households for kitchen CO concentrations, and from 22 households for kitchen PM_{2.5} concentrations. Measurements could not be equally distributed across locations or seasons on account of equipment unavailability.

In the baseline phase, the mean 24-hour personal exposures for PM_{2.5} and CO ranged from 72 to 297 µg/m³ and 3.9 to 7.5 ppm, respectively, whereas the mean 24-hour kitchen area concentrations for PM_{2.5} and CO ranged from 158 to 600 µg/m³ and 1.2 to 17 ppm, respectively. In the postintervention phase the mean 24-hour personal exposures for PM_{2.5} and CO ranged from 92 to 323 µg/m³ and 1.7 to 4.3 ppm, respectively, with the corresponding mean 24-hour kitchen area concentrations for PM_{2.5} and CO ranging from 185 to 410 µg/m³ and 2.5 to 5.2 ppm, respectively.

Reductions in paired mean 24-hour personal CO exposures ranged from 16% to 57% with a statistically significant reduction in median concentrations of 37% in the postintervention phase (*P* < 0.05). The changes in median 24-hour PM_{2.5} exposures and 24-hour kitchen area concentrations of CO and PM_{2.5} were not statistically significant (with several households/participants recording increases from baseline to postintervention phase measurements).

Although households were requested to refrain from using additional traditional cookstoves including the haroo during the postintervention monitoring period, some households reported using additional stoves (information on which was collected through the postmonitoring questionnaire). Comparison of reductions in paired measurements after exclusion of these households (*n* = 15), however, did not affect the observed changes significantly (Table 3).

Comparison of Real-time Concentrations of PM_{2.5} and CO During Cooking Periods Between Baseline and Intervention Phases. Previous studies have shown that multiple factors affect measured 24-hour concentrations and exposures, including the number of meals cooked, cooking duration, type of meal, type of fuel, ventilation parameters, and contributions from ambient concentrations.²⁰ Although it was not feasible to control for these variables across phases, we compared paired cooking-period concentrations (Table 4), as these

Table 2. Distribution of 24-h personal exposures and area concentrations for PM_{2.5} and CO during baseline and postintervention phases

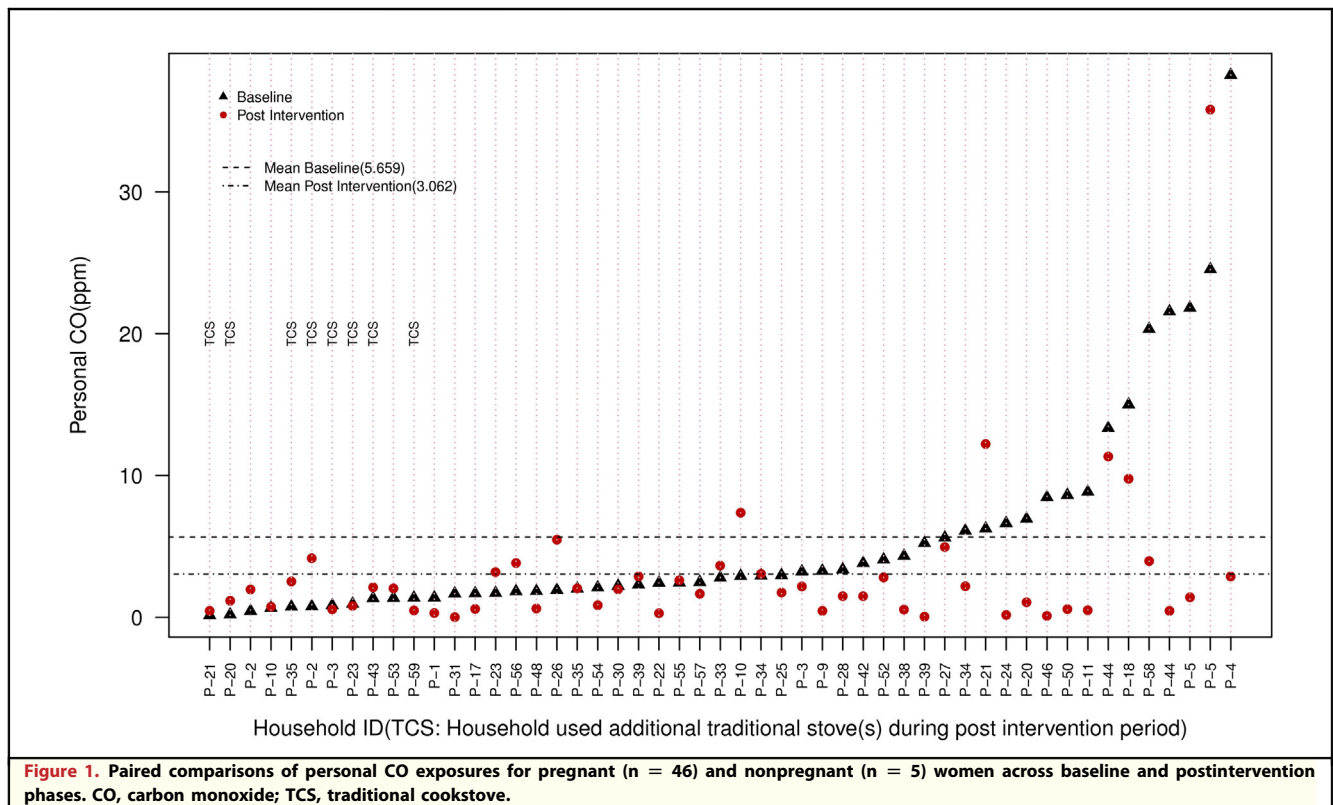
Season of monitoring	Monitoring period	N	Median	Mean (SD)	% change in median	% change in mean	P value (Wilcoxon signed-rank test [*])
Personal CO exposure (ppm)							
Summer	Baseline	17	1.9	4.6 (7.2)	-6	16	0.89
	Postintervention	17	2.1	3.9 (8.4)			
Winter	Baseline	34	3.1	6.2 (7.7)	45	57	0.001
	Postintervention	34	1.7	2.7 (3.1)			
Pooled	Baseline	51	2.8	5.7 (7.5)	37	46	0.009
	Postintervention	51	1.8	3.1 (5.4)			
Personal PM_{2.5} exposure (µg/m³)							
Winter	Baseline	8	148	184 (168)	-11	-13	0.844
	Postintervention	8	165	207 (172)			
Kitchen area CO concentration (ppm)							
Summer	Baseline	3	8	9.1 (4.7)	54	58	0.25
	Postintervention	3	3.7	3.9 (0.8)			
Kitchen area PM_{2.5} concentration (µg/m³)							
Summer	Baseline	11	46	92 (71)	-154	-130	0.054
	Postintervention	11	117	213 (237)			
Winter	Baseline	11	372	670 (767)	37	43	0.365
	Postintervention	11	235	381 (352)			
Pooled	Baseline	22	161	381 (608)	-16	22	0.750
	Postintervention	22	186	297 (305)			
PM concentrations reported in this table were measured using gravimetric samplers. The data include measurements from pregnant and nonpregnant women. The pool for personal CO measurements included 46 pregnant and 5 nonpregnant women, whereas the pool for PM _{2.5} measurements included only nonpregnant women. CO, carbon monoxide; PM, particulate matter. * For paired comparison of median reductions.							

are more likely to be influenced by direct emissions from the stove. For PM measurements, this was possible only for households monitored using the real-time UCB-PATS monitors. The cooking period comparisons (Table 4) resulted in greater reductions being observed across baseline and postintervention phases, although (similar to 24-hour measurements) only reductions in CO personal exposures were statistically significant.

Addressing Contributions of Seasonality Across Baseline and Intervention Phases. Because the field site was located in an area subject to temperature inversions in winter, considerable seasonal variations could be expected in background ambient air pollution levels. We addressed this through a limited set of 24- to 72-hour ambient measurements of PM_{2.5} performed using MiniVol® samplers. The levels in winter (n = 17; median: 175 µg/m³; mean ± SD 177 [50] µg/m³) mean were nearly twice as high as recorded in summer (n = 11; median: 69 µg/m³; mean ± SD 75 [22] µg/m³), indicating the potential for differential contributions to area concentrations and personal exposures across seasons.

DISCUSSION

In each season, measurements showed inconsistent improvements in 24-hour average concentrations and exposures for PM_{2.5} and CO with the use of the Philips stoves, and only those for CO showed statistically significant reductions. There was, however, considerable heterogeneity in the reductions obtained across households under conditions of actual use. Furthermore, the PM_{2.5} concentrations/exposures recorded in the postintervention phase consistently exceeded the highest of the recommended by the WHO-AQGs (ie, WHO interim target-1 (IT-1) values of 35 µg/m³ and 75 µg/m³, respectively for annual mean and 24-hour concentrations for PM_{2.5}) and frequently exceeded the 24-hour guideline value for CO of 6 ppm. We explored the reasons for the observed variability under actual field conditions and the implications of such variability for long-term exposure and elaborate here on the likely health relevance of exposure reductions achieved by the Philips model used in the study.



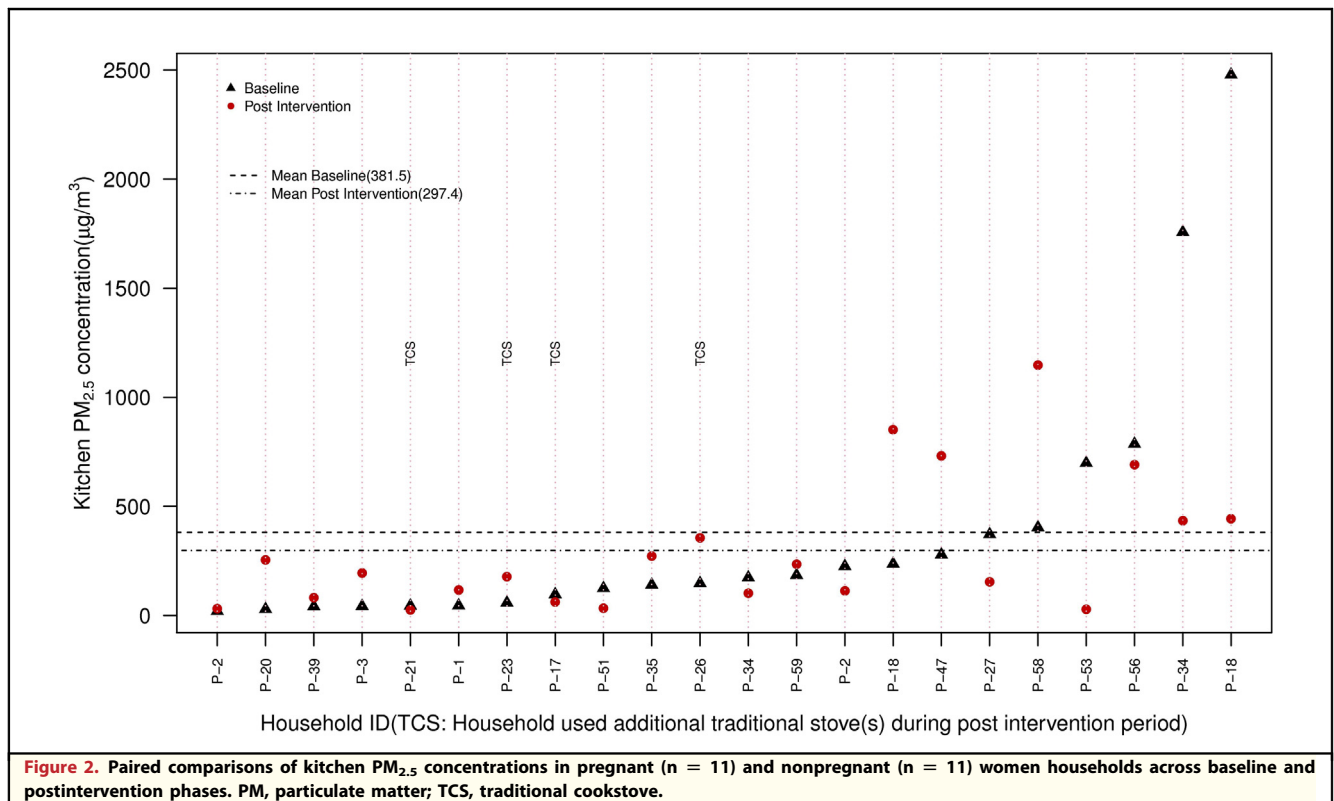
Variability in Household Concentrations and Personal Exposures: Role of Household-level Determinants and Ambient Concentrations. In pregnant women, reduction in the median 24-hour personal exposure and cooking period exposure to CO following the use of the Philips stove was found to be statistically significant. Reductions in kitchen concentrations of CO and PM_{2.5} were, however, not statistically significant and neither were personal exposures to CO and PM_{2.5} in nonpregnant women.

Emissions testing of the Philips stove demonstrated a greater than 90% reduction in emissions of PM_{2.5} and CO under controlled laboratory conditions.¹⁴ Several observations offer plausible explanations for the observed modest exposure reductions in the field.

1. Households reported requiring multiple stoves to satisfy household cooking needs. Fifteen (23%) of the 65 households reported using traditional stoves along with the Philips stoves during the post-intervention phases of monitoring. This was supported by quantitative measurements of stove use.²⁴ Excluding households that simultaneously used the traditional and Philips cookstoves during the

postintervention measurement phase limited the sample size for reliable comparisons.

2. The location of the kitchen in this setting may have limited the exposure reduction potential of a household-level cookstove intervention. Most women cooked in semienclosed outdoor spaces within their household compounds. With less than 5% of households within the village targeted with the ACS, neighborhood contributions to background ambient concentrations are likely to have influenced both kitchen area and personal exposure estimates in all households. This coupled with the observations from stove-use monitor measurements (that suggest only modest levels of displacement of traditional stoves within households that received the intervention), make it difficult to detect a consistent signal for exposure reduction within this setting. The observed reductions in area and personal exposure concentrations may not thus be representative of the potential exposure reductions achievable with the Philips stove in other populations. Use in communities with predominantly indoor kitchens and/or replacement of a high enough percentage of traditional stoves with cleaner stoves may produce substantial exposure reductions.
3. Ambient PM_{2.5} concentrations were significantly higher in winter than in summer. This necessitated



making same-season-paired measurements to prevent biases introduced by contributions from background concentrations across the baseline and post-intervention phases. Some of the same-season-paired measurements were performed a full year after the installation of the ACS (ie, in the same season). Independent assessments by the INCLEN team (results not shown) and stove-use monitoring results have recorded households experiencing considerable difficulties in maintaining the Philips stove for a full year. Thus, although same-season-paired measurements were made, it may not have represented the optimal comparison for such a measurement, given stove failures.

- The women in these villages commonly used dung as a major fuel. Because dung is a low energy-density fuel, women reported having to refuel the ACS more often, potentially leading to additional exposures during lighting as well as some inconvenience. This can tempt women to overfill the ACS combustion chamber with dung fuel, leading to higher emissions and exposures than would be the case with optimal fueling.²⁸
- Finally, 16 (25%) of the women reported staying indoors during the monitoring period on account of having to wear the personal monitoring equipment. Without serial time-activity records to assess their

behavior, it was not possible to discern how this shift in behavior may have affected exposure estimates.

Implications of User Acceptability for Long-term Exposure Reductions.

In studies after our choice of the Philips because of its good laboratory performance, user acceptance and sustained adoption have been less consistent.^{17,19,20,23,24} One factor was that the model we used was available only in a single-pot configuration. The need for an additional cooking pot often was reported and thus resulted in concurrent traditional stove use to fulfill specific meal requirements (stacking). The current configuration of the Philips stove model, therefore, appears to be poorly suited for exclusive use by households in the study area.²⁰ Although emissions reductions are a prerequisite for achieving reductions in exposures, without appropriate levels of user acceptance and reduction in use of the traditional stove, any gains observed in the laboratory may be lost under actual field-use conditions.

Health Relevance of Observed Reductions in PM_{2.5} Concentrations. The present study was designed to assess how close an ACS would lower PM_{2.5} exposures in relation to annual average WHO-IT-1

Table 3. Distribution of 24-h personal exposures and area concentrations for PM_{2.5} and CO during baseline and postintervention phases*

Season of monitoring	Monitoring period	N	Median	Mean (SD)	% change in median	% change in mean	P value (Wilcoxon signed-rank [†])
Personal CO exposure (ppm)							
Summer	Baseline	13	1.7	2.2 (1.8)	55	28	0.542
	Postintervention	13	0.8	1.6 (1.4)			
Winter	Baseline	30	2.9	5.4 (7.3)	49	61	0.002
	Postintervention	30	1.5	2.1 (2.6)			
Pooled	Baseline	43	2.8	4.4 (6.3)	46	56	0.002
	Postintervention	43	1.5	1.9 (2.3)			
Personal PM_{2.5} exposure (µg/m³)							
Winter	Baseline	7	99	133 (96)	−48	−54	0.469
	Postintervention	7	147	206 (186)			
Kitchen area CO concentration (ppm)							
Summer	Baseline	2	9.7	9.7 (6.5)	56	56	0.500
	Postintervention	2	4.2	4.2 (0.7)			
Kitchen area PM_{2.5} concentration (µg/m³)							
Summer	Baseline	7	45	66 (52)	−82	−32	0.688
	Postintervention	7	82	87 (58)			
Winter	Baseline	10	325	489 (503)	37	23	0.625
	Postintervention	10	206	374 (371)			
Pooled	Baseline	17	174	315 (435)	33	19	0.747
	Postintervention	17	117	256 (316)			

PM concentrations reported in this table were measured using gravimetric samplers. The data include measurements from pregnant and nonpregnant women. The pool for personal CO measurements reported in this table included only pregnant women, whereas the pool for PM_{2.5} measurements included only nonpregnant women. CO, carbon monoxide; PM, particulate matter.
 * Excludes households reporting the use of an additional traditional cookstove during the postintervention phase.
 † For paired comparisons of median reductions.

values for PM_{2.5} of 35 µg/m³. Recent progress in the development of integrated exposure response curves²⁹ over a continuous range of PM_{2.5} concentrations in relation to ambient air pollution, HAP, and passive and active tobacco smoking have allowed comparisons of excess risks for a range of health endpoints, including ischemic heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and child acute lower respiratory infections (ALRIs). The exposure-response functions for all of these except lung cancer are strikingly nonlinear, with the most discernible risk reductions beginning to appear well below 100 µg/m³ for ALRI.² Here, as shown in Table 2, mean exposures for the female cooks both before and after stove introduction were well above 100 µg/m³. Although, there are as yet no accepted exposure-response functions for birth outcomes, the apparent inability of the stove to bring exposures of women below 100 µg/m³ was disappointing.

Although, measurements of personal exposures to PM_{2.5} were limited, they were significantly ($P < 0.05$) correlated with kitchen area

concentrations ($r = 0.65$). With the mean 24-hour kitchen area concentrations ranging from to 150 to 650 µg/m³ and limited evidence of sustained use of the Philips stove in this population, the results from this study indicated that the stove is unlikely to accomplish health-relevant exposure reductions under current conditions of field use and expected level of adoption within a community. **Study Limitations.** Considerable efforts were devoted to planning the air sampling strategy to adequately capture the exposure reductions accompanying the use of the ACS for pregnant women. However, field constraints related to both personal and ambient monitoring precluded several planned measurements, thus posing limitations for generalizability of the conclusions.

Personal monitoring for PM_{2.5} was limited by the reluctance of both pregnant and nonpregnant women to wear the UCB-PATs monitor. The available gravimetric samplers could not be worn by pregnant women because they were too bulky. Limitations of available gravimetric equipment necessitated restricting the number of nonpregnant women to 15 for

Table 4. Distribution of cooking period personal exposures and area concentrations for PM_{2.5} and CO during baseline and postintervention phases

Season of monitoring	Monitoring period	N	Median	Mean (SD)	% change in median	% change in mean	P value (Wilcoxon signed-rank test [*])
Personal CO exposure (ppm)							
Summer	Baseline	17	13.4	22.9 (25.5)	9	30	0.329
	Postintervention	17	12.2	16.1 (16.4)			
Winter	Baseline	32	13.7	25.5 (26.7)	46	62	<0.001
	Postintervention	32	7.4	9.6 (8.1)			
Pooled	Baseline	49	13.4	24.6 (26)	27	52	<0.001
	Postintervention	49	9.8	11.9 (11.9)			
Kitchen area CO concentration (ppm)							
Summer	Baseline	3	57.6	56.2 (13.8)	65	62	0.250
	Postintervention	3	20	21.5 (4.8)			
Kitchen area PM_{2.5} concentration (µg/m³)							
Summer	Baseline	11	689	1090 (1130)	−2	−11	0.898
	Postintervention	11	702	1206 (1201)			
Winter	Baseline	9	2801	3092 (2451)	60	17	0.426
	Postintervention	9	1117	2555 (3770)			
Pooled	Baseline	20	1451	1991 (2060)	28	9	0.546
	Postintervention	20	1046	1813 (2686)			

PM concentrations reported in this table were measured using the UCB-PATS monitors. The data include measurements from pregnant and nonpregnant women. The pool for personal CO measurements reported in this table included 46 pregnant and 3 nonpregnant women, whereas the pool for PM_{2.5} measurements included only nonpregnant women
CO, carbon monoxide; PM, particulate matter; UCB-PATS, University of California-Berkeley Particle and Temperature Sensor.
^{*} For paired comparisons of median reductions.

personal PM_{2.5} measurements. This limited the sample size for comparing the reductions in PM_{2.5} exposures. Equipment availability also limited the ability to perform sufficient number of simultaneous (paired same season) area and exposure measurements for PM_{2.5} and CO, making it difficult to assess correlations across these measures.

The significant role of ambient pollution in influencing both personal exposures and kitchen area concentrations was not realized until direct observation of the kitchen locations in the field and winter time ambient measurements were analyzed. Although same-season measurements attempted to address some of this limitation, the time since distribution was significantly longer for the summer season measurements. The timings of measurements also may be important according to the woman's stage of pregnancy. Although all women were enrolled at less than 15 weeks pregnant, the cooking habits of someone who is heavily pregnant may well be different to that of someone in early pregnancy. The potential influence of these factors could not be examined within the limited number of samples available.

We could not perform paired ambient measurements in baseline and intervention phases as household receiving the interventions were staggered

across both seasons. Although the density of intervention households was fairly low (<15 out of >200 households) in each village, the differential effect in the 2 phases could not be discerned in ambient measurements.

CONCLUSION

The results of this study did not support the widespread use of this stove in this population as a means to reliably reduce CO and PM_{2.5} exposures of pregnant women cooks, compared with open biomass cookstoves, the original focus of this feasibility study. Although we observed reductions in CO exposures, more field evidence is needed to indicate that both PM_{2.5} and CO exposures are significantly lowered for both women and children over time so as to increase the likelihood of seeing the benefits for both birth outcomes and early child health in intervention studies and create sufficient exposure gradients to be able to determine an exposure–response relationship for birth outcomes, as has been done for other health conditions.

The HAP measurements performed in this feasibility assessment revealed multiple factors that need to be considered while assessing the efficacy

of household cookstove interventions. In particular, quantifying and monitoring the continuing use of all available stoves is crucial for understanding the dynamics of the stove adoption process, as well as estimating long-term exposure reductions that are achievable with household-level interventions targeted at replacing individual traditional stoves.²⁴ The exposure-monitoring protocols provided insights for sampling strategies to address multiple

sources of variability and to avoid exposure misclassification in intervention trials concerning HAP.

Finally, although the study represents only an initial assessment of one specific advanced biomass cookstove, the results support the need for alternative ways of exploring cleaner fuel choices that could provide far greater exposure reductions and reduce the overall public health burden from HAP effects.

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