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Exposure to Household Air Pollution from Biomass Cookstoves and Blood Pressure Among Women in Rural Honduras: A Cross-Sectional Study

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Abstract

Growing evidence links household air pollution exposure from biomass cookstoves with elevated blood pressure. We assessed cross-sectional associations of 24-hour mean concentrations of personal and kitchen fine particulate matter (PM2.5), black carbon (BC), and stove type with blood pressure, adjusting for confounders, among 147 women using traditional or cleaner-burning *Justa* stoves in Honduras. We investigated effect modification by age and body mass index. Traditional stove users had mean (standard deviation) personal and kitchen 24-hour PM2.5 concentrations of 126 µg/m3 (77) and 360 µg/m3 (374), while *Justa* stove users' exposures were 66 µg/m3 (38) and 137 µg/m3(194), respectively. BC concentrations were similarly lower among *Justa* stove users. Adjusted mean systolic blood pressure was 2.5 mm Hg higher (95% CI, 0.7-4.3) per unit increase in natural log-transformed kitchen PM2.5 concentration; results were stronger among women of 40 years or older (5.2 mm Hg increase, 95% CI, 2.3-8.1). Adjusted odds of borderline high and high blood pressure (categorized) were also elevated (odds ratio = 1.5, 95% CI, 1.0-2.3). Some results included null values and are suggestive. Results suggest that reduced household air pollution, even when concentrations exceed air quality guidelines, may help lower cardiovascular disease risk, particularly among older subgroups.

Keywords

household air pollution, blood pressure, Honduras

Disciplines

Environmental Public Health | Other Medicine and Health Sciences | Public Health

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TITLE PAGE

EXPOSURE TO HOUSEHOLD AIR POLLUTION FROM BIOMASS COOKSTOVES AND BLOOD PRESSURE AMONG WOMEN IN RURAL HONDURAS: A CROSS-SECTIONAL STUDY

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ABSTRACT

Growing evidence links household air pollution exposure from biomass cookstoves with elevated blood pressure. We assessed cross-sectional associations of 24-hour mean concentrations of personal and kitchen fine particulate matter ($PM_{2.5}$), black carbon (BC), and stove type with blood pressure, adjusting for confounders, among 147 women using traditional or cleaner-burning *Justa* stoves in Honduras. We investigated effect modification by age and body mass index. Traditional stove users had mean (standard deviation) personal and kitchen 24-hour $PM_{2.5}$ concentrations of 126 μg/m^3 (77) and 360 μg/m^3 (374), while *Justa* stove users' exposures were 66 μg/m^3 (38) and 137 μg/m^3 (194), respectively. BC concentrations were similarly lower among *Justa* stove users. Adjusted mean systolic blood pressure was 2.5 mmHg higher (95% CI, 0.7 to 4.3) per unit increase in natural log transformed kitchen $PM_{2.5}$ concentration; results were stronger among women 40 years or older (5.2 mmHg increase, 95% CI, 2.3 to 8.1). Adjusted odds of borderline high and high blood pressure (categorized) were also elevated (odds ratio=1.5, 95% CI, 1.0 to 2.3). Some results included null values and are suggestive. Results suggest that reduced household air pollution, even when concentrations exceed air quality guidelines, may help lower cardiovascular disease risk, particularly among older subgroups.

Key words: household air pollution; blood pressure; biomass; cookstoves; global health; Latin America

PRACTICAL IMPLICATIONS

Household air pollution and elevated blood pressure are leading contributors to morbidity and premature death worldwide. We observed elevated systolic and diastolic blood pressure associated with exposure to household air pollution from biomass cookstoves among women in rural Honduras. The association was stronger in older women. Cleaner-burning cookstove interventions may potentially reduce exposure to household air pollution with likely benefits for blood pressure and cardiovascular disease risk. The growing evidence of a link between household air pollution and blood pressure presents an opportunity to mitigate a modifiable and globally important risk factor for cardiovascular disease.

MANUSCRIPT

EXPOSURE TO HOUSEHOLD AIR POLLUTION FROM BIOMASS COOKSTOVES AND BLOOD PRESSURE AMONG WOMEN IN RURAL HONDURAS: A CROSS-SECTIONAL STUDY

INTRODUCTION

Household air pollution generated from burning solid biomass fuels, such as wood, coal, animal dung, and crop residues, for cooking, lighting, and heating homes is a leading risk factor for premature deaths and morbidity worldwide. In 2016, an estimated 2.6 million premature deaths (95% confidence interval [CI], 2.2-3.0 million) and 77.2 million disability-adjusted life-years (95% CI, 66.1-88.0 million) were attributed to household air pollution.[1] Cardiovascular health contributes substantially to the burden of disease attributed to household air pollution, yet these estimates are extrapolated from exposure-response effects associated with other sources of combustion-related pollution, such as active smoking, secondhand smoke, and ambient air pollution.[2] A limited number of studies with quantitative exposure measurements of air pollutants have evaluated the cardiovascular effects of household air pollution.[3-9] In order to understand the full burden of disease, including household air pollution exposure-response associations, cookstove research needs to incorporate direct exposure assessments and relevant cardiovascular endpoints. This research is especially crucial in developing countries, which are disproportionately affected by household air pollution and have increasing rates of cardiovascular morbidity and mortality. In Honduras, a low middle-income country in Central America,[10] high systolic blood pressure and household air pollution from burning solid fuels were ranked first and seventh for risk factors for disability-adjusted life-years, respectively.[11]

One approach to reduce household air pollution is for families to transition from biomass fuel to cleaner energy sources, such as liquefied petroleum gas or electricity. However, many regions worldwide have limited access to cleaner fuels, as 1.3 billion people lack electricity and 2.7 billion people still rely on biomass fuel for cooking.[12] In Honduras, 89% of homes in rural areas cook with solid fuels.[13] In rural areas where cleaner fuels are not accessible, it is critical to evaluate the impact of cleaner-burning biomass stoves on health outcomes, given the economic feasibility and appropriateness for cooking needs.

One cleaner-burning biomass stove that was designed for Central American homes is the *Justa* stove (Figure 1). The *Justa* stove has a rocket type (L-shaped) insulated ceramic combustion chamber, chimney, griddle, and side compartment to remove soot.[14] Two to three pots can be cooked on the griddle at once, which is also used for making tortillas. Lab tests showed the *Justa* emitted one-third the particulate matter emitted by an open 3-stone fire while boiling and simmering five liters of water for 45 minutes (792 mg vs. 2,363 mg, respectively).[14] A study comparing 8-hour average concentrations between *Justa* stoves and traditional stoves during normal daily cooking events among 59 women in Honduras reported 64% lower levels of personal $PM_{2.5}$ and 73% lower levels of indoor $PM_{2.5}$ for the *Justa* stoves.[15] Cleaner-burning cookstove interventions often report major reductions in household air pollution,[16-18] despite remaining well above the World Health Organization's 2005 air quality guidelines of a 24-hour mean $PM_{2.5}$ concentration of 25 µg/m^3 and an interim target-1 guideline of 75 µg/m^3.[19] For example, a wood-burning chimney stove intervention in Guatemala reported 61% lower personal $PM_{2.5}$ exposure among those cooking on an improved *plancha* woodstove versus those cooking on open fires, although daily average concentrations among the intervention group were still above WHO guidelines at 102 μg/m^3.[3] Evidence on the health effects with direct air pollution measures from cookstove interventions is sparse and have not focused on exposure-response relationships for cardiovascular endpoints.

Our primary objectives were to 1) evaluate the cross-sectional associations between household air pollution, as measured by 24-hour kitchen and personal air pollution concentrations and stove type, and systolic and diastolic blood pressure among 147 female primary cooks in rural Honduras using traditional or cleaner-burning *Justa* stoves, and 2) assess if age and body mass index (BMI) modified the associations between exposure and blood pressure. We hypothesized higher blood pressure among women with elevated air pollution concentrations and traditional cookstoves, compared to women with lower concentrations and *Justa* stoves. Based on previous evidence,[6,7,9,20] we hypothesized stronger associations between exposure to household air pollution and blood pressure among older women and women with higher BMI.

MATERIALS and METHODS

Study location and population

Our study took place in 11 rural communities near the town of La Esperanza, Department of Intibucá, Honduras. Elevation of the study location ranged from 1,730 to 2,200 meters above sea level, and families relied almost exclusively on biomass fuels for daily energy needs. The primary economy is agriculture, with corn, beans, potatoes, and other fruits and vegetables cultivated for personal consumption and selling in markets. The ethnic background in this region is predominately indigenous Lenca.

Participant recruitment

One hundred and fifty women were recruited between February 9 and April 30, 2015. Women were selected through a convenience sample from 500 households screened in 2014 among people that attended open community meetings. Interested people wrote their names, or family members' and neighbors' names, on a list, and study personnel visited households during formative research to classify stove types and sociodemographic characteristics of the study population. The original group of 500 potential participants was reduced based on availability, interest, and the following selection criteria. Owners of *Justa* stoves and traditional stove users were selected if they were a female, primary cook, non-pregnant, non-smoking, and between 25 and 56 years old. Traditional stove owners could not have any type of improved stove. Participants gave verbal informed consent and received $5 of food items. *Justa* stoves were installed at least 4 months prior to our data collection, and were given to participants by non-governmental organizations. The study protocol was approved by Colorado State University's Institutional Review Board, and community leaders gave their approval prior to data collection.

Exposure to household air pollution

We measured exposure to household air pollution by 24-hour average concentrations of personal and kitchen fine particulate matter ($PM_{2.5}$) and black carbon (BC), and by stove type categories. We calculated 24-hour time-weighted average concentrations for kitchen and personal $PM_{2.5}$ and BC. Kitchen air pollutants were collected by exposure monitors placed 76-127 centimeters from the front stove edge within the woman's breathing zone. The monitors were located away from the direct plume of smoke and a window or doorway. Personal air pollutants were collected as women wore a small bag with exposure monitors clipped on the strap near their breathing zone. Women were asked to continue their normal routine while wearing the bag, and to place the bag nearby only to bathe or sleep. Women self-reported during the interview if they had removed the personal bag, other than to bathe or sleep, and for how many minutes it was removed. No samples were collected on Sundays due to church attendance and other family activities that may have led to atypical daily cooking-related exposures.

The $PM_{2.5}$ size fraction was selected by cyclones (Triplex, BGI, Inc., NJ, USA) and collected on 37-mm filters (Fiberfilm, Pall Corporation, NY, USA) using pumps (AirChek XR5000, SKC Inc., PA, USA) calibrated to 1.5 liters per minute (DryCal Lite, Mesa Labs, NJ, USA) and run for 24 hours. Similar gravimetric exposure assessment methods have been previously used in a similar study population.[15] Samples that ran for less than 24 hours were removed from the analysis. Flow rates stayed within 10% of pre- and post-sampling calibrations. Filters were equilibrated for 24 hours and weighed (MX5, Mettler, OH, USA) at Colorado State University. Loaded filters were stored at -22 °C prior to shipment. Seven field blanks were used to determine a limit of detection (LOD) of 54 µg.[21] Masses below the limit of detection (LOD), equivalent to a 24-hour average concentration of approximately 25 μg/m^3 (kitchen: n=7; personal: n=4) were substituted by LOD/(square root of 2).

We estimated $PM_{2.5}$ BC concentrations based on the optical transmission of light through the air sampling filters[22] using a transmissometer (model OT-21, Magee Scientific, CA, USA). Transmission data were converted to mass concentrations based on published mass-absorption values for combustion aerosol[23] and corrected for a filter loading artifact that leads to an underestimation of the BC concentration at high sample loading.[24] The LOD was estimated to be 0.86 μg/m^3 corresponding to three times the standard deviation of 54 blank samples (additional blank filters were used from field sampling campaigns conducted within the same year to estimate the reference values for the transmissometer since pre-sampling transmission data were not collected on sample filters). Values below the LOD (kitchen: n=3; personal: n=10) were substituted by LOD/(square root of 2). Further details on BC are presented as supplemental material.

Stove type as an exposure measure was defined as primary stove type (traditional vs. cleaner-burning *Justa* stove), use of multiple stoves (stove stacking), and age of the *Justa* stove. Traditional stoves were classified as those that had never had a modified combustion chamber, even if there was a chimney or a griddle (Figure 1). *Justa* stoves, as described above, were wood-burning stoves with a rocket type insulated combustion chamber and a chimney (Figure 1).[14,25] Women self-reported if they practiced stove stacking, defined as using a secondary stove for cooking. The secondary stoves were traditional stoves, typically without a chimney and most often located outside. The four categories of stove stacking were traditional stove only, traditional stove with a secondary stove, *Justa* stove only, or *Justa* stove with a secondary stove. The age of the *Justa* stove was based the installation date, categorized by the median as an older *Justa* of ≥19 months, a newer *Justa* of 4-19 months, or a traditional stove of any age.

Blood pressure measurements

Non-fasting systolic and diastolic blood pressure were measured using the SphygmoCor XCEL Central Blood Pressure Measurement System (AtCor Medical Pty Ltd, Australia), recorded by the same study investigator at the brachial artery on the woman's right arm with a 23-33 cm cuff. Three consecutive measurements were taken after the woman had been sitting in a chair in a relaxed position for 10 minutes; the average of the 2nd and 3rd measurements was recorded. The investigator who collected all blood pressure measurements followed the at-home procedures, as described by the American Heart Association.[26] Blood pressure was taken between 7 am and 12 noon after the 24-hour period of household air pollution measurements.

Sociodemographic and other measurements

Women self-reported sociodemographic and health characteristics. The in-person questionnaires were developed with community leaders and our local coordinator to ensure comprehensibility and appropriateness. Questionnaire data were recorded in Samsung tablets using Open Data Kit (ODK Collect 1.4.5, UK, https://opendatakit.org/).[27] Age was confirmed by the woman's national identification card. Indicators of socioeconomic status included beds per person in the household, the sum of seven primary household assets (bicycle, motorcycle, television, radio, refrigerator, sewing machine, working electricity), education (reported as the highest grade completed in school), and a dietary diversity score (a sum of ten food groups categorized from 19 commonly eaten food items from a 24-hour dietary recall). Women reported if anyone smoked in their home, the total number of people living in the house, and the number of people that typically ate a meal. Women self-reported how much time they typically spent inside the kitchen while the stove was burning (hours), and how many times they cooked or made coffee during the past 24 hours. Current use of anti-hypertensive medications was self-reported and confirmed by reviewing bottles or prescriptions.

Physical activity was estimated using the updated 2011 Compendium of Physical Activities, based on typical lifestyle activities for the study population, assessed as metabolic equivalents (METs) and calculated as MET adjusted hours per week (i.e., MET-hours).[28] A MET is the ratio of the rate of energy expended during an activity to the rate of energy expended at rest.[29] For example, 1 MET is the rate of energy expenditure during rest, while an activity that expends 4 times that energy for 30 minutes would be 4 x 30 = 120 MET-minutes (2 MET-hours).[29,30] Moderate intensity activities range from 3.0-5.9 METs, and vigorous activities are defined as 6.0 METs or more.[29] As reference, running at a pace of a 10-minute mile is a 9.8 MET vigorous activity, whereas general gardening is a 3.8 MET moderate activity. The U.S. Department of Health and Human Services reports that most health benefits occur with at least 2.5 hours of moderate intensity activity, which equals 10 MET-hours (600 MET-minutes at a 4.0 MET activity).[29] The lifestyle activities that were queried in this study came from formative research identifying usual activities done by our agricultural-based study population. Physical activities were self-reported by women as hours per week (hours per day x days per week) the woman cut wood (MET=5.5), ground corn (MET=3.3), washed clothes (MET=4.0), milked cows (MET=3.5), worked in the field (MET=4.8), carried heavy items or children (MET=5.0), and walked normally outside of the house (MET=3.5).[28] We converted these weekly hours of activity to MET-hours by multiplying the activity by the 2011 Compendium MET score and then summed all values for a total MET-hours per week of physical activity. This approach to sum typical lifestyle activities as hours per week is used in other study populations with very high levels of physical activity.[31]

Weight and height were measured without shoes, with weight measured by an electronic scale placed on a wooden board, and height measured using measuring tape and level against a wall. An individual's weight (kilograms) divided by height (meters squared) was used to calculate BMI. Diet was assessed by self-reported daily intake of salt, vegetable shortening, and sugar; women were shown an example of a typical bag of each food item and asked how many days it took their family to finish that item. Daily consumption per person was then calculated by dividing the grams of the item by reported days of consumption, by total number of people that eat in the house. For example, if a woman reported it took 22 days to consume one bag of salt of 400 grams among 8 people in the home, her daily salt consumption was estimated as [(400/22)/8]. These calculations offered approximations of true intake based on self-reported estimates of consumption and may not perfectly capture dietary salt; for example, pre-packaged food items that may have high salt content are not included.

Household elevation and GPS coordinates were recorded on smart phones with the mobile app *Maps.Me* (MapsWithMe GmbH, Zurich, https://maps.me/). Kitchen temperature was recorded with the Lascar EL-USB-2 relative humidity and temperature logger, which was placed in the cluster of kitchen exposure equipment (Lascar Electronics Inc., PA, USA). The location of primary stoves was coded by the interviewer through direct observation as in a separate building (outside the main house), inside a main living area (e.g., bedroom or living room), or in a separate room but attached to the house. Long-term history of cookstove smoke exposure was estimated as “cook-years,” by subtracting the self-reported age at which the woman started cooking from her current age.

Statistical analysis

We removed three women from the analysis who reported current use of anti-hypertensive medications, for a final sample of 147 women. For analyses of pollution measurements, the sample was reduced for $PM_{2.5}$ (personal n=104, kitchen n=105) and BC (personal n=105, kitchen n=106) due to DryCal malfunctions at the beginning of the sampling period and missing data with two post-sample filters. The main outcomes of interest were systolic and diastolic blood pressure, assessed as continuous and dichotomized variables: normal blood pressure (systolic <120 mmHg and diastolic <80 mmHg) and borderline high or high blood pressure (systolic ≥120 mmHg and/or diastolic ≥80 mmHg). Too few women with systolic blood pressure ≥ 140 mmHg and/or diastolic ≥90 mgHg warranted a separate category.

Age and BMI were included as continuous variables when adjusting for potential confounding, and dichotomized for interaction analyses (age <40 years and ≥40 years, BMI <25 and ≥25). Years of education was dichotomized as <6 years and ≥6 years because of the compulsory number of school years in Honduras, and household wealth was dichotomized as 0-1 or ≥2 material assets. Beds per household member, MET-hours per week, dietary intake of salt, shortening, and sugar, household elevation, cook-years, and kitchen temperature were assessed as continuous variables. Time of day for the blood pressure measurement was assessed as a continuous variable and dichotomized at the median as 7:10 – 9:59 am and 10:00 am – 12:00 pm. The 11 communities were grouped into six categories based on geographic proximity. Exposure to secondhand smoke was treated as a dichotomous yes/no variable.

Descriptive analyses summarized the means, standard deviations, ranges, frequencies, and outliers. We calculated Spearman correlation coefficients between all 24-hour air pollution measurements. To ensure that *Justa* and traditional stove users were comparable for key sociodemographic and health-related variables, we compared mean values using independent sample t-tests. We used multivariable linear regression for continuous blood pressure, and logistic regression for dichotomized blood pressure (borderline high or high blood pressure versus normal). Full models included the main exposure (24-hour air pollution concentration or stove type), plus a priori confounders: age, an indicator of socioeconomic status (beds per person, which had the strongest crude association with the outcomes compared to the other SES indicators), BMI, and physical activity. Continuous kitchen and personal air pollution concentrations were natural log transformed to meet the assumptions of regression modeling, specifically to achieve normality in the residuals and avoid nonlinearity, as diagnosed in residual outputs with quantile plots of the residuals and tests for heteroscedasticity. Potential confounders assessed were dietary intake, elevation, kitchen temperature, timing of the blood pressure measure, other SES indicators, and lifetime cooking exposure (cook-years). Potential confounding was assessed by observing meaningful changes in the estimate and precision (95% confidence interval) of the association between exposure and health endpoints based on adding and removing covariates individually.

We assessed effect measure modification in the adjusted linear and logistic regression models by adding an interaction term between the exposure variable and age or BMI. We conducted the following sensitivity analyses on the full model: timing of blood pressure measure (removed n=11 with measures taken before 8 am and after 11:30 am), community (included as a fixed-effect term in the final model), secondhand smoke exposure (removed n=4 with self-reported secondhand smoke exposure), removing blood pressure outliers (e.g., n=4 observations of low diastolic blood pressure with readings less than 60 mmHg), recent added salt intake (removed n=17 who reported eating packaged chips in the past 24 hours), and $PM_{2.5}$ pump monitors with flow faults (removed observations with post-measurement calibration flow of less than 1.35 liters/minute, personal n=5, kitchen n=3). All statistical analyses were performed in SAS 9.4 (SAS Institute Inc., NC, USA).

RESULTS

Descriptive summary

In Table 1, we present a descriptive summary of the full sample and by stove type. Women were on average (SD) 37.0 (8.7) years of age, and had a mean of 0.5 (0.2) beds per person in the house. Approximately half of the women (n=67, 46%) had less than six years of education, and reported owning one or fewer household assets (n=71, 49%). Mean BMI was 25.7 (4.2) kg/m^2, and mean activity level was 212 (107) MET-hours per week. The mean 24-hour kitchen temperature was 21.4 (3.0) degrees Celsius, and mean number years of cooking on a biomass stove was 25.4 (9.6). Women self-reported that they typically spent an average of 5.6 (2.4) hours inside their kitchen with the stove burning, and they had an average of 5.6 (1.6) cooking events (including making coffee) during the past 24 hours. Mean household elevation was 1917 (108) meters. Mean household member intake per day of salt, vegetable shortening, and sugar was 8.6 (6.2), 13.1 (10.1), and 42.5 (25.2) grams, respectively. Only 4 women (3%) had been exposed to secondhand smoke. Mean systolic and diastolic blood pressure in mmHg were 118.3 (12.4) and 73.1 (8.7), respectively, with 90 women (61%) within a normal blood pressure range, and 46 (31%) and 11 (7%) women categorized as having borderline high or high blood pressure, respectively (Table 1). Results from independent sample t-tests showed that *Justa* and traditional stove users had no significant differences in age, education, household size, number of people eating meals, time spent inside the kitchen on a typical day, cooking events in past 24 hours, total years cooking on a biomass stove, BMI, physical activity, and salt intake.

Primary stoves were located in a separate building (n=49, 33%), inside a main living space (n=13, 9%), or in a separate room in the house (n=85, 58%), with no differences in location between traditional and *Justa* stoves. The sample was split between women who used a traditional stove (n=74, 50%) versus *Justa* stove (n=73, 50%) (Table 1). In terms of using more than one stove to cook, known as stove stacking, 47 (32%) women used only their traditional stove, 27 (18%) used a traditional with another stove, 38 (26%) used only their *Justa* stove, and 35 (24%) used their *Justa* stove with another stove. Among *Justa* users, mean time since installation of *Justa* stoves was 24 (17) months, with a median of 19 months.

Personal and kitchen air pollution concentrations

Table 2 includes personal and kitchen air pollution concentrations for all households and by stove type. For all households, mean 24-hour concentrations of personal $PM_{2.5}$ and BC were 101 (70) μg/m^3 and 17 (22) μg/m^3, respectively. Mean 24-hour concentrations for kitchen $PM_{2.5}$ and BC were 266 (329) μg/m^3 and 75 (149) μg/m^3, respectively. Despite substantial overlap in air pollution concentrations between stove types, as shown in Figure 2, the average personal and kitchen $PM_{2.5}$ concentrations were 48% and 62% lower, respectively, for *Justa* stove users compared to traditional stove users (Table 2). Average concentrations for BC were also lower among *Justa* stove users, with 71% lower personal and kitchen BC concentrations compared to traditional stove users (Table 2). Regarding self-reported compliance among the 104 women with available personal air pollution data, 21 (20%) reported removing the bag for an average of 60 minutes (range: 2-180 minutes); there were no significant differences in personal $PM_{2.5}$ or BC between those who reportedly removed the bag versus those who were supposedly compliant.

All four household air pollution concentrations were strongly correlated. The Spearman correlation coefficient between personal and kitchen $PM_{2.5}$ was 0.81, and the correlation between personal and kitchen BC was 0.78. Personal $PM_{2.5}$ had a Spearman correlation coefficient of 0.78 with personal BC, and kitchen $PM_{2.5}$ was 0.89 with kitchen BC.

Associations between exposure and blood pressure

Table 3 summarizes the findings from multivariable linear regression analyses of continuous systolic blood pressure. After adjusting for confounders (age, socioeconomic status as beds per person, BMI, and physical activity), we observed higher blood pressure in relation to higher kitchen pollution concentrations. A one unit increase in natural log transformed kitchen $PM_{2.5}$ concentration was associated with 2.5 mmHg higher systolic blood pressure (95% CI, 0.7 to 4.3). Similar results were observed for kitchen BC and systolic blood pressure (Table 3), and kitchen $PM_{2.5}$ with diastolic blood pressure (Supplementary Table 1). Results for personal pollutant concentrations and blood pressure were consistent with a null association (Table 3).

A suggestive association was observed between stove type and systolic blood pressure; women with traditional stoves had a 2.8 mmHg higher systolic blood pressure compared to women with *Justa* stoves (95% CI, -1.1 to 6.6) (Table 3). Using the four-category stove type variable (based on the use of a secondary stove), we further observed an association of suggestive significance; women with traditional stoves who also stove stacked had a 4.2 mmHg higher systolic blood pressure compared with women who only used a *Justa* stove (95% CI, -1.8 to 10.2) (Table 3). The age of the *Justa* stove was also suggestively associated with systolic blood pressure, as women with traditional stoves or older *Justa* stoves (≥19 months) had higher systolic blood pressure (4.5 mmHg (95% CI, -0.2 to 9.2) and 3.5 mmHg (95% CI, -1.9 to 9.0), respectively), compared to women with newer *Justa* stoves (<19 months) (Table 3).

Results for the 24-hour air pollution measures suggested an increased odds for the dichotomized outcome of borderline high and high blood pressure for women with higher kitchen concentrations (Table 4). For example, the adjusted odds ratio for borderline high and high blood pressure per unit increase in natural log transformed kitchen $PM_{2.5}$ concentration was 1.5 (95% CI, 1.0 to 2.3). Similar patterns were observed for kitchen BC (Table 4); for both exposures, the precision estimates of the odds ratios included the null value of 1.0, and therefore results are considered suggestive. Results for personal air pollution exposure measurements were consistent with a null association (Table 4). For stove type, women using traditional stoves were almost twice as likely to have prevalent borderline high or high blood pressure compared to women using *Justa* stoves (OR = 1.8; 95% CI, 0.9 to 3.7), after adjusting for confounders, although the association is suggestive given the inclusion of the null value in the precision estimate (Table 4).

For all measured air pollutants, we observed evidence that age modified the associations with continuous systolic blood pressure, with stronger associations among women who were 40 years or older compared to women who were less than 40 years (Table 5). For example, among women who were 40 or older, a one unit increase in natural log transformed kitchen $PM_{2.5}$ concentration was associated with 5.2 mmHg higher systolic blood pressure (95% CI, 2.3 to 8.1), whereas women who were less than 40 did not show evidence of an association (p-value for interaction=0.02). Similar results were observed for diastolic blood pressure (Supplementary Table 2). Similar patterns of effect modification by age were observed with the dichotomized blood pressure variable; however, the confidence intervals were not as precise (Table 6). We did not observe effect measure modification by age when evaluating stove type (Tables 5 and 6), or by BMI in linear and logistic regression models (Supplementary Tables 3-5).

Sensitivity analyses

We conducted sensitivity analyses on the full models per exposure variable, as described under Methods, including adjustment for community of residence and removal of those with blood pressure measurements at early or late times, exposure to secondhand smoke, blood pressure outliers, added salt intake via self-report of prepackaged chip consumption in the past 24 hours, or exposure monitors with air pump flow faults. None of the final model results for effect or precision were meaningfully changed based on the sensitivity analyses.

DISCUSSION

We evaluated the cross-sectional association between exposure to household air pollution and systolic and diastolic blood pressure among 147 women living in rural Honduras, while considering effect modification by age and BMI. All women used biomass cookstoves- half used traditional stoves without a modified combustion chamber, and half used a cleaner-burning *Justa* stove. Traditional stoves produced substantially higher 24-hour mean personal and kitchen $PM_{2.5}$ and BC concentrations compared to *Justa* stoves. Study results provide suggestive evidence to support our hypothesis that higher levels of air pollution concentrations in kitchens were associated with elevated systolic and diastolic blood pressure. Similarly, we observed an increased adjusted odds of borderline high and high blood pressure among women using a traditional stove and with higher kitchen air pollution concentrations. Results suggest that age modified associations with blood pressure for all air pollutants, as seen with stronger associations among women 40 years or older compared to women less than 40 years. Adjusted analyses showed suggestive evidence of associations in the hypothesized direction between stove type and stove stacking. Our observed association of stove stacking with elevated blood pressure (as compared to using only the *Justa* stove) supports the argument that any continued use of traditional stoves diminishes the health benefits expected from a cleaner-burning stove intervention.[32-34]

The associations between kitchen $PM_{2.5}$ concentrations and blood pressure were stronger than those for personal $PM_{2.5}$, although general consensus supports personal exposure concentrations as a better estimate of personal exposure.[35] For this study, however, 24-hour kitchen $PM_{2.5}$ concentration measurements may have offered a more accurate depiction of long-term personal exposure to biomass smoke than a 24-hour personal $PM_{2.5}$ measurement, perhaps due to lower daily variability for a one-time 24-hour kitchen measurement.

Our main study results are consistent with previous studies, which also report associations between household air pollution and blood pressure outcomes. [3,7,9] A cross-sectional study among 280 women in rural China reported almost identical results as ours: each unit increase in natural log $PM_{2.5}$ concentration was associated with 2.2 mmHg higher systolic blood pressure (95% CI, 0.8 to 3.7).[7] Stronger effects of household air pollution on blood pressure among older women is further supported by other studies [20], such as the rural China study [7] and a cookstove intervention in Guatemala.[3] Previous cookstove interventions also reported reduced pollution measures between traditional and cleaner-burning biomass stoves. For example, a substantial drop was observed in 24-hour mean kitchen $PM_{2.5}$ concentrations from 240 $\mu g/m^3$ (210) to 48 $\mu g/m^3$ (41) between pre- and post-intervention in a study in rural Bolivia,[9] with a mean decrease in systolic blood pressure from 114.5 (SD 13) to 109.0 (SD 10.4) mmHg.[9] We did not find evidence of effect modification by BMI, which is not consistent with previous research in Latin America, [9,20] and it is unclear why our study population differed. Overall, previous studies, as well as our own, support the idea that meaningful changes in blood pressure are possible even when cleaner-burning stoves produce household air pollution concentrations above the World Health Organization's 2005 air quality guidelines of a 24-hour mean $PM_{2.5}$ concentration of 25 $\mu g/m^3$ and an interim target-1 guideline of 75 $\mu g/m^3$.[19]

The impact of household air pollution on blood pressure is gaining recognition, particularly in low- to middle-income countries that rely heavily on biomass fuels for cooking, heating, and lighting homes,[3,8,36,37] and for susceptible population subgroups based on age or overweight/obesity.[6,7,9,20] Elevated blood pressure is a consistent and independent risk factor for cardiovascular disease[38] and is no longer limited to wealthy, developed nations. The most recent Global Burden of Disease study reported elevated systolic blood pressure as the number one contributor to disability-adjusted life-years worldwide, including Latin America.[1] In

Honduras in 2015, high systolic blood pressure and household air pollution were ranked first and seventh, respectively, for disability-adjusted life-years among men and women.[2] Previous mechanistic studies from animals and humans support an association between air pollution and elevated blood pressure, possibly via sympathetic nervous system activation and vascular dysfunction.[39] The link between household air pollution and blood pressure presents a key opportunity for prevention on a large-scale in the global epidemic of cardiovascular disease.

Strengths and Limitations

Several strengths of this research included measuring air pollution concentrations in a population previously not well-studied, demonstrating the feasibility of the SphygmoCor device in a field setting to measure blood pressure, and quantitatively assessing a range of potential confounders. Our two study groups were comparable with respect to the measured characteristics. The *Justa* stove is reliable, well-accepted in this region, and locally sourced. Our results on BC are novel and closely track the findings for $PM_{2.5}$, contributing to a gap in the literature on this particular exposure measure.

Several limitations are important to note. The cross-sectional design did not allow for a temporal relationship to be established between the exposures and blood pressure outcomes. We did, however, address this limitation to an extent by including only participants who owned their current stove for four months or longer. The 24-hour exposure period may not have been representative of normal cooking routines, especially if the woman was measured on a day that she did not cook normally. We were unable to measure all potential pollutants from combustion, and $PM_{2.5}$ and BC may be indicators of other health-damaging pollutants that were not measured.[35]

Salt and physical activity are important contributing factors to blood pressure, and our estimates of these two variables were proxies for true values, given self-reported measures of consumption and weekly activity. It is possible that effect estimates might change with more accurate values of salt intake and physical activity. Our estimated MET-hours per week represents an upper extreme for lifestyle activity compared to urbanized populations,[30] although it reflects other, perhaps more similar, populations living traditional lifestyles. For example, an Old Order Amish community in Ontario had similarly high levels of activity and reported levels much greater than other populations (mean MET-hours per week for men and women was 255).[31] This may offer a useful comparison to our study population that also lacks access to cars, electrical appliances, and still uses labor-intensive farming methods.

Justa stove users received their stoves from non-governmental organizations prior to our data collection, and some NGO projects had criteria for installation (e.g., at least one child less than 5 years old), which could possibly have created systematic differences in *Justa* versus traditional stove users. While we did not find significant differences in sociodemographic characteristics (age, education, household size, number of people eating meals), physical activity, diet, or cooking patterns between stove type groups, there may still be residual confounding not accounted for by the study, as well as other relevant confounders not captured. Lastly, the relatively small sample size in our study (N=147) may be a limitation given the cross-sectional study design, based on previous studies with a blood pressure endpoint that reported limited power.

There are several potential sources of bias in this study design and implementation. Women were selected to participate based mostly on reviewing lists created at community meetings, so women who did not attend the meetings, such as if they were too sick to attend, would have been left out of recruitment, thus making results difficult to generalize. It is possible that women were not fully compliant with wearing the personal exposure bag for 24 hours, and that our self-reported measure of compliance underestimated the actual amount of time that the bag was removed. If there was a difference in compliance based on women's daily activities, such as some women being more likely to remove the bag when cooking, then it is possible that personal exposure concentrations might be artificially low in a subgroup of women.

Significance

The differences in blood pressure and household air pollution concentrations by stove type support the argument that cleaner-burning biomass cookstoves may have the potential to effectively reduce health-damaging exposure to household air pollution, even in the absence of electric or gas stoves. Although some results by stove type had wide confidence intervals or included null values, stove type is the largest source of exposure to air pollution in these rural communities, indicating that the installation of cleaner-burning stoves should be targets for interventions. Furthermore, despite observing concentrations higher than the WHO air quality guidelines among homes with both *Justa* and traditional stoves, we observed suggestive evidence of clinically meaningful differences in blood pressure between users of the two stove types.[40] A reduction of as little as 2 mmHg in systolic blood pressure could lead to 10% lower stroke mortality and 7% lower mortality from ischemic heart disease or other vascular causes in middle age.[40] The results of this study support previous research that intervening at the household level with acceptable and well-functioning biomass stoves can reduce household air pollution and have potentially important impacts on population health for cardiovascular disease risk, especially among older subgroups, even when pollution levels remain above target guidelines.

CONCLUSION

Consistent with previous studies, higher air pollution concentrations in kitchens showed suggestive associations with elevated systolic and diastolic blood pressure in women. This association was stronger in older women. Kitchen air pollution concentrations may better represent long-term exposure to biomass combustion than personal exposures, particularly when a single 24-hour sample is collected. Intervening at the household level with culturally-appropriate, accepted, accessible biomass cookstoves that reduce household air pollution may have beneficial impacts on blood pressure with the potential to decrease risk of cardiovascular disease.

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FIGURES AND TABLES FOR MANUSCRIPT

EXPOSURE TO HOUSEHOLD AIR POLLUTION FROM BIOMASS COOKSTOVES AND BLOOD PRESSURE AMONG WOMEN IN RURAL HONDURAS: A CROSS-SECTIONAL STUDY

A
Traditional stove with griddle and chimney

B
Traditional stove without chimney

C
Cleaner-burning *Justa* stove

Figure 1. Examples of traditional (A, B) and cleaner-burning *Justa* biomass cookstoves (C) among the study population, February – April 2015, Department of Intibucá, Honduras.

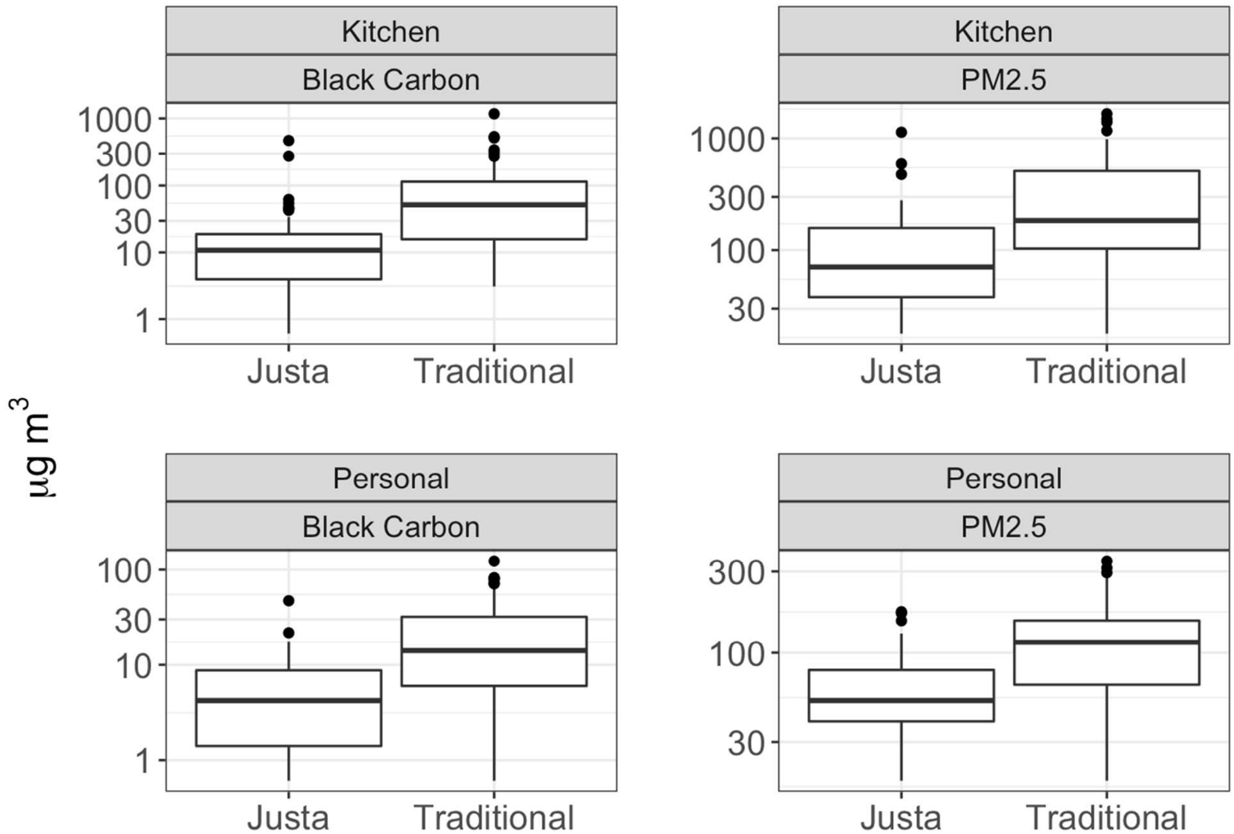

Figure 2. Distributions of 24-hour mean personal and kitchen $PM_{2.5}$ and black carbon concentrations ($\mu g/m^3$) by stove type. The black line inside the box shows the median concentration, the box shows the interquartile range, the whiskers show 1.58 times the interquartile range divided by the square root of the sample size, and black circles show values outside this range.

Table 1. Descriptive summary of participants for all households and by stove type

Participant characteristics	**All households N=147**	**Traditional stove owners N=74**	***Justa* stove owners N=73**
	Mean (SD) or N (%)	Mean (SD) or N (%)	Mean (SD) or N (%)
Age (years)	37.0 (8.7)	38.1 (9.7)	35.8 (7.6)
Beds per person in the household	0.5 (0.2)	0.5 (0.20)	0.5 (0.20)
Education			
Less than six years	67 (46%)	38 (52%)	29 (40%)
Six or more years	78 (54%)	35 (48%)	43 (60%)
Material wealth[1]			
0-1 household assets	71 (49%)	35 (47%)	36 (50%)
2 or more household assets	75 (51%)	39 (53%)	36 (50%)
Total number of people living in the house, including infants	6.4 (2.5)	6.3 (2.7)	6.4 (2.4)
Number of people typically eating meals	6.1 (2.4)	5.8 (2.5)	6.3 (2.4)
Typical amount of time spent inside kitchen each day with stove burning (hours)	5.6 (2.4)	5.8 (3.0)	5.4 (2.5)
Cooking events in past 24 hours[2]	5.6 (1.6)	5.7 (1.6)	5.5 (1.6)
Total years cooking with a biomass stove (cook-years)	25.4 (9.6)	26.5 (10.7)	24.4 (8.3)
Household elevation (meters)	1917 (108)	1,895 (99)	1,939 (113)
Body mass index (kg/m^2)	25.7 (4.2)	25.5 (4.6)	25.9 (3.8)
Physical activity[3] (metabolic equivalents, MET adjusted hours per week)	212 (107)	216 (116)	209 (97)
24-hour average kitchen temperature (degrees Celsius)	21.4 (3.0)	21.9 (2.9)	20.9 (2.9)
Salt intake per day per household member (grams)	8.6 (6.2)	9.0 (6.0)	8.2 (6.0)
Vegetable shortening intake per day per household member (grams)	13.1 (10.1)	14.9 (11.0)	11.2 (9.0)
Sugar intake per day per household member (grams)	42.5 (25.2)	43.9 (26.0)	41.1 (24.0)
Start time of blood pressure measure (split at the median value)			
7:10 – 9:58 am	72 (49%)	34 (46%)	38 (52%)
9:59 am – 12:00 pm	75 (51%)	40 (54%)	35 (48%)
Continuous blood pressure (mmHg)			
Systolic	118.3 (12.4)	119.9 (11.6)	116.6 (13.0)
Diastolic	73.1 (8.7)	73.8 (8.5)	72.3 (8.9)
Categorized blood pressure[4]			
Normal	90 (61%)	40 (54%)	50 (68%)
Borderline high blood pressure	46 (31%)	28 (38%)	18 (25%)
High blood pressure	11 (7%)	6 (8%)	5 (7%)

[1] Sum of household assets: bike, motorcycle, television, radio, refrigerator, sewing machine, electricity, categorized at the median split
[2] Self-reported times cooking or making coffee during the past 24 hours.
[3] Physical activity was assessed by assigning metabolic equivalents from the 2011 Compendium of Physical Activities for the following lifestyle physical activities, calculated as hours per week: cut wood, grind corn, wash clothes, milk the cow, work in the field, carry a heavy weight and walk normally outside the house.
[4] Blood pressure categories defined as: normal = systolic <120 mmHg and diastolic <80 mmHg; borderline high blood pressure = systolic 120-139 mmHg, diastolic 80-89 mmHg; high blood pressure = systolic ≥140 mmHg, diastolic ≥90 mmHg.

Table 2. Personal and kitchen air pollution concentrations for all households and by stove type, 24-hour averages

24-hour average air pollution concentrations	**All households**	**Traditional stoves**	***Justa* stoves**
	Mean (SD); 10^{th} to 90^{th} percentiles	Mean (SD); 10^{th} to 90^{th} percentiles	Mean (SD); 10^{th} to 90^{th} percentiles
Personal $PM_{2.5}$ (µg/m^3) (n=104)	101 (70); 37 to 196	126 (77); 43 to 241	66 (38); 31 to 121
Kitchen $PM_{2.5}$ (µg/m^3) (n=105)	266 (329); 37 to 643	360 (374); 62 to 838	137 (194); 28 to 265
Personal BC (µg/m^3) (n=105)	17 (22); 1 to 43	24 (26); 4 to 67	7 (8); 1 to 15
Kitchen BC (µg/m^3) (n=106)	75 (149); 4 to 173	106 (177); 7to 261	31 (80); 3 to 47

Table 3. Adjusted mean differences in systolic blood pressure (mmHg) comparing continuous (natural log transformed) pollution concentrations and stove types among 147 Honduran women using either a traditional or *Justa* stove*

24-hour average air pollution concentrations[1]	**Adjusted mean difference (mmHg) in systolic blood pressure (95% CI)**
Personal $PM_{2.5}$ ($\mu g/m^3$) (n=104)	0.8 (-2.2 to 3.8)
Kitchen $PM_{2.5}$ ($\mu g/m^3$) (n=105)	2.5 (0.7 to 4.3)
Personal BC ($\mu g/m^3$) (n=105)	0.5 (-1.0 to 2.0)
Kitchen BC ($\mu g/m^3$) (n=106)	1.7 (0.3 to 3.0)
Stove type	
Stove type:	
Traditional stove (n=74)	2.8 (-1.1 to 6.6)
Justa stove (n=72)	Reference
Stove type:	
Traditional with use of a secondary stove (n=27)	4.2 (-1.8 to 10.2)
Traditional only (n=47)	2.8 (-2.2 to 7.8)
Justa with use of a secondary stove (n=34)	1.2 (-4.3 to 6.6)
Justa only (n=38)	Reference
Stove type:	
Traditional only (n=74)	4.5 (-0.2 to 9.2)
Justa installed ≥19 months ago (n=36)	3.5 (-1.9 to 9.0)
Justa installed <19 months ago (n=36)	Reference

BC=black carbon; CI=confidence interval; PM=particulate matter<2.5 µm.

***Adjusted for: age (continuous), beds per person (continuous), body mass index (continuous), physical activity (continuous).

[1] Per one unit increase in natural log transformed air pollution concentration.

Table 4. Adjusted odds ratios in hypertensive status (borderline high or high blood pressure compared to normal) comparing continuous (natural log transformed) pollution concentrations and stove types among 147 Honduran women using either a traditional or *Justa* stove*

24-hour average air pollution concentrations[1]	**Odds Ratio (95% CI)**
Personal $PM_{2.5}$ (µg/m^3) (n=104)	1.1 (0.6 to 2.1)
Kitchen $PM_{2.5}$ (µg/m^3) (n=105)	1.5 (1.0 to 2.3)
Personal BC (µg/m^3) (n=105)	1.1 (0.8 to 1.6)
Kitchen BC (µg/m^3) (n=106)	1.3 (1.0 to 1.8)
Stove type	
Stove type:	
Traditional stove (n=74)	1.8 (0.9 to 3.7)
Justa stove (n=72)	Reference
Stove type:	
Traditional with use of a secondary stove (n=27)	1.6 (0.5 to 4.7)
Traditional only (n=47)	2.3 (0.9 to 5.8)
Justa with use of a secondary stove (n=34)	1.2 (0.4 to 3.3)
Justa only (n=38)	Reference
Stove type:	
Traditional only (n=74)	2.3 (0.9 to 5.7)
Justa installed ≥19 months ago (n=36)	1.6 (0.6 to 4.4)
Justa installed <19 months ago (n=36)	Reference

BC=black carbon; CI=confidence interval; PM=particulate matter<2.5 µm.

*Adjusted for: age (continuous), beds per person (continuous), body mass index (continuous), physical activity (continuous).

[1] Per one unit increase in natural log transformed pollution concentration.

Table 5. Effect modification by age for the adjusted mean differences in systolic blood pressure (mmHg) comparing continuous (natural log transformed) pollution concentrations and stove types among 147 Honduran women using either a traditional or *Justa* stove*

24-hour average air pollution concentrations[1]	Age category	Adjusted mean difference in systolic blood pressure (95% CI)	P-value for interaction
Personal $PM_{2.5}$ (μg/m^3) (n=104)	≥40 years (n=35) <40 years (n=69)	3.9 (-1.5 to 9.3) -0.7 (-4.4 to 3.1)	0.17
Kitchen $PM_{2.5}$ (μg/m^3) (n=105)	≥40 years (n=36) <40 years (n=69)	5.2 (2.3 to 8.1) 0.7 (-1.7 to 3.0)	0.02
Personal BC (μg/m^3) (n=105)	≥40 years (n=35) <40 years (n=70)	1.6 (-1.0 to 4.2) -0.2 (-2.1 to 1.7)	0.29
Kitchen BC (μg/m^3) (n=106)	≥40 years (n=36) <40 years (n=70)	3.3 (1.1 to 5.5) 0.7 (-1.1 to 2.4)	0.06
Stove type (Traditional vs. *Justa*)	≥40 years (n=52) <40 years (n=95)	1.0 (-5.7 to 7.1) 3.6 (-1.2 to 8.5)	0.54

BC=black carbon; CI=confidence interval; PM=particulate matter<2.5 μm.

***Adjusted for: age (continuous), beds per person (continuous), body mass index (continuous), physical activity (continuous).

[1] Per one unit increase in natural log transformed pollution concentration.

Table 6. Effect modification by age for the adjusted odds ratios in hypertensive status (borderline high or high blood pressure compared to normal) comparing continuous (natural log transformed) pollution concentrations and stove types among 147 Honduran women using either a traditional or *Justa* stove*

24-hour average air pollution concentrations[1]	**Age category**	**Odds ratio (95% CI)**	**p-value for interaction**
Personal $PM_{2.5}$ (µg/m^3) (n=104)	≥40 years (n=35) <40 years (n=69)	1.6 (0.7 to 3.5) 1.2 (0.7 to 1.9)	0.29
Kitchen $PM_{2.5}$ (µg/m^3) (n=105)	≥40 years (n=36) <40 years (n=69)	2.3 (1.1 to 5.1) 1.7 (1.1 to 2.8)	0.19
Personal BC (µg/m^3) (n=105)	≥40 years (n=35) <40 years (n=70)	1.4 (0.7 to 3.2) 1.1 (0.7 to 1.8)	0.23
Kitchen BC (µg/m^3) (n=106)	≥40 years (n=36) <40 years (n=70)	2.3 (1.0 to 5.4) 1.9 (1.1 to 3.1)	0.39
Stove type (Traditional vs. *Justa*)	≥40 years (n=52) <40 years (n=95)	1.1 (0.6 to 2.0) 1.3 (0.9 to 1.9)	0.39

BC=black carbon; CI=confidence interval; PM=particulate matter<2.5 µm.
***Adjusted for: age (continuous), beds per person (continuous), body mass index (continuous), physical activity (continuous).
[1] Per one unit increase in natural log transformed pollution concentration.

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SUPPLEMENTARY MATERIAL

EXPOSURE TO HOUSEHOLD AIR POLLUTION FROM BIOMASS COOKSTOVES AND BLOOD PRESSURE AMONG WOMEN IN RURAL HONDURAS: A CROSS-SECTIONAL STUDY

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Supplemental Information: Black Carbon Estimation

We estimated $PM_{2.5}$ black carbon concentrations based on the optical transmission of light through the air sampling filters. A transmissometer (model OT-21, Magee Scientific, USA) estimated the attenuation at 880 nm light intensity through the sample filter, which is proportional to the amount of black carbon on the filter. To estimate the black carbon loading we first define a measure of attenuation (ATN) as the natural log of the ratio of light transmittance of a reference filter (I_0) to a sample filter (I) multiplied by 100:

$$ATN = 100 \times ln\left(\frac{I_0}{I}\right) \qquad (1)$$

We used a single value for reference transmittance (I_0 = 224571), taken as the average transmittance of 54 field blank filters. This reference method is similar to that reported previously with laboratory blank filters[1] and one that also allows us to account for contamination that may have occurred with filter handling during non-sampling periods.

Although these field blanks were not collected during the same sampling period, samples were collected within a year and with similar field methods.

The measured attenuation was then used to derive the attenuation coefficient (b_{atn}) in units of inverse megameters (Mm^{-1}), adjusting for field sampling factors such as the sampled area on the filter (m^2), and the volume of the air sampled (m^3, calculated using the sample flow rate and the sample duration). The attenuation coefficient was calculated as described by Presler-Jur et al:[1]

$$b_{atn} = \frac{Filter\ Area}{Sample\ Volume} \times ATN \times 10^4 \qquad (2)$$

Assumptions of black carbon concentration estimates have uncertainties given the properties of particles (e.g. differences in light scattering and combustion source). We used a mass attenuation cross-section), σ_{atn}, to convert from ATN to an equivalent BC concentration, which implies a linear relationship between the BC and the ATN of the sample filter. To account for the primarily wood-burning nature of the exposure, we defined σ_{atn} = 12.5 m^2/g as derived previously for carbonaceous smoke by Chylek and colleagues.[2] Additionally, previous studies have demonstrated a measurement artifact wherein an underestimation of the ATN becomes more pronounced at higher black carbon concentration. We therefore used a loading correction r, calculated according Kirchstetter and Novakov:[3]

$$r = \left(exp^{-ATN/100}\right) \times 0.88 + 0.12 \qquad (3)$$

The final estimated BC concentration (BC, $\mu g/m^3$) was calculated as follows:

$$BC = \frac{b_{atn}}{\sigma_{atn} \times r} \qquad (4)$$

SUPPLEMENTAL TABLES

Supplementary Table 1. Adjusted mean differences in diastolic blood pressure (mmHg) comparing continuous (natural log transformed) pollution concentrations and stove types among 147 Honduran women using either a traditional or *Justa* stove*

24-hour average air pollution concentrations[1]	**Adjusted mean difference (mmHg) in diastolic blood pressure (95% CI)**
Personal $PM_{2.5}$ (µg/m^3) (n=104)	0.4 (-2.0 to 2.7)
Kitchen $PM_{2.5}$ (µg/m^3) (n=105)	1.5 (0.2 to 2.8)
Personal BC (µg/m^3) (n=105)	0.03 (-1.2 to 1.2)
Kitchen BC (µg/m^3) (n=106)	0.8 (-0.2 to 1.8)
Stove type	
Stove type:	
Traditional stove (n=74)	1.3 (-1.5 to 4.1)
Justa stove (n=72)	Reference
Stove type:	
Traditional with use of a secondary stove (n=27)	2.2 (-1.4 to 5.9)
Traditional only (n=47)	2.2 (-2.2 to 6.5)
Justa with use of a secondary stove (n=34)	2.0 (-2.0 to 6.0)
Justa only (n=38)	Reference
Stove type:	
Traditional only (n=74)	2.8 (-0.6 to 6.2)
Justa installed ≥19 months ago (n=36)	3.0 (-1.0 to 6.9)
Justa installed <19 months ago (n=36)	Reference

BC=black carbon; CI=confidence interval; PM=particulate matter<2.5 µm.

***Adjusted for: age (continuous), beds per person (continuous) or total material wealth (categorical), body mass index (continuous), physical activity (continuous).

[1] Per one unit increase in natural log transformed air pollution concentration.

Supplementary Table 2. Effect modification by age for the adjusted mean differences in diastolic blood pressure (mmHg) comparing continuous (natural log transformed) pollution concentrations and stove types among 147 Honduran women using either a traditional or *Justa* stove*

24-hour average air pollution concentrations[1]	**Age category**	**Adjusted mean difference in diastolic blood pressure (95% CI)**	**P-value for interaction**
Personal $PM_{2.5}$ (µg/m^3) (n=104)	≥40 years (n=35) <40 years (n=69)	3.4 (-0.7 to 7.4) -1.0 (-3.9 to 1.8)	0.09
Kitchen $PM_{2.5}$ (µg/m^3) (n=105)	≥40 years (n=36) <40 years (n=69)	3.0 (0.9 to 5.0) 0.4 (-1.3 to 2.1)	0.06
Personal BC (µg/m^3) (n=105)	≥40 years (n=35) <40 years (n=70)	1.0 (-0.9 to 2.9) -0.4 (-1.8 to 1.1)	0.27
Kitchen BC (µg/m^3) (n=106)	≥40 years (n=36) <40 years (n=70)	1.6 (-0.1 to 3.3) 0.3 (-1.0 to 1.6)	0.22
Stove type (Traditional vs. *Justa*)	≥40 years (n=52) <40 years (n=95)	1.0 (0.6 to 1.6) 1.1 (0.8 to 1.5)	0.46

BC=black carbon; CI=confidence interval; PM=particulate matter<2.5 µm.

***Adjusted for: age (continuous), beds per person (continuous) or total material wealth (categorical), body mass index (continuous), physical activity (continuous).

[1] Per one unit increase in natural log transformed pollution concentration.

Supplementary Table 3. Effect modification by body mass index for the adjusted mean differences in systolic blood pressure (mmHg) comparing continuous (natural log transformed) pollution concentrations and stove types among 147 Honduran women using either a traditional or *Justa* stove*

24-hour average air pollution concentrations[1]	Body mass index (BMI) category	Adjusted Mean Difference Systolic Blood Pressure (95% CI)	p-value for interaction
Personal $PM_{2.5}$ (µg/m^3) (n=104)	≥25 BMI (n=54) <25 BMI (n=50)	0.4 (-3.8 to 4.5) 1.7 (-2.4 to 5.7)	0.67
Kitchen $PM_{2.5}$ (µg/m^3) (n=105)	≥25 BMI (n=56) <25 BMI (n=49)	2.4 (0.1 to 4.7) 2.3 (-0.5 to 5.1)	0.97
Personal BC (µg/m^3) (n=105)	≥25 BMI (n=55) <25 BMI (n=50)	0.6 (-1.4 to 2.6) 0.7 (-1.4 to 2.8)	0.91
Kitchen BC (µg/m^3) (n=106)	≥25 BMI (n=56) <25 BMI (n=50)	2.0 (0.3 to 3.7) 1.1 (-0.9 to 3.1)	0.51
Stove type (Traditional vs. *Justa*)	≥25 BMI (n=73) <25 BMI (n=74)	1.0 (0.7 to 1.6) 1.3 (1.0 to 1.7)	0.12

BC=black carbon; CI=confidence interval; PM=particulate matter<2.5 µm.

*Adjusted for: age (continuous), beds per person (continuous), body mass index (continuous), physical activity (continuous).

[1] Per one unit increase in natural log transformed pollution concentration.

Supplementary Table 4. Effect modification by body mass index for the adjusted mean differences in diastolic blood pressure (mmHg) comparing continuous (natural log transformed) pollution concentrations and stove types among 147 Honduran women using either a traditional or *Justa* stove*

24-hour average air pollution concentrations[1]	Body mass index (BMI) category	Adjusted Mean Difference Diastolic Blood Pressure (95% CI)	p-value for interaction
Personal $PM_{2.5}$ (µg/m^3) (n=104)	≥25 BMI (n=54) <25 BMI (n=50)	1.4 (-1.9 to 4.8) -0.1 (-3.4 to 3.2)	0.51
Kitchen $PM_{2.5}$ (µg/m^3) (n=105)	≥25 BMI (n=56) <25 BMI (n=49)	1.5 (-0.2 to 3.3) 1.3 (-0.8 to 3.4)	0.84
Personal BC (µg/m^3) (n=105)	≥25 BMI (n=55) <25 BMI (n=50)	0.4 (-1.2 to 2.0) -0.1 (-1.8 to 1.6)	0.67
Kitchen BC (µg/m^3) (n=106)	≥25 BMI (n=56) <25 BMI (n=50)	1.0 (-0.3 to 2.4) 0.6 (-1.0 to 2.1)	0.66
Stove type (Traditional vs. *Justa*)	≥25 BMI (n=73) <25 BMI (n=74)	1.1 (0.7 to 1.6) 1.1 (0.8 to 1.5)	0.72

BC=black carbon; CI=confidence interval; PM=particulate matter<2.5 µm.

*Adjusted for: age (continuous), beds per person (continuous), body mass index (continuous), physical activity (continuous).

[1] Per one unit increase in natural log transformed pollution concentration.

Supplementary Table 5. Effect modification by body mass index for the adjusted odds ratios in hypertensive status (borderline high or high blood pressure compared to normal) comparing continuous (natural log transformed) pollution concentrations and stove types among 147 Honduran women using either a traditional or *Justa* stove*

24-hour average air pollution concentrations[1]	Body mass index category	Odds ratio (95% CI)	p-value for interaction
Personal $PM_{2.5}$ (µg/m^3) (n=104)	≥25 BMI (n=54) <25 BMI (n=50)	1.0 (0.6 to 1.8) 1.1 (0.7 to 1.7)	0.80
Kitchen $PM_{2.5}$ (µg/m^3) (n=105)	≥25 BMI (n=56) <25 BMI (n=49)	1.5 (0.8 to 2.6) 1.6 (1.0 to 2.6)	0.77
Personal BC (µg/m^3) (n=105)	≥25 BMI (n=55)	1.1 (0.6 to 1.9)	0.74

	<25 BMI (n=50)	1.0 (0.6 to 1.6)	
Kitchen BC (μg/m³) (n=106)	≥25 BMI (n=56) <25 BMI (n=50)	1.7 (1.0 to 3.0) 1.7 (1.0 to 2.7)	0.92
Stove type (Traditional vs. *Justa*)	≥25 BMI (n=73) <25 BMI (n=74)	1.2 (0.7 to 1.9) 1.4 (1.0 to 2.1)	0.32

BC=black carbon; CI=confidence interval; PM=particulate matter<2.5 μm.
*****Adjusted for: age (continuous), beds per person (continuous), body mass index (continuous), physical activity (continuous).
[1] Per one unit increase in natural log transformed pollution concentration.

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