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Although evidence suggests associations between maternal exposure to air pollution and adverse birth outcomes, pregnant women's exposure to household air pollution in developing countries is understudied. Personal exposures of pregnant women (N = 100) in Trujillo, Peru, to air pollutants and their indoor concentrations were measured. The effects of stove-use-related characteristics and ambient air pollution on exposure were determined using mixed-effects models. Significant differences in 48-hour kitchen concentrations of particulate matter (PM2.5), carbon monoxide (CO), and nitrogen dioxide (NO2) concentrations were observed across fuel types (p < 0.05). Geometric mean PM2.5 concentrations where 112 µg/m³ (confidence limits [CLs]: 52, 242 µg/m³) and 42 µg/m³ (21, 82 µg/m³) in homes where wood and gas were used, respectively. PM2.5 exposure was at levels that recent exposure-response analyses suggest may not result in substantial reduction in health risks even in homes where cleaner burning gas stoves were used.

Keywords: biomass, carbon monoxide, cookstove, household air pollution, nitrogen dioxide, pregnant women, volatile organic compounds

Air pollution has been established as an important risk factor for human health.1,2 Considering that people spend more than 60% of their time indoors,3 the risk from exposure to indoor air pollutants becomes even more significant. Biomass burning is a major contributor to household air pollution, especially in the developing world. It is estimated that 50% of the global population and up to 90% of rural households in developing countries still utilize biomass in the form of wood, dung, and crop residue for residential energy.4 Biomass combustion emits a complex mixture of organic compounds and gases, which include carbon monoxide (CO), nitrogen and sulfur oxides (NOx and SOx), aldehydes, polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), chlorinated dioxins, particulate matter with diameters <2.5 microns (PM2.5), and free radicals.3,5,6

Exposure to biomass smoke has been associated with a number of health outcomes in developing countries, especially in rural women and children who spend disproportionately longer times indoors and in the kitchen compared with men. These adverse health outcomes include respiratory illnesses such as acute lower respiratory tract infections, upper respiratory tract infections, otitis media, chronic obstructive pulmonary disease (COPD), and the development of tuberculosis (TB) in women.7–12 In addition, exposure to indoor pollution from biomass burning has been associated with perinatal outcomes such as low birth weight and still births.13–16

Although the evidence suggests associations between maternal exposure to air pollution and adverse birth outcomes, pregnant women's exposure to household air pollution in developing countries is understudied. As part of a larger exposure assessment study investigating the exposure of pregnant women to various environmental contaminants,
including persistent organic pollutants and metals, in urban and periurban Trujillo, Peru, a study of household air pollution (HAP) was conducted in the first trimester of pregnancy. Personal exposure to, and indoor and ambient concentrations of, nitrogen dioxide (NO₂), CO, PM₂.₅, and VOCs were measured. Opportunity was also afforded through the study to investigate the effect of stove-use-related characteristics (type of cookstove/fuel, cooking time, and whether the women opened windows during cooking) and ambient concentrations on personal exposures and indoor levels of the pollutants in the urban/periurban setting.

Methods

Study Location

The larger exposure assessment study took place between May 2004 and February 2005. However, the HAP component of the study took place from May to July 2004. The study was conducted in Trujillo, Peru, which at the time of this study had an estimated population of 757,266. Trujillo is located just west of the foothills of the Andes Mountains and is the third most populous city in Peru. Trujillo has a dry climate with an average temperature of 21°C (range: 14°C to 32°C).

Subject Selection

A total of 106 women were initially recruited from a target population of nonsmoking women residing in Trujillo as they exited/entered clinics throughout Trujillo to participate in a study assessing exposures to various environmental contaminants, including air pollution and persistent organic pollutants. The women were all in the first trimester of pregnancy according to reported date of last menstrual period at the clinics from which the women were recruited. Recruitment took place between April and July of 2004, with the intention of recruiting 25 women each for 4 different types of cooking fuels (wood, gas, kerosene, and coal briquette). However, due to time constraints and availability of women for each fuel category, the number of subjects recruited were 17 for wood, 33 for liquefied petroleum gas (LPG), 13 for coal briquette, and 5 for kerosene. Thirty subjects used a combination of fuels while one of the subjects used electricity. This study was approved by institutional review boards (IRBs) from University of Georgia (UGA), the Centers for Disease Control and Prevention (CDC), and Trujillo; we obtained written informed consent from all participants. We administered questionnaires to the participants in Spanish during the first trimester to obtain information on stove-use-related characteristics (type of cookstove/fuel, cooking time, and whether the women opened windows during cooking), and demographics (socioeconomic status [SES], education, and age). The women also provided urine and blood samples, which were used to assess exposures to other environmental pollutants, including persistent organic pollutants, polycyclic aromatic hydrocarbons, metals, and phthalates.

Air Sampling

Residential Air Pollution Sampling

The indoor air of each participant’s home was sampled over one 48-hour period. Air monitoring was conducted in the kitchen and main living room of the houses. Samplers were hung on a wall at approximately 2 m from the ground. Samplers included 48-hour time-integrated PM₂.₅, NO₂, and VOCs and real-time CO. Area VOCs were only measured in the kitchen of each home. Measurements were conducted over 48-hour periods in order to reduce the within and day-to-day variation associated with exposures in indoor environments.¹⁷,¹⁸

Time-integrated (48-hour) PM₂.₅ concentrations were determined gravimetrically. Particles were collected on 37-mm Teflon filters (Pall; 2.0 µm) that were preloaded into Triplex PM₂.₅ cyclones (BGI, model SCC 1.062; Waltham, MA). Air was drawn through the cyclones using AirChek 2000 pumps (SKC, Eighty Four, PA) that were set to flow at 1.5 L/min. The filters were unloaded from the cyclones and stored in a freezer at −30°C within 30 minutes of the end of the 48-hour sampling periods. The filters were transported on dry ice to Athens, Georgia, after the completion of the HAP study. The filters were kept in a climate-controlled laboratory (70.0 ± 0.0°F; 35.0 ± 4% relative humidity) for a 48-hour period before they were weighed pre- and post-sample collection in the Air Quality Laboratory in the Department of Environmental Health Science at UGA. The 2 weights were measured at least twice using a Cahn C-35 microbalance with a sensitivity of ±1.0 µg following the US Environmental Protection Agency’s (US EPA) Quality Assurance Guidance Document.¹⁹ Air densities during weighing sessions, nominal densities of calibration masses were used to adjust the balance readings for the buoyancy effect of air.²⁰ The time-integrated 48-hour concentration of PM₂.₅ was calculated as the weight of PM₂.₅ per cubic meter of air. The average field blank concentration was subtracted from the samples to determine their final concentrations.

Real-time CO levels were measured using the Dräger Pac III with CO sensor and datalogger (Draeger Safety, Pittsburgh, PA) concurrently with PM₂.₅ sample collection. The instrument was set to log CO concentration every 30 seconds and was calibrated at UGA at the beginning and the end of the study. The poststudy CO calibration tests were within 5% of the prestudy calibration settings. The CO monitors were calibrated with a >99.999% N₂ (zero gas) and a 50 ppm CO gas.

Time-integrated (48-hour) NO₂ concentrations were determined using Palmes Tubes,²¹ which collects NO₂ at a rate of 0.92 mL/min. NO₂ analysis was done at the Environmental Exposure Assessment Laboratory at Emory University (Atlanta, GA). NO₂ concentrations were determined spectrophotometrically (Milton Roy Company, Spectronic 20D; Iyland, PA) using a 10-point, cubic-spline fit calibration curve.

Time-integrated VOCs were collected using passive diffusion stainless steel tubes (90 mm long, 6.3 mm OD and 5 mm ID; PerkinElmer, Waltham, MA) packed with Tenax TA (60/80 mesh, 200 mg) as an adsorbent. The tubes had a passive uptake rate of 0.54 mL/min. VOC samples were analyzed at the Georgia Tech Research Institute using an automated thermal desorption system (ATD400) coupled to a
Hewlett-Packard model 5890A gas chromatograph/VG model Trio 1 mass spectrometer. External calibration standards from authentic sources of BTEX (benzene, toluene, ethylbenzene, and xylenes) were analyzed to produce a calibration curve for the quantification of BTEX in the samples. Since the VOC contents in the air samples other than BTEX were unknown prior to analysis of the samples, an internal standard was used as a surrogate to provide semiquantitative concentrations for all VOCs other than BTEX identified in the air samples. The surrogate internal standard, toluene-d8, provides a chemical surrogate that analytically responds similarly as toluene, but does not interfere with the analysis of toluene. The analytical response of toluene-d8 provides a response factor that is used for the calculation of all other identified VOCs in the air samples. Not all VOCs have the same analytical response as toluene-d8, so the concentrations derived using toluene-d8 response factors are semiquantitative. Sample volumes were calculated from the passive uptake rate of 0.54 mL/min.22–24

Personal Exposure Monitoring
Personal air monitoring was conducted on each subject over the same 48-hour period of residential sampling. Sampler inlets were placed on the participant’s chest in the approximate breathing zone. PM2.5, CO, and NO2 were monitored. Due to limited number of VOC samplers, personal air VOCs were not measured on the study participants. The importance of leaving the samplers in place during the monitoring period was stressed to each study participant, and the subjects were instructed to keep the monitors on their bodies at all times except when sleeping or when taking their baths, during which they were instructed to place the monitors near their bodies on a night stand or equivalent. Time-integrated PM2.5 and NO2, and real-time CO were sampled using the samplers described previously.

Ambient Air Pollution Sampling
Air pollution monitoring was conducted on the roof of Trujillo City Hall in downtown Trujillo and at the airport weather station 9 miles outside of Trujillo, with one set of samplers being placed in each location for each 48-hour period of indoor air and personal exposure measurements. The residences are within 10 miles of the Trujillo City Hall, whereas the airport is located approximately 6 miles away from the city center/City Hall in a sparsely populated area. Forty-eight-hour time-integrated PM2.5 and 48-hour time-integrated VOCs and NO2 were collected with collocated instruments. Samplers used for ambient air pollution sampling are as described for residential air sampling.

Statistical Analysis
Descriptive statistics were computed for each pollutant by location of sampling, ie, kitchen, secondary room, personal exposure, Trujillo airport, and City Hall. The secondary room was identified by the study participant as the room other than the kitchen where most time was spent while the subject was awake. Concentrations of pollutants were log-transformed for all subsequent statistical analyses due to the approximate log-normal distribution of the untransformed data.

Linear mixed-effect models were used to determine the effect of stove-use-related characteristics (type of cook-stove/fuel, cooking time, whether window was opened during cooking), SES, education, and corresponding ambient air concentrations on kitchen concentrations of HAP. Kitchen concentrations were included as explanatory variables in the models for the main living/secondary room concentrations of HAP, whereas secondary room concentrations in addition to the kitchen concentrations were added to the models used to determine the effect of the various factors on personal exposures. The response variables in the models included personal exposure to 48-hour time-weighted average (TWA) PM2.5, CO, NO2, and their concentrations in the kitchen and a secondary room in the homes of the women. Other CO measures that were analyzed include maximum 8-hour, 15-minute, and 30-second concentrations. Kitchen concentrations of benzene and toluene were also analyzed. Ambient air concentrations and cooking time were centered on their means before their inclusion as covariates in the models. Kitchen concentrations of ethylbenzene, o-xylene, and m,p-xylene levels were not analyzed because detectable levels were measured in less than 30% of all the homes in the study. The sampling day was treated as a random effect to account for heterogeneity in environmental conditions from day to day. Fisher’s least significant difference (LSD) test was used to correct for multiple comparisons.

Spearman rank correlations were computed between all pollutants measured in the kitchen. Finally, canonical correlations were computed between 2 groups of pollutants—PM2.5, CO, and NO2 in one group and VOCs in the other group—to determine whether measures of PM2.5, CO, and NO2 can be used as a proxy for VOCs. All analyses were carried out using SAS version 9.2 (SAS Institute, Cary, NC, USA) and statistical tests were considered significant at $p = .05$.

Results
One hundred out of the 106 pregnant women who were initially recruited participated in this study. The average age of the women was 25 ± 6 years (mean ± SD) (range: 14–46 years). Seventy-eight percent ($n = 78$) of the participants had acquired at least a secondary school level education. Use of fuel in the kitchen included LPG ($n = 33$ households), wood ($n = 17$), coal briquette ($n = 13$), kerosene ($n = 5$), electricity ($n = 1$), a combination of fuel types including LPG ($n = 24$), a combination of fuel types with no use of LPG ($n = 6$), and electricity ($n = 1$). All of the participants were self-reported nonsmokers. Smoking status was confirmed by finding no detectable levels of 2,5-dimethylfuran, a VOC tobacco biomarker, in maternal blood samples (limit of detection [LOD] = 0.011 ng/mL).25

Overall unadjusted 48-hour time-integrated mean concentrations of pollutants by location of sampling are presented in Table 1. Overall, average personal exposure and indoor levels of PM2.5 and NO2 were higher than outdoor concentrations. Average personal exposures to PM2.5 and NO2 were higher than average kitchen and secondary room levels, whereas average kitchen CO concentration was higher than the average
Tables 1 and 2. Unadjusted Levels of Pollutants Monitored Over 48 Hours at Different Locations and Effects of Fuel Sources and Other Variables on the Levels of Pollutants Measured Over 48-Hour Period in the Participants' Kitchens

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**Table 1. Unadjusted Levels of Pollutants Monitored Over 48 Hours at Different Locations**

<table>
<thead>
<tr>
<th>Pollutant (concentration unit)</th>
<th>Kitchen Mean</th>
<th>Kitchen SD</th>
<th>Personal Mean</th>
<th>Personal SD</th>
<th>Secondary room Mean</th>
<th>Secondary room SD</th>
<th>City Hall Mean</th>
<th>City Hall SD</th>
<th>Airport Mean</th>
<th>Airport SD</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PM$_{2.5}$ (mg/m$^3$)</strong></td>
<td>92.1</td>
<td>118.8</td>
<td>122.8</td>
<td>135.2</td>
<td>48.2</td>
<td>44.6</td>
<td>29.3</td>
<td>9.1</td>
<td>27.0</td>
<td>12.0</td>
<td>97, 93, 88, 52, 49</td>
</tr>
<tr>
<td><strong>CO (ppm)</strong></td>
<td>3.4</td>
<td>6.7</td>
<td>1.1</td>
<td>1.7</td>
<td>0.6</td>
<td>1.3</td>
<td>NM</td>
<td>NM</td>
<td>NM</td>
<td>NM</td>
<td>95, 98, 90, 0, 0</td>
</tr>
<tr>
<td><strong>NO$_2$ (ppb)</strong></td>
<td>18.4</td>
<td>17.5</td>
<td>10.4</td>
<td>8.8</td>
<td>9.4</td>
<td>8.6</td>
<td>7.9</td>
<td>5.1</td>
<td>2.8</td>
<td>2.4</td>
<td>92, 93, 88, 52, 52</td>
</tr>
<tr>
<td><strong>Benzene (mg/m$^3$)</strong></td>
<td>8.7</td>
<td>17.3</td>
<td>NM</td>
<td>NM</td>
<td>16.6</td>
<td>8.5</td>
<td>153.7</td>
<td>137.8</td>
<td>1.9</td>
<td>3.4</td>
<td>54, 0, 0, 52, 48</td>
</tr>
<tr>
<td><strong>Toluene (mg/m$^3$)</strong></td>
<td>39.3</td>
<td>77.3</td>
<td>NM</td>
<td>NM</td>
<td>16.4</td>
<td>7.3</td>
<td>25.2</td>
<td>10.1</td>
<td>0.1</td>
<td>0.3</td>
<td>54, 0, 0, 52, 48</td>
</tr>
<tr>
<td><strong>Ethylbenzene (mg/m$^3$)</strong></td>
<td>1.6</td>
<td>4.6</td>
<td>NM</td>
<td>NM</td>
<td>155.7</td>
<td>137.8</td>
<td>3.4</td>
<td>0.3</td>
<td>54, 0, 0, 52, 48</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>o-Xylene (mg/m$^3$)</strong></td>
<td>1.9</td>
<td>5.7</td>
<td>NM</td>
<td>NM</td>
<td>8.6</td>
<td>1.2</td>
<td>7.3</td>
<td>1.1</td>
<td>0.2</td>
<td>0.8</td>
<td>54, 0, 0, 52, 48</td>
</tr>
<tr>
<td><strong>m/p-Xylene (mg/m$^3$)</strong></td>
<td>5.0</td>
<td>13.2</td>
<td>NM</td>
<td>NM</td>
<td>78.2</td>
<td>34.4</td>
<td>0.7</td>
<td>2.0</td>
<td>54, 0, 0, 52, 48</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note. NM = not measured.*

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**Table 2. Effects of Fuel Sources and Other Variables on the Levels of Pollutants Measured Over 48-Hour Period in the Participants’ Kitchens**

<table>
<thead>
<tr>
<th>Pollutant (concentration unit)</th>
<th>Fuel type$^1$</th>
<th>Window (when it is open)</th>
<th>Cooking time</th>
<th>Ambient concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p$ value</td>
<td>Effect</td>
<td>$p$ value</td>
<td>Effect</td>
</tr>
<tr>
<td><strong>PM$_{2.5}$ (mg/m$^3$)</strong></td>
<td>.03</td>
<td>.07</td>
<td>.74</td>
<td>.001</td>
</tr>
<tr>
<td><strong>CO (ppm)</strong></td>
<td>.02</td>
<td>-.40</td>
<td>.77</td>
<td>-.005</td>
</tr>
<tr>
<td><strong>NO$_2$ (ppb)</strong></td>
<td>.01</td>
<td>.28</td>
<td>.60</td>
<td>.002</td>
</tr>
<tr>
<td><strong>Benzene (mg/m$^3$)</strong></td>
<td>.08</td>
<td>-.78</td>
<td>.18</td>
<td>-.001</td>
</tr>
<tr>
<td>(mg/m$^3$)</td>
<td>.11</td>
<td>.25</td>
<td>.11</td>
<td>-.110</td>
</tr>
</tbody>
</table>

$^1$Parameter estimates are change in log unit per unit change in the variable or change in log unit if window is open vs closed.

$^2$p values are the only results presented for fuel type, since there are 6 categories and an estimate for each category. The levels by category of fuel type have been presented in Figures 1-3 for pollutants that were significantly affected by fuel type.

$^3$NM = not measured for CO.
exposure ($p = .08$) and secondary room concentrations ($p = .06$) of PM$_{2.5}$. Cooking time was significantly positively associated with secondary room ($p = .003$) NO$_2$. Forty-eight-hour personal exposures to both PM$_{2.5}$ ($p = .04$) and CO ($p = .03$) were both positively associated with 48-hour secondary room concentrations of the pollutants. These relationships were all positive. Association between personal exposure to NO$_2$ and cooking time was, however, negative ($p = .01$). Ambient air

![Graph](image1)

**Fig. 1.** Model-derived geometric mean time-integrated (48-hour) kitchen concentrations of PM$_{2.5}$ by fuel type, with adjustments for outdoor PM$_{2.5}$ (City Hall), cooking time, SES, education, and whether window was opened during cooking. Combo + Gas = fuel combination with gas; Combo − Gas = fuel combination without gas; CB = coal briquette.

![Graph](image2)

**Fig. 2.** Model-derived geometric mean kitchen concentrations of CO by fuel type, with adjustments for cooking time, SES, education, and whether window was opened during cooking. Combo + Gas = fuel combination with gas; Combo − Gas = fuel combination without gas; CB = coal briquette.
Archives of Environmental & Occupational Health

pollution was monitored on the roof of City Hall and at the Trujillo airport. However, the pollutant concentrations at the airport (approximately 6 miles away from the city center/City Hall in a sparsely populated area) were consistently lower than measurements at City Hall and can be considered to be background concentrations. The airport ambient pollution was initially included in the analysis but was not significant for all pollutants. Therefore, only the City Hall concentrations are included in the models.

Cross-correlations between all pollutants measured in the kitchen are presented in Table 3. Most of the correlations between the BTEX compounds and the other pollutants were insignificant. Only benzene and PM$_{2.5}$, (Spearman correlation coefficient, $r_s = 0.42$, $p = 0.002$) and toluene and CO ($r_s = 0.34$, $p = 0.014$) were significantly correlated. The correlations between the BTEX compounds were moderate to high ($r_s$ ranged from 0.27 to 0.86). The cross-correlations between the pollutants (PM$_{2.5}$, CO, and NO$_2$) in the secondary room and for personal exposure (not presented) are smaller than those observed for the kitchen. Finally, the utility of using measurements of PM$_{2.5}$, NO$_2$, and CO as proxies for BTEX was investigated by computing the canonical correlations between these 2 groups. The first canonical correlation between PM$_{2.5}$, CO, and NO$_2$ as a group and BTEX as the other group was 0.57, $p = 0.035$, indicating low correlations between these 2 groups. Second and higher canonical correlations were nonsignificant.

Comment

Unlike most of the previous biomass-related HAP studies that have been conducted in rural areas with high prevalence of residential biomass use, the current study was conducted in urban and periurban areas of Trujillo, Peru. There is a relatively high proportion of residential use of cleaner burning LPG among its population. In 2003, prior to this study, one of the researchers and Trujillo City Hall personnel conducted a survey of 1,200 households in Trujillo Province to identify the use of fuels for cooking. This survey indicated that 91% of the participating households used LPG for cooking (data not published). A large proportion of the subjects in the current study used LPG exclusively (33%) or LPG with other fuels (24%) for cooking. Therefore, indoor concentrations and personal exposures are expected to be relatively low compared with levels reported in previous studies conducted in rural areas in developing countries where larger proportions of the population rely on biomass fuel for residential energy supply. Kitchen concentrations of PM$_{2.5}$ and/or CO in indoor environments of homes in rural communities in India, Guatemala, Mexico, and in the Province of Santiago de Chuco in Peru prior to the installation of improved stoves are higher than those measured in this study. NO$_2$ levels measured in rural residences in Ethiopia are also higher than those measured in the current study.

The type of fuel used to cook had a significant effect on kitchen 48-hour concentrations of PM$_{2.5}$, NO$_2$, and CO, and on maximum 8-hour CO, 15-minute CO, and 30-second CO. As expected, the concentrations of the pollutants were higher in homes using wood or coal briquette compared with homes using the cleaner burning LPG as cooking fuel. Similar results have been reported in other studies. Geometric mean maximum kitchen 8-hour CO concentration derived from the models did not exceed the US EPA 8-hour ambient air standard of 9 ppm for any of the fuel types. However, it was exceeded by the kitchen 8-hour CO concentrations in 20 homes: 8 of them using wood, and another 8 using coal briquette. The standard was also exceeded by the personal exposures of 7 of the subjects. The US EPA ambient air standard for annual outdoor NO$_2$ is 53 ppb. The US EPA standard was exceeded in kitchens of 6 homes.

Model-derived geometric mean for kitchen PM$_{2.5}$ was lowest in homes using LPG exclusively ($42 \mu g/m^3$) or in

Fig. 3. Model-derived geometric mean time-integrated (48-hour) kitchen concentrations of NO$_2$ by fuel type, with adjustments for outdoor NO$_2$ (City Hall), cooking time, SES, education, and whether window was opened during cooking. Combo + Gas = fuel combination with gas; Combo − Gas = fuel combination without gas; CB = coal briquette.
combination with other fuels (41 µg/m^3). However, these levels are still above the US EPA 24-hour ambient air standards of 35 µg/m^3 and a lot higher than the annual standard of 12 µg/m^3. The PM_2.5 standards together with standards for other criteria pollutants, including CO and NO_2, were set to protect public health, including the health of susceptible populations such as pregnant women. Overall personal PM_2.5 exposures were even higher compared with the kitchen concentrations in this population (Table 1), unlike the results of previous studies. Exposures to other indoor sources of exposures in rooms other than the kitchen and to commercial outdoor cooking, which was common in the study area, could have contributed to these observations. The exposures mentioned above would be expected to have more impact on personal exposures compared with kitchen concentrations in homes with the less polluting fuel type. This is consistent with the results (data not presented) showing that the trend of higher personal exposures compared with kitchen concentrations was only not true in homes where wood was used for cooking and where kitchen concentrations were by far the highest (see Figure 1). The possible influence of sources in other rooms on personal exposure is also indicated by the significant positive associations between 48-hour secondary room concentrations and 48-hour personal exposures of PM_2.5 and NO_2.

These results could be relevant to various current and planned cookstove intervention programs geared towards the reduction of HAP in homes in developing countries. The exposure-response relationship between PM_2.5 and risk of cardiovascular disease (CVD)-related mortality has been identified as being most likely nonlinear. The slope of the determined relationship is very steep at the very low exposure levels based on ambient air PM_2.5 and secondhand smoke exposure, and flattens at higher levels represented by active cigarette smoking. Smith and Peel also highlighted the implication of the determined exposure-response relationship with regards to HAP from residential combustion of biomass fuel and the degree of HAP reduction that may be needed to achieve significant cardiovascular health benefits. Although HAP exposure, which was not used in the determination of the PM_2.5-CVD exposure-response relationship, is expected to be in the range between exposures to ambient air PM_2.5 and active smoking, the data used for airborne PM_2.5 occupying the very low exposure range were mostly below 30 µg/m^3. As was stated earlier, the model geometric mean estimates for kitchen concentrations were higher than 35 µg/m^3, even in homes where the much cleaner burning LPG was being used. This may have been a consequence of other indoor factors, some of which may not be directly related to cooking activities. Although there was a relationship between PM_2.5 exposure and its levels outdoors, personal exposures and indoor levels were higher than outdoor concentrations. Activities such as the burning of wax candle, mosquito coil, and incense release particulate matter. Cooking style, especially frying, has also been shown to increase particulate matter concentration. Occurrence of such activities combined with inadequate ventilation could result in high exposure levels in homes where LPG is used in the current study. In all, the elevated levels of kitchen and personal PM_2.5 exposure in homes using LPG in this study relative to the relevant ambient air pollution standard and the lower risk levels as suggested by the PM_2.5-CVD exposure-response relationship indicate that intervention programs need to be more comprehensive beyond cookstove change-outs.

Information regarding cooking, cooking fuel, other sources of HAP, and secondhand smoke were self-reported. We also relied on the measurement of outdoor pollution at one central location (City Hall) rather than outside individual homes due to limited resources and collected one set of 48-hour measurements for exposures to household air pollutants, which may have not have been sufficient to account for longer-term day-to-day variation in exposure. The generalizability of the results is also limited, since sampling was not randomized. The relatively small sample size in the study may have contributed to the inability to detect significant associations between pollutant exposures, especially BTEX and some of the covariates that were tested in the study. Nonetheless, the study provides

### Table 3. Correlations Between the Levels of Different Pollutants Measured Over 48-Hour Period in Participants’ Kitchens*

<table>
<thead>
<tr>
<th></th>
<th>NO2</th>
<th>CO</th>
<th>Benzene</th>
<th>Toluene</th>
<th>Ethylbenzene</th>
<th>m/p-Xylene</th>
<th>o-Xylene</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM_2.5</td>
<td>.250</td>
<td>.510</td>
<td>.420</td>
<td>.150</td>
<td>−.070</td>
<td>−.200</td>
<td>−.160</td>
</tr>
<tr>
<td></td>
<td>.017</td>
<td>&lt;.001</td>
<td>.002</td>
<td>.296</td>
<td>.601</td>
<td>.159</td>
<td>.247</td>
</tr>
<tr>
<td>NO_2</td>
<td>.560</td>
<td>.160</td>
<td>.220</td>
<td>.110</td>
<td>.140</td>
<td>.100</td>
<td>.100</td>
</tr>
<tr>
<td></td>
<td>&lt;.001</td>
<td>.253</td>
<td>.119</td>
<td>.428</td>
<td>.327</td>
<td>.480</td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>.240</td>
<td>.091</td>
<td>.014</td>
<td>.180</td>
<td>.170</td>
<td>.200</td>
<td>.163</td>
</tr>
<tr>
<td>Benzene</td>
<td></td>
<td></td>
<td>.340</td>
<td>.270</td>
<td>.170</td>
<td>.260</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>.012</td>
<td>.046</td>
<td>.208</td>
<td>.063</td>
<td></td>
</tr>
<tr>
<td>Toluene</td>
<td></td>
<td></td>
<td>.460</td>
<td>.430</td>
<td>.440</td>
<td>&lt;.001</td>
<td>.001</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td></td>
<td></td>
<td></td>
<td>.710</td>
<td>&lt;.001</td>
<td>.890</td>
<td></td>
</tr>
<tr>
<td>m/p-Xylene</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.860</td>
<td>&lt;.001</td>
<td></td>
</tr>
</tbody>
</table>

* Spearman rank correlation coefficients (r_s) are on the first rows, whereas p values are on the second rows. Sample sizes for the correlation analyses are 92 for PM_2.5 vs NO_2; 90 for PM_2.5 vs CO; 87 for NO_2 vs CO; and 51–54 for VOCs vs PM_2.5, CO, or NO_2.
exposure data for NO₂, which is rather rare for residential biomass combustion-related HAP in the literature. This is especially important because exposure to outdoor and indoor NO₂ has been associated with adverse respiratory effects, especially among children. 13,24

The health risks posed by the levels of kitchen BTEX that was observed are not clear, although it should be noted that benzene and ethylbenzene are classified as known and possible human carcinogens, respectively, by the International Agency for Research on Cancer. 15,46 Further, studies have shown an association between acute childhood leukemia and residential benzene sources. 47,48 However, kitchen BTEX levels were low relative to outdoor concentrations. Indoor levels were 2 to 15 times lower than concentrations measured at the City Hall in downtown Trujillo. BTEX concentrations were much lower at Trujillo airport, which was located 6 miles outside of the city’s downtown in a sparsely populated area. These results show that ambient air in Trujillo contains modest levels of VOC pollution and is a significant source of BTEX compared with cooking fuels in many residences. The major source of BTEX pollution in downtown Trujillo may be vehicle exhaust. 49,50

Opportunity was afforded through the current study to investigate the exposure of pregnant women to HAP, and the effect of various factors, particularly type of cooking fuel, on HAP exposure in the urban/periurban setting in a developing country; both of which have rarely been done. Additionally, the exposure measurements were comprehensive in terms of the pollutants that were measured, including both VOCs and NO₂. Only 1 study was found in the literature to have reported on the indoor levels of NO₂ in relation to residential biomass fuel combustion. In conclusion, air pollution in the residences of pregnant women in Trujillo, Peru, is significantly associated with the types of fuels they use for cooking. Pregnant women who used biomass fuels had higher levels of PM₂.₅, CO, and NO₂. Although the levels measured were low to moderate compared with levels measured in other studies, the public health concern of exposures at levels measured in this study on the developing fetus and pregnant women is justifiable considering that the PM₂.₅ levels are higher than standards for ambient air. Exposures to ambient air PM₂.₅ has been associated with low birth weight in the United States. 51,52 Efforts to reduce HAP exposures in households in developing countries have largely focused on the installation of improved stoves and/or the use of cleaner burning fuel. The results of this study support the evidence that such efforts may lead to the reduction of HAP exposures in these households. However, the elevated levels of kitchen PM₂.₅, especially in homes using the cleaner burning LPG fuel, indicate the influences of other factors on the exposures of the pregnant women, and that any intervention to successfully reduce exposures of these pregnant women and similar populations must be comprehensive and incorporate efforts beyond fuel or stove substitution.

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References

15. Thompson LM, Bruce N, Ekenazi B, Diaz A, Pope D, Smith KR. Impact of reduced maternal exposures to wood smoke from an


