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Maternal exposure to carbon monoxide and fine particulate matter during pregnancy in an urban Tanzanian cohort

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Abstract

Low birth weight contributes to as many as 60% of all neonatal deaths; exposure during pregnancy to household air pollution has been implicated as a risk factor. Between 2011 and 2013, we measured personal exposures to carbon monoxide (CO) and fine particulate matter ($PM_{2.5}$) in 239 pregnant women in Dar es Salaam, Tanzania. CO and $PM_{2.5}$ exposures during pregnancy were moderately high (geometric means 2.0 ppm and 40.5 μg/m^3); 87% of $PM_{2.5}$ measurements exceeded WHO air quality guidelines Median and high (75th centile) CO exposures were increased for those cooking with charcoal and kerosene versus kerosene alone in quantile regression. High $PM_{2.5}$ exposures were increased with charcoal use. Outdoor cooking reduced median $PM_{2.5}$ exposures. For $PM_{2.5}$, we observed a 0.15 kilogram reduction in birth weight per interquartile increase in exposure (23.0 μg/m^3) in multivariable linear regression; this finding was of borderline statistical significance (95% confidence interval −0.30, 0.00 kilograms; p=0.05). $PM_{2.5}$ was not significantly associated with birth length or head circumference nor were CO exposures associated with newborn anthropometrics. Our findings contribute to the evidence that

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exposure to household air pollution, and specifically fine particulate matter, may adversely affect birth weight.

Keywords

Household air pollution; personal exposure; birth outcome; carbon monoxide; particulate matter

INTRODUCTION

Forty percent of the world's population and more than 75% of Africans rely on solid fuels (wood, charcoal, and crop residues) as the primary energy source for their household according to 2010 estimates (Bonjour et al., 2013). Air pollution generated from the inefficient combustion of these solid fuels has been recognized as a major contributor to the global disease burden and ranked as the second-most important risk factor for disability-adjusted life years lost among women and girls globally (Lim et al., 2012). As women of reproductive age are often the primary cooks in their households, there is interest in determining whether and how household air pollution is harmful to pregnant women and their babies.

The impact of household air pollution from biomass burning on pregnancy outcomes was recently systematically reviewed (Amegah et al., 2014); nineteen studies published before April 2013 were identified for inclusion. The authors concluded that household solid fuel combustion results in an average 86 gram reduction in birth weight (95% CI: −55, −117), a 35% increase in risk of low birth weight (effect estimate of 1.35, 95% CI 1.23, 1.48), and a 29% increase in the risk of stillbirth (effect estimate 1.29, 95% CI 1.18, 1.41). Fewer studies evaluated preterm birth and growth restriction but summary risks for both were also increased with household solid fuel use (effect estimates of 1.30, 95% CI 1.06, 1.59 for preterm birth and 1.23, 95%CI 1.01, 1.49 for growth restriction).

While the evidence base for household air pollution and adverse reproductive effects is growing, considerable methodologic shortcomings remain. Of particular interest is the almost complete reliance on indirect methods to classify exposure to household air pollution through questionnaires rather than direct measurement. Exposure to household air pollution has been defined fairly crudely by the primary fuel (or fuel mixtures) used by the woman or household. The only study which attempted direct exposure assessment was a randomized trial where 48-hour personal carbon monoxide (CO) levels were obtained at baseline and after deployment of a chimney stove intervention (Smith et al., 2011). However, CO exposures were only obtained in a subset of the enrolled pregnant women.

Measurement of personal exposure to air pollutants has been conducted successfully in several cohorts of pregnant women in more developed settings with a focus on ambient air pollution rather than cook stove related pollution (Tonne et al., 2004; Choi et al., 2006; Jedrychowski et al., 2006; Jedrychowski et al., 2007). Successful personal measurements of exposure to cook stove pollution among children (Dionisio et al., 2008; Dionisioet al., 2012a; Dionisio et al., 2012b; Baumgartner et al., 2011) and nonpregnant adults (Baumgartner et al., 2011; Van Vliet et al., 2013) have also been achieved in resource limited settings. Recognizing a scarcity of direct exposure measurements in the literature surrounding household air pollution from biomass burning and pregnancy outcomes, we undertook this study to assess the feasibility of obtaining personal exposure measurements to cook smoke-related pollutants among pregnant women in Tanzania, a sub-Saharan African setting where an estimated 94% of the population uses solid fuels as their primary energy source (Bonjour et al., 2013). We aimed to characterize personal exposure to CO and $PM_{2.5}$ during pregnancy in an urban/periurban setting in and around Dar es Salaam and to identify predictors of exposure, high exposure, and their relation to individual cooking behaviors. We also sought to investigate the association of these personal exposure measurements with newborn anthropometrics to strengthen the exposure-response evidence base.

MATERIALS AND METHODS

This study protocol was approved by the Institutional Review Boards of Muhimbili University of Health and Allied Sciences and the Harvard T. H. Chan School of Public Health.

Study location, population and participants

Between January 2011 and May 2013, pregnant women aged 15 years or older who were the primary cooks in their household and estimated to be in their second or third trimester of pregnancy by menstrual dating were enrolled into this study on personal air exposure to air pollutants during pregnancy. Women who were enrolled in one of two trials underway at Muhimbili University in Dar es Salaam, Tanzania were recruited for participation in this substudy at the time of a follow up antenatal care visit from participating antenatal clinics in and around the city. The Prenatal Iron Supplements study (NIH 1U01HD061232-01), whose primary aim was to assess the safety of iron supplementation among iron replete women in a malarious area, recruited a mostly urban cohort of 1500 women. The Nutrition and Immunologic Effects of Malaria in Pregnancy Study (NIH 1R01HD057941) enrolled a total of 2500 women to evaluate the efficacy of zinc and vitamin A supplements in reducing the risk of malaria in pregnancy. Both trials included only HIV negative women in their first or second pregnancies. Protocols for determination of birth weight and newborn anthropometrics, described below, were similar in both trials, allowing us to recruit from both studies.

Study Design

In this prospective observational cohort study, after written informed consent was obtained by trained research staff, study subjects answered a number of questions specific to their cooking practices including types of fuel used, hours spent cooking, stove design, cooking area ventilation, as well as exposure to other sources of pollution such as traffic, tobacco, incense, and the burning of rubbish. Study staff also observed and recorded details about the cooking area including visible soot on the wall, size of the kitchen, presence of ventilation and distance to nearest road. Additional covariates from the parent studies were made available for our analysis including age, parity, body mass index, prenatal vitamin compliance, history of preexisting hypertension, treatment for malaria during pregnancy and a household asset index. The asset index was constructed after tallying household ownership of ten items (car, generator, bicycle, sofa, television, radio, refridgerator, fan, electricity, and potable aqua). Counts of 0 to 5 were categorized as a low household asset index, counts between 6 and 8 categorized as a medium household asset index, and counts of 9 or 10 as a high asset index.

Exposure monitoring

Carbon monoxide exposure—Maternal exposure to carbon monoxide was measured over 72 hours using Draeger Carbon Monoxide 50/a-D (cumulative CO exposure 50–600 ppm-h) passive diffusion tubes (Draeger USA, Andover, MA) attached to the mother with a lanyard clipped to her clothing near her breathing zone. Length of color change in the dosimeter tube was measured with metric rulers in the field at 24 hour intervals by research staff until completion of the 72 hour exposure period. A third-order polynomial was fit to the millimeter measurements corresponding to preprinted ppm-h markings on the batch of CO tubes used in the study ($y = -0.006x^3 + 1.0075x^2 + 5.1726x - 0.3053$; y = cumulative exposure in ppm-h and x = dosimeter tube color change in mm), allowing for conversion of color change length in millimeters to exposure in ppm-h. The cumulative exposure in ppm-h was converted to average exposure in ppm through division by the duration of measurement in hours. If available, mean exposure over 72-h was used. In the absence of a valid 72-h measurement, then a 48-h measurement was used if available and valid. The lower limit of detection (LOD) for the tubes was 1 mm of measured color change over 48 or 72 hours, equivalent to 0.12 or 0.08 ppm respectively. This method has been previously validated in field settings (Smith et al., 2010; Edwards et al., 2007; Dionisio et al., 2012b). We simultaneously measured cooking area CO concentrations with a separate CO diffusion tube suspended in the cooking area and calculated cooking area CO concentrations in the same manner.

Fine particulate matter exposure—$PM_{2.5}$ exposure measurements occurred during the first and third 24 hours of the CO measurement using a portable, battery operated Casella Apex Lite Personal Sampling Pump (Casella USA, Amherst, NH). Particulate matter was collected onto 37mm Teflon membrane filters (Pall Life Sciences; Teflo, 0.2-mm pore size) in conductive polypropylene cassettes (SKC Inc., Eighty Four, PA) using a GK2.05SH KTL cyclone (BGI by Mesa Labs, Butler, NJ) with a 50% cut point of 2.5 micrometers at 3.5 liters per minute (LPM) (±10%). $PM_{2.5}$ mass concentrations were measured on a Mettler Toledo MT5 microbalance at the Harvard School of Public Health Laboratory, after being conditioned in a temperature and humidity controlled environment (20.5±0.2°C, 39±2% relative humidity) for at least 24 hours and statically discharged via a polonium source.

The pump was programmed to run one minute out of every four minutes as battery life would not sustain a full 24 hours of operation; the pump therefore ran a total of 6 hours during each 24 hour period. Measurements were not obtained during the second day as the battery required recharging. The cyclone inlet was clipped near the maternal breathing zone, while the sampling pump was worn by the subjects in either a small fanny pack or over the shoulder purse based on subject preference.

In both pre- and post-weighing, filters were weighed twice; if these two masses were not within 5 μg of one another, they were weighed a third time. The mean of the two masses within 5 μg of one another was used for calculating concentrations. Final filter weights were adjusted using an air buoyancy correction (Schoonover and Jones, 1981). The average of the two 24-hour $PM_{2.5}$ mass concentrations was used to represent the personal particulate matter exposure of the subject over the sampling period. Samples were excluded from analysis if the sampling duration was less than 80% of planned, if there was a broken connection between the pump and the inlet for a significant period of time leading to an implausible mass, or if a pump error was noted.

Birth Measures

Women were incentivized to deliver at one of the study facilities in the parent malaria trials so that facility-based research staff could obtain birth anthropometrics in the first 24 hours following delivery. Birth weight was measured using digital scales available on the labor wards. As the catchment area of the parent trials included many facilities throughout Dar es Salaam and the primary outcome of these trials was placental malaria, scales were not standardized across labor wards nor calibrated routinely against standardized weights. For these reasons, birth weight in the parent trials was recorded only to the nearest 0.1 kilogram. The newborn was placed in a recumbent position on a measuring board and the birth length measured from head to heel using a tape measure affixed to the board and recorded to the nearest 0.1 cm. The head circumference was measured to the nearest 0.1 cm using a soft flexible tape.

A postnatal new Ballard examination was performed scoring both neurologic and external features for gestational age assessment (Ballard et al., 1991). The total score was correlated with gestational age using the published Ballard maturity-rating tables. Infants born at home did not have birth anthropometrics recorded.

Data Analysis

Geometric mean concentrations and standard deviations were calculated for personal CO exposure and cooking area CO concentrations (in parts per million, or ppm), and personal $PM_{2.5}$ exposures (in $\mu g/m^3$). A variety of factors including cooking behaviors, fuel and stove types, season, ambient air pollution sources and the cooking area CO levels were evaluated for their association with personal exposure to CO and separately to $PM_{2.5}$. Two rainy seasons are typical for Dar es Salaam—exposure measurements during either the short or long rains were considered to be conducted during the rainy season. Fuels used during exposure measurements were therefore limited to three categories (kerosene only, charcoal only, and kerosene/charcoal mixtures) for inclusion in models as these categories represented more than 95 percent of the fuels used by subjects. Less than two percent of subjects used wood only, less than one percent used gas/electricity only, and less than two percent used wood or gas/electricity in combination with kerosene and/or charcoal.

Given the skew in exposure distribution, multivariable median quantile regression rather than ordinary least squares linear regression was chosen to explore the association of the potential predictors with personal exposure. The regression coefficients estimated and corresponding 95% confidence intervals represent the change in median exposure with the predictor compared to without, holding all else constant. Covariates with unstable regression coefficient estimates were excluded from the final multivariable analysis. A multivariable 75^{th} quantile regression model, similar to the median quantile regression model, was used to evaluate the association of predictors with higher exposures, exploring how the predictors altered the 75^{th} centile of exposure. In sensitivity analysis, unconditional logistic regression models were used to estimate the univariate odds ratios (ORs) and associated 95% confidence intervals (CIs) for the association of each of the potential predictors with high exposure, defined as the uppermost quartile of exposure for CO or $PM_{2.5}$. All predictors found to be significant at a $p < 0.05$ level were included in a multivariable logistic model.

The distributions of both raw and natural log transformed CO and $PM_{2.5}$ were evaluated for normality and the natural log transformed data used to calculate a Pearson product-moment correlation coefficient when correlating personal with cooking area CO, day 1 with day 3 $PM_{2.5}$, and CO with $PM_{2.5}$ exposure.

The linear association of personal CO and personal $PM_{2.5}$ exposure levels with birth weight, birth length, and head circumference was evaluated by fitting regression models. Natural log transformed CO and $PM_{2.5}$ were used as the dependent exposure variables as transformation improved the assumption of normality and stabilized the variance. Box and whisper plots were used to visually identify outliers of exposure which were excluded from these anthropometric regression models. Scatterplots of birth anthropometrics with pollutant exposures were assessed for potential nonlinear associations and in sensitivity analyses, a quadratic term for exposure was explored.

A number of demographic and obstetric variables were incorporated in the multivariable regression models as potential confounders of the association between air pollution exposure and newborn anthropometrics. The covariates included age, parity, body mass index, sex of infant (male versus female), compliance with prenatal vitamins, household asset index, neighborhood location, housing type (single family home versus apartment/multifamily home, year of measurement, and parent trial. History of hypertension was excluded as only eight individuals reported this history leading to unstable coefficient estimates. Similarly, antenatal malaria was left out of the models as none of our subjects had this diagnosis. In addition, models were not adjusted for gestational age as this is a potential mediator in the causal pathway between exposure and outcome and can lead to biased estimates of association (Wilcox et al., 2011). Instead, sensitivity analyses were conducted limiting models to term births alone. Unadjusted beta coefficients estimated for the association between CO or $PM_{2.5}$ exposure and newborn anthropometrics are reported alongside coefficients from fully adjusted models including all considered confounders.

Exact logistic regression models were fit to estimate the univariate odds ratios and 95% confidence intervals associated with the uppermost quartile of CO and $PM_{2.5}$ exposure with low birth weight, defined as a birth weight less than 2.5 kilograms (SAS/STAT(R) 0.3 User's Guide, n.d.). Given limitations in sample size, multivariable logistic models to adjust for potential confounders were not fit.

For all analyses, models for personal CO and personal $PM_{2.5}$ were considered separately. Statistical analyses were performed using SAS software version 9.4.

RESULTS

Cohort characteristics and cooking behaviors

From 2011 through 2013, a cohort of 239 pregnant women was recruited from two ongoing pregnancy trials in Dar es Salaam, Tanzania; 184 subjects were enrolled through the Prenatal Iron Supplements study and the remaining 55 from the Nutrition and Immunologic Effects of Malaria in Pregnancy study. Exposure measurements were obtained for 236 of the 239 enrolled subjects; three did not complete sampling on account of discomfort with the equipment.

Demographics, cooking behaviors, kitchen characteristics, and other sources of household air pollution are summarized in Table 1 for those enrolled. The cooking behaviors emphasized in Table 1 and used for predicting exposure in subsequent analyses were those observed and reported during the exposure measurement period. Described in more detail here are general cooking behaviors and kitchen characteristics not specific to the measurement period in order to capture a more general understanding of cooking in this population. 232 of 239 (97.1%) subjects were the primary cooks in their household and almost all cooked on average three meals per day (212 of 239, 88.7%). The cooking area was located indoors for the majority of participants both in the dry (154 of 239, 64. 0%) and rainy season (188 of 239, 79.0%). For those cooking inside, a separate cooking area located in a different structure from the main house was utilized for 57 of 154 women (37.0%) in the dry season and 64 of 188 (34.0%) in the rainy seasons. When cooking occurred outside, approximately half of the areas were located under a roof and the remainder in the open air. Cooking areas were commonly shared with other families (118 of 239, 49.4%). Few women cooked food for commerce (7 of 239, 2.9%).

The fuel used most commonly was charcoal in both the rainy season (119 of 239, 49.8%) and the dry season (189 of 239, 79.1%). Kerosene ranked as the second most common fuel used by households in the rainy season (99 of 239, 46.2%) with use dropping off during the dry season (25 of 239, 10.5%). Gas and electricity were rare in both seasons (8 of 239, 3.4% during rainy season; 5 of 239, 2.1% in dry season). Other potential factors contributing to household air pollution were not uncommon in the cohort and included tobacco use among other household members, use of incense, use of mosquito coils, burning of rubbish in the compound, and proximity to roads.

Roughly one-third of the women noted that they cooked less as a result of the pregnancy (76 of 239, 31.8%) whereas most did not alter their cooking practices (151 of 239, 63.2%). Only a small minority (12 of 239, 5%) reported increased cooking during pregnancy. When subjects were queried in an open-ended fashion about whether they believed pregnant women should cook more or cook less, 117 of 239 opined that there should be no change in cooking habits as pregnancy is not a disease. Of the 105 that believed pregnant women should reduce their cooking, 85 (81%) cited a need for rest given the fatigue associated for pregnancy. Seventeen women suggested that pregnant women should cook more, and among these women the predominant rationale for this opinion (13 of 17, or 76%) was that pregnant women are hungry and need to eat more. Only two subjects cited health concerns for the fetus or risks to the pregnancy from cooking smoke as a reason to change cooking practices while pregnant.

Exposure measurements and predictors of high exposure

Carbon monoxide—Adequate personal CO measurements were available for 236 subjects. The geometric mean personal CO exposure in our cohort of pregnant women was 2.0 ppm (± 1.3) (Table 2). The highest measured personal exposure was 25.2 ppm; all other measurements were less than 10 ppm.

In the multivariable median quantile regression model, the only factors significantly influencing median personal CO exposures were measurement during the rainy season and use of a charcoal/kerosene fuel mixture (Table 3). The rainy season lowered median exposure by 0.6 ppm (95% CI −1.0 to −0.2). Median exposure was increased by 0.9 ppm for women using a mixture of kerosene and charcoal compared with those cooking with kerosene alone (95% CI 0.0 to 1.8). Rainy season and use of both charcoal and kerosene also influenced higher CO exposures in 75th multivariable quantile regression (Table 4). Measurements during the rainy season were associated with a 0.7 ppm reduction in the 75th centile of CO exposure. Use of both charcoal and kerosene increased the 75th centile of exposure by 1.3 ppm compared to using kerosene alone (95% CI 0.2 to 2.5). In addition, cooking area kitchen CO measurements were associated with increases in the 75th centile of exposure. In multivariable logistic regression, the two predictors that retained significance for the prediction of high (>75th percentile) personal CO exposure were measurement during the rainy season and cooking area CO measurements, similar to quantile regression models (Supporting Information Table A). Cooking behaviors otherwise did not appear related to median or higher CO measurements.

While cooking area CO concentration was one of the few covariates influencing exposure levels and predicting high personal CO exposures, the strength of the correlation of cooking area CO and personal CO exposures was only moderate (Pearson's $r=0.38$, $p<0.001$ after *ln*-transformation of cooking area and personal CO). Only 14 percent of the variance in personal CO was explained by the cooking area CO ($R^2= 0.1434$ after *ln*-transformation).

Fine particulate matter—Adequate $PM_{2.5}$ measurements were available for 118 subjects. Of the measurements excluded, 1 was attributed to inadequate sampling time, 1 subject's filters were misplaced, and 4 had pump errors. The remaining subjects' filters had implausible weights secondary to incorrect pump setup by one field worker; all filter weights from this field worker were excluded. The geometric mean $PM_{2.5}$ exposure among our cohort was 40.5 $\mu g/m^3$ (± 21.2) (Table 2). Four outliers were noted in the distribution of $PM_{2.5}$ measurements, all above 100 $\mu g/m^3$; the remaining measurements were less than 100 $\mu g/m^3$. Correlation was moderate between day 1 and day 3 $PM_{2.5}$ measurements (Pearson's $r=0.48$, $p<0.001$ after *ln*-transformation).

As with CO, a variety of demographics, cooking behaviors, cooking area characteristics and other environmental factors were evaluated for their influence on median and 75th centiles of exposure. From the multivariable quantile regression model, the only factor influencing median exposure to personal $PM_{2.5}$ was having cooked outdoors or partially outdoors (Table 3). Outdoor cooking reduced median exposure by 14.5 μg/m^3 (95% CI −18.3 to −2.5) Cooking with charcoal only compared with kerosene only was the one predictor associated with the 75th centile of exposure increasing the 75th centile by 17.0 μg/m^3 (95% CI 0.3 to 27.6) (Table 4). Notably, cooking area CO measurements did not influence the median or 75th centile of $PM_{2.5}$ exposure. In univariate logistic regression, cooking outdoors was associated with a decreased odds of having exposure in the uppermost quartile of $PM_{2.5}$ exposure (OR 0.35, 95% CI 0.13 to 0.94) (Supporting Information Table A). Visible soot on the walls was associated with an increased odds of $PM_{2.5}$ exposure (OR 4.93, 95%CI 1.09 to 22.39). Neither retained significance in multivariable regression.

Correlation of CO and $PM_{2.5}$ exposure

The strength of the correlation between CO and $PM_{2.5}$ measurements for a given subject was only moderately positive in bivariate analysis (Pearson's r=0.33, p=0.0003 after *ln*-transformation). Only 10.5 percent of the variance in personal $PM_{2.5}$ exposures was explained by the personal CO exposure (R^2= 0.1058 after *ln*-transformation).

Relation of household air pollutants with newborn anthropometrics

Ninety five percent (228 of 239) subjects enrolled in this study had available birth weights for analysis. Birth length measurements were available in 174 subjects and head circumference measurements in 173 subjects. The mean birth weight we observed among study subjects was 3.2 kilograms (standard deviation ± 0.5), mean birth length was 48.4 cm (standard deviation ± 3.2), and mean head circumference was 35.4 cm (standard deviation ± 1.6 cm).

The relationship between personal CO and personal $PM_{2.5}$ with birth weight, birth length, and head circumference was assessed in linear regression models after excluding the one CO and the four $PM_{2.5}$ outliers (Table 5). Given a skew in the distributions of personal CO and personal $PM_{2.5}$, measurements were natural log transformed prior to inclusion in the linear models to improve normality and stabilize variance. After fitting these univariate (unadjusted) models, we considered inclusion of quadratic CO and $PM_{2.5}$ terms in each of the models. None of the squared terms included were significant at a level of $p<0.05$, adjusted R^2 either did not increase or changed by less than 1 percent, and therefore only the linear term was retained. Visual inspection of scatterplots between CO or $PM_{2.5}$ with newborn anthropometric measurements also were not suggestive of nonlinear relationships.

$PM_{2.5}$ appeared inversely related to birth weight in unadjusted regression although not reaching statistical significance (p=0.10). After adjusting for a number of covariates that potentially confounded the unadjusted estimate, we observed a 0.15 kilogram reduction in birth weight per interquartile increase in maternal $PM_{2.5}$ exposure of borderline statistical significance (95% CI −0.30 to 0.00; p=0.05) (Table 5). An interquartile change in exposure represents a change from the 25th to 75th percentile of exposure and for $PM_{2.5}$ was 23.0 μg/m^3. Our models suggested that higher maternal $PM_{2.5}$ exposure may additionally be associated with a decrement in birth length. We observed a 1.13 cm reduction per interquartile increase in maternal $PM_{2.5}$ exposure after adjustment although this did not reach statistical significance in the more limited sample of birth length measurements (95% CI −2.55 to 0.29; p=0.11). Personal $PM_{2.5}$ exposures were not associated with head circumference measurements (p=0.66). Likewise, personal CO exposures were not associated with birth weight (p=0.72), birth length (p=0.93), or head circumference (p=0.93). To gauge the robustness of our models, a sensitivity analysis was performed restricting multivariable models to only include covariates that were associated with the outcomes (birth weight, birth length or head circumference) at a significance level of $p \leq 0.10$. Effect estimates and confidence intervals were not greatly altered (Supporting Information Table B). Restricting analyses to only terms births, defined as 37 weeks or more at delivery, also did not alter our findings.

The prevalence of low birth weight, defined as a birth weigh less than 2.5 kilograms, was 11.4 % among our study subjects (26 of 228 subjects with birth weight measurements). Using exact logistic regression, we calculated odds ratios and 95% confidence intervals for the association of low birth weight with exposure in the uppermost quartile for both CO and $PM_{2.5}$. The odds of low birth weight were not higher among subjects with CO exposures in the uppermost quartile (exact OR 0.83, 95% CI 0.26 to 2.3) nor among subjects with $PM_{2.5}$ exposures in the uppermost quartile (exact OR 1.2; 95% CI 0.25 to 4.4). Limitations of sample size precluded multivariable adjustment.

DISCUSSION

This study is one of the first to directly measure personal exposures to specific air pollutants during pregnancy in a population that cooks predominantly with solid fuels. We found that placing exposure equipment in a locally-sourced, over-the-shoulder purse made wearing the equipment for 72 hours comfortable and acceptable to the pregnant Tanzanian women. Nonetheless, exposure assessment was both a time and resource intensive endeavor. The personal exposures we measured among our urban/perirurban cohort were lower compared to exposures reported from rural populations using solid fuels (Dionisio et al., 2012a; Van Vliet et al., 2013;Smith et al., 2010;Jiang and Bell, 2008) and instead closer to those measured during the winter season among pregnant women living in Krakow, Poland where the use of coal and wood stoves for heating is common (Jedrychowski et al., 2006; Jedrychowski et al., 2007). The difference in exposure levels we observed compared to rural settings may relate to a reliance on solid fuels such as charcoal that combust more efficiently than wood or crop residues. Alternately, rural populations relying on wood and crop residues may keep the fire smoldering throughout the day to reduce time required to light the fire (Ezzati et al., 2000). Charcoal and kerosene stoves, in common use among our cohort, are easier to light and extinguish. Regardless, the levels we measured exceed the guidelines enumerated by the World Health Organization for acceptable air quality (*World Health Organization Guidelines for Indoor Air Quality: Selected Pollutants.*, 2010) (mean 24-hour $PM_{2.5}$ not to exceed 25 $\mu g/m^3$) for 87 percent (103 of 118) of the women with $PM_{2.5}$ measurements in our study.

We observed a seasonal pattern in personal exposure to CO with exposures lower during the rainy season. This is in contrast to work from The Gambia among a rural population of children whose exposures were higher during rains (Dionisio et al., 2012b). We hypothesize this is related to the observed increase in kerosene use during the rains among our cohort, a fuel that may be inaccessible to rural populations. Seasonal variation in cooking areas is likely higher among rural populations where outdoor space is more available; indoor cooking during rains consequently may increase exposure levels during the rains. The majority of women in our cohort cooked indoors regardless of season.

Only a few of the considered residential environment factors, cooking behaviors, cooking area characteristics, and other household air pollution sources were associated with personal median exposure levels or predicted high exposure. We found that the fuels used during the measurement period did influence exposure. Cooking with kerosene alone was associated with reductions in both CO and $PM_{2.5}$ exposure. Fuel choice represents a potential target for exposure reduction during pregnancy. That said, international agencies discourage the use of kerosene as a household fuel source as emissions continue to exceed air quality standards and there are additional risks of accidental burns and poisonings (*World Health Organization Indoor Air Quality Guidelines: Household Fuel Combustion. 2012*). Only a handful of subjects cooked with gas or electricity and we were therefore unable to determine how exposure with kerosene use compares to these cleaner energy alternatives. Similarly, we were unable to make comparisons with other biomass fuels such as wood or crop residues given their limited use in this mostly urban population. The other cooking behavior associated with exposure in our analysis was outdoor cooking, which was linked with reductions in median $PM_{2.5}$ exposure. Ideally, we would have been able to assess whether the degree of indoor cooking area ventilation was associated with exposure but our forms did not discriminate between the number of windows, their location, and whether they were open during exposure measurements. Likewise, we were unable to distinguish mothers cooking fully outdoors from partially outdoors. This limited our ability to evaluate this potentially modifiable cooking behavior.

To explain a lack of association of exposure with other cooking behaviors, we speculate that personal exposure in an urban environment may reflect neighborhood air pollution from the collective cooking behaviors of all households given the proximity of subjects' households to other households. This was demonstrated in a study conducted in a densely populated urban setting in Bangladesh where even those households cooking with non-biomass fuels such as gas or electricity had peak area $PM_{2.5}$ concentrations exceeding 1000 $\mu g/m^3$ during times of the day when cooking is common in the community (Salje et al., 2014). Personal exposures are also likely affected by noncombustion sources such as traffic, as has been described in other work (Zhou et al., 2011). From the few source apportionment studies available from settings where solid fuel use is common, it appears that while solid fuels are important contributors to ambient air pollution and personal exposure, other sources contribute to the majority of daily exposures in urban settings (Zhou et al., 2014;Liu et al., 2014). Our findings together with these prior studies suggest that strategies to reduce personal exposure to air pollution in pregnancy may require more than individual level cooking interventions; this may be particularly relevant for urban populations.

Our study is one of the first to relate direct personal measures of household air pollution to newborn anthropometrics. Our findings contribute to the evidence that exposure to household air pollution can negatively impact birth weight. In contrast, other anthropometrics did not appear related to exposure. In our study, $PM_{2.5}$ was the more relevant pollutant. We acknowledge that a major limitation of our birth weight analysis was that weights were only recorded to the nearest 0.1 kilogram in the parent trials from which we recruited our cohort and routine calibrations were not performed, thus blurring the effect size we could detect and likely contributing to the borderline significance and wide confidence interval. Additionally, while we adjusted for a number of characteristics that could potentially confound the association between exposure and birth anthropometrics, the possibility of residual confounding still exists.

We chose not to explore the associations of exposure with gestational length, preterm birth or stillbirth. Gestational age in the parent trials was assessed by means of a Ballard examination, The accuracy of the Ballard when administered by research personnel in a similar setting was found to be accurate only to +/− 4 or 5 weeks and the sensitivity to detect preterm birth reported to be only 39% (Karl et al, 2015), thereby limiting our ability to evaluate these outcomes in relation to maternal CO or $PM_{2.5}$ exposure. Stillbirth was rare (10 of 229 subjects) and therefore not included. We invite others working in the field to pool data to increase the power to discriminate associations as well as strengthen exposure response curves across a broader range of exposures.

Our aim with this work was to improve exposure classification in the literature evaluating the potential adverse impact of household air pollution during pregnancy, moving beyond categorization of primary household fuel to direct personal measurement of air pollutants. That said, we measured exposure during only one 72-hour period in the latter half of gestation for each subject. This may not adequately represent prenatal exposure over the course of pregnancy. Windows of particular susceptibility or vulnerability would not be discernible from our work. Moreover, we measured exposure to only two pollutants, CO and $PM_{2.5}$; other pollutants released during the incomplete combustion of solid fuels such as polycyclic aromatic hydrocarbons may contribute to the adverse impact during pregnancy and have been implicated in prior work (Perera et al., 2005). The absence of a strong correlation between CO and $PM_{2.5}$ from this study and prior work (Dionisio et al., 2012a; Ezzati et al., 2000) underscores that one pollutant may not be a good proxy for another, particularly in settings of high charcoal use. Finally, prior studies have demonstrated considerable within-person variability in personal exposure to household air pollutants (Dionisio et al., 2012b; McCracken et al., 2013); a longitudinal design during the course of pregnancy with repeated measurements of personal exposure might have increased power to detect effects on pregnancy outcome. In summary, exposure misclassification remains possible even if we improved classification relative to prior studies.

Our results contribute to the evidence that exposure to household air pollution may affect birthweight. Moreover, our findings suggest that community air pollution, which itself may be partly or largely due to solid fuel use in these urban/periurban settings, may be a key contributor to household air pollution beyond the activities and practices of the individual or family. To be most effective, policies for the reduction of air pollution from solid fuel use in urban settings may need to be directed towards entire communities as well as to individual households.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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PRACTICAL IMPLICATIONS

Our results contribute to the evidence that exposure to household air pollution in utero may affect birth weight. Pregnancy represents an attractive time to target health behavior change as mothers are often motivated by the health of their fetus; moreover, existing antenatal care networks can be utilized to deliver interventions such as improved cook stoves or messaging around the risks of household air pollution. Fuel choice did appear linked with exposure and represents a potential target for exposure reduction during pregnancy. However, many of the other individual cooking characteristics we considered were not correlated with exposure. This suggests the possibility that community air pollution, which itself may be partly or largely due to solid fuel use in these urban/periurban settings, may be a key contributor to household air pollution beyond the activities and practices of the individual or family. To be most effective, policies for the reduction of air pollution from solid fuel use in urban settings may need to be directed towards entire communities rather than individual households in isolation.

Table 1

Cohort characteristics and cooking behaviors during exposure measurement

	Overall cohort n=239	**Number Missing**
	n (%) or median (IQR)	
Maternal characteristics		
Age category		12
18–20 years	67 (29.5%)	
21–25 years	97 (42.7%)	
≥26 years	63 (27.8%)	
Parity		4
Nulliparous	146 (62.1%)	
Primiparous	89 (37.9%)	
BMI category		0
< 18.5 kg/m^2	21 (8.8%)	
18.5–24.9 kg/m^2	134 (56.1%)	
25–29.9 kg/m^2	61 (25.5%)	
30+ kg/m^2	23 (9.6%)	
Prenatal vitamin compliance >80%	171 (75.3%)	12
History of hypertension	8 (3.5%)	12
Treated for antepartum malaria episode	0 (0%)	0
Socio-Demographics		
Household asset index[a]		12
Low	13 (5.7%)	
Medium	114 (50.2%)	
High	100 (44.1%)	
Neighborhood		1
Urban	64 (26.9%)	
Periurban or rural	174 (73.1%)	
Housing		4
Apartment or multifamily home	186 (79.2%)	
Single family home	49 (20.5%)	
Year of exposure measurements		0
2011	85 (35.6%)	
2012	113 (47.3%)	
2013	41 (17.2%)	
Rainy season during measurements	130 (54.4%)	0
Cooking behaviors during measurement		
Cooked meals for family	231 (97.9%)	3
Number of meals cooked per day	2.7 (1.3)[b]	3

	Overall cohort n=239	**Number Missing**
	n (%) or median (IQR)	
Fuels used		3
Did not cook	5 (2.1%)	
Wood only	4 (1.7%)	
Charcoal only	73 (30.9%)	
Kerosene only	22 (9.3%)	
Gas/electricity only	2 (0.9%)	
Both charcoal and kerosene	130 (55.1%)	
Cooked outdoors/partially outdoors	87 (36.4%)	0
Cooks for commerce	7 (2.9%)	0
Cooking area characteristics		
Number of stoves	2.0 (0)[b]	0
Cooking area shared with other families	107 (44.8%)	0
Visible soot on walls	181 (77.7%)	6
Other sources of household air pollution		
Use of incense	42 (17.6%)	0
Use of mosquito coils	17 (7.1%)	0
Burning of rubbish	36 (15.1%)	1
Tobacco use	3 (1.3%)	0
Secondhand smoke	27 (11.3%)	0
Nearest major road ≤ 200 meters	156 (66.1%)	3
Nearest road is paved	106 (45.9%)	8

BMI= body mass index in kilograms/meters. IQR= interquartile range.

[a] Household asset index constructed after tallying ownership of ten items (car, generator, bicycle, sofa, television, radio, refridgerator, fan, electricity, and potable aqua). Low asset index= counts of 0–5; medium asset index= counts of 6–8; high asset index= counts of 9–10.

[b] Median (±IQR).

Table 2

Carbon monoxide and fine particulate matter exposures and cooking area concentrations among pregnant women in Dar es Salaam, Tanzania.

	Number of samples	Geometric Mean (± geometric STD)	Minimum	Maximum	Interquartile Range
CO, personal samples (ppm)	236	2.0 (±1.3)	0.3	25.2	1.7
CO, cooking area samples (ppm)	235	4.8 (±4.6)	0.5	56.2	6.2
$PM_{2.5}$, personal samples (μg/m^3)	118	40.5 (±21.2)	13.1	528.2	23.0

CO= carbon monoxide; $PM_{2.5}$= fine particulate matter < 2.5 micrometers in diameter; m = cubic meters; ppm= parts per million; STD=standard deviation.

Table 3

Influence of residential environment, cooking behaviors, and other household air pollution sources on median (50th centile) personal exposure to carbon monoxide and fine particulate matter

	CO	$PM_{2.5}$
	Regression coefficient[a] (95% CI)	**Regression coefficient[a] (95% CI)**
Sociodemographics		
Household Asset Index		
Low	−0.0 (−1.5, 1.4)	9.0 (−17.3, 80.9)
Medium	−0.1 (−0.4, 0.3)	−3.0 (−10.7, 4.1)
High	Referent	Referent
Urban neighborhood	0.1 (−0.4, 0.7)	−2.3 (−10.3, 4.2)
Single family home	−0.3 (−0.8, 0.3)	−9.3 (−24.6, 0.1)
Year of measurements		
2011	Referent	Referent
2012	−0.3 (−0.8, 0.3)	−9.7 (−14.0, 0.0)
2013	−0.2 (−1.0, 0.7)	--
Rainy season[b]	−0.6 (−1.0, −0.2)	−2.4 (−11.2, 5.1)
Cooking area CO measurements (ppm)	0.0 (−0.0, 0.1)	−0.1(−0.4, 0.7)
Cooking behaviors during measurement		
Number of meals cooked	−0.1 (−0.5, 0.2)	−0.6 (−4.3, 7.8)
Fuels used		
Kerosene only	Referent	Referent
Charcoal/kerosene mix[b]	0.9 (0.0,1.8)	5.3 (−10.6, 10.2)
Charcoal only	0.7 (−0.2, 1.7)	14.4 (−8.2, 19.4)
Cooks for commerce	−0.7 (−2.8, 1.3)	--
Kitchen characteristics		
Shared with other families	0.0 (−0.5, 0.5)	−7.2 (−15.4, 2.1)
Outdoors/partially outdoors[c]	−0.4 (−0.8, 0.0)	−14.5 (−18.3, −2.5)
Visible soot on walls	0.0 (−0.5, 0.5)	2.3 (−9.8, 17.0)
Other sources of household air pollution		
Use of incense	0.1 (−0.7, 0.8)	−4.6 (−13.5, 8.7)
Use of mosquito coils	−0.6 (−1.7, 0.6)	3.8 (−12.5, 15.0)
Burning of rubbish	−0.2 (−0.9, 0.5)	6.1 (−9.3, 20.0)
Tobacco smoke	--	--
Secondhand smoke	0.2 (−0.6, 1.0)	−11.0 (−28.1, 4.2)
Distance to nearest road >200m	0.3 (−0.3, 0.9)	--
Nearest road paved	0.1 (−0.4, 0.6)	−0.7 (−7.2, 9.2)

CI=confidence interval; CO=carbon monoxide; $PM_{2.5}$= fine particulate matter < 2.5 micrometers in diameter.

[a] For categorical variables, the regression coefficient represents the change in the median exposure with the predictor (compared to without). For continuous variables, the coefficient represents the change in median exposure from a one unit increase in the predictor. The referent category is listed in the table for variables with more than two categories. For dichotomous variables, the referent response category is no (e.g., the referent category for use of incense would be those who reported no use of incense). Variables with cell counts of less than 5 were not included in multivariable models

[b] $p < 0.05$ for CO model.

[c] $p < 0.05$ for $PM_{2.5}$ model.

Table 4

Influence of residential environment, cooking behaviors, and other household air pollution sources on the 75th centiles of personal exposure to carbon monoxide and fine particulate matter

	CO	**PM$_{2.5}$**
	Regression Coefficient[a] (95% CI)	**Regression Coefficient[a] (95% CI)**
Sociodemographics		
Household Asset Index		
Low	1.2 (−0.7, 3.1)	--
Medium	−0.1 (−0.7, 0.5)	--
High	Referent	Referent
Urban neighborhood	0.3 (−0.6, 1.3)	0.8 (−9.9, 7.7)
Single family home	−0.4 (−1.4, 0.6)	−9.1 (−20.3, 14.1)
Year of measurements		
2011	Referent	Referent
2012	−0.1 (−0.9, 0.7)	−3.7 (−10.7, 7.7)
2013	−0.3 (−1.6, 0.9)	--
Rainy season[b]	−0.7 (−1.3, −0.1)	−3.1 (−12.1, 7.5)
Cooking area CO measurements (ppm)[b]	0.1 (0.0, 0.2)	−0.2 (−0.5, 2.0)
Cooking behaviors during measurement		
Number of meals cooked	−0.4 (−0.9, 0.2)	3.7 (−6.7, 6.5)
Fuels used		
Kerosene only	Referent	Referent
Charcoal/kerosene mix[b]	1.3 (0.2, 2.5)	5.7 (−5.0, 15.5)
Charcoal only[c]	1.0 (−0.2, 2.3)	17.0 (0.3, 27.6)
Cooks for commerce	−0.3 (−4.5, 3.8)	--
Kitchen characteristics		
Shared with other families	−0.2 (−0.8, 0.4)	−7.6 (−14.7, 4.4)
Outdoors/partially outdoors	−0.2 (−1.0, 0.4)	−16.5 (−23.5, 6.6)
Visible soot on walls	0.5 (−0.2, 1.3)	6.9 (−2.3, 16.6)
Other sources of household air pollution		
Use of incense	−0.3 (−1.2, 0.6)	−7.6 (−14.6, 7.8)
Use of mosquito coils	−0.3 (−1.8, 1.2)	2.8 (−6.4, 12.2)
Burning of rubbish	0.2 (−0.8, 1.2)	11.8 (−1.1, 19.8)
Tobacco use	--	--
Secondhand smoke	0.4 (−0.9, 1.6)	−5.8 (−15.4, 71.1)
Distance to nearest road >200m	0.5 (−0.4, 1.3)	--
Nearest road paved	0.6 (−0.1, 1.4)	3.8 (−10.1, 14.1)

CI= confidence interval; CO=carbon monoxide; $PM_{2.5}$= fine particulate matter < 2.5 micrometers in diameter.

[a] For categorical variables, the regression coefficient represents the change in the 75th centile of exposure with the predictor (compared to without). For continuous variables, the coefficient represents the change in median exposure from a one unit increase in the predictor. The referent category is listed in the table for variables with more than two categories. For dichotomous variables, the referent response category is no (e.g., the referent category for use of incense would be those who reported no use of incense). Variables with cell counts of less than 5 were not included in multivariable models.

[b] $p < 0.05$ for CO model.

[c] $p < 0.05$ for $PM_{2.5}$ model.

Table 5

Linear association of ln-transformed CO or $PM_{2.5}$ exposure with newborn anthropometrics

	lnCO			$lnPM_{2.5}$		
	β coefficient (95% CI)	**p-value**	**Change in outcome per interquartile increase[a] in CO exposure (95% CI)**	**β coefficient (95% CI)**	**p-value**	**Change in outcome per interquartile increase[a] in $PM_{2.5}$ exposure (95% CI)**
Birth weight (kg)						
Unadjusted	− 0.01 (−0.11, 0.13)	0.85	− 0.01 kg (−0.09, 0.10)	− 0.21 (−0.46, 0.05)	0.10	−0.12 grams (−0.26, 0.03)
Adjusted[b]	− 0.02 (−0.14, 0.10)	0.72	−0.02 kg (−0.11, 0.08)	− 0.27 (−0.54, 0.00)	0.05	−0.15 grams (−0.30, 0.00)
Birth length (cm)						
Unadjusted	0.22 (−0.59, 1.03)	0.59	0.17 cm (−0.46, 0.81)	− 1.89 (−4.02, 0.24)	0.08	−1.06 cm (−4.02, 0.13)
Adjusted[b]	− 0.03 (−0.88, 0.80)	0.93	−0.02 cm (−0.69, 0.63)	− 2.02 (−4.55, 0.52)	0.11	−1.13 cm (−2.55, 0.29)
Head circumference (cm)						
Unadjusted	0.07 (−0.32, 0.46)	0.72	0.06 cm (−0.25, 0.36)	0.24 (−0.78, 1.27)	0.64	0.13 cm (−0.44, 0.71)
Adjusted[b]	− 0.02 (−0.04, 0.39)	0.93	−0.02 cm (−0.03, 0.31)	0.26 (−0.95, 1.48)	0.66	0.15 cm (−0.53, 0.83)

CI= confidence interval. cm= centimeter. CO =carbon monoxide. kg=kilograms. $PM_{2.5}$= fine particulate matter < 2.5 micrometers in diameter.

[a] Interquartile change in exposure represents change from 25th to 75th centile of exposure. For CO, the interquartile range was 1.7 ppm and for $PM_{2.5}$ this was 23.0 $\mu g/m^3$. The effect size has been translated to a nonlogarithmic scale for ease of interpretation.

[b] Adjusted for age, parity, sex of infant, compliance with prenatal vitamins, household asset index, body mass index, urban neighborhood, housing (single family home versus apartment/multifamily home), parent trial and year of measurements.