Environmental Research 142 (2015) 424–431

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Low correlation between household carbon monoxide and particulate matter concentrations from biomass-related pollution in three resource-poor settings

Elizabeth M. Klasen [a], Beatriz Wills [a], Neha Naithani [a,b], Robert H. Gilman [c], James M. Tielsch [d], Marilu Chiang [e], Subarna Khatry [b], Patrick N. Breysse [f], Diana Menya [g,h], Cosmas Apaka [h], E. Jane Carter [h,i], Charles B. Sherman [h,i], J. Jaime Miranda [j], William Checkley [a,c,j,*], COCINAS Trial Working Group

[a] Division of Pulmonary and Critical Care, School of Medicine, Johns Hopkins University, Baltimore, USA
[b] Nepal Nutrition Intervention Project Sarlahi, Kathmandu, Nepal
[c] Program in Global Disease Epidemiology and Control, Bloomberg School of Public Health, Johns Hopkins University, Baltimore, USA
[d] Department of Global Health, School of Public Health and Health Services, George Washington University, Washington DC, USA
[e] Biomedical Research Unit, A.B. PRISMA, Lima, Peru
[f] Department of Environmental Health Sciences, Bloomberg School of Public Health, Johns Hopkins University, Baltimore, USA
[g] School of Public Health, Moi University, Eldoret, Kenya
[h] AMPATH (Academic Model Providing Access to Healthcare), Eldoret, Kenya
[i] Division of Pulmonary Medicine, The Warren Alpert School of Medicine, Brown University, Providence, USA
[j] CRONICAS Center of Excellence in Chronic Diseases, Universidad Peruana Cayetano Heredia, Lima, Peru

ARTICLE INFO

Article history:
Received 7 July 2015
Received in revised form
16 July 2015
Accepted 17 July 2015

Keywords:
Biomass fuel smoke
Rndomized field trial
Particulate matter
Carbon monoxide

ABSTRACT

Household air pollution from the burning of biomass fuels is recognized as the third greatest contributor to the global burden of disease. Incomplete combustion of biomass fuels releases a complex mixture of carbon monoxide (CO), particulate matter (PM) and other toxins into the household environment. Some investigators have used indoor CO concentrations as a reliable surrogate of indoor PM concentrations; however, the assumption that indoor CO concentration is a reasonable proxy of indoor PM concentration has been a subject of controversy. We sought to describe the relationship between indoor $PM_{2.5}$ and CO concentrations in 128 households across three resource-poor settings in Peru, Nepal, and Kenya. We simultaneously collected minute-to-minute $PM_{2.5}$ and CO concentrations within a meter of the open-fire stove for approximately 24 h using the EasyLog-USB-CO data logger (Lascar Electronics, Erie, PA) and the personal DataRAM-1000AN (Thermo Fisher Scientific Inc., Waltham, MA), respectively. We also collected information regarding household construction characteristics, and cooking practices of the primary cook. Average 24 h indoor $PM_{2.5}$ and CO concentrations ranged between 615 and 1440 $\mu g/m^3$, and between 9.1 and 35.1 ppm, respectively. Minute-to-minute indoor $PM_{2.5}$ concentrations were in a safe range (<25 $\mu g/m^3$) between 17% and 65% of the time, and exceeded 1000 $\mu g/m^3$ between 8% and 21% of the time, whereas indoor CO concentrations were in a safe range (<7 ppm) between 46% and 79% of the time and exceeded 50 ppm between 4%, and 20% of the time. Overall correlations between indoor $PM_{2.5}$ and CO concentrations were low to moderate (Spearman ρ between 0.59 and 0.83). There was also poor agreement and evidence of proportional bias between observed indoor $PM_{2.5}$ concentrations vs. those estimated based on indoor CO concentrations, with greater discordance at lower concentrations. Our analysis does not support the notion that indoor CO concentration is a surrogate marker for indoor $PM_{2.5}$ concentration across all settings. Both are important markers of household air pollution with different health and environmental implications and should therefore be independently measured.

Published by Elsevier Inc.

1. Introduction

Biomass fuels, which include wood, charcoal, dung, and crop waste, are the source of domestic energy for an estimated 40% of the world population (Bonjour et al., 2013). Households without

* Correspondence to: Division of Pulmonary and Critical Care, School of Medicine, Johns Hopkins University, 1800 Orleans Ave, Suite 9121, Baltimore, MD 21287, USA.
E-mail address: wcheckl1@jhmi.edu (W. Checkley).

http://dx.doi.org/10.1016/j.envres.2015.07.012
0013-9351/Published by Elsevier Inc.

access to improved stove technologies burn biomass fuels in unventilated, open-fire stoves for cooking, heating, and other domestic chores (Smith et al., 2014; Chafe et al., 2014). When cooking indoors, incomplete combustion of biomass fuels releases a complex mixture of inhalable particulate matter (PM), carbon monoxide (CO), polycyclic aromatic hydrocarbons, and other toxins into the household environment (Bonjour et al., 2013). Associations between multiple negative health outcomes and household air pollution have been established in both children and adults (Sood, 2012; Gordon et al., 2014; Fullerton et al., 2008; Burnett et al., 2014). Consequently, household air pollution is now recognized as the third greatest contributor to global disease burden (Lim et al., 2012).

Assessment of gravimetric PM in field conditions is difficult, because the equipment required to perform an accurate measurement is expensive; it requires pre- and post-weighing of filters that collect PM using ultra-sensitive scales (Northcross et al., 2015); and, filter clogging is common during prolonged measurements of biomass fuel smoke. On the other hand, CO is relatively easy to assess using inexpensive real-time monitors. Results from previous studies have shown strong correlations between indoor CO and PM concentrations (Northcross et al., 2010; McCracken et al., 2013). Therefore, some investigators have proposed using CO concentrations as a reliable surrogate of PM concentrations since devices to measure CO are cheaper, highly reproducible, and easier to use and deploy in field settings. The assumption that CO is a reasonable proxy of PM, however, is controversial, as new evidence suggests that PM emissions have high intra-household variability and that PM concentrations vary widely for a given CO concentration (Dionisio et al., 2012; Pollard et al., 2014; Gu et al., 2015; Yamamoto et al., 2014).

In this analysis, we sought to assess the relationship between 24 h average household $PM_{2.5}$ and CO concentrations in three resource poor-settings in Africa, Asia and South America; and, describe household characteristics associated with indoor air quality. Finally we explored the variability of indoor $PM_{2.5}$ and CO concentrations by setting.

2. Methods

2.1. Study sites

This study was conducted in three rural, resource-poor regions of Peru, Nepal and Kenya as previously described (Klasen et al., 2013): the Vinchos district in Ayacucho, Peru, comprised of steep, rocky hills at an altitude range of 3000 to 4000 m; the Sarlahi District in southwestern Nepal at 200 m above sea level in a flat, densely population region; and the Ndanai sub-location of the Uasin Gishu district located in western Kenya at an elevation of 2300 to 2500 m in an sloping, heavily forested area.

2.2. Study design

We evaluated baseline (pre-intervention) pollutant concentration data collected as part of multi-center field intervention trial of two types of improved cookstoves. Detailed information regarding the multi-center field intervention trial has been published elsewhere (Klasen et al., 2013). Specifically, we summarized baseline indoor environmental exposures in households of women using an open-fire stove. The study was conducted according to uniform procedures and protocols at each location (Klasen et al., 2013); however, the season of enrollment varied by study setting. We also collected information on potential factors that may influence indoor pollutant concentrations.

2.3. Recruitment and consent

Following a census of the study areas, eligible women were randomly selected for participation. We aimed to enroll 138 women into the trial (i.e., a total of 46 women per site) with the expectation that we would have at least 120 (i.e., 40 women per site) who completed an entire year of follow-up. All participants provided verbal informed consent after our research team read the entire informed consent document to them and any questions were answered. Informed consents were verbal because of high illiteracy rates. This study was approved by the Institutional Review Boards of Universidad Peruana Cayetano Heredia (Lima, Peru), Johns Hopkins Bloomberg School of Public Health (Baltimore, USA), Asociación Benefica PRISMA (Lima, Peru), Moi University (Eldoret, Kenya), Institute of Medicine at Tribhuvan University (Kathmandu, Nepal) and Lifespan/The Miriam Hospital (Providence, USA).

2.4. Pollutant exposure assessments

Indoor $PM_{2.5}$ and CO concentrations were simultaneously assessed every minute for a 24 h period and placed approximately 1.5 m off the floor and within one meter of the cooking fire to best capture the exposure to individuals who were cooking and we measured nephelometric PM with the personal DataRAM-1000AN (pDR-1000) (Thermo Fisher Scientific Inc., Waltham, MA). Empirical evidence suggests that the pDR-1000 detects particles in the size range of 0.3–2 μm more efficiently than those of 2–10 μm (Howard-Reed et al., 2000; Liu et al., 2002). Moreover, Quintana et al. reported a high degree of correlation between the PM determined by the pDR-1000 and $PM_{2.5}$ (i.e., 2.5 μm or smaller in size) measurements (Quintana et al., 2000). Real-time measurements had to be conducted for at least 18 h to be included in our analysis. Temperature and relative humidity were also measured every minute using a HOBO Data Logger (Onset Corp., Bourne MA). Relative humidity data was used to adjust nephelometric PM concentrations as previously described (Chakrabarti et al., 2004). Nephelometric PM concentrations were converted to $PM_{2.5}$ gravimetric-equivalent concentrations using a previously validated equation (Pollard et al., 2014). The EasyLog-USB-CO data logger (Lascar Electronics, Erie, PA) captured direct-reading CO emission concentrations. We defined 24-h indoor PM concentrations $< 25\ \mu g/m^3$ and indoor CO concentrations < 7 ppm as safe per international recommendations (World Health Organization, 2010).

2.5. Biostatistical methods

Primary objectives of this analysis were to explore the relationship between indoor $PM_{2.5}$ and CO concentrations, and identify household factors associated with each of these exposures. To characterize the inter-relationship between indoor $PM_{2.5}$ and CO concentrations, we calculated Spearman correlation coefficients. We also constructed a linear regression model for indoor $PM_{2.5}$ concentrations as a function of a natural cubic spline of indoor CO concentrations, indicators for site, and an interaction between the elements of the natural cubic spline of indoor CO concentrations and site. We used this model to obtain an expected value for indoor $PM_{2.5}$ concentration for a given indoor CO concentration, and measured agreement between observed and expected indoor $PM_{2.5}$ concentrations using the Bland–Altman method (Bland and Altman, 1986).

To determine factors linked to household air quality, we constructed multivariable linear regression models of indoor $PM_{2.5}$ and CO concentrations as a function of socioeconomic status (household income, assets, education of primary cook, and