Published in final edited form as:

Environ Res. 2015 November ; 143(0 0): 107–111. doi:10.1016/j.envres.2015.09.017.

A cross-sectional study of exhaled carbon monoxide as a biomarker of recent household air pollution exposure

Alison Lee, MD¹, Tiffany R. Sanchez², Muhammad Hasan Shahriar, MD³, Mahbubul Eunos, MD³, Matthew Perzanowski, PhD², and Joseph Graziano, PhD²

¹Division of Pulmonary, Critical Care and Sleep Medicine, Icahn School of Medicine at Mount Sinai

²Department of Environmental Health Sciences, Columbia University Mailman School of Public Health

³University of Chicago Research Bangladesh

Abstract

RATIONALE—Household air pollution causes 3.5 million deaths annually. Personal exposure assessments required for examining health associations are expensive and require technical expertise, limiting the quality of research in resource-poor settings.

OBJECTIVES—To assess the feasibility of exhaled carbon monoxide and its relationship to continuous personal carbon monoxide monitoring and markers of respiratory health in female cooks primarily cooking with biomass fuels in Araihasar, Bangladesh.

METHODS & MEASURES—For a 24-hour period, exhaled carboxyhemoglobin (eCOHb) % saturation was measured before and after each cooking episode while simultaneous 24-hour personal carbon monoxide monitoring was conducted. The Coburn-Forester-Kane (CFK) equation was used to convert continuous personal CO exposures to predicted COHb % saturation. Respiratory symptoms were assessed by St. George's Respiratory Questionnaire, airway inflammation measured by exhaled breath condensate pH, and lung function determined by spirometry. Spearman's correlation was used to examine the relationship between eCOHb and CFK-derived COHb, EBC pH, and lung function variables. eCOHb % saturation was dichotomized around the median and odds ratios calculated for each respiratory symptom.

MAIN RESULTS—Measurement of eCOHb % saturation is feasible in a resource-poor setting. eCOHb % saturation responds to cooking episodes and demonstrates consistency when measured at the same time point 24-hours later, suggesting that eCOHb may be a sensitive biomarker of recent HAP exposures.

Corresponding Author: Alison Lee, One Gustave L. Levy Place, Box 1232, New York, NY 10029, USA. Telephone: +1 (212) 241-5900, Facsimile +1 (212) 876-5519; Alison.Lee@mssm.edu.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Each woman provided informed consent before the start of the study. This study was approved by the Columbia University Medical Center IRB and by the Bangladesh Medical Research Council.

Keywords

household air pollution; carbon monoxide; carboxyhemoglobin; biomarker; exposure assessment

INTRODUCTION

Three billion people worldwide have daily exposure to toxic levels of household air pollution (HAP) secondary to the burning of solid fuels, such as biomass (wood, animal dung, crop residuals) or coal (1, 2). The combustion of biomass fuels is inefficient and produces harmful substances such as carbon monoxide (CO) and particulate matter less than 2.5 microns in diameter (PM_{2.5}). Persons who burn solid fuels as their primary source of household energy may experience enormous cumulative lifetime CO exposures (3).

Epidemiologic studies have implicated HAP in respiratory tract cancers, respiratory infections and chronic lung diseases (4-8). Personal exposure assessment is necessary to understand the association between HAP and health outcomes (9-11) and define exposure response relationships (12); use of exposure proxies such as questionnaires may lead to substantial exposure misclassification. CO and PM_{2.5} are likely important contributors to HAP-associated morbidity and mortality. Performing personal PM_{2.5} exposure measurements is expensive, cumbersome for participants and requires technical expertise; a laboratory-validated biomarker of exposure has yet to be developed (13). Importantly, carbon monoxide levels may correlate strongly with PM_{2.5} levels, particularly if measured for 24 hours or more (14-16).

When inhaled, carbon monoxide rapidly combines with hemoglobin to form carboxyhemoglobin (COHb); ambient CO and duration of exposure are the most important determinants of COHb % saturation (17, 18). The half-life of COHb varies from 2 – 6 hours depending on physiologic factors such as respiratory rate, making it a potential marker of recent exposure (19, 20). COHb % saturation levels in non-smoking women have been reported to be approximately 0.5% (21). Measuring blood COHb is invasive and requires adequate storage and laboratory facilities and trained personnel. However, COHb levels can be accurately measured non-invasively in exhaled breath ($r = 0.97-0.98$) (22, 23) and portable, lightweight devices are available that can measure COHb % saturation after a brief inspiratory breath hold (24). Moreover, in women who cook regularly multiple times each day, COHb is likely at a pseudo-steady state.

In this cross-sectional study, we assessed the feasibility of measuring exhaled COHb (eCOHb) % saturation in 28 female cooks primarily cooking with biomass fuels in Araihaazar, Bangladesh. We simultaneously performed continuous 24-hour personal carbon monoxide air monitoring and pre- and post-cooking eCOHb % saturation. Personal CO monitor exposures were input into the Coburn, Forster and Kane (CFK) equation to predicted COHb % saturation for comparison to eCOHb % saturation (25). We administered respiratory questionnaires, performed spirometry and collected and evaluated exhaled breath condensate (EBC) pH, a marker of airway inflammation. We hypothesized that eCOHb measurements would be feasible in this population and that eCOHb % saturation would be at an elevated pseudo-steady state and correlate with acute measures, such as respiratory

symptoms and airway inflammation. However, we also hypothesized that eCOHb % saturation would not correlate with lung function measurements, reflective of chronic HAP exposures.

MATERIALS AND METHODS

Study Design and Oversight

We conducted a cross-sectional study of HAP exposure, respiratory symptoms and pulmonary function testing in 28 adult women residing in Araihaazar, Bangladesh. Each woman provided informed consent before the start of the study. Study objectives, procedures, risks and benefits were explained and all questions answered. Study forms were read aloud to illiterate respondents. This study was approved by the Columbia University Medical Center IRB and by the Bangladesh Medical Research Council.

Study Participants

We recruited a convenience sample of female participants from the Health Effects of Arsenic Longitudinal Study (HEALS) in Araihaazar, Bangladesh, who were the primary cooks for their households or compound, cooked with biomass fuels, and provided informed consent (26). Women were excluded if they were not the primary cook for their household or compound, used alternate cooking fuels or were unable to provide informed consent. Participants were recruited from villages that were not in close proximity with major roadways. Participant demographics were obtained from the HEALS database.

Field workers familiar with the villages and households disseminated study information to female head of households. Women interested in participating were approached and, if inclusion criteria were met, they were consented by the field worker.

Study Visit

In February 2014, field workers visited participants at their homes prior to the first daily cooking episode. Study procedures were re-explained and verbal consent confirmed. The 24-hour continuous CO air-monitoring device was clipped to the women's shoulder in her "breathing zone". The woman was instructed not to remove the monitor except for when bathing. A field worker performed eCOHb testing immediately before and after each cooking session (i.e., breakfast, lunch and dinner) and prior to removal of the Lascar CO monitor after the breakfast cooking session the following morning. Prior to cooking dinner, all participants performed exhaled breath condensate collection, underwent pulmonary function testing using the EasyOne Spirometer and completed respiratory questionnaires.

Questionnaires

St George's Respiratory Questionnaire (27), translated to Bangla, was used to assess respiratory symptoms, including cough, phlegm, shortness of breath, wheezing, attacks of chest trouble in the past year and activities that make the participant feel short of breath. Due to the small number of participants, the responses were collapsed into two groups, with answers "None", "Never" coded as "No". Associations were sought between chronic

respiratory symptoms and eCOHb, thus the answer “only with infections” was collapsed into “No”.

Lung Function Testing

Spirometry was performed in accordance with the American Thoracic Society guidelines using an EasyOne spirometer (28). Participants were seated without a nose clip and measurements were classified as acceptable if the woman had at least three acceptable trials with the best and second best forced expiratory volume in one second (FEV1) and forced vital capacity (FVC), respectively, not differing by more than 0.2L. All lung function data were reviewed by the study physician (AL).

Exhaled Breath Condensate

Exhaled breath condensate (EBC) was collected by having the participants breathe through their mouths into an R-TubeTM breath condensate collection device (Respiratory Research Inc., Charlottesville, VA, U.S.A) for 10 minutes. The aluminum sleeve was kept at -20°C until use. Following the EBC collection period, the Rtube was capped and placed on ice until transported to the field laboratory in Araihaazar, where the EBC samples were divided into aliquots and stored at -80°C until shipment on dry ice to Columbia University Medical Center (CUMC) for analysis. At CUMC, samples were kept at -80°C until analysis.

The pH of EBC samples was measured with a pH meter (Cole-Parmer Instrument Co, Vernon Hills, IL, U.S.A.), which was calibrated immediately prior to use. The initial pH was recorded as “Pre-Aeration pH”. Argon gas was then bubbled through the EBC samples for 10 minutes to remove carbon dioxide.(29) The pH was then reanalyzed and this pH was recorded as “Post-Aeration pH.”

Exposure Monitoring

24-hour personal carbon monoxide monitoring was performed using the EasyLog USB CO Monitor (Lascar Electronics, Erie, PA), which sampled the air every 10 seconds. Trained field workers placed the monitors in the “breathing zone” of the participants and instructed participants to remove the monitors only while bathing. Field workers visually inspected monitor compliance before and after every cook period and also prior to removing the monitor at the end of the 24-hour study period.

eCOHb testing was performed up to seven times per participant, i.e., immediately before and after each cooking episode and prior to removing the CO monitor. The coVita Micro+ Carbon Monoxide Monitor (coVita, Haddonfield, NJ) with D piece and SteriBreath mouthpieces was used to measure CO parts per million (ppm) and eCOHb % saturation. The device was calibrated using coVita Bedfont 50ppm CO in air calibration gas a week prior to the study. Participants were instructed to inhale to total lung capacity, hold their breaths for 20 seconds and then exhale completely through their mouths into the mouthpiece. Measurements were repeated twice and, if not identical, were repeated a third time and an average of the three trials is reported.

ANALYSIS

The CFK equation, considered the fundamental equation to relate environmental CO to blood COHb, was used to calculate COHb levels at each 10 second interval recorded by the Lascar CO monitor (30). Given the rural nature of our study setting, previously published assumptions were utilized to employ the CFK equation (31). Specifically, the Haldane constant was 218, the rate of endogenous CO production was assumed steady at 0.007ml of gas per minute, the diffusion capacity of the lungs for CO was assumed to be 30ml/min/mmHg, the volume of blood in the body was assumed to be 73ml/kg, and the alveolar ventilation rate was assumed to be 11,000 ml/min. Given these assumptions, standard CO exposure levels from the US Occupational Safety and Health Administration were entered into the CFK equation with our parameters to predict COHb levels and demonstrate the functionality of the CFK equation using our aforementioned assumptions.

Using the CFK equation with these reasonable assumptions enabled us to take time-varying personal CO monitor air levels to determine time-varying COHb levels. Therefore the consecutive 10-second CO air monitor readings were entered into our CFK equation to determine consecutive blood COHb levels. Spearman correlations were then calculated between time-matched CFK-calculated COHb and eCO COHb % saturation.

We averaged 24-hour pre- and post-cooking session eCOHb % saturation and Spearman correlations were calculated between lung function and exhaled breath condensate pH and eCOHb averages. eCOHb was then dichotomized around the median and unadjusted odds ratios were calculated for respiratory symptoms, including cough, phlegm, shortness of breath, wheezing, attacks of chest trouble in the past year, activities that make the participant feel short of breath, and any respiratory symptoms. Due to the small sample sizes, confidence intervals were unable to be calculated.

RESULTS

This analysis involved 28 women, whose characteristics are summarized in Table 1. Women in the study were on average 35 years of age with 4.4 years of education. Ten women (35.7%) cooked two meals a day (labeled breakfast and dinner) while 18 (64.3%) cooked three meals a day (labeled breakfast, lunch and dinner) (Table 2). Most women cooked in a cooking area surrounded by three metal sheets (n=19, 67.9%) and a roof (n=22, 78.9%). The majority of women burned wood (n=16, 57.1%), while others used a combination of leaves and wood. For both the 2-meal and 3-meal cookers, breakfast was the longest cook time (2-meal mean = 148min, 3-meal mean = 140min).

eCOHb testing was successfully performed in all 28 women before and after each cooking event (n=132). The 24-hour average eCOHb % saturation was 1.21 (range 1.01-1.53). The women who cooked 2 meals a day had the highest eCOHb % saturation after the breakfast cook event (eCOHb 1.26, range 1.00-1.500), while the women who cooked 3 meals a day had the highest eCOHb % saturation before the dinner cook event (eCOHb 1.36, range 1.0-2.2). The pre-breakfast eCOHb % saturation was the lowest for both groups (2-meal eCOHb 1.16, range 1.00-1.40; 3-meal eCOHb 1.12, range 1.00-1.60).

eCOHb % saturation trends are shown in Figure 1. Regardless of number of cooking episodes per day, the eCOHb % saturation fluctuates with cooking events, suggesting the changes in eCOHb % saturations are due to the cooking events themselves and not endogenous COHb production. The post-breakfast eCOHb on day two moderately correlates with the day one post-breakfast reading ($r=0.59$, p -value 0.0011) suggesting the eCOHb values and patterns of fluctuations may be reproducible over the short-term with similar cooking environments. The strongest correlations between time-matched CFK-predicted COHb and eCOHb % saturation were after breakfast on both day 1 and 2 (day 1 $r=0.37$, day 2 $r=0.43$), otherwise the correlations were poor (r range -0.04 to 0.34).

Overall, 20 (71.4%) women complained of at least one respiratory symptom (Table 2). The odds of any respiratory symptom in women with high eCOHb % saturations were 4.5 times that the odds of those with low eCOHb % saturations. Of all respiratory symptoms, phlegm was the most common ($n=14$, OR 3.2). While confidence intervals were unable to be calculated, all respiratory symptom odds ratios demonstrated increased odds in those with higher eCOHb % saturations.

Average pre-aeration EBC pH was 5.9 (range 4.8 to 7.0), while average post-aeration EBC pH was 7.9 (range 6.5 to 8.6) (Table 3). No relationship was seen between post-aeration EBC pH levels and average eCOHb levels ($r=0.07$) or time-matched eCOHb levels ($r=-0.03$).

Spirometry was successfully performed in 19 (68%) women (Supplement Table 1). The average FEV1 was 1.89L (SD 0.62), FVC 2.48 (SD 0.77), and FEF₂₅₋₇₅ 2.04 (SD 0.84). 4 (21.1%) had FEV1/FVC ratios less than 0.70. No relationship between average eCOHb levels and lung function parameters were seen (data not shown).

CONCLUSIONS

To our knowledge, these are the first cross-sectional data to show trends of eCOHb % saturation over a 24-hour period with before and after cooking event fluctuations secondary to HAP exposures. The fluctuations in eCOHb over the 24-hour period suggest that if eCOHb was used as an HAP exposure measurement, the timing of readings must be standardized amongst participants. Additionally, as peak exposure compared to average exposure may have health-related significance, collecting eCOHb readings over a 24-hour period, such as performed in our study, should be done to determine peak exposure periods. Further, despite our small sample size, we demonstrate consistent results between post-breakfast cooking eCOHb from two consecutive days ($r=0.59$, p -value 0.001) suggesting that with consistent cooking habits, eCOHb % saturation may be reflective of HAP exposure over time.

eCOHb is a feasible method of measuring COHb levels, reflective of CO exposures secondary to HAP. All women in our study were able to perform quality eCOHb maneuvers repeatedly. Our data demonstrate an average eCOHb % saturation of 1.21 (range 1.01-1.53), significantly higher than the normal COHb % saturation in non-smoking females (COHb=0.5) with peak exposures of 1.26 or 1.36 in those cooking two or three times a day,

respectively (21). Importantly, eCOHb % saturation and CKF-predicted CO monitor COHb levels did not correlate well, possibly reflective of the poor sensitivity of the CO monitors in the 0-5ppm range, the predominant between-cooking exposures (approximately 19 hours a day in our sample) and cooking exposures for some women in our study. Inaccuracies for this duration of time may lead to substantial discrepancies between measured and actual average HAP exposures.

Our data demonstrate that the average eCOHb % saturation is higher than has been reported in non-smoking women consistent with our hypothesis that, due to the 2-6 hour half-life of COHb and the chronic, repeat HAP exposures, eCOHb % saturation may plateau. eCOHb % saturation levels fluctuate with each cooking episode, suggesting that the elevated levels are not due to endogenous COHb production. However, a study with a washout period (ie, no biomass exposure) followed by return to usual cooking habits, would be helpful to conclusively determine that the elevated COHb % saturation is in fact an CO exposure plateau with intermittent fluctuations due to continued cooking patterns and not the result of elevated endogenous COHb production in this population.

Importantly, eCOHb levels were associated with all respiratory symptoms examined, including cough, phlegm, shortness of breath, breathlessness, wheeze or any respiratory symptoms. These findings support the association between HAP and respiratory symptoms. We were unable to demonstrate a relationship between eCOHb % saturation and EBC pH, a marker of airway inflammation. As eCOHb % saturation is reflective of recent HAP exposures and cooking behaviors change with fuel availability and seasons, we did not, as hypothesized, demonstrate a relationship between lung function and eCOHb in this small study sample; longitudinal, repeat measures would likely be needed to demonstrate this association.

Every year, HAP exposures directly cause 3.5 million premature deaths (4). Research opportunities in developing countries, where the burden of disease largely lies, are limited due to the expense and technical expertise required to accurately measure HAP exposures. We demonstrate that exhaled breath carbon monoxide testing is feasible in a resource-poor setting, responds to cooking episodes, and demonstrates consistency when measured serially at the same time point, suggesting that exhaled CO markers, such as eCOHb % saturation, may be used as a biomarker of recent HAP exposures.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

Parvez, DrPH, Columbia University; Habibul Ahsan, MD, MPH, University of Chicago, PI of the HEALS cohort; Tariqul Islam, University of Chicago Research Bangladesh

Funding: This work was supported by a National Institute of Environmental Health Sciences grant P42 ES 10349.

References

1. Mehta SGF, Prüss-Üstün A, Rehfuess E, Smith K. Modeling household solid fuel use towards reporting of the Millennium Development Goal indicator. *Energy for Sustainable Dev.* 2006; 10:36–45.
2. Bonjour S, Adair-Rohani H, Wolf J, Bruce NG, Mehta S, Pruss-Ustun A, Lahiff M, Rehfuess EA, Mishra V, Smith KR. Solid fuel use for household cooking: country and regional estimates for 1980–2010. *Environmental health perspectives.* 2013; 121:784–790. [PubMed: 23674502]
3. Smith, KR.; Mehta, S.; Maeuzeugh-FeuzGore, FP-ÜA.; Rehfuess, E.; Smith, K. Comparative quantification of health risks: global and regional burden of disease attributable to selected major risk factors. World Health Organization; Geneva: 2004.
4. Gordon SB, Bruce NG, Grigg J, Hibberd PL, Kurmi OP, Lam KB, Mortimer K, Asante KP, Balakrishnan K, Balmes J, Bar-Zeev N, Bates MN, Breyse PN, Buist S, Chen Z, Havens D, Jack D, Jindal S, Kan H, Mehta S, Moschovis P, Naeher L, Patel A, Perez-Padilla R, Pope D, Rylance J, Semple S, Martin WJ 2nd. Respiratory risks from household air pollution in low and middle income countries. *The Lancet Respiratory medicine.* 2014; 2:823–860. [PubMed: 25193349]
5. Smith KR, Bruce N, Balakrishnan K, Adair-Rohani H, Balmes J, Chafe Z, Dherani M, Hosgood HD, Mehta S, Pope D, Rehfuess E. Millions dead: how do we know and what does it mean? Methods used in the comparative risk assessment of household air pollution. *Annual review of public health.* 2014; 35:185–206.
6. Bruce N, Dherani M, Liu R, Hosgood HD 3rd, Sapkota A, Smith KR, Straif K, Lan Q, Pope D. Does household use of biomass fuel cause lung cancer? A systematic review and evaluation of the evidence for the GBD 2010 study. *Thorax* 2015. 70:433–441.
7. Ezeh OK, Agho KE, Dibley MJ, Hall JJ, Page AN. The effect of solid fuel use on childhood mortality in Nigeria: evidence from the 2013 cross-sectional household survey. *Environmental health : a global access science source.* 2014; 13:113. [PubMed: 25514998]
8. Kleimola LB, Patel AB, Borkar JA, Hibberd PL. Consequences of household air pollution on child survival: evidence from demographic and health surveys in 47 countries. *International journal of occupational and environmental health.* 2015:2049396715Y0000000007.
9. Baumgartner J, Schauer JJ, Ezzati M, Lu L, Cheng C, Patz J, Bautista LE. Patterns and predictors of personal exposure to indoor air pollution from biomass combustion among women and children in rural China. *Indoor air.* 2011; 21:479–488. [PubMed: 21692855]
10. Bruce N, McCracken J, Albalak R, Schei MA, Smith KR, Lopez V, West C. Impact of improved stoves, house construction and child location on levels of indoor air pollution exposure in young Guatemalan children. *J Expo Anal Environ Epidemiol.* 2004; 14(Suppl 1):S26–33. [PubMed: 15118742]
11. Cynthia AA, Edwards RD, Johnson M, Zuk M, Rojas L, Jimenez RD, Riojas-Rodriguez H, Masera O. Reduction in personal exposures to particulate matter and carbon monoxide as a result of the installation of a Patsari improved cook stove in Michoacan Mexico. *Indoor air.* 2008; 18:93–105. [PubMed: 18333989]
12. Smith-Sivertsen T, Diaz E, Pope D, Lie RT, Diaz A, McCracken J, Bakke P, Arana B, Smith KR, Bruce N. Effect of reducing indoor air pollution on women's respiratory symptoms and lung function: the RESPIRE Randomized Trial, Guatemala. *American journal of epidemiology.* 2009; 170:211–220. [PubMed: 19443665]
13. Lee A, Adobamen PROC, Agboghroma O, Ahmed FO, Aigbokhaode A, Amusa GA, Avokpaho E, Awokola B, Ibeh J, Isiguzo G, Kagima J, Kuti BP, Lawin H, Lufesi N, Mokogwu N, Ngadaya E, Nganda MM, Nwankwo ON, Obiajunwa P, Oghuvwu S, Ozoh O. Household air pollution: a call to action. *Lancet Respiratory.* 2015; 3
14. McCracken JP, Schwartz J, Diaz A, Bruce N, Smith KR. Longitudinal relationship between personal CO and personal PM2.5 among women cooking with woodfired cookstoves in Guatemala. *PloS one.* 2013; 8:e55670. [PubMed: 23468847]
15. Naeher LP, Smith KR, Leaderer BP, Neufeld L, Mage DT. Carbon monoxide as a tracer for assessing exposures to particulate matter in wood and gas cookstove households of highland Guatemala. *Environmental science & technology.* 2001; 35:575–581. [PubMed: 11351731]

16. Northcross A, Chowdhury Z, McCracken J, Canuz E, Smith KR. Estimating personal PM_{2.5} exposures using CO measurements in Guatemalan households cooking with wood fuel. *Journal of environmental monitoring* : JEM. 2010; 12:873–878. [PubMed: 20383368]
17. Bauer I, Pannen BH. Bench-to-bedside review: Carbon monoxide--from mitochondrial poisoning to therapeutic use. *Critical care (London, England)*. 2009; 13:220.
18. Clayton CE, Carraway MS, Suliman HB, Thalmann ED, Thalmann KN, Schmechel DE, Piantadosi CA. Inhaled carbon monoxide and hyperoxic lung injury in rats. *American journal of physiology Lung cellular and molecular physiology*. 2001; 281:L949–957. [PubMed: 11557599]
19. Lawther PJ. Carbon monoxide. *British medical bulletin*. 1975; 31:256–260. [PubMed: 764910]
20. Tikuisis, P. Carbon Monoxide. CRC Press; Boca Raton: 1996.
21. Yarlioglu M, Kaya MG, Ardic I, Calapkorur B, Dogdu O, Akpek M, Ozdogru M, Kalay N, Dogan A, Ozdogru I, Oguzhan A. Acute effects of passive smoking on blood pressure and heart rate in healthy females. *Blood pressure monitoring*. 2010; 15:251–256. [PubMed: 20729727]
22. Jarvis MJ, Russell MA, Saloojee Y. Expired air carbon monoxide: a simple breath test of tobacco smoke intake. *British medical journal*. 1980; 281:484–485. [PubMed: 7427332]
23. Wald NJ, Idle M, Boreham J, Bailey A. Carbon monoxide in breath in relation to smoking and carboxyhaemoglobin levels. *Thorax*. 1981; 36:366–369. [PubMed: 7314006]
24. Andersson MF, Moller AM. Assessment of carbon monoxide values in smokers: a comparison of carbon monoxide in expired air and carboxyhaemoglobin in arterial blood. *European journal of anaesthesiology*. 2010; 27:812–818. [PubMed: 20520557]
25. Sharan M, Selvakumar S. A mathematical model for the simultaneous transport of gases to compute blood carboxyhaemoglobin build-up due to CO exposures: application to the end-expired breath technique. *Environmental Pollution*. 1999; 105:231–242.
26. Ahsan H, Chen Y, Parvez F, Argos M, Hussain AI, Momotaj H, Levy D, Van Geen A, Howe G, Graziano J. Health Effects of Arsenic Longitudinal Study (HEALS): Description of a multidisciplinary epidemiologic investigation. *Journal of Exposure Analysis and Environmental Epidemiology*. 2005:1–15. [PubMed: 15562291]
27. Jones PW, Quirk FH, Baveystock CM. The St George's Respiratory Questionnaire. *Respiratory medicine*. 1991; 85(Suppl B):25–31. discussion 33–27. [PubMed: 1759018]
28. Miller MR, Hankinson J, Brusasco V, Burgos F, Casaburi R, Coates A, Crapo R, Enright P, van der Grinten CP, Gustafsson P, Jensen R, Johnson DC, MacIntyre N, McKay R, Navajas D, Pedersen OF, Pellegrino R, Viegi G, Wanger J. Standardisation of spirometry. *The European respiratory journal*. 2005; 26:319–338. [PubMed: 16055882]
29. Hoffmeyer F, Berresheim H, Beine A, Sucker K, Bruning T, Bunker J. Methodological implications in pH standardization of exhaled breath condensate. *Journal of breath research*. 2015; 9:036003. [PubMed: 25972098]
30. Coburn RF, Forster RE, Kane PB. Considerations of the physiological variables that determine the blood carboxyhemoglobin concentration in man. *The Journal of clinical investigation*. 1965; 44:1899–1910. [PubMed: 5845666]
31. Dale Andreatta, NM. The Effects of Carbon Monoxide and Particulates on the Human Body.. Aprovecho [serial online]. 2008. Available from: <http://www.aprovecho.org/lab/images/stories/camp08/HealthEffects.pdf>

Highlights

- Every year, household air pollution (HAP) exposures directly cause 3.5 million premature deaths. Research opportunities in developing countries, where the burden of disease largely lies, are limited due to the expense and technical expertise required to accurately measure HAP exposures.
- Personal exposure assessment is necessary to understand the association between HAP and health outcomes. Carboxyhemoglobin is easily measured noninvasively in exhaled breath and may be a biomarker of recent HAP exposure.
- We demonstrate that exhaled breath carbon monoxide testing is feasible in a resource-poor setting, responds to cooking episodes, and demonstrates consistency when measured serially at the same time point.
- These data suggest that exhaled carbon monoxide markers, such as carboxyhemoglobin % saturation, may be used as a biomarker of recent HAP exposures.

Figure 1.

Exposure-response relationship between cooking events and eCOHb % saturation. Box plots demonstrating the relationship between all study women and eCOHb % saturation. CO Correlation: Spearman correlation comparing time-matched CO monitor CFK-predicted COHb and eCOHb % saturation.

*denotes p-value <0.05

Table 1**Study Participant Characteristics**

	Mean	SD
Continuous Variables		
Age, yr	35.7	9.0
Weight, kg	45.2	6.1
Children		
Alive	2.6	1.2
Deceased	0.4	0.5
Breakfast Cooking Length (min)		
Two Cooking (n=10)	147.7	45.3
Three Cooking (n=18)	139.9	53.8
Lunch Cooking Length (min) (n=18)	103.4	30.7
Dinner Cooking Length (min)		
Two Cooking (n=10)	115.8	53.2
Three Cooking (n=18)	96.8	47.9
Categorical Variables		
Cooking Area (n, %)		
Open	4	14.3
2 Metal Sheets	4	14.3
3 Metal Sheets	20	71.4
Roof Type (SES Indicator) (n, %)		
No Roof	6	21.4
Sheet Metal	7	25
Other	15	53.6
Three-Stone Stove (n, %)	28	100
Fuel Source (n, %)		
Firewood	16	57.1
Other	12	42.9

Definition of abbreviations: yr=year; kg=kilogram; min=minutes; n=number; SES = socioeconomic status

Table 2Relationship between chronic respiratory symptoms and eCOHb % saturation[†]

	n (%)	High	Low	OR
Cough				
Yes	3 (10.7%)	2	1	2.2
No	25 (89.3%)	12	13	
Phlegm				
Yes	14 (50%)	9	5	3.2
No	14 (50%)	5	9	
Shortness of Breath				
Yes	8 (28.6%)	6	2	4.5
No	20 (71.4%)	8	12	
Wheeze				
Yes	8 (28.6%)	8	0	>1
No	20 (71.4%)	8	12	
Any Respiratory Symptom				
Yes	20 (71.4%)	12	8	4.5
No	8 (28.6%)	2	6	

[†]eCOHb % saturation dichotomized around median, 1.20, to high and low, respectively

Table 3

Spearman correlations between eCOHb % saturation and pre-aeration and post-aeration EBC pH

	<u>Pre-Aeration pH</u>		<u>Post-Aeration pH</u>	
	r	p	r	p
Time-Matched eCOHb	−0.35	0.08	−0.03	0.87
Average eCOHb	−0.06	0.79	0.07	0.75
EBC pH (mean, range)	5.92	4.8-7.0	7.9	6.5-8.6

Definition of abbreviations: EBC = exhaled breath condensate, eCOHb = carboxyhemoglobin, measured in exhaled breath