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Performance of low-cost monitors to assess household air pollution

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A B S T R A C T

Exposure to household air pollution is a leading cause of morbidity and mortality globally. However, due to the lack of validated low-cost monitors with long-lasting batteries in indoor environments, most epidemiologic studies use self-reported data or short-term household air pollution assessments as proxies of long-term exposure. We evaluated the performance of three low-cost monitors measuring fine particulate matter ($PM_{2.5}$) and carbon monoxide (CO) in a wood-combustion experiment conducted in one household of Spain for 5 days (including the co-location of 2 units of HAPEX and 3 units of TZOA-R for $PM_{2.5}$ and 3 units of EL-USB-CO for CO; a total of 40 unit-days). We used Spearman correlation (ρ) and Concordance Correlation Coefficient (CCC) to assess accuracy of low-cost monitors versus equivalent research-grade devices. We also conducted a field study in India for 1 week (including HAPEX in 3 households and EL-USB-CO in 4 households; a total of 49 unit-days). Correlation and agreement at 5-min were moderate-high for one unit of HAPEX (ρ = 0.73 / CCC = 0.59), for one unit of TZOA-R (ρ = 0.89 / CCC = 0.62) and for three units of EL-USB-CO (ρ = 0.82–0.89 / CCC = 0.66–0.91) in Spain, although the failure or malfunction rate among low-cost units was high in both settings (60% of unit-days in Spain and 43% in India). Low-cost monitors tested here are not yet ready to replace more established exposure assessment methods in long-term household air pollution epidemiologic studies. More field validation is needed to assess evolving sensors and monitors with application to health studies.

1. Introduction

Inefficient combustion of solid fuels such as wood, animal dung, and coal are used by nearly half of the world's population (~ 3 billion people) for cooking, lighting, and heating (Smith et al., 2004). Household air pollution from combustion of solid fuels was ranked the eighth leading risk factor for non-communicable diseases globally in 2015, accounting for an estimated 2.9 million deaths and 85.6 million disability-adjusted life years lost (Forouzanfar et al., 2016). Household air pollution is particularly relevant in resource-limited regions where a substantial proportion of the population lacks access to clean household energy, such is the case for South Asia and sub-Saharan Africa, where household air pollution represents the fourth leading environmental risk factor (Forouzanfar et al., 2016).

Fine particulate matter (particulate matter with aerodynamic diameter of 2.5 µm or less; $PM_{2.5}$) and carbon monoxide (CO) are commonly used as indicators of exposure to the mixture of particulate and gaseous products of incomplete combustion resulting from inefficient household fuel use (Smith et al., 2004; Naeher et al., 2007). Epidemiologic studies focused on quantifying the adverse health effects of chronic exposure to household air pollution would ideally assess participants' exposure to household air pollution over the long-term, perhaps over weeks to months rather than hours or days. However, many of the devices currently available are expensive and have high logistical barriers or suffer from technical constraints (e.g. low battery life, high cleaning frequency, filter exchange, etc.) that preclude continuous and long term monitoring of household air pollution in population-based studies, particularly in low- and middle-income countries where often electricity supply is lacking or unreliable (Pillarisetti et al., 2017; Gordon et al., 2014; Clark et al., 2013). Thus, most household air pollution studies have relied on self-reported data or short-term measurements taken in 24 h (Naeher et al., 2001; Bruce et al., 2004; Balakrishnan et al., 2004; Gao et al., 2009; Rehman et al., 2011; McCracken et al., 2013; Van Vliet et al., 2013; Yamamoto et al., 2014;

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Pokhrel et al., 2015; Chen et al., 2016) or in two or three 24-h increments (i.e. 48 h, 72 h) (Helen et al., 2015; Downward et al., 2015; Hu et al., 2014; Pope et al., 2014; Jiang and Bell, 2008) as proxies for long-term exposure. Although short-term measurements can serve as useful indicators of long-term exposures when taken repeatedly in panel studies, longer term measurements may be preferable to reduce some forms of exposure misclassification and for the study of chronic disease risk. Recent rapid growth of low-cost, easy-to-use, battery-operated, portable air pollution sensors potentially offers important new opportunities for long-term sampling in population-based studies (Koehler and Peters, 2015; Kumar et al., 2016; McKercher et al., 2017). These off-the-shelf sensors are commonly custom-built in aerosol monitors for different air pollutants and research purposes (Edwards et al., 2006; Mead et al., 2013; Holstius et al., 2014; Gao et al., 2015; Barakeh et al., 2017; Cao and Thompson, 2017). Sensors' performance characteristics have been summarized elsewhere (Rai et al., 2017; Aleixandre and Gerboles, 2012), although most of the emerging monitors have not yet been thoroughly characterized (Snyder et al., 2013; Lewis and Edwards, 2016). Most of the existing field-validation studies have been done in outdoor environments (Mead et al., 2013; Holstius et al., 2014; Gao et al., 2015; Olivares and Edwards, 2015; Hojaiji et al., 2017; Mukherjee et al., 2017; Zikova et al., 2017) such that their performance in real-world indoor environments remains hard to predict. Although remarkable efforts have been done to develop inexpensive and rugged household air pollution-based monitors (Pillarisetti et al., 2017), validation of affordable measurement technology and approaches to accurately assess long-term household air pollution exposure remains a research priority (Clark et al., 2013).

We therefore tested and benchmarked low-cost monitors with potential application for monitoring PM and CO related to household air pollution exposure, by characterizing monitors in terms of accuracy, within-device variability (or intra-variability), response to wide ranges of concentrations and environmental conditions, and ease of use. Specifically, our objective was to evaluate the performance of three monitors (HAPEX, TZOA-R, and EL-USB-CO) with potentially long-lasting batteries in two scenarios: i) a semi-controlled wood-combustion validation study using co-located equivalent benchmark monitors under different concentration and ventilation conditions, and ii) a 1-week field-based pilot study in households in southern India.

2. Material and methods

2.1. Selection of low-cost monitors

Among all devices available in January 2016, we considered those that met the criteria required for long-term, unattended monitoring of household air pollution in epidemiologic studies: (i) low-cost (< US $600), (ii) battery-operated with long battery life (> 48 h), (iii) not filter-based, (iv) having wide measurement range, and (v) suitable for use across meteorological extremes. All information was extracted from manufacturer datasheets. Based on these considerations, we selected HAPEX (HAPEX Nano, Climate Solutions Consulting, VT, USA) and TZOA-R (Model RD02, MyTZOA, SFO, USA) for assessing $PM_{2.5}$ and EL-USB-CO (Lascar Electronics Ltd., PA, USA) for assessing CO. A table summarising characteristics of all the devices used in the study is shown in Table 1. For more details of these devices and those excluded, see expanded version in Table S1.

2.2. Low-cost monitors

HAPEX Nano is a passive data-logger designed to monitor household air pollution exposure (Climate Solutions, 2016). HAPEX is built on the Sharp sensor GP2Y1010AU0F (Sharp GP for simplification, Sharp Corporation, Osaka, Japan), which is based on 90° light-scattering technology. Briefly, the Sharp's sensor diode emits a beam of infrared light that illuminates part of the stream of particles that enters

Table 1
Summary of device characteristics.

Device (Model/Version)	Measure(s)	Raw output	Sampling site	Number of units used	Range[a]	Type	Approximate battery life[a]	Maximum Operating Temperature (°C)[a]	Cost per unit (US Dollars)
DustTrak DRX (Model 8534, hand-held)	PM_1, $PM_{2.5}$, PM_4, PM_{10}	Mass concentration	Spain	1	0.001–150 mg/m^3 ($PM_{2.5}$)	Benchmark	6 hours	+ 50	7900
BGI/Mesa Labs pump (Model BGI4004)- discontinued	$PM_{2.5}$, absorbance[b]	Non applicable	Spain	1	Non applicable	Benchmark	24 hours	+ 50	> 1000
SKC pump (Model Universal PCXR8)	$PM_{2.5}$, absorbance[b]	Non applicable	India	1	Non applicable	Benchmark	12 hours (with extended times with intermittent sampling)	+ 40	> 1000
TZOA-R (version RD02)	PM_1, $PM_{2.5}$, PM_{10}, T, RH	Particle counts	Spain	3	Not reported	Testing	60 days (10 min logging rate)	+ 40	400
HAPEX Nano (version 1.0)	$PM_{2.5}$	Unit less	Spain / India	2	5 µg/m^3 to 150 mg/m^3	Testing	2 years	Not reported	95
Q-Trak (Model 7575)	CO_2, CO, T, RH	Concentration	Spain	1	0–500 ppm (CO)	Benchmark	6 hours	+ 45	3100
EL-USB-CO	CO	Concentration	Spain / India	3	3–1000 ppm	Testing	3 months (10 min logging rate)	+ 40	125
EL-USB − 2-LCD	T, RH	T and RH levels	Spain	1	− 35 to + 80 °C, 0–100%	Complementary	3 months	+ 80	95
LabJack (Model Digit-TLH)- discontinued	T, RH	T and RH levels	India	1	− 35 to + 85 °C, 5–95%	Complementary	3.3 years	+ 85	36

PM_1: particles less than 1 µm; $PM_{2.5}$: particles less than 2.5 µm; PM_4*: particles less than 4 µm*; PM_{10}: particles less than 10 µm; T: Temperature; RH: Relative Humidity; CO_2: Carbon Dioxide; CO: Carbon Monoxide.
[a] According to operating manufacturer manuals or datasheets. Battery life varies according to the settings specified.
[b] Absorbance was also measured both in Spain and India, but data are not shown.