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Evaluation of consumer monitors to measure particulate matter

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A B S T R A C T

Recently, inexpensive (< \$300) consumer aerosol monitors (CAMs) targeted for use in homes have become available. We evaluated the accuracy, bias, and precision of three CAMs (Foobot from Airoxlab, Speck from Carnegie Mellon University, and AirBeam from HabitatMap) for measuring mass concentrations in occupational settings. In a laboratory study, $PM_{2.5}$ measured with the CAMs and a medium-cost aerosol photometer (personal DataRAM 1500, Thermo Scientific) were compared to that from reference instruments for three aerosols (salt, welding fume, and Arizona road dust, ARD) at concentrations up to 8500 µg/m^3. Three of each type of C AM were included to estimate precision. Compared to reference instruments, mass concentrations measured with the Foobot (r-value = 0.99) and medium-cost photometer (r-value = 0.99) show strong correlation, whereas those from the Speck (r-value range 0.91–0.99) and AirBeam (0.7–0.96) were less correlated. The Foobot bias was (−12%) for ARD and measurements were similar to the medium-cost instrument. Foobot bias was (< −46%) for salt and welding fume aerosols. Speck bias was at 18% for ARD and −86% for welding fume. AirBeam bias was (−36%) for salt and (−83%) for welding fume. All three photometers had a bias (< −82%) for welding fume. Precision was excellent for the Foobot (coefficient of variation range: 5–8%) and AirBeam (2–9%), but poorer for the Speck (8–25%). These findings suggest that the Foobot, with a linear response to different aerosol types and good precision, can provide reasonable estimates of $PM_{2.5}$ in the workplace after site-specific calibration to account for particle size and composition.

1. Introduction

In occupational studies, exposure to respirable particulate matter (PM), the fraction of particles that can penetrate to the alveolar regions of the lungs (Antonini, 2003), is associated with respiratory diseases (Antonini, 2003, Antonini, Taylor, Zimmer, & Roberts, 2004), lung cancer (Sørensen et al., 2007), and cardiovascular diseases (Li et al., 2015). To avoid the development of adverse health effects from inhaling particles, the Occupational Safety and Health Administration (OSHA) requires employers to maintain workplace, 8-h time-weighted average, respirable PM below 5 mg/m^3 for particles not otherwise regulated (PNOR) (OSHA, 2006). These measurements are based on gravimetric, filter-based methods (the "gold standard"), or methods deemed equivalent to filter-based methods (NIOSH, 1975). Although accurate and precise, filter-based measurements are expensive, time-consuming, and provide little temporal information. Equivalent methods (e.g.,personal dust monitor; PDM 3700, Thermo Scientific, TSI Inc., Shoreview, MN, USA) often provide high temporal resolution, but are expensive (> \$15,000 per monitor), resulting in little spatial information (White, 2009).

Direct-reading instruments are available to measure PM at high temporal resolution and in situ (Cheng, 2008; Yanosky, Williams,

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& MacIntosh, 2002). Some of these instruments depend on light scattering, such as optical particle counters (OPCs) or photometers. OPCs use the light scattered from individual particles to estimate number concentration for different particle size ranges. These data along with assumptions of particle shape and density can be converted to estimate mass concentrations that compare favorably to reference instruments (Peters, Ott, & O'Shaughnessy, 2006). Photometers (e.g., personal DataRAM 1500, pDR, Thermo Scientific., Shoreview, MN, USA) rely on the fact that the mass concentration of aerosol scales linearly with the amount of light scattered by an assembly of particles captured at a discrete angle from the incident light (Görner, Bemer, & Fabriés, 1995). The cost of these instruments ($15,000 for OPCs and > $6000 for photometers) limits their use in the study of occupational PM exposures.

Several original equipment manufacturers (OEMs) now offer low-cost sensors to measure aerosol mass concentrations, including a photometer from Sharp (Sharp GP) and OPCs from Syhitech and Shinyei. These sensors are integrated with other electronics to convert output voltage to a meaningful signal in a variety of commercial products, such as air cleaners, air purifiers, and air quality monitors. Researchers have compared the output of OEM sensors to mass concentrations measured with gravimetric samplers and other direct reading instruments in occupational settings (Sousan et al., 2016). Whereas traditional, high-cost OPCs count particle number concentrations in many particle size ranges (multiple bins), the low-cost OPC sensors from Syhitech and Shinyei sprovide an indication of number counts over a single size range. Wang et al. (2015), Sousan et al. (2016) observed high coefficients of determination ($R^2 \geq 0.95$) among the voltage from the Sharp GP and mass concentrations measured with commercial photometers under laboratory conditions. Wang et al. (2015) observed less favorable agreement ($R^2=0.89$) among output from the Syhitech DSM501A with the SidePak AM510 (TSI, Shoreview, MN, USA) photometer in laboratory conditions. In an urban setting, Johnson, Bergin, Russell, and Hagler (2016) observed poor agreement ($R^2 = 0.3$) between output from the Shinyei PPD60PV-T2 and an EPA federal equivalent method sampler. To our knowledge, no one has evaluated the Shinyei PPD60PV-T2 for occupational settings.

Multiple manufacturers package these OEM sensors in consumer aerosol monitors (CAMs), including the Foobot ($200, from Airoxlab, Esch-sur-Alzette, Luxembourg), the Speck ($200, from Carnegie Mellon University, PA, USA), and the AirBeam ($250, from HabitatMap, NY, USA). These inexpensive CAMs use a microprocessor to collect sensor output, convert it to $PM_{2.5}$ (particles smaller than 2.5 µm), and store the data internally or transmit it wirelessly to a remote server. Often, these CAMs include additional sensors for measurement of temperature, relative humidity, carbon dioxide and total volatile organic compounds. Manufacturers of these devices use a variety of protocols to convert aerosol sensor output to mass concentration. The calibration protocol can have a dramatic impact on sensor precision, accuracy, and bias. Recently, researchers evaluated the Speck for use in the laboratory, outdoors and in-home. In laboratory tests, Manikonda, Zíková, Hopke, and Ferro (2016) observed a high coefficient of determination for cigarette smoke ($R^2 = 0.92$) and Arizona test dust ($R^2=0.96$) among the Speck mass concentration and the calculated mass concentration from an aerodynamic particle sizer (APS; 3321, TSI, United States). In contrast in field work, the same group (Zikova, Hopke, and Ferro (2017)), observed less favorable agreement for indoors ($R^2=0.3$) and outdoors ($R^2=0.1$–0.2) between mass concentrations measured with the Speck and a GRIMM 1.109 optical particle counter. To our knowledge, no one has rigorously evaluated the performance of the Foobot and AirBeam.

The objective of the current study was to evaluate the performance of the three CAMs (Foobot, AirBeam, and Speck) over a wide range of mass concentrations typical of occupational settings. In laboratory tests, we assessed the linear relationship (slope, intercept, r-value) and bias of mass concentrations ($PM_{2.5}$) measured with CAMs and a pDR compared to reference instruments for three aerosols (salt, welding fume, and Arizona road dust, ARD). We also assessed precision by measuring mass concentrations with three of each type of CAM.

2. Methods and materials

2.1. Consumer Air Quality Monitors (CAMs)

In the first quarter of 2016, we identified three CAMs available for purchase that support $PM_{2.5}$ measurement and data download for post processing and analysis (Table 1; Foobot, Speck, and AirBeam). The Foobot relies on natural convection to passively move air through a Sharp GP sensor (cost ~$12) that measures $PM_{2.5}$ for particles ranging in size from 0.3 µm to 2.5 µm and concentrations up to 1300 µg/m^3 (Airoxlab, 2016). It offers no internal storage, requiring an internet connection to upload measurements to the manufacturer's server. The manufacturer hosts a website where the uploaded data can be visualized and downloaded. The manufacturer considers the Foobot calibration proprietary (personal communication with the manufacturer). Although not tested in this work, the base model of the Foobot also includes sensors for total volatile organic carbons, carbon dioxide, temperature, and relative humidity.

The Speck uses an internal fan to pull air through a single-bin OPC (Syhitech DSM501A, cost ~$10, Syhitech Co., Ltd). The manufacturer of the Speck states that $PM_{2.5}$ is measured for particles ranging from 0.5 µm to 3.0 µm and concentrations up to 640 µg/m^3 (Speck, 2016). Each Speck was calibrated by the manufacturer alongside a multi-channel OPC (Met One HHPC-6+, Beckman Coulter, Brea, CA, USA) with polydisperse diatomaceous earth as the reference aerosol (Speck, 2016). A regression model was derived to convert sensor output in millivolts to number concentration based on particle counts from the OPC. Then a proprietary method was used to calculate mass concentrations from number concentrations. The CAM reports number concentration alongside $PM_{2.5}$. The Speck includes a temperature sensor and internally stores data that can be download to a personal computer via supplied software.

The AirBeam contains sensors for temperature, relative humidity, and particulate matter. It uses an internal fan to pull air into the particle sensing region of a single-bin OPC (Shinyei PPD60PV-T2, cost ~$250, Shinyei technology Co., LTD) to detect particles ranging from 0.5 µm to 2.5 µm and $PM_{2.5}$ concentrations up to 400 µg/m^3, according to the manufacturer specifications (HabitatMap, 2016). The AirBeam converts sensor voltage to mass concentrations using a linear regression model, developed in side-by-side tests of