Received: 10 January 2018 | Accepted: 12 April 2018

DOI: 10.1111/ina.12463

ORIGINAL ARTICLE

WILEY

Response of consumer and research grade indoor air quality monitors to residential sources of fine particles

B. C. Singer | W. W. Delp

Indoor Environment Group and Residential Building Systems Group, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Correspondence
Brett C. Singer, Indoor Environment Group and Residential Building Systems Group, Lawrence Berkeley National Laboratory, Berkeley CA, USA.
Email: bcsinger@lbl.gov

Funding information
U.S. Dept. of Housing and Urban Development Office of Healthy Homes and Lead Hazard Control, Grant/Award Number: Interagency Agreement I-PHI-01070; U.S. Environmental Protection Agency Indoor Environments Division, Grant/Award Number: Interagency Agreement DW-89-9232201-7; U.S. Dept. of Energy Building Technologies Office, Office of Energy Efficiency and Renewable Energy, Grant/Award Number: DOE Contract DE-AC02-05CH11231

Abstract

The ability to inexpensively monitor $PM_{2.5}$ to identify sources and enable controls would advance residential indoor air quality (IAQ) management. Consumer IAQ monitors incorporating low-cost optical particle sensors and connections with smart home platforms could provide this service if they reliably detect $PM_{2.5}$ in homes. In this study, particles from typical residential sources were generated in a 120 m^3 laboratory and time-concentration profiles were measured with 7 consumer monitors (2-3 units each), 2 research monitors (Thermo pDR-1500, MetOne BT-645), a Grimm Mini Wide-Range Aerosol Spectrometer (GRM), and a Tapered Element Oscillating Microbalance with Filter Dynamic Measurement System (FDMS), a Federal Equivalent Method for $PM_{2.5}$. Sources included recreational combustion (candles, cigarettes, incense), cooking activities, an unfiltered ultrasonic humidifier, and dust. FDMS measurements, filter samples, and known densities were used to adjust the GRM to obtain time-resolved mass concentrations. Data from the research monitors and 4 of the consumer monitors—AirBeam, AirVisual, Foobot, Purple Air—were time correlated and within a factor of 2 of the estimated mass concentrations for most sources. All 7 of the consumer and both research monitors substantially under-reported or missed events for which the emitted mass was comprised of particles smaller than 0.3 μm diameter.

KEYWORDS
air pollutant exposure, air quality monitoring, indoor aerosol, $PM_{2.5}$, ultrafine particles

1 | INTRODUCTION

Fine particulate matter is a substantial health hazard. The U.S. Environmental Protection Agency[1] has determined that both short- and long-term exposures to elevated concentrations of ambient particles smaller than 2.5 μm in diameter, $PM_{2.5}$, cause increased cardiovascular morbidity and mortality. EPA also found robust associations to respiratory effects that are likely causal. Much of our exposure to particles of outdoor (ambient) origin occurs in our homes, where we are also exposed to particles generated by indoor activities. Fine particles are emitted from activities such as smoking, cooking, burning incense and candles, secondary aerosol formation, and resuspension of settled dust among other sources.[2-15] Ultrafine particles, which are smaller than 100 nm in diameter and thought to present a hazard independent of $PM_{2.5}$, are emitted by smoking, candle-burning, and activities related to cooking.[7,11,16,17]

Exposure to $PM_{2.5}$ from indoor sources can be reduced by limiting particle-producing activities, providing source control ventilation,[18] increasing general ventilation, and circulating indoor air through filters.[19-23] Controls may be activated manually if occupants are aware of the emission sources or automatically using information from communicating particle sensors.

Measurement of $PM_{2.5}$ is complicated by variations in composition and size distribution, and by partitioning of organics, water vapor, and ammonium nitrate between condensed and gaseous phases, that can dynamically affect airborne particle concentrations.

In the United States, the Federal Reference Method (FRM) for $PM_{2.5}$[24] involves drawing air through filters using specified equipment and flow rates. Filters are conditioned within prescribed temperature and humidity bounds and weighed pre- and post-sampling to determine the collected mass; air concentrations are then calculated as mass divided by sampled air volume. The time resolution of filter-based sampling is constrained by the need to collect enough particles to reliably discern a change in filter mass; in homes, this can range from roughly 1 hour when concentrations are high from recent emissions to tens of hours without emissions. A Federal Equivalent Method (FEM) designation is obtained by demonstrating correlation to an FRM.[24] Some FEM monitors provide hourly or better resolution but they are designed for ambient monitoring and not suitable for homes owing to size and noise.

Most measurements of time-resolved $PM_{2.5}$ in homes have been made with photometers and optical particle counters.[25-30] Photometers measure the light scattered by the ensemble of particles and relate it to mass concentration via a calibration developed for a test aerosol. Particle counters analyze the scattering signals of individual particles and assign each to a size bin. Mass concentrations can be estimated from size-resolved number concentrations if particle shape and density are known or may be estimated.[31]

Several studies have examined the response of research grade photometers to aerosols relevant to residential exposures. Wallace et al[27] compared data from DustTrak 8520 monitors to gravimetric samples inside and outside homes and compared data from modified pDR Model 1100 monitors to personal exposure samples in Windsor Ontario; they also summarized results of prior studies. Jiang et al[32] compared the Sidepak AM510 to gravimetric samples for outdoor aerosols and 4 indoor combustion sources: cigarettes, incense, wood chips, and toasting bread. Dacunto et al[33] compared the Sidepak AM510 to gravimetric measurements to determine response factors for indoor sources, including cigarettes, incense, cooking, candles, and fireplaces. These studies reported that the research grade photometers correlated with gravimetric measurements with moderate variations (roughly 30%-50%) when measuring over time in varied environments and larger variations across specific sources.

In recent years, the availability of inexpensive optical particle sensors has enabled the development of consumer grade monitors that cost under $300. These monitors typically include a data visualization platform (via on-device display, mobile phone app, or website), data storage, and the ability to communicate with control equipment using one or more smart home platforms (Amazon, IFTTT, etc.). Most consumer grade monitors report mass concentration units, for example micrograms of PM per cubic meter of air ($\mu g\ m^{-3}$). The Dylos family of monitors report the measured number concentrations of particles with diameters >0.5 μm and > 2.5 μm.

Performance evaluations of consumer monitors have focused mostly on ambient PM and laboratory-generated, single-component aerosols. The South Coast Air Quality Management District's Air Quality Sensor Performance Evaluation Center (AQ-SPEC) (www.aqmd.org/aq-spec) and the US EPA (www.epa.gov/air-sensor-toolbox) have conducted the most systematic and expansive evaluations.

Practical Implications

- The capability to detect when indoor emissions lead to high concentrations of fine particles in a home can lead to lower exposures by informing occupants and enabling automatic controls. This study evaluated the performance of 7 consumer air quality monitors that can be purchased for under $300 per unit for their ability to quantify concentrations resulting from common residential particle sources.

For outdoor particles, the tested monitors are deployed adjacent to regulatory ambient air monitors over periods of weeks to months. The methods used by AQ-SPEC are described in a recent paper,[34] and evaluation reports are provided on their website. EPA methods and results are summarized in 2 published reports.[35,36] Manikonda et al[37] evaluated several consumer and research monitors measuring cigarette smoke and Arizona Test Dust in a room-sized laboratory chamber. Sousan et al[38] tested 3 consumer monitors for measuring salt, welding fumes, and Arizona Test Dust at levels relevant to occupational exposures. Holstius et al[39] evaluated a custom-built sensor-based monitor against beta-attenuation monitors at an ambient monitoring site in Oakland, CA. Wang et al[40] and Sousan et al[41] studied the performance of low-cost sensors measuring particles of varying sizes and compositions in controlled laboratory testing. Findings from these reports that are relevant to this study will be discussed in the Results and Discussion section.

The objective of this study was to evaluate the performance of consumer grade monitors in measuring common residential sources of fine particles. The study evaluated how accurately the monitors reported mass concentrations as determined with reference equipment and correlations of time-resolved measurements.

2 | METHODS

2.1 | Overview

Experiments in which particles were generated from typical residential activities were conducted in single-story 120 m^3 laboratory that is attached on 1 side to an adjacent laboratory. The laboratory has a 5.8 m by 7.1 m floorplan with cathedral ceiling (Figure 1). Consumer and research particle monitors were placed on a wire shelving unit co-located with reference instruments in the central area, several meters from sources. In a subset of experiments, filter samples were collected for time-integrated, gravimetric mass determination. During source activities, outdoor air exchange was provided solely by infiltration. After the source activity ended, particles were allowed to naturally decay over a period of variable duration. During most experiments, after about 1 hour, exterior doors at opposite ends of the laboratory were opened to rapidly ventilate the room and remove residual particles and co-pollutants. The outdoor air exchange

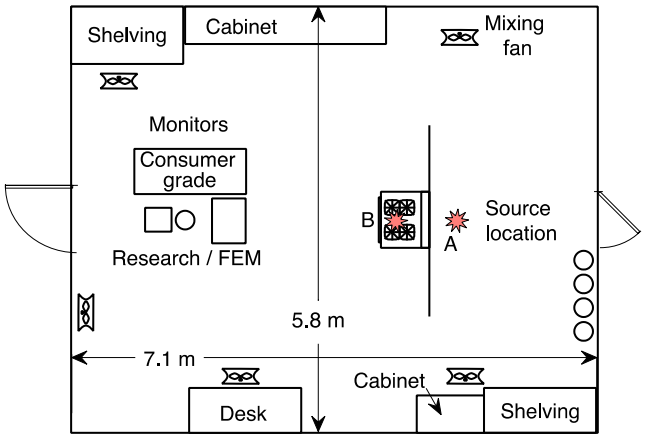

FIGURE 1 Plan view of test laboratory (approximately to scale). Wire shelving units and cabinets were 200 cm high; desk was 94 cm high

rate was measured by a tracer decay method during all phases of testing. Several mixing fans were placed in the test chamber to create uniform particle concentrations. Baseline concentrations of particles from outdoors were determined from measurements before and after each source activity. Baselines were subtracted from measurements taken during the source activities to calculate a time-integrated particle concentration for each source event.

2.2 | Source activities

Table 1 presents brief descriptions of the 24 source experiments. There were 16 distinct sources; several were used in multiple experiments, although sometimes with variations. Through the paper, the sources are discussed in the following groups. Recreational combustion included candles, cigarettes, and incense. Mineral sources included an ultrasonic humidifier with the filter removed, Arizona Test Dust, and shaking of a workshop dust mop. Cooking sources that generated large quantities of $PM_{2.5}$ included heating oil in a steel wok on gas or electric burners, frying bacon, and toasting 4 slices of bread in a toaster oven, and stir-frying green beans in oil on a gas burner. Cooking sources that produced large numbers of particles with low to moderate mass concentrations and almost all below 0.3 μm included heating water in a covered pot on a gas stove, heating a gas oven, cooking a pizza in the gas oven, cooking pancakes on a lightly oiled pan over medium heat, and toasting bread in a well-used electric toaster oven. Table S1 presents additional details about the experiments.

2.3 | Measurement of room air exchange rate

Room air exchange rates were determined using a tracer decay method.[42] A tracer, refrigerant R124 (CAS 2837-89-0), was released into the room on many days when experiments were conducted and measured with a MIRAN 205 SapphIRe gas analyzer (Thermo Fisher). This procedure was applied to measure ventilation rates during 23 injection-decay events, including 16 with a rapid ventilation flush. When a flush occurred, decays were fitted separately for infiltration and rapid ventilation periods. The infiltration rate varied from 0.5 to 1.1 $hour^{-1}$ with a median of 0.7 $hour^{-1}$. The rapid ventilation air exchange varied from 8.5 to 39 $hour^{-1}$ with a median of 13 $hour^{-1}$. The rate during this mode depended on the extent that opposing exterior doors were open.

2.4 | Particle monitoring devices

A TEOM-FDMS Model 1405-DF (Thermo Fisher Scientific)—henceforth "Filter Dynamic Measurement System (FDMS)"—was used as a reference monitor for integrated $PM_{2.5}$ mass during source experiments. It was operated to provide data at 5 minute resolution. The FDMS quantifies mass concentration by measuring the change in oscillating frequency of a hollow glass tube as particles are collected on a filter at the tube inlet. The FDMS alternately samples directly from the environment, collecting particles onto a Pallflex TX40, Teflon-coated borosilicate filter held at 30°C, then goes through a clean air reference interval in which the sample air stream is first run through a filter and chiller at 4°C to remove particles and greatly reduce the concentration of potentially sorbing gases before it is directed through the mass determination filter. The change in mass during each clean air reference interval is used to adjust the mass collected during intervals of environmental sampling using a proprietary algorithm. The adjustment is designed to account for gas adsorption or mass loss by volatilization of collected PM constituents, providing mass measurements with low deposition and volatilization artifacts. From the FDMS output, we logged the "MC" and "Raw" values. MC is a 1 hour running average of the mass concentration. Raw data estimate the mass concentration over a defined averaging period (5 minute for this study). The FDMS operated continuously during all experiments.

A Grimm Mini Wide-Range Aerosol Spectrometer Model 1.371 (GRM) was used as a reference for 1 minute resolved data and also to provide distributions of particle number and mass concentrations. The GRM combines an electrical mobility analyzer that counts particles in 10 size bins from 10 to 200 nm with a laser-based optical particle counter that provides counts in 15 bins from 200 nm to 2.5 μm and 16 bins between 2.5 and 35 μm. The Grimm estimates volume concentration by assuming all particles are spheres, then calculates mass assuming a density of 1.68 g cm^{-3}, relevant to many outdoor air applications. The density is a user-adjustable parameter that enables the GRM to measure aerosols with varying composition.

Seven consumer grade monitors that were available for retail purchase in early 2017 were selected for testing (Table 2). The consumer devices were operated continuously in the laboratory for all experiments.

The study also evaluated 2 aerosol photometers that have been used in residential indoor air quality (IAQ) research studies: the Thermo pDR-1500 and the MetOne BT-645. Summary information is provided in Table 2. Each of the research monitors allows the user

TABLE 1 Summary descriptions of the sources of the aerosol used to evaluate fine particulate matter monitors

Date (2017)	Identifier	Description	Peak mass[a] ($\mu g\ m^{-3}$)	Peak number[b] ($\#\ cm^{-3}$)	Peak MMD[c] (nm)	Density for GRM[d] ($g\ cm^{-3}$)
7/25	Humidifier 1	Ultrasonic humidifier, cleaning cartridge removed, operated ~10 min	57	8.6×10^3	414	3.00 ± 0.75
7/25	Incense 1	Incense stick (Shanthimalai Red Nag Champa) burned 10 min	99	3.5×10^4	298	1.26 ± 0.13
7/25	AZ Dust 1	Arizona Test Dust (0-3 μm) manually puffed from bag	77	1.9×10^3	1821	2.65 ± 0.00
7/26	Beans 1	150 g frozen green beans, 15 g canola oil stir fried in steel wok on gas stove	163	8.9×10^4	298	1.17 ± 0.12
7/26	Beans 2	150 g frozen green beans, 15 g canola oil stir fried in steel wok on gas stove	721	9.8×10^4	1310	1.02 ± 0.10
7/26	Beans 3	150 g frozen green beans, 15 g canola oil stir fried in steel wok on gas stove	363	4.4×10^4	1545	1.12 ± 0.10
7/27	Toast	Single piece of bread, medium-toasted in used electric coil toaster oven	98	1.4×10^5	139	0.94 ± 0.10
7/27	Bacon+Toast	280 g bacon fried on gas stove; 4 slices bread med-toasted in toaster oven	186	2.2×10^5	253	1.04 ± 0.10
7/27	GB Oil 1	15 g of canola oil brought to bubble in steel wok on gas stove	281	6.7×10^4	488	1.46 ± 0.10
8/1	Incense 2	Incense stick (Shanthimalai Red Nag Champa) burned for ~15 min	159	6.1×10^4	298	1.19 ± 0.12
8/1	Humidifier 2	Ultrasonic humidifier, cleaning cartridge removed, operated 15 min	82	1.7×10^4	253	3.00 ± 0.75
8/2	AZ Dust 2	Arizona Test Dust (0-3 μm) manually puffed from bag	98	3.1×10^3	1821	2.65 ± 0.00
8/2	Burnt toast	Slice of bread, dark-toasted in used electric coil toaster oven	55	1.1×10^5	139	0.79 ± 0.15
8/3	Dust mop	Aggressive shaking of a 90 cm wide workshop dust mop	57	5.2×10^3	1821	1.63 ± 1.00
8/3	Candles	5 unscented dinner candles, lit with butane lighter, burned for 11 min	272	1.2×10^5	253	1.40 ± 0.14
8/3	Gas+Pots	Two covered 5 L pots, half-filled w/ H_2O, heated on gas stove 13 min	27	8.4×10^4	100	0.90 ± 0.10
8/3	Oven	Gas oven heated to 204°C over 12 min after ~4 y of no use	32	8.8×10^4	100	0.90 ± 0.10
8/3	Oil 2	15 g of canola oil brought to bubble in steel wok on gas stove	131	7.2×10^4	298	1.19 ± 0.20
8/4	Pancakes	Two batches pancakes cooked on a lightly oiled fry pan on gas burner	21	3.5×10^4	139	0.90 ± 0.10
8/4	Pizza	Gas oven heated to 204°C over 14 min; frozen pizza cooked 16 min	52	9.0×10^4	139	0.90 ± 0.10
8/4	Cigarettes	3 cigarettes lit with butane lighter, smoldered until self-extinguished	164	1.4×10^5	139	1.14 ± 0.11
8/7	Elec Oil	15 g canola oil brought to bubble in fry pan on an electric coil burner	222	1.0×10^5	253	1.19 ± 0.12
8/10	GB Oil 3	15 g canola oil brought to bubble in fry pan on the gas stove	297	1.3×10^5	253	1.32 ± 0.13
8/10	Incense 3	Incense stick (Shanthimalai Red Ng Champa) burned 10 min	131	4.4×10^4	298	1.34 ± .14

[a]Peak mass: highest 5 min mass concentration.
[b]Peak number: highest 5 min number concentration.
[c]Peak MMD: mass median diameter at or near highest concentration during emission event.
[d]Density of source, generally based on comparing integrated concentration estimate from Grimm Mini Wide-Range Aerosol Spectrometer (GRM) to Filter Dynamic Measurement System during same experiment; sometimes also considers published estimates of source density. See Table S1 for more information.

TABLE 2 Consumer and research grade monitors evaluated in this study

Device name	Code	Cost[a] ($US)	Data	Particle sensor	Notes from product literature
Consumer monitors					
AirBeam 1	AB	$249	1 s	Shinyei PPD60PV	Site: http://www.takingspace.org/aircasting/airbeam/Sensor detects particles >0.5 μm. Website refers to $PM_{2.5}$. Full schematics and firmware available on github
Air Quality Egg	AQE	$280	1 min	Shinyei PPD60	Site: https://shop.wickeddevice.com/product/air-quality-egg-2-particulate-pollution/Manual reports operating range 0.5-10 μm, claims device "Provides an aggregate measure of both PM10 and PM2.5, reported in micrograms per cubic meter"
AirVisual Node	AVN	$200	10 s	AVPM25b	Sensor developed by AirVisual. Nominally reports $PM_{2.5}$ for particles 0.3-2.5 μm. Currently available product is AirVisual Pro, for $269
Awair	AWA	$199	10 s[b]	Sharp GP2Y-1010	Identified sensor from pictures on the manufacturers website. Product lit describes measurement as "PM." Range of 0-500 μg m^{-3} (This corresponds to linear range for voltage output as specified on Sharp sensor sheet.)
Foobot	FOB	$199	5 min	Sharp GP2Y-1021	Site: https://foobot.io/ Sensor info provided by Foobot. Factory calibrated with proprietary learning algorithm applied to signal. Measures $PM_{2.5}$, over range of 0.3-2.5 μm diameters. Range: 0-1300 μg m^{-3}. Precision: ±4 μg or ±20%
Purple Air PA-II	PA	$229[c]	80 s[d]	Plantower PMS5003	Site: https://www.purpleair.com/sensors. Includes 2 sensors in each device. Reports total number conc. and mass conc. for PM_1, $PM_{2.5}$, PM_{10}. Counting efficiency: 50% for 0.3 μm, 98% for ≥0.5 μm diameter particles. Consistency: ±10 μg m^{-3} @0-100 μg m^{-3}, ±10% @100-500 μg m^{-3}. Range: 0-500 μg m^{-3}
Speck	SPK	$200	1 min[d]	Syhitech DSM501A	Calibrated with Arizona Test Dust. Machine learning algorithms applied to sensor signal. Product literature notes range of 0.5-3 μm
Research monitors					
Thermo pDR-1500	PDR	Approx. $6000	20 s	Proprietary	Calibrated with SAE Fine Arizona Test Dust. Precision: Larger of ±0.5% of reading or ±0.0015 mg m^{-3} (10 s averaging). Accuracy: ±5% of reading ±precision
MetOne BT-645	BT	Approx.$3000	1 min	Proprietary	Calibrated with 0.54 μm diameter polystyrene latex spheres Accuracy: 5%

[a]In early 2017.
[b]Air Visual saves data at variable interval depending on rate of change; 10-s resolution during all experiments.
[c]We purchased PA-II with extra onboard data storage for $259; price shown is for base device with same sensor pair.
[d]Purple Air and Speck allow the user to set data resolution; values in table were used for this study.

to adjust the scaling factor that relates instrument response to mass concentration, and the user guides for these devices recommend collecting coincident filter samples to determine the appropriate scaling factor for the aerosol being measured.

2.5 | Filter-based gravimetric samples

During a subset of experiments and 1 overnight background period, an AirCon2 High Volume Air Sampler (Sensidyne) pulled air through 37 mm

diameter, 2 μm pore-size, TEFLO (Pall) PTFE filters at a target flow rate of 10.0 lpm. This pump features an internal flow sensor, actively adjusts flow based on sensor output, and reports an error if the measured flow deviates by more than 5% from the setting. The flow was checked before each sample using a Gilian Gilibrator2 (Sensidyne). Size selection was accomplished using an MSP Model 200 Personal Environmental Monitor (PEM-10-2.5) filter holder that provides a 50% cut point at 2.5 μm for a flow rate of 10 lpm. Filter samples were started just before the source emission event and continued until the concentrations on the GRM had dropped to pre-experiment levels. Filters were equilibrated at a temperature of 19.5 ± 0.5°C and relative humidity of 47.5 ± 1.5% for at least 24 hour before weighing pre- and post-sampling. Filter weights were determined using a Sartorius SE2-F ultra-microbalance (Sartorius).

2.6 | Processing and analysis of data

2.6.1 | Data recording

Each of the consumer devices provided wireless connectivity and data display (on device and/or by mobile phone app); but the availability and ease of capturing data for analysis varied. Before starting the experiments, we determined the appropriate settings and operated the devices in the presence of residential sources to confirm that we could retrieve data. We configured the AirBeam to use direct serial communication to a computer, recording data every second. For the AirVisual and Speck, we used available on-board storage and downloaded data via a Chrome-browser extension applet (Speck) or by connecting to the device over a local wifi network using the SAMBA protocol (AirVisual). These devices also communicate data to the cloud; but we determined that data retrieval was easier through the on-board storage. Foobot provided an IFTTT recipe that stored data every 5 minute to a Google sheet. Data from the Air Quality Egg and Purple Air units were obtained using an online request form. Data from the Awair devices were provided by the company via email after we had difficulty downloading via the web form.

All of the consumer monitors (except AirBeam) synchronized their internal clocks with official time through a wifi connection to the cloud. The AirBeam was connected directly to a computer that was regularly synchronized to official time. For several of the instruments, the time records had to be adjusted to match the hour of the local time.

The GRM clock was reset each day to the same computer used to log the AirBeam devices. The FDMS clock is regularly synchronized to official time via the Internet. The internal clocks on the pDR-1500 and BT-645 were set at the start of the study, and timing alignment from these instruments was checked at 6 points in the study by aligning the timing of a sharp peak with the same source peak on the GRM. For each of these 2 devices, data from individual source experiments were time-adjusted using the empirically determined drift rates before analyzing for correlations with the GRM.

2.6.2 | Data processing

Instruments recorded data over a range of time steps, from 1 second (AirBeam) to 5 minute (Foobot and FDMS), although most recorded at 1 minute resolution (Table 2). The AirVisual was set to a mode that records data in varying time steps according to the rate of change; but resolution during source activities was always 10 second.

We used version 0.20.3 of the Pandas package[43] to manage and analyze all of the time series data. Pandas is an open-source, general-purpose python-based package that provides data structures to facilitate analysis of time series and relational data (https://pandas.pydata.org/pandas-docs/stable/index.html). Pandas accesses analysis methods from other packages in the SciPy stack (https://www.scipy.org/about.html).

2.6.3 | Calculation of time-integrated concentrations by source event

An integration interval was set for each source event by visually inspecting the FDMS and GRM data to ensure that the entire period of elevated concentration was included. The same integration interval was used to integrate source-related concentrations for all devices, using the highest time resolution data available. For each device, the baseline was identified by first masking all data points that were >2 μg m^{-3} above the highest of the measurements at the start and end times of the interval, then fitting the remaining data to least-square regression line. This baseline was then subtracted from each data point in the interval and the baseline-subtracted concentrations were integrated over time. Results for consumer and research monitors within a factor of 2 (approximately 50%-200%) of the density-adjusted GRM are characterized as "quantitative," or reasonably accurate given the many challenges inherent in measuring $PM_{2.5}$.

2.6.4 | Estimation of time-resolved mass concentration using reference monitors

Source-specific density adjustments, presented for each experiment in Table 1, were applied to the background-subtracted GRM data to calculate our best estimate of time-resolved and time-integrated mass concentrations. Density adjustments were determined primarily by comparing the background-subtracted, integrated results obtained with the unadjusted GRM and the FDMS for each experiment; but we also considered densities reported for the sources in prior literature. Table S2 provides notes on the density selected for each experiment. Uncertainty in the density was assumed to be at least 10%, and larger in some cases. For the Arizona Test Dust, we used the density provided by the supplier, without uncertainty.

2.6.5 | Correlation of temporal profiles

A monitoring device can provide value if it successfully identifies sources, even if it does not respond quantitatively. To assess this type of performance, we created data pairs that included the baseline-subtracted measurement from a device and the density-adjusted and baseline-subtracted value from the GRM. These data

pairs were linearly regressed; and for each regression, we calculated both the slope and the Pearson's correlation coefficient. To conduct this analysis, we used the Resample method (pandas.dataframe.resample) to align data from all devices, using a 5 minute, right hand aligned averaging period. Then, we used the Statsmodel OLS linear regression model to determine the regression slopes and correlation statistics (http://www.statsmodels.org/dev/index.html).

3 | RESULTS

3.1 | Summary characteristics of source events

Table 1 provides summary statistics for the 24 source experiments. The highest 5-minute baseline-subtracted mass concentrations (adjusted GRM data) varied from 21 μg m^{-3} for the pancakes to 721 μg m^{-3} for one of the green-bean stir-fry experiments. The highest number concentrations varied from 2-5 × 10^3 cm^{-3} for the Arizona Test Dust and dust mop experiments to 2 × 10^5 cm^{-3} for the Bacon + Toast experiment. The 5 experiments with the lowest peak mass concentration (Pancakes, Pots on gas burners, Oven, Pizza, Burnt Toast) were in the upper part of the distribution of peak number concentrations (6th to 18th highest among 32 experiments). The mean temperature and relative humidity over the integration period for each experiment are presented in Table S1. These data show that none of the experiments produced high humidity levels that would impact the particle measurements.

3.2 | Example data

Figure 2 presents example results from experiments conducted on August 3, 2017. The plot shows 2 very large sources—candles and oil heated on a gas burner—that produced clear and substantial, although not fully quantitative responses by all analyzers. The Egg (AQE), Awair (AWA), and Speck (SPK) all reported only a small fraction of the actual mass concentration, represented by the GRM signal. The dust mop emitted mostly large particles and produced responses in some but not all devices; for this source, the Speck response was higher than the estimate of actual mass concentration. Using the gas cooktop burners to heat water in covered pots and heating the empty oven produced large numbers of particles centered at or below 100 nm and modest mass concentrations as indicated by the GRM, but no perceptible response from consumer or research monitors. The Speck baseline appears to have shifted following the candle event.

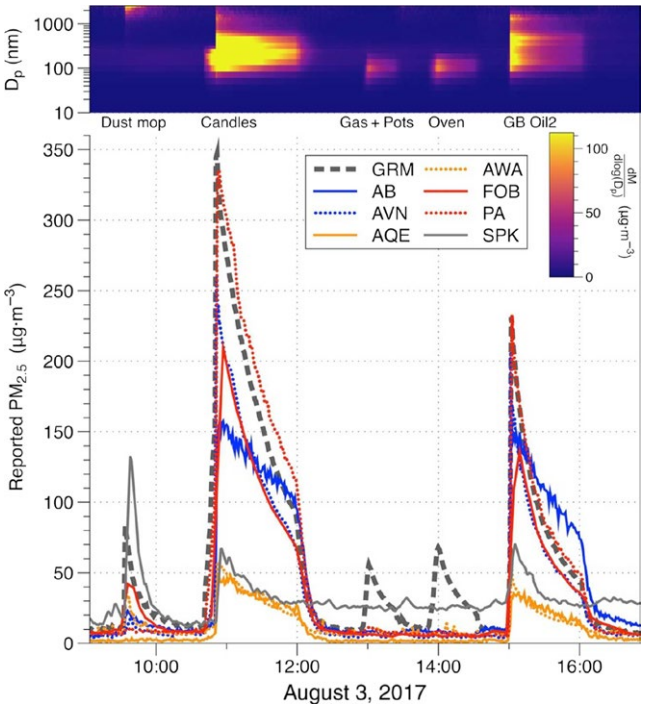

FIGURE 2 Example results from 5 source experiments. For devices that sampled more frequently than each minute, data have been averaged for 1-min resolution. The top portion of plot shows the distribution of mass by particle size. Refer to Table 2 for monitor abbreviations

3.3 | Comparison of FDMS and GRM to filter samples

Table 3 presents the time-integrated mass concentrations reported by the FDMS and *unadjusted* GRM for periods in which filter samples were collected. For the single background sample, the concentration reported by the FDMS was 9% higher and the GRM was 46% lower than the filter-based measurement. The GRM underestimate may be partly explained by the density of the ambient aerosol being higher than the device default value of 1.68 g cm^{-3}. In a study in Los Angeles, Hasheminnasab et al[44] reported (in their Figure 6) an effective density of ~2.2 g cm^{-3} for overnight periods (1600-0800) during the warm weather season. During source experiments, integrated FDMS mass concentration estimates ranged from 13% lower to 12% higher than filter-based estimates, indicating agreement without bias. The unadjusted GRM mass concentration estimates varied from 55% (unfiltered ultrasonic humidifier) to 230% (Burnt toast) of the filter-based measurement. Assuming densities of 3.1 g cm^{-3} for the unfiltered humidifier aerosol and 0.73 g cm^{-3} for the toast aerosol would align the GRM to the filter-based measurements. For the humidifier, this density is a bit higher than the values of 2.0 g cm^{-3} suggested by Rodes et al[45] and 2.5 g cm^{-3} suggested by Highsmith et al.[46] We could not find a prior study reporting the density of aerosol from toast or burnt toast.

3.4 | Performance of consumer and research monitors for mass concentrations

In the following sections, we compare baseline-subtracted, time-integrated concentrations reported by consumer and research monitors to the estimated "true" mass concentrations obtained from density-adjusting the GRM data. Table 1 lists the densities and Table S2 provides

TABLE 3 Mass concentrations measured for experiments that included filter sampling

Event	Start	End	ΔMass on filter (μg)	Filter (μg m^{-3})	Filter Dynamic Measurement System (FDMS) (μg m^{-3})	GRM[a] (μg m^{-3})	FDMS/Filter	GRM/Filter
Overnight	7/31 15:00	8/1 9:05	50.9	4.7	5.1	2.1	1.09	0.44
Incense 2	8/1 9:50	8/1 12:30	82.3	51.3	54.4	69.9	1.06	1.36
Humidifier 2	8/1 12:58	8/1 14:55	41.8	36.0	31.2	19.7	0.87	0.55
AZ Dust 2	8/2 9:55	8/2 11:19	27.7	33.0	29.2	24.4	0.88	0.74
Burnt toast	8/2 12:05	8/2 13:41	17.3	17.9	18.9	41.2	1.06	2.30
Candles	8/3 10:35	8/3 12:15	115.0	115	120	144	1.04	1.25
GB Oil 2	8/3 14:50	8/3 16:00	45.2	64.6	72.1	86.2	1.12	1.33

[a]Mass concentration reported by device, assuming all particles spherical with measured aerodynamic diameter and density of 1.68 g cm^{-3}.

notes about the selection for each experiment. We used the density-adjusted GRM as the reference because it provided data resolved to 1 minute with no apparent delay. The FDMS reported data at 5 minute intervals with varied delay depending on the instrument switching cycle. For the consumer monitors, the columns in Figures 3-6 show the means and the error bars show the standard deviations (for n = 3) or ranges (for n = 2) of mass concentrations across the multiple devices tested; the variation is an indication of the consistency across devices. The number of units of each type of monitor can be seen in Figure 7. For the GRM and research monitors, error bars reflect the combined uncertainties of manufacturer reported instrument accuracy and the baseline-subtraction, added in quadrature. An inset in each panel shows the estimated size-resolved mass distribution provided by the GRM, extended to 10 μm particles because many of the consumer monitors do not restrict sampling to 2.5 μm particles. The ratio of the time-integrated mass concentration reported by a monitor to the analogous result for the GRM (reference) monitor is described as a response factor. The data presented in Figures 3-6 are provided in Tables S3 and S4.

3.4.1 | Unfiltered humidifier and dust aerosols

Figure 3 presents results for the unfiltered humidifier and dust aerosols, which are known (for Arizona Test Dust), or assumed (for the other sources) to consist primarily of minerals. The GRM (reference) and research grade monitor results are presented to the left of the vertical line and consumer monitor results are to the right. $PM_{2.5}$ mass from the unfiltered ultrasonic humidifier was measured quantitatively by the research monitors, AirBeam, Foobot, and Purple Air. The AirVisual reported only 14%-24% and the Egg reported <5% of the estimated true mass, whereas the Speck reported 27% in 1 experiment and <1% in the other. The vastly different Speck responses in the 2 humidifier experiments could result from the Speck being more sensitive to large particles, as Humidifier 1 had a larger fraction of emitted mass above 1 μm. For Arizona Test Dust, the Speck was almost identical to the adjusted GRM. The research monitors reported 38%-49%, and the AirBeam and Foobot reported 53%-63% of the estimated true mass concentration. The other consumer monitors reported low (17%-29% for AirVisual and Awair) to very low (4%-12% for the Egg and Purple Air) mass for the Test Dust. The dust mop emitted very small quantities of $PM_{2.5}$ (as most of the airborne particles were larger than 2.5 μm diameter), but both the Speck and Foobot had quantitative responses. The AirBeam reported 32% of the estimated actual concentration and the research monitors and other consumer monitors reported 20% or less. The relatively low response of the Purple Air to the 3 dust-related samples is consistent with that device being most responsive to submicron particles and apparently not very responsive to super-micron particles. Responses for the Speck and Foobot may result from those devices measuring particles larger than 2.5 μm diameter.

3.4.2 | Recreational combustion

Figure 4 presents results for candles, cigarettes, and incense. For the candles and incense, the AirBeam, AirVisual, Foobot, and Purple

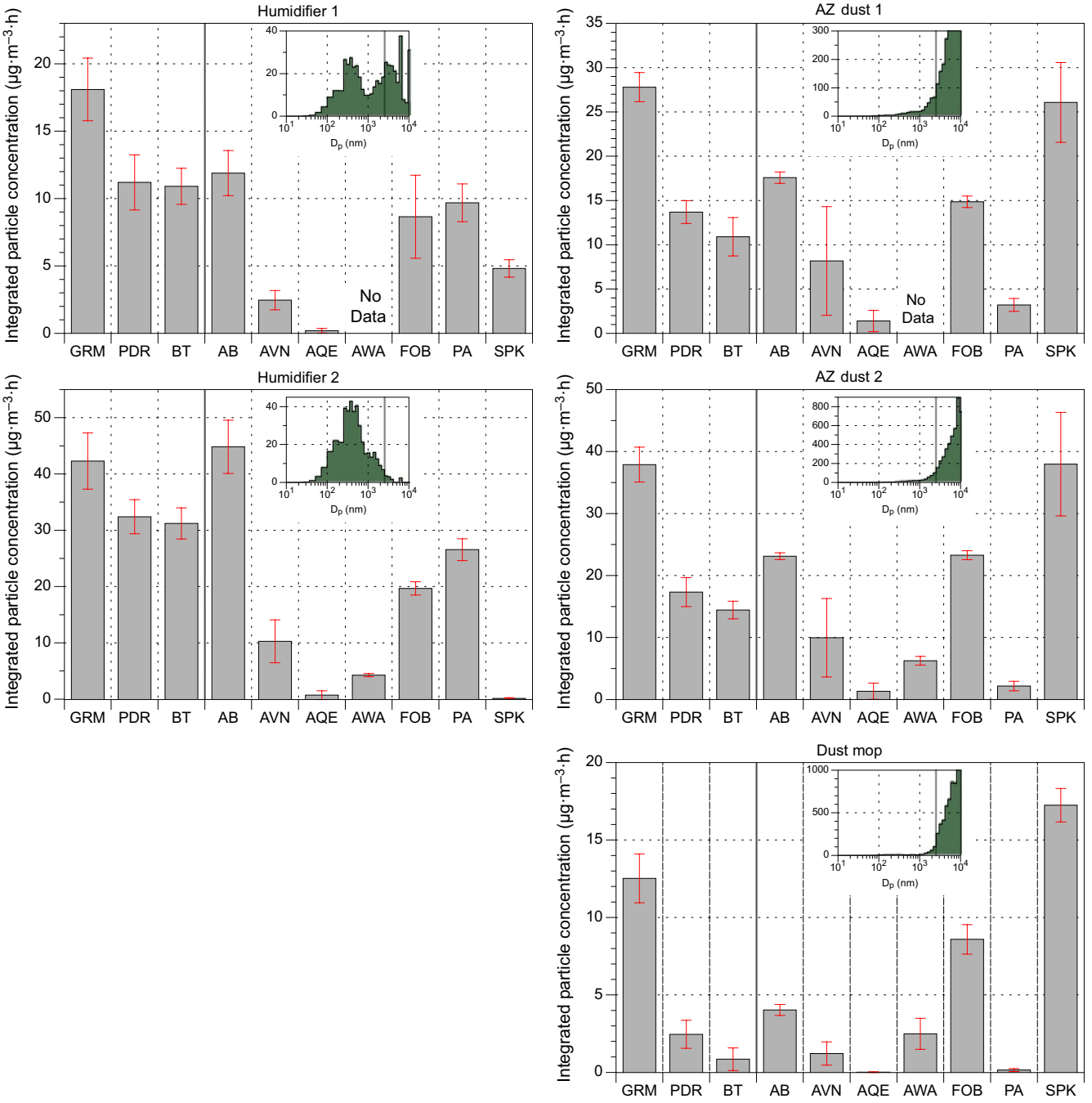

FIGURE 3 Baseline-subtracted, time-integrated particle concentrations for ultrasonic humidifier without filter and dust sources. The Grimm Mini Wide-Range Aerosol Spectrometer (GRM) is the estimated true mass concentration. Inset panels show the distribution of mass by particle size ($dM/dlopD_p$) at the peak

Air measurements were 79%-160% of the adjusted GRM, and the research monitors were 122%-171%. For the smoldering cigarettes, the Purple Air reported at 92%; the AirBeam, AirVisual, and research monitors reported at 40%-61%; and the Foobot reported at 27% of the adjusted GRM. The Egg had modest responses to all 3 sources, reporting 30%-46% of the actual mass across 3 incense experiments, 21% for candles and 9% for the smoldering cigarette aerosol. The Awair and Speck results were lower and less consistent, suggesting they may not be suitable for quantifying (and perhaps not even reliably detecting) recreational combustion sources. The distribution of mass was similar for the candles and incense and centered at ~0.3 µm, whereas the mass for the smoldering cigarette aerosol was shifted to smaller sizes. Both research monitors and the 4 consumer monitors with the largest responses to these sources all had lower responses relative to the GRM for cigarettes than for candles and incense. In other words, these monitors showed higher response factors to aerosols for which more of the mass was above 0.3 µm than to the aerosols with more mass in particles smaller than 0.3 µm diameter.

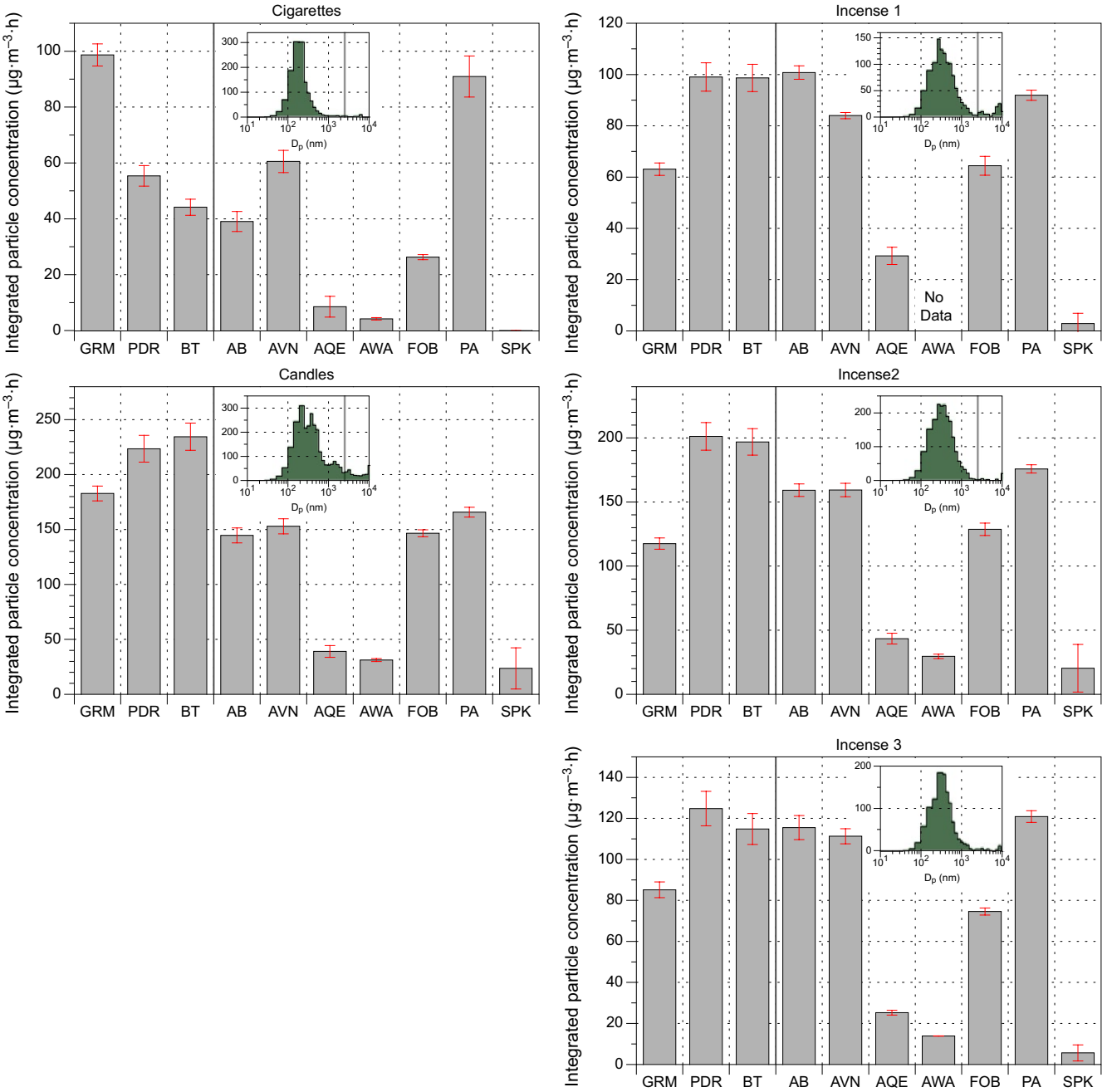

FIGURE 4 Baseline-subtracted, time-integrated particle concentrations for recreational combustion sources. The Grimm Mini Wide-Range Aerosol Spectrometer (GRM) is the estimated true mass concentration. Inset panels show the distribution of mass by particle size ($dM/dlopD_p$) at the peak

3.4.3 | Cooking activities involving frying or heating oil

Figure 5 presents results for triplicate implementations of stir-frying green beans with oil on a gas burner, of heating oil on a gas burner, heating oil on an electric burner, and a combined experiment of pan-frying bacon and toasting 4 slices of bread in a toaster oven. For all of these sources, both research monitors and the AirBeam, AirVisual, Foobot, and Purple Air provided quantitative data. The research monitors were biased high in 7 of 8 experiments, over-reporting by a factor of 1.3-1.7 in all but 1 experiment. The Egg responses were mostly in the range of 20%-30% and the Speck response varied widely. The pattern of responses across instruments was very similar for experiments displayed in horizontally adjacent panels, corresponding to similar mass size distributions for each pair. The Speck had its highest response, at 74%-94% of the GRM, for the 2 experiments dominated by large particles (Beans2 and Beans3); but the concentration was 7% of the adjusted GRM when there was little mass above 1 µm (bottom row). The Awair monitors had

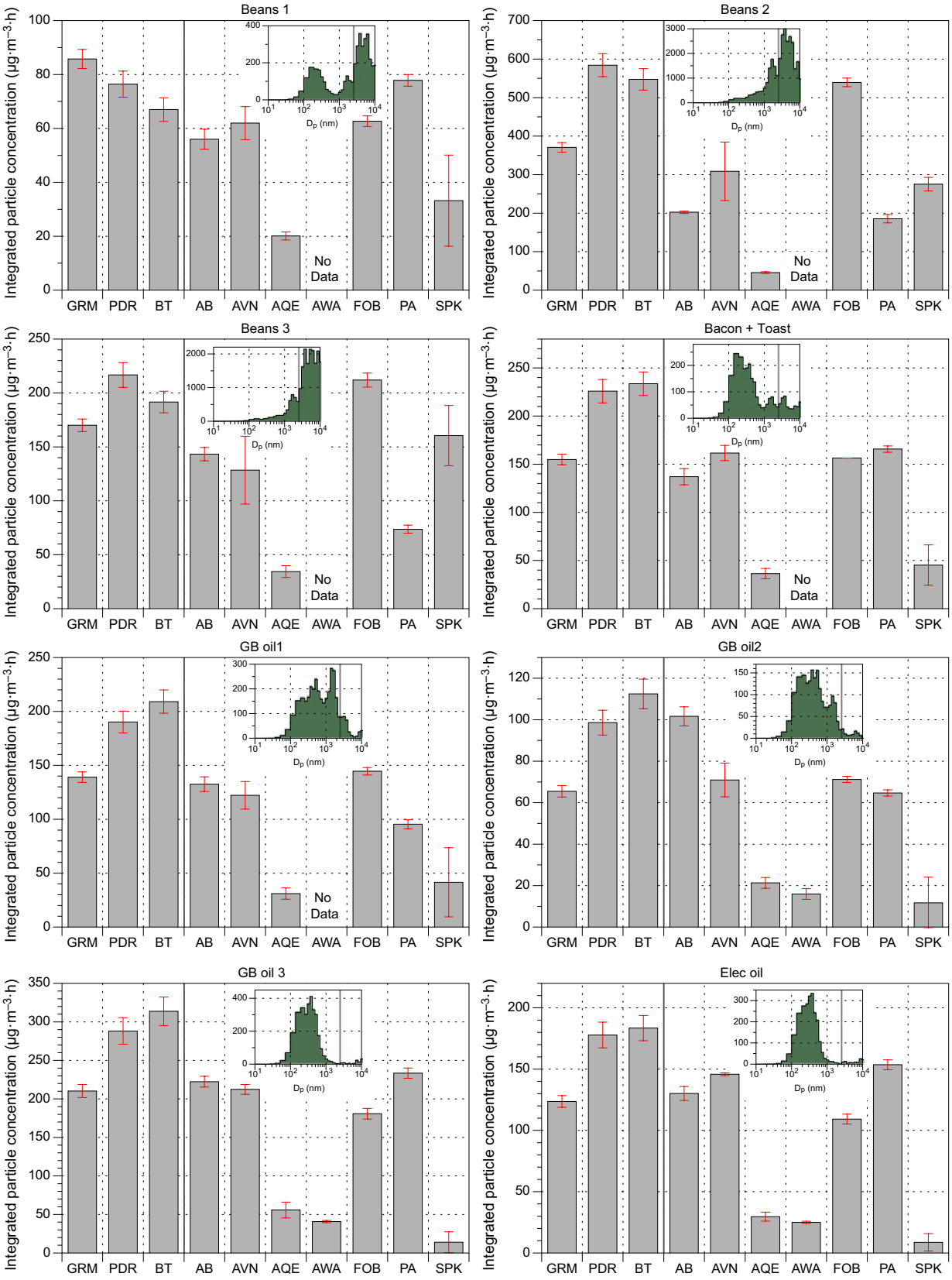

FIGURE 5 Baseline-subtracted, time-integrated particle concentrations for frying or heating oils. The Grimm Mini Wide-Range Aerosol Spectrometer (GRM) is the estimated true mass concentration. Inset panels show the distribution of mass by particle size ($dM/dlopD_p$) at the peak

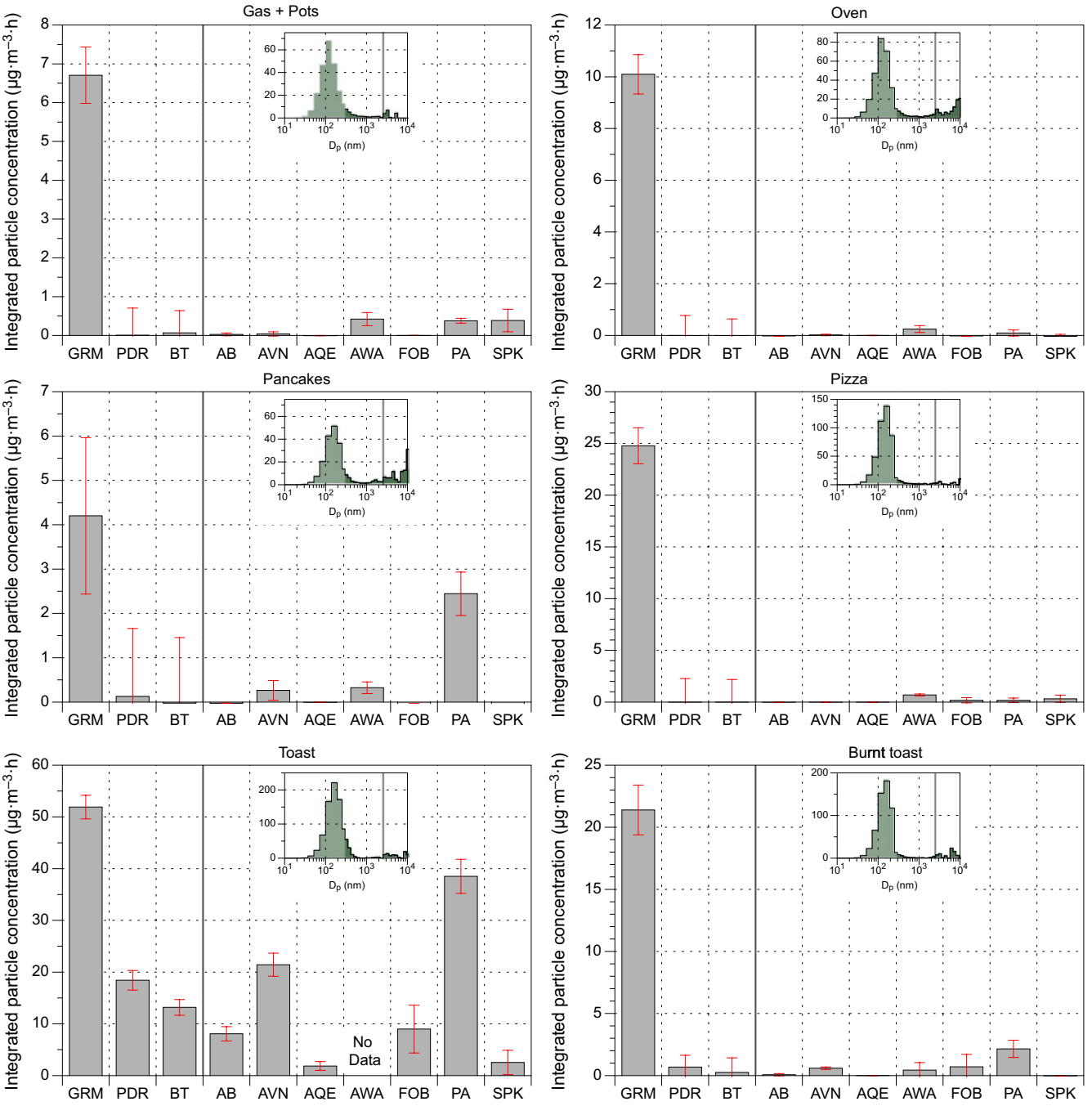

FIGURE 6 Baseline-subtracted, time-integrated particle concentrations for cooking sources that generated substantial quantities of ultrafine particles but relatively little mass. The Grimm Mini Wide-Range Aerosol Spectrometer (GRM) is the estimated true mass concentration. Inset panels show the distribution of mass by particle size ($dM/dlopD_p$) at the peak

consistently low output for the 3 experiments for which data were obtained.

3.4.4 | Cooking activities with mass emissions in particles smaller than 0.3 µm diameter

The last grouping of sources comprises cooking events that produced moderate to large numbers of particles but almost no mass in particles with diameters >0.3 µm (Figure 6). The event with the largest mass concentration—toasting 4 slices of bread—was measured quantitatively only by the Purple Air (74%). Several other consumer monitors had substantial responses, with the AirVisual at 41% and the AirBeam and Foobot at 16%-17% of the adjusted GRM. The research monitors were also short of the quantitative response threshold, with the pDR at 35% and BT at 25% of the GRM. For the next 4 largest events, none of the analyzers reported above 10%. Particles from pancakes, which produced the lowest integrated concentrations, were measured quantitatively only by the Purple Air (58%).

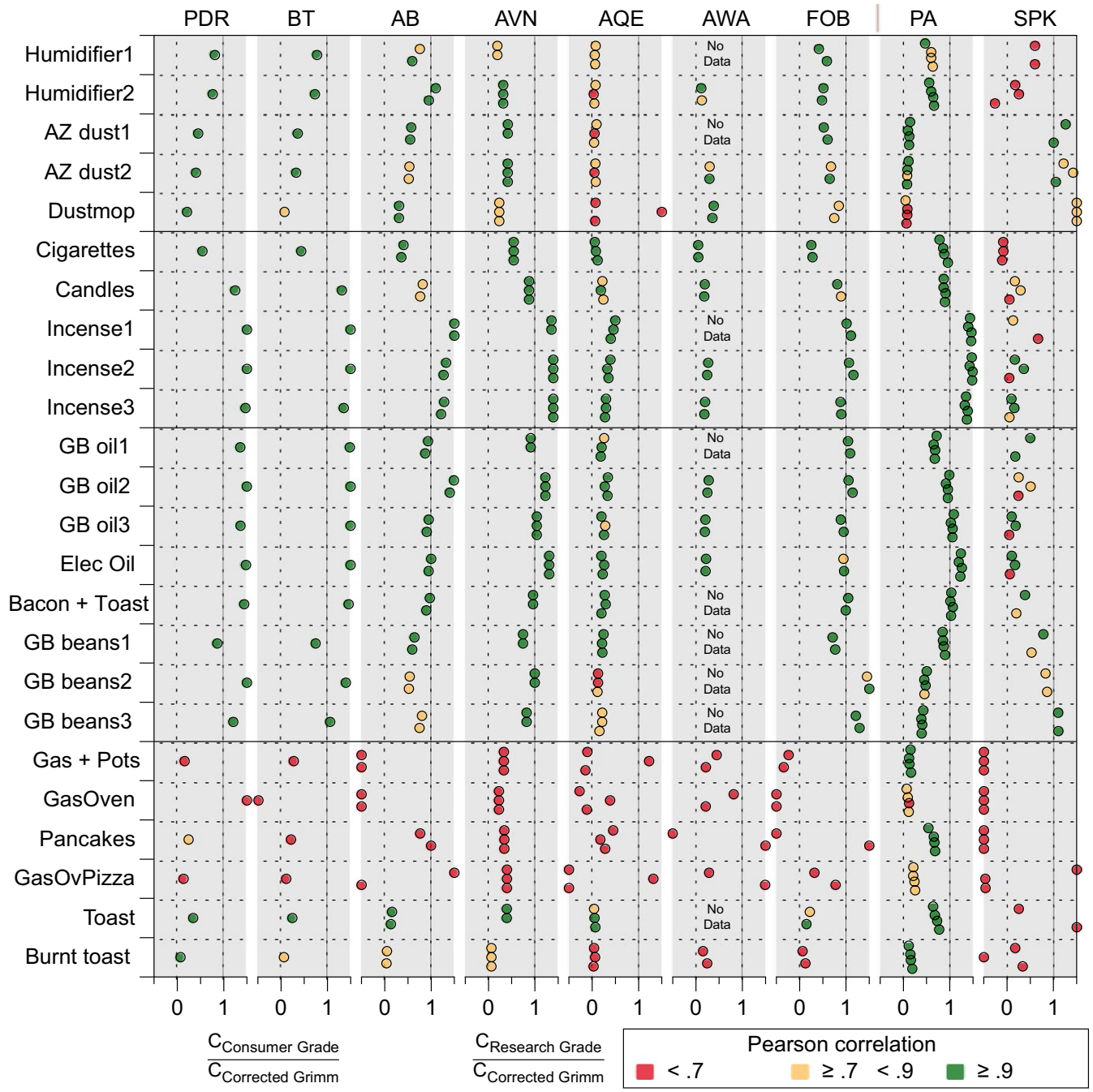

FIGURE 7 Regression coefficients and correlation statistics for baseline-subtracted, time-resolved data from tested devices related to density-adjusted data from Grimm Mini Wide-Range Aerosol Spectrometer. For PA, the 4 data points come from 2 devices which each had 2 sensors. Ratios of 1.5 or greater plotted at 1.5. Ratios below zero indicate inaccurate readings by consumer monitors

3.4.5 | Temporal correlations

Figure 7 presents results of the zero-offset linear regression analysis relating the time-resolved data for each monitor to the adjusted GRM. In this figure, a result close to unity indicates good accuracy and green indicates a strong correlation. Green circles that are far from unity (eg, <0.5 or >2) indicate that the tested monitor tracked the timing of concentration changes, but not quantitatively; such performance may still enable event detection. This plot elucidates and reinforces several of the results developed in the preceding sections. First, at the base of the plot, it shows that many of the devices did not reliably detect and respond to the cooking-related aerosols with little mass in particles above 0.3 μm diameter. The prominent exception was the Purple Air, which tracked the pattern of mass concentration increase for 4 of the 6 sources, even as the response was quantitative for only 2 of them. Even the research monitors did not provide clear responses to the cooking aerosols comprised mostly of smaller particles. The second key finding is that 4 of the consumer monitors (AirBeam, AirVisual, Foobot, and Purple Air) and both research monitors provided quantitative data for many

of the sources. And even when the response was not quantitative, it was often highly enough correlated that it may be possible to use the devices for event detection to activate controls. The Egg and Awair had high correlations but very low response factors to many of the sources for which valid data were obtained with these monitors. The Speck performed particularly inconsistently among the monitors tested.

3.4.6 | Results by monitor and comparisons to published performance evaluations

This section discusses results by monitor and relates relevant findings from peer-reviewed papers and AQ-SPEC reports (www.aqmd.org/aq-spec), accessed on December 22, 2017. Figures S1 and S2 present the response factors by monitor, across all experiments, elucidating the effect of emission source magnitude and particle size.

The AirBeam and AirVisual both had highly correlated and quantitative results for most of the large cooking and combustion sources, under-reported the dust and humidifier sources, and missed sources with little mass above 0.3 μm particles. Sousan et al[38] also found the AirBeam under-reported road dust and welding aerosol. For ambient air measurements in May-June 2015, the AQ-SPEC evaluation reported a correlation of 0.66, slopes of 0.10-0.18, and an offset of 10 μg m^{-3} to adjust the 3 tested AirBeam monitors to match the regulatory monitor. We found no published reports of AirVisual performance.

The Air Quality Egg and Awair were correlated but greatly under-reported mass for large cooking and combustion sources, and largely missed dust and humidifier emissions and small particles from cooking. The AQ-SPEC evaluation of the Egg showed a quantitative response to ambient $PM_{2.5}$ measured in February-March 2016. The EPA found poor correlation between the Egg and reference monitors at an Atlanta area site in 2014-2015.[35]

The Foobot was highly correlated with quantitative responses for most of the large cooking and combustion sources. The response was correlated but sub-quantitative for cigarettes and quantitative or almost so for the humidifier and dust sources. The AQ-SPEC evaluation reported poor correlation (r^2 < 0.6) between the Foobot and reference monitor for ambient monitoring in July-September 2016. Sousan et al[38] reported linear correlations with quantitative agreement for salt (slope = 0.5) and road dust (slope = 0.7), but underreporting for welding aerosol (slope = 0.08).

The Purple Air was the monitor most correlated with the GRM, but the relative response varied in direction: sometimes higher, sometimes lower. The AQ-SPEC evaluation found the Purple Air to reliably and quantitatively report ambient PM in December 2016 and January 2017.

The Speck did not reliably respond across sources in any of the groups in this study and did not correlate reliably with reference measurements of ambient PM in April-June 2015 in the AQ-SPEC evaluation. Sousan et al[38] found the Speck greatly under-reported mass concentrations for salt and welding fumes, and over-reported road dust at concentrations below 300 μg m^{-3}.

4 | DISCUSSION

It is well established that the response of monitors based on light scattering varies as aerosol size distribution, composition, and optical properties vary. No single calibration can enable accurate performance for all particle sources in homes. This challenge applies to both research and consumer monitors. While gravimetric measurements may be used to determine a source- or environment-specific calibration for a research study, the approach is not practical for routine monitoring in homes. A key objective of continuous monitoring—to activate controls—can be achieved if the monitor reliably and clearly responds to sources that account for the majority of particles in the home even if responses are not quantitative.

In this study, 4 consumer grade aerosol monitors (AirBeam, AirVisual, Foobot, and Purple Air) provided quantitative (within a factor of 2) or nearly quantitative results for moderate to large emissions from common indoor particle sources including cooking with oils, recreational combustion, and dust suspension. These devices were not appreciably less accurate than 2 research grade aerosol photometers that were tested in the same experiments. This study did not evaluate performance over the durations of months to years that consumer monitors are likely to be used in homes. Research grade monitors utilize a sheath of filtered air around the sample stream to avoid deposition of particles onto the sensor components. As the low-cost sensors used in consumer monitors do not offer this feature, their sensitivity may degrade over time.

This study evaluated performance of the packaged consumer monitors, not the component sensors, for example, as evaluated by Wang et al.[40] Whereas at least one of the monitors—the Purple Air II—presents and records data provided directly from the component sensor, other monitors report using proprietary algorithms to set or update calibrations. The use of such algorithms may explain differences observed in results reported by monitors that use the same sensor. The AirBeam and Egg both use the Shinyei PPD sensor; yet the AirBeam consistently came much closer to the estimated true mass concentration. Likewise, Foobot provided measurements that were much closer than the Awair data to the true mass concentrations despite the 2 monitors using Sharp GP sensors.

For sources with mass distributions centered above 2.5 μm particles and having substantial mass in particles larger than 2.5 μm, the reported mass concentrations may depend greatly on the performance curve of the size-selective inlet and the sensitivity of the sensor to super-micron particles. The reference and research monitors used 4 different mechanisms to select for $PM_{2.5}$. The FDMS uses a virtual impactor. The filter samples used a PEM, which is a physical impactor. The BT and pDR use cyclones. The GRM assigns particles to size bins by analysis of the optical signal and the sensor used in the Purple Air appears to do the same. The other consumer monitors provide varied information about the size range of particles sampled, with some claiming to report $PM_{2.5}$ and others not specifying (Table 2), but none having a size-selective inlet. The devices that use scattering-based sensors likely measure particles larger than 2.5 μm diameter. Our study did not attempt to characterize performance

for mono-disperse aerosols of varying sizes; so our only window into that question is the overall responses of the devices to sources that had most of their $PM_{2.5}$ mass in super-micron particles. Figure 3 shows that the research monitors, Speck, and Foobot responded quantitatively to aerosols with larger particles except for the dust mop. The Egg, Awair, and Purple Air all had low responses.

An important caveat to the results presented here is that the consumer IAQ market is highly dynamic, both in terms of new products being introduced, and existing products being modified, for example by changing the component sensors or data processing algorithms. An industry standard test method and certification process to provide users with up-to-date information on monitor performance would be extremely valuable.

5 | CONCLUSIONS

This study compared time-resolved measurements reported by 7 consumer and 2 research grade optical aerosol monitors to estimates of the true mass concentrations resulting from common residential sources of fine particulate matter generated in a 120 m^3 laboratory. Four of the consumer monitors (AirBeam, AirVisual, Foobot, and Purple Air II) provided measurements that were time correlated and within a factor of 2 of estimated true concentrations for the majority of sources. Two monitors (Air Quality Egg and Awair) responded to most of the sources but the reported mass concentrations were much less than half of the estimated true values. One monitor (Speck) did not consistently respond to source emissions. Neither the consumer nor research monitors responded quantitatively to sources for which the emitted mass was almost entirely contained in particles smaller than 0.3 μm diameter.

The evaluated versions of the AirBeam, AirVisual, Foobot, and Purple Air II monitors were of sufficient accuracy and reliability in detecting large sources that they appear suitable for measurement-based control to reduce exposures to $PM_{2.5}$ mass in homes. The logical next steps in evaluating these monitors are to study their performance in occupied homes and to quantify their performance after months of deployment. These monitors are not suitable for detecting all sources of ultrafine particle emissions; however, as many sources of ultrafine particles also emit mass in particles above 0.3 μm diameter, the monitors could also help reduce ultrafine particle exposures.

ACKNOWLEDGEMENTS

Funding was provided by the U.S. Department of Energy Building America Program under DOE Contract No. DE-AC02-05CH11231; by the U.S. Department of Housing and Urban Development Office of Healthy Homes and Lead Hazard Control through Interagency Agreement I-PHI-01070; and by the U.S. Environmental Protection Agency Indoor Environments Division through Interagency Agreement DW-89-9232201-7. The authors thank Bill Roe of Grimm Technologies USA Operations for providing the Mini Wide-Range Aerosol Spectrometer for the duration of testing. Simon Walker assisted by executing many of the experiments and assisting with data capture. Iain Walker, Dustin Poppendieck, Rich Sextro, and Melissa Lunden provided helpful comments on the draft manuscript.

ORCID

B. C. Singer http://orcid.org/0000-0001-5665-4343

REFERENCES

1. US EPA. *Final Report: Integrated Science Assessment for Particulate Matter*. Washington, DC: U.S. Environmental Protection Agency; 2009.
2. Fortmann R, Kariher P, Clayton R. Indoor Air Quality: Residential Cooking Exposures. ARB Contract Number 97-330; Sacramento, CA: Prepared for California Air Resources Board; November 30, 2001; 2001.
3. Glytsos T, Ondracek J, Dzumbova L, Kopanakis I, Lazaridis M. Characterization of particulate matter concentrations during controlled indoor activities. *Atmos Environ*. 2010;44:1539-1549.
4. Hussein T, Glytsos T, Ondracek J, et al. Particle size characterization and emission rates during indoor activities in a house. *Atmos Environ*. 2006;40:4285-4307.
5. He CR, Morawska LD, Hitchins J, Gilbert D. Contribution from indoor sources to particle number and mass concentrations in residential houses. *Atmos Environ*. 2004;38:3405-3415.
6. Long CM, Suh HH, Koutrakis P. Characterization of indoor particle sources using continuous mass and size monitors. *J Air Waste Manag Assoc*. 2000;50:1236-1250.
7. Wallace L. Indoor sources of ultrafine and accumulation mode particles: size distributions, size-resolved concentrations, and source strengths. *Aerosol Sci Technol*. 2006;40:348-360.
8. Sarwar G, Corsi R. The effects of ozone/limonene reactions on indoor secondary organic aerosols. *Atmos Environ*. 2007;41:959-973.
9. Ozkaynak H, Xue J, Spengler J, Wallace L, Pellizzari E, Jenkins P. Personal exposure to airborne particles and metals: results from the particle team study in Riverside, California. *J Expo Anal Environ Epidemiol*. 1996;6:57-78.
10. Stabile L, Fuoco FC, Buonanno G. Characteristics of particles and black carbon emitted by combustion of incenses, candles and anti-mosquito products. *Build Environ*. 2012;56:184-191.
11. Afshari A, Matson U, Ekberg LE. Characterization of indoor sources of fine and ultrafine particles: a study conducted in a full-scale chamber. *Indoor Air*. 2005;15:141-150.
12. Fan CW, Zhang JJ. Characterization of emissions from portable household combustion devices: particle size distributions, emission rates and factors, and potential exposures. *Atmos Environ*. 2001;35:1281-1290.
13. Corsi RL, Siegel JA, Chiang C. Particle resuspension during the use of vacuum cleaners on residential carpet. *J Occup Environ Hyg*. 2008;5:232-238.
14. Ferro AR, Kopperud RJ, Hildemann LM. Source strengths for indoor human activities that resuspend particulate matter. *Environ Sci Technol*. 2004;38:1759-1764.
15. Morawska L, Afshari A, Bae GN, et al. Indoor aerosols: from personal exposure to risk assessment. *Indoor Air*. 2013;23:462-487.
16. Isaxon C, Gudmundsson A, Nordin EZ, et al. Contribution of indoor-generated particles to residential exposure. *Atmos Environ*. 2015;106:458-466.
17. Bhangar S, Mullen NA, Hering SV, Kreisberg NM, Nazaroff WW. Ultrafine particle concentrations and exposures in seven residences in northern California. *Indoor Air*. 2011;21:132-144.

18. Lunden MM, Delp WW, Singer BC. Capture efficiency of cooking-related fine and ultrafine particles by residential exhaust hoods. *Indoor Air*. 2015;25:45-58.
19. Fisk WJ, Chan WR. Health benefits and costs of filtration interventions that reduce indoor exposure to PM2.5 during wildfires. *Indoor Air*. 2017;27:191-204.
20. Batterman S, Du L, Mentz G, et al. Particulate matter concentrations in residences: an intervention study evaluating stand-alone filters and air conditioners. *Indoor Air*. 2012;22:235-252.
21. Zhao D, Azimi P, Stephens B. Evaluating the long-term health and economic impacts of central residential air filtration for reducing premature mortality associated with indoor fine particulate matter (PM2.5) of outdoor origin. *Int J Environ Res Public Health*. 2015;12:8448-8479.
22. Singer BC, Delp WW, Black DR, Walker IS. Measured performance of filtration and ventilation systems for fine and ultrafine particles and ozone in an unoccupied modern California house. *Indoor Air*. 2016;27:780-790.
23. Spilak MP, Karottki GD, Kolarik B, Frederiksen M, Loft S, Gunnarsen L. Evaluation of building characteristics in 27 dwellings in Denmark and the effect of using particle filtration units on PM2.5 concentrations. *Build Environ*. 2014;73:55-63.
24. Noble CA, Vanderpool RW, Peters TM, McElroy FF, Gemmill DB, Wiener RW. Federal reference and equivalent methods for measuring fine particulate matter. *Aerosol Sci Technol*. 2001;34:457-464.
25. MacNeill M, Kearney J, Wallace L, et al. Quantifying the contribution of ambient and indoor-generated fine particles to indoor air in residential environments. *Indoor Air*. 2014;24:362-375.
26. Kearney J, Wallace L, MacNeill M, Heroux ME, Kindzierski W, Wheeler A. Residential infiltration of fine and ultrafine particles in Edmonton. *Atmos Environ*. 2014;94:793-805.
27. Wallace LA, Wheeler AJ, Kearney J, et al. Validation of continuous particle monitors for personal, indoor, and outdoor exposures. *J Expo Sci Environ Epidemiol*. 2011;21:49-64.
28. Wallace L, Williams R, Rea A, Croghan C. Continuous weeklong measurements of personal exposures and indoor concentrations of fine particles for 37 health-impaired North Carolina residents for up to four seasons. *Atmos Environ*. 2006;40:399-414.
29. Noris F, Adamkiewicz G, Delp WW, et al. Indoor environmental quality benefits of apartment energy retrofits. *Build Environ*. 2013;68:170-178.
30. Morawska L, He CR, Hitchins J, Mengersen K, Gilbert D. Characteristics of particle number and mass concentrations in residential houses in Brisbane, Australia. *Atmos Environ*. 2003;37:4195-4203.
31. Sioutas C, Abt E, Wolfson JM, Koutrakis P. Evaluation of the measurement performance of the scanning mobility particle sizer and aerodynamic particle sizer. *Aerosol Sci Technol*. 1999;30:84-92.
32. Jiang RT, Acevedo-Bolton V, Cheng KC, Klepeis NE, Ott WR, Hildemann LM. Determination of response of real-time SidePak AM510 monitor to secondhand smoke, other common indoor aerosols, and outdoor aerosol. *J Environ Monit*. 2011;13:1695-1702.
33. Dacunto PJ, Cheng KC, Acevedo-Bolton V, et al. Real-time particle monitor calibration factors and PM2.5 emission factors for multiple indoor sources. *Environ Sci Process Impacts*. 2013;15:1511-1519.
34. Papapostolou V, Zhang H, Feenstra BJ, Polidori A. Development of an environmental chamber for evaluating the performance of low-cost air quality sensors under controlled conditions. *Atmos Environ*. 2017;171:82-90.
35. Jiao W, Hagler G, Williams R, et al. Community Air Sensor Network (CAIRSENSE) project: evaluation of low-cost sensor performance in a suburban environment in the southeastern United States. *Atmos Meas Tech*. 2016;9:5281-5292.
36. Williams R, Kaufman A, Hanley T, Rice J, Garvey S. *Evaluation of Field-Deployed Low Cost PM Sensors*. EPA/600/R-14/464 (NTIS PB 2015-102104); Washington, DC: U.S. Environmental Protection Agency; 2014.
37. Manikonda A, Zikova N, Hopke PK, Ferro AR. Laboratory assessment of low-cost PM monitors. *J Aerosol Sci*. 2016;102:29-40.
38. Sousan S, Koehler K, Hallett L, Peters TM. Evaluation of consumer monitors to measure particulate matter. *J Aerosol Sci*. 2017;107:123-133.
39. Holstius DM, Pillarisetti A, Smith KR, Seto E. Field calibrations of a low-cost aerosol sensor at a regulatory monitoring site in California. *Atmos Meas Tech*. 2014;7:1121-1131.
40. Wang Y, Li JY, Jing H, Zhang Q, Jiang JK, Biswas P. Laboratory evaluation and calibration of three low- cost particle sensors for particulate matter measurement. *Aerosol Sci Technol*. 2015;49:1063-1077.
41. Sousan S, Koehler K, Thomas G, et al. Inter-comparison of low-cost sensors for measuring the mass concentration of occupational aerosols. *Aerosol Sci Technol*. 2016;50:462-473.
42. ASTM E1827-11. *Standard Test Method for Determining Airtightness of Buildings Using an Orifice Blower Door*. West Conshohocken, PA: ASTM International; 2011. http://www.astm.org.
43. McKinney W. Data structures for statistical computing in python. In Python in Science Conference, Austin, TX; 2010.
44. Hasheminassab S, Pakbin P, Delfino RJ, Schauer JJ, Sioutas C. Diurnal and seasonal trends in the apparent density of ambient fine and coarse particles in Los Angeles. *Environ Pollut*. 2014;187:1-9.
45. Rodes C, Smith T, Crouse R, Ramachandran G. Measurements of the size distribution of aerosols produced by ultrasonic humidification. *Aerosol Sci Technol*. 1990;13:220-229.
46. Highsmith VR, Hardy RJ, Costa DL, Germani MS. Physical and chemical characterization of indoor aerosols resulting from the use of tap water in portable home humidifiers. *Environ Sci Technol*. 1992;26:673-680.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Singer BC, Delp WW. Response of consumer and research grade indoor air quality monitors to residential sources of fine particles. *Indoor Air*. 2018;28:624–639. https://doi.org/10.1111/ina.12463