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Laboratory assessment of low-cost PM monitors

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ABSTRACT

Recently, a number of optical particulate matter (PM) monitors employing low-cost PM sensors have become available on the consumer market. These portable low-cost monitors can be used to characterize PM concentrations with high spatial and temporal resolution. This study evaluates the performance of four low-cost PM monitors (Speck, Dylos, TSI AirAssure, and UB AirSense) against well-characterized reference instruments, and studies their suitability for PM field exposure studies. The low-cost monitors were characterized in a room-sized laboratory chamber with standard relative humidity and temperature conditions, with two PM sources: cigarette smoke and Arizona Test Dust. This study found that any of the monitors tested perform with adequate precision for monitoring air quality in an indoor microenvironment, although the field calibration of the monitor with a standard instrument for specific types of particles would be required. Other factors such as flexibility in data download methods, connectivity, compatibility with environmental conditions, and quality of technical support should also be considered when selecting low-cost PM monitors for human inhalation exposure assessment studies.

1. Introduction

The effects of particulate matter < 2.5 μm in diameter ($PM_{2.5}$) on human health, both morbidity and mortality, have been extensively studied over the past 15 years (USEPA, 2009). Particulate matter (PM) is reported to be a serious health hazard, causing cardiovascular and respiratory disease. As a result, many governments around the world have set air standards that define limits for PM concentrations that may not be exceeded (Vahlsing & Smith, 2012) and have established compliance monitoring networks to determine the ambient air quality relative to those standards. Monitoring for particulate matter generally involves the collection of integral filters or using relatively expensive equipment such as beta attenuation monitors (BAM) or tapered element oscillating microbalances (TEOM), which limited the quality of spatial distribution of ambient PM data (Wang et al., 2015). Recently, relatively low-cost ($200–$600), easy-to-use, portable PM monitors, employing available off-the-shelf sensors, have become available on the consumer market.

PM monitors can be categorized into those that measure either mass concentration or number concentration. PM mass can be measured directly by changes in the penetration of electrons through the sample (BAM) (Krost, Sawicki, & Bell, 1977), changes in frequency of an oscillating sensor element (Paprotny, Doering, Solomon, White, & Gundel, 2013; Patashnick & Rupprecht, 1991; Snyder et al., 2013), or indirectly based by light scattering, with the particle diameter estimated by the amount of scattered light (Snyder et al., 2013). Currently, only the light scattering systems can be produced inexpensively.

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These low-cost monitors have recently gained attention because they can increase our ability to characterize PM concentrations with high spatial and temporal resolution at an acceptable cost since many such devices can be deployed concurrently (Holstius, Pillarisetti, Smith, & Seto, 2014). Commercially available devices include the Speck (Airviz Inc., Pittsburgh, PA) and the Dylos 1100 Pro/Dylos 1700 (Riverside, CA).

Recent studies have characterized the performance of low-cost PM monitors. Williams, Kaufman, Hanley, and Rice (2014) characterized the initial version of the Speck monitor and the Dylos DC1100 monitor. The study showed that Speck did not correlate well with the reference instrument ($R^2=10^{-5}$), a Grimm model EDM180 dust monitor (Federal Equivalent Method, FEM), but the Dylos monitor compared well with the Grimm EDM180 ($R^2=0.533$). For other studies, comparisons were not made with FEM, but with other research instruments. For example, Wang et al. (2015) characterized three low-cost PM sensors: Shinyei PPD42NS, Samyoung DSM501A, and Sharp GP2Y1010AU0F. They found that all three sensors demonstrated high linearity with a TSI (Shoreview, MN) SidePak AM510 Model AM-510 Personal Aerosol Monitor, and their output was highly dependent on particle size and composition. Dacunto et al. (2015) provided $PM_{2.5}$ calibration curves for the Dylos DC1100 from a set of 64 experiments using common indoor particle sources for which the Dylos DC1100 was collocated with the TSI SidePak and found a wide range of calibration factors based on source type. A validation study of two continuous particle monitors measuring $PM_{2.5}$, including the TSI DustTrak 8520 and a Thermo Scientific (Waltham, MA) personal DataRAM was carried out by Wallace et al. (2010), and demonstrated that the two instruments were in reasonable agreement with gravimetric $PM_{2.5}$ measurements. Sousan et al. (2016) evaluated the performance of the Dylos DC1700 monitor and two Sharp sensors in measuring different aerosols at high concentrations. They demonstrated that all the three sensors had high regression ($R^2>0.97$) when the sensor output was compared to the mass concentrations measured with a pDR-1500, and after calibration, all the sensors showed high precision. Budde, Busse, and Beigl (2012) compared different commercial-off-the-shelf PM sensors, including the Sharp GP2Y1010AU0F and Syhitech DSM501A. They report that although there was general correspondence of the sensor responses to reference methods, they were not sufficiently accurate for use as compliance monitors. However, they could be adequate for high spatial/temporal monitoring over extended time intervals where the volume of data produced provides useful information. Thus, the use of these inexpensive air quality monitors to control air quality and characterize the effect of air quality in different microenvironments on personal exposure remains a challenge.

In this study, a series of measurements were made with current low-cost PM monitors to investigate and compare their accuracy and precision for the measurement of particulate matter relative to the well-characterized reference instruments, and their suitability for PM exposure field studies.

2. Methods

Four low-cost PM monitors were obtained and evaluated in this study: Speck (Airviz Inc., Pittsburgh, PA), Dylos 1100 Pro/Dylos 1700 (Riverside, CA), AirAssure $PM_{2.5}$ IAQ Monitor (TSI Inc., Shoreview, MN) and AirSense (Buffalo, NY).

2.1. Study location and parameters

Laboratory experiments were performed in Clarkson University's Indoor Air Quality Chamber with dimensions of 2.24 m wide, 3.91 m long and 2.44 m high. The mixing volume of the chamber is 21.37 m^3. The chamber was built with standard residential materials (wood, drywall). The air flow rate was previously determined to be 0.01 air changes per hour under passive ventilation conditions. The chamber has a HVAC system installed, but the system was switched off during the experiment. The aerosol generator was placed in the corner of the chamber. The test monitors were collocated in the center of the chamber with three well-characterized reference instruments, a Grimm 1.109 (Grimm Technologies), an APS 3321 (TSI Inc.) and an FMPS 3091 (TSI Inc.).

Table 1
Specifications of test monitors according to the manufacturer's data sheets.

Monitor (Sensor)	Measuring principle	Size fraction	Limit of detection	Units of measurement	Power accessory	Data retrieval	Number of units tested
Speck (Syhitech DSM501A)	LED optical sensor	0.5–3 μm	NR	#/L or $\mu g/m^3$	Mini-USB	USB or WI-FI upload to web-based account	2
Dylos 1100 PRO/Dylos 1700	Laser particle counter	> 0.5 μm > 2.5 μm	NR	#/ft^3	AC Adapter	9 pin serial cable	1 each
TSI AirAssure (Sharp GP2Y1010AU0F)	Light scattering photometer	NR	5–300 $\mu g/m^3$	$\mu g/m^3$	24 VDC cable	WI-FI	3
UB AirSense (Sharp GP2Y1010AU0F)	IR optical sensor	NR	NR	$\mu g/m^3$	9 V Battery	SD Card	1

NR: not reported.

Fig. 1. Monitors used in this study: (a) Speck (https://www.specksensor.com/), (b) Dylos 1700 (http://www.dylosproducts.com/), (c) TSI AirAssure (http://www.tsi.com/airassure-pm2-5-indoor-air-quality-monitor-en/), and (d) UBAS (photo taken from a manual).

The inlets of the devices were approximately one meter away from the aerosol generator, and the devices were within 30 cm from each other. An overhead fan was operating throughout the experiment to completely mix the aerosol inside the chamber. Manthena (2010) characterized the mixing rates inside the chamber using a tracer gas (SF_6) in six locations for different scenarios, including with the overhead head fan switched on and off. She estimated that with the overhead fan on, the concentration in the center area of chamber, where the monitors were located for this study, becomes uniform within a few minutes after the source is shut off. The well-mixed aerosol lowers the significance of the particle losses to the surfaces since all the monitors and reference instruments were challenged to the same aerosol.

2.2. Particle generation

Cigarette smoke was generated using a CH Technologies' Single Cigarette Smoking Machine (CSM-SCSM) (Westwood, NJ). The ISO 12103-1 A1 Ultrafine Test Dust (Arizona Test Dust or ATD; Powder Technology, Inc., South Burnsville, MN) was generated using Topas Dust Generator (model SAG 410) (Dresden, Germany). The cigarette smoke particles had a geometric mean diameter of 328.3 nm and a standard deviation of 1.524 (Li & Hopke, 1993). The ATD particles are in the size range of 0.1–10 μm, with a size distribution in 0.8–10 μm range, and are composed of 68–76% SiO_2, 10–15% Al_2O_3, 2–5% Fe_2O_3 and CaO, and other metal oxides (PTI Inc., 2014). Two experiments were conducted using cigarette smoke, and one experiment used ATD as the test particles.

For each experiment, the PM source was operated in short pulses of approximately 20 s duration until a peak concentration was reached. The generation was then discontinued and the particles were allowed to equilibrate inside the chamber. The next pulse was emitted when the particle concentration decayed by particle deposition and exfiltration to approximately 2 $\mu g/m^3$ and was constant for approximately 15 min. Three such pulses were generated in each experiment. Ancillary variables such as temperature and the relative humidity inside the chamber were monitored.

2.3. Monitor selection

Table 1 lists the low-cost test monitors evaluated in this study, their measuring principle, sensor type etc. The optical monitors are based on the same operation principle; a light beam is emitted into a chamber, light is scattered by the particles present, and the scattered light intensity is detected (Budde et al., 2012). The Syhitech and also Sharp sensor showed a saturation concentration of 4 mg/m^3 (Wang et al.,2015), but such concentration was not reached during any of the experiment. All of the monitors were newly acquired for this study. Each of the monitors is described below, and also shown in Fig. 1.

Speck (Airviz Inc., 2015): Speck is a product of Airviz Inc., and was developed in the CREATE Lab at the Carnegie Mellon University Robotics Institute. The Speck reports airborne particle concentration in both counts and mass per volume. The Speck employs a Syhitech DSM501A sensor, which is a LED based particle counter. The PM data from the Speck can be retrieved by downloading directly via the Speck Chrome application, or the monitor can connect to WI-FI and the data can be accessed from the specksensor.com account. The monitor has a sampling interval from 5 s to 4 min, with a default value of 1 min. The Speck uses its WI-FI connection to correct its internal clock. An earlier version of Speck was tested by the EPA, and was found to be poorly correlated with a Grimm EDM180 dust monitor, with the data containing groupings of very small values interspersed with large spikes, most of which could not be explained (Williams et al., 2014). The Speck has been upgraded since then, including changing the sensor from a Shinyei PPD42NS to the DSM501A, increasing the averaging time, and improving the mass estimation algorithm (I. Nourbakhsh, personal communication, 2015). The updated Speck version 3 was tested in this study.

Dylos 1100 PRO (Dylos Corporation, 2008) **and Dylos 1700** (Dylos Corporation, 2013): The Dylos Air Quality Monitors are laser particle counters with two size channels, particle diameters (D_p) 2.5 μm or larger (large channel), and 0.5 μm or larger (small channel). The two size channels are estimated from the signal and are not true size fractions based on size-selective sampling (Northcross et al., 2013). The $PM_{2.5}$ particles counts can be approximated by subtracting the counts reported in the >2.5 μm channel, from the counts in the >0.5 μm channel (Williams et al., 2014). The Dylos 1700 and the Dylos 1100 Pro have identical sensors, but the 1700 monitor records the time-stamp of the data being stored, while the 1100 Pro does not record the time-stamp unless it is connected to a PC. The Dylos monitors have an average sampling interval of 1 min, and requires a 9 pin serial cable or USB-to-COM port to connect to the PC and download the data. The time and date for Dylos monitors can be adjusted manually.

TSI AirAssure (TSI Inc, 2015): The AirAssure uses a Sharp GP2Y1010AU0F sensor (Sharp Corporation, 2006) to measure mass concentrations of particles less than 2.5 μm in diameter. The particles pass through the sensor by convective flow, via a fan attached to the side of the monitor. The data output is in terms of mass concentrations in the range from 5 to 300 μg/m^3, with concentrations above this upper limit reported as 300 μg/m^3. The AirAssure monitor needs to connect to WI-FI to access the data, reported as a 5 min trailing averages.

UB AirSense (W. Xu, personal communication, 2015): UB AirSense (UBAS) is a prototype air monitor being developed by Dr. Wenyao Xu and his group at University of Buffalo, New York. Like the AirAssure, the AirSense employs a Sharp GP2Y1010AU0F sensor (Sharp Corporation, 2006) with an infrared emitting diode to detect and measure the particulate matter concentration. The system also includes a GPS sensor, accelerometer sensor and temperature and relative humidity sensor. The sensor estimates particle concentrations in terms of mass, and stores data on an SD card. The device will update its time stamp when connected to a GPS signal. The prototype that was evaluated for this study was a passive device, without a mechanism to move the particles to the sensor.

2.4. Methods

2.4.1. Precision of measurements

The relative precision of the monitors measuring the same aerosol was defined using the normalized Root Mean Square Error (nRMSE) between the two monitors (A and B) of the same type.

$$\mathrm{nRMSE} = \frac{\sqrt{\mathrm{Mean}(A-B)^2}}{\mathrm{Mean}(A+B)/2} \tag{1}$$

where A is the concentration recorded by monitor A and B is the concentration recorded by monitor B for a given time interval, and Mean(A+B) is the mean concentrations of (A+B) over all the measurements. Smaller values of nRMSE denote better precision between the monitors.

2.4.2. Aerodynamic diameter to optical diameter

An adjustment was applied to the APS 3321 data to convert the aerodynamic diameter to the associated optical diameter (Murphy, Cziczo, Hudson, Schein, & Thomson, 2004).

$$D_{opt} = D_a/(\rho)^{0.5} \tag{2}$$

where D_{opt} is the optical diameter, D_a is the aerodynamic diameter and ρ is the mean particle density. The density of cigarette smoke was assumed to be 1180 kg/m^3 (Johnson et al., 2014), and the density of ATD particles was reported to be 2650 kg/m^3 (PTI Inc., 2014).

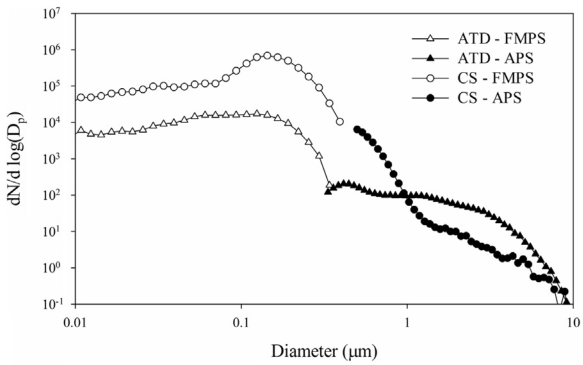

Fig. 2. Number-based size distributions of Arizona Test Dust (ATD) and cigarette smoke (CS) as measured by FMPS 3091 and APS 3321.

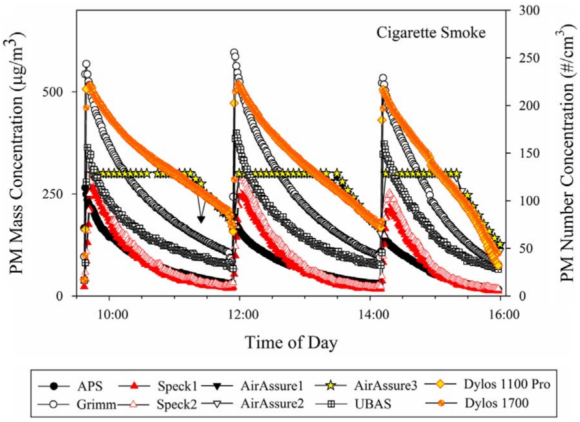

Fig. 3. Concentration time-series from the experiment using cigarette smoke source. Dylos 1100 Pro and Dylos 1700 data reported in #/cm^3 (right axis). All other monitor data reported in μg/m^3 (left axis).

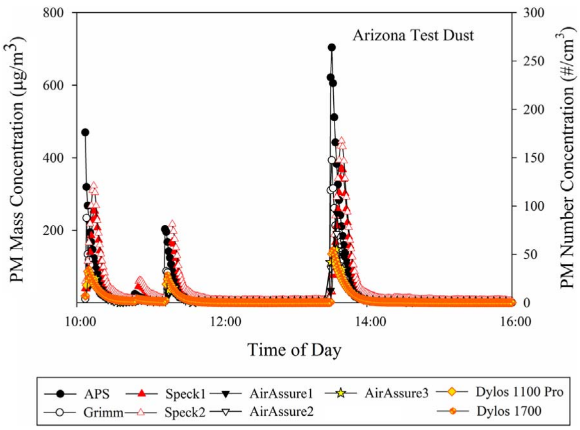

Fig. 4. Concentration times-series from the experiment using ATD source. Dylos 1100 Pro and Dylos 1700 data reported in #/cm^3 (right axis). All other monitor data reported in μg/m^3 (left axis).

Table 2
Summary of nRMSE values between same type low-cost monitors.

Particle type	Monitor A	Monitor B	nRMSE
Cigarette smoke	Speck1	Speck2	0.223
	Dylos 1100 Pro	Dylos 1700	0.134
	AirAssure1	AirAssure2	0.026
		AirAssure3	0.040
ATD	Speck1	Speck2	0.527
	Dylos 1100 Pro	Dylos 1700	0.461
	AirAssure1	AirAssure2	0.969
		AirAssure3	1.182

3. Results

3.1. Size distribution

Particle size distributions of cigarette smoke and ATD particles were characterized using the FMPS 3091 and APS 3321. The number size distributions were estimated by averaging the measurements taken 1 min after the emission event. As shown in Fig. 2, cigarette smoke has an accumulation mode prevailing at a mode diameter of 131 ± 1 nm. This compares well with the mode diameter of the mainstream cigarette smoke particles measured by Okada and Matsunuma (1974).

Table 3
Summary of linear and non-linear regression fits between test monitors and APS 3321.

	Instrument		Counts		Mass	
			Regression	R^2	Regression	R^2
Cigarette smoke	Speck1		$y=0.0019x-1.1$	0.94	$y=1.6x-35$	0.92
	Speck2		$y=0.0023x-1.2$	0.95	$y=1.8x-35$	0.92
	Dylos 1100 Pro	Linear	$y=0.054x+50$	0.93	$y=0.95x+67$	0.88
		Non-Linear	$y=22.92+0.09x-(1*10^{-5})x^2$	0.86	$y=30.10+1.99x-0.0056x^2$	0.96
		PM_{10}	$y=0.046x+61.56$	0.72	$y=0.70x+77.65$	0.67
	Dylos 1700	Linear	$y=0.052x+57$	0.93	$y=0.89x+73$	0.87
		Non-Linear	$y=27.14+0.10x-(1*10^{-5})x^2$	0.94	$y=38.86+1.86x-0.0052x^2$	0.93
		PM_{10}	$y=0.044x+66.75$	0.75	$y=0.68x+82.21$	0.70
	AirAssure1		NA	NA	$y=3.1x+107$	0.45
	AirAssure2		NA	NA	$y=7.7x-7.3$	0.99
	AirAssure3		NA	NA	$y=2.8x+122$	0.42
	UBAS		NA	NA	$y=1.6x+40$	0.85
	Grimm		$y=1.7x+856$	0.99	$y=2.5x+53$	0.89
ATD	Speck1		$y=181.3x-69.91$	0.96	$y=2x+2.9$	0.96
	Speck2		$y=210.2x-37.13$	0.96	$y=2.3x+5.3$	0.96
	Dylos 1100 Pro	Linear	$y=0.41x-0.11$	0.95	$y=0.1x+0.91$	0.94
		Non-Linear	$y=-0.65+0.57x-0.0023x^2$	0.81	$y=0.42+0.15x-(1.54*10^{-4})x^2$	0.82
		PM_{10}	$y=0.47x-0.26$	0.99	$y=0.094x+2.1$	0.89
	Dylos 1700	Linear	$y=0.44x-0.084$	0.87	$y=0.11x+0.99$	0.93
		Non-Linear	$y=-0.83+0.66x-0.0029x^2$	0.76	$y=0.42+0.17x-(1.85*10^{-4})x^2$	0.78
		PM_{10}	$y=0.52x-0.34$	0.95	$y=0.10x+2.27$	0.85
	AirAssure1		NA	NA	$y=0.45x+3.24$	0.98
	AirAssure2		NA	NA	$y=0.30x+3.4$	0.94
	AirAssure3		NA	NA	$y=0.41x+1.56$	0.98
	Grimm		$y=4.1x+2.1$	0.99	$y=0.51x-0.42$	0.98

Additional modes at 33 nm and 56 nm are also visible. The size distribution for ATD shows three distinct modes, with peaks at 146 ± 1 nm, 427 ± 3 nm and 1.22 ± 0.02 μm respectively. Vlasenko, Sjögren, Weingartner, Gäggeler, and Ammann (2005) observed that the number mode diameter of the ATD dust aerosol was 140 nm, when measured using a scanning mobility particle sizer in tandem with a Grimm 1.108.

3.2. *Concentration time series*

The concentration time-series data for the low-cost monitors and the reference instruments measuring cigarette smoke and ATD emissions are shown in Figs. 3 and 4, respectively. The concentration recorded by each instrument increases during the generation period and decays over time until the next generation period. The Dylos 1100 Pro and 1700 only report particle counts, so the time-series data for these monitors have been presented as number concentrations, while the other monitors are presented as mass concentrations.

For the cigarette smoke time-series, shown in Fig. 3, concentrations reported by the Grimm 1.109 for particles >0.25 μm were consistently higher than the other monitors. The APS 3321, which measures particles larger than 0.5 μm in diameter, reported much lower concentrations. The APS 3321 also reported lower concentrations than the low-cost monitors, for approximately the first hour after the particles were generated.

Table 2 provides a summary of the nRMSE values between the same type of low-cost monitor for both particle types. For the cigarette smoke, the Speck monitors displayed moderate relative precision, with Speck2 having an nRMSE value of 0.223 with respect to Speck1. Both the Speck monitors reported concentrations higher than the APS 3321. The AirAssure monitors reported multiple data points at 300 μg/m^3, its maximum cut-off value. All three AirAssure monitors showed good precision, AirAssure2 had an nRMSE of 0.026 and AirAssure3 had an nRMSE of 0.040, with respect to AirAssure1. The UBAS monitor reported higher concentrations compared to the Speck monitors. Both the Dylos 1100 Pro and the Dylos 1700 showed moderate relative precision, with the Dylos 1700 having an nRMSE of 0.134 compared to Dylos 1100 Pro.

For the ATD time-series data, shown in Fig. 4, concentrations reported by the APS 3321 were higher compared to the other monitors, while the Grimm 1.109 reported lower concentrations compared to the APS 3321 (mean concentration measured by Grimm 1.109 was 6.4 μg/m^3, while APS 3321 measured 13.8 μg/m^3). One of the Speck monitors (Speck2) reported about 30% higher peak concentrations compared to the other Speck monitor, but at lower concentrations they both showed moderate precision (nRMSE=0.527). Similar to the cigarette smoke results, both the Dylos monitors displayed moderate precision (nRMSE=0.461) while measuring ATD concentrations. The three AirAssure monitors reported up to 50% lower peak concentrations compared to the APS 3321. The AirAssure monitors displayed poor relative precision; AirAssure2 had an nRMSE of 0.969 and AirAssure3 had an nRMSE of 1.182 compared to AirAssure1. The UBAS did not record any data during the measurement of ATD emissions because of an operator error.

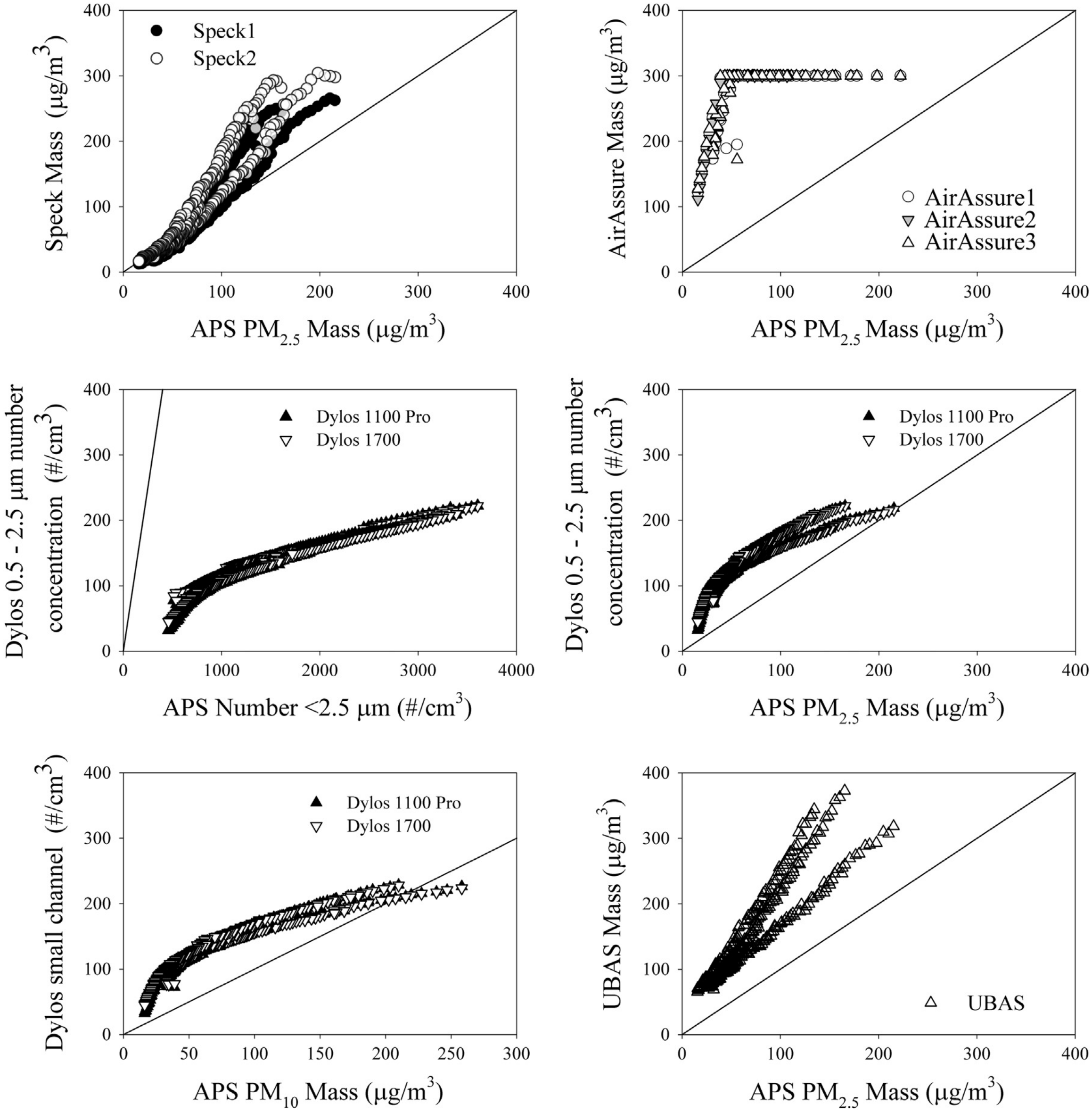

Fig. 5. Scatter plots between APS 3321 and tested low-cost monitors for cigarette smoke emissions. Speck, AirAssure, and UBAS monitor results were compared to $PM_{2.5}$ mass, Dylos monitor results compared to $PM_{2.5}$ number concentration and PM_{10} mass.

3.3. Linear and non-linear relations

The low-cost PM monitors tested have a stated lower size limit of detection (LOD) of 0.5 µm, which is in the range of the Grimm 1.109 and APS 3321 measurements, but near the upper limit of the measurement range of the FMPS 3091. Because the Grimm 1.109 and the APS 3321 do not directly measure particle mass concentrations, but use different properties of the aerosol to estimate the mass concentrations, the measurements made by these two instruments were compared as a check on their performance for the aerosol types used in this study. A true mass-based measurement for each aerosol type would be needed to confirm the accuracy of the instruments. Grimm 1.109 and APS 3321 display high correlation (R^2=0.89–0.99, Table 3) for both the PM types, as shown in Fig. S1 in Supplemental Information. Section S1 in Supplemental Information discusses the changes in the regression between different runs when the Grimm 1.109 and APS 3321 were measuring mass concentration of cigarette smoke. For the purposes of this paper, the PM test monitors were correlated with the APS 3321 as a reference. Comparisons of the low-cost monitors with the Grimm 1.109 are similar to those with the APS 3321 due to the high correlation of the two reference instruments.

Figure 5 summarizes the scatter plots between cigarette smoke mass concentrations reported by the test monitors and the $PM_{2.5}$ mass concentrations reported by APS 3321. The Dylos monitors only report particle number concentrations, so the

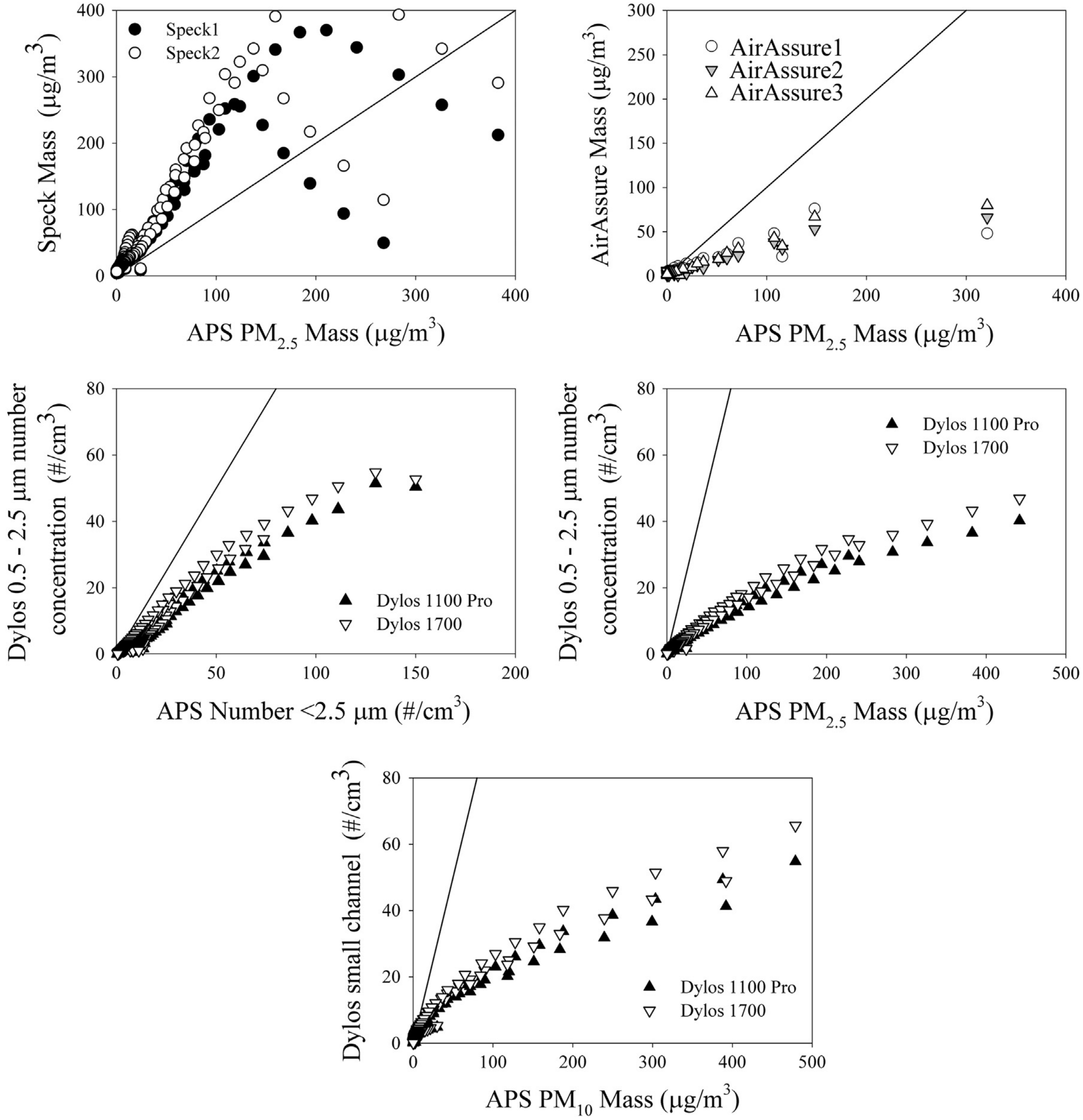

Fig. 6. Scatter plots between APS 3321 and tested low-cost monitors for ATD emissions. Speck, AirAssure, and UBAS monitor results were compared to $PM_{2.5}$ mass, Dylos monitor results compared to $PM_{2.5}$ number concentration and PM_{10} mass.

comparison was made with both the number concentration (<2.5 μm) and the estimated $PM_{2.5}$ mass concentration data from the APS 3321. The number concentration data from the >0.5 μm channel of the Dylos monitors was also compared to the number concentrations (<10 μm) and the PM_{10} mass concentrations reported by the APS 3321.

High correlations were found between the Speck, Dylos, and UBAS monitors and the APS 3321 (R^2=0.85–0.92, Table 3), while the correlations between the small channels of the Dylos monitors and APS 3321 were moderate (R^2=0.67–0.75, Table 3). Correlations between two of the AirAssure monitors and the APS 3321 were low (R^2=0.45–0.42, Table 3), but one of the AirAssure monitors (AirAssure2) had a high correlation (R^2=0.99, Table 3). However, AirAssure2 only measured over one decay period, because of connectivity issues and so there are significantly fewer data points.

Figure 6 shows the scatter plots between all the test monitors and the APS 3321 for the ATD experiments. Similar to the cigarette smoke correlations, the Dylos monitors were compared to the mass and number concentration data reported by the APS 3321, and the counts data from the >0.5 μm channel was compared to particle and mass concentrations. High correlations were found between the Speck, AirAssure, and Dylos monitors and the APS 3321 (R^2=0.93–0.98, Table 3). The correlations between the small channels of the Dylos monitors and APS 3321 were also found to be high (R^2=0.85–0.99, Table 3).

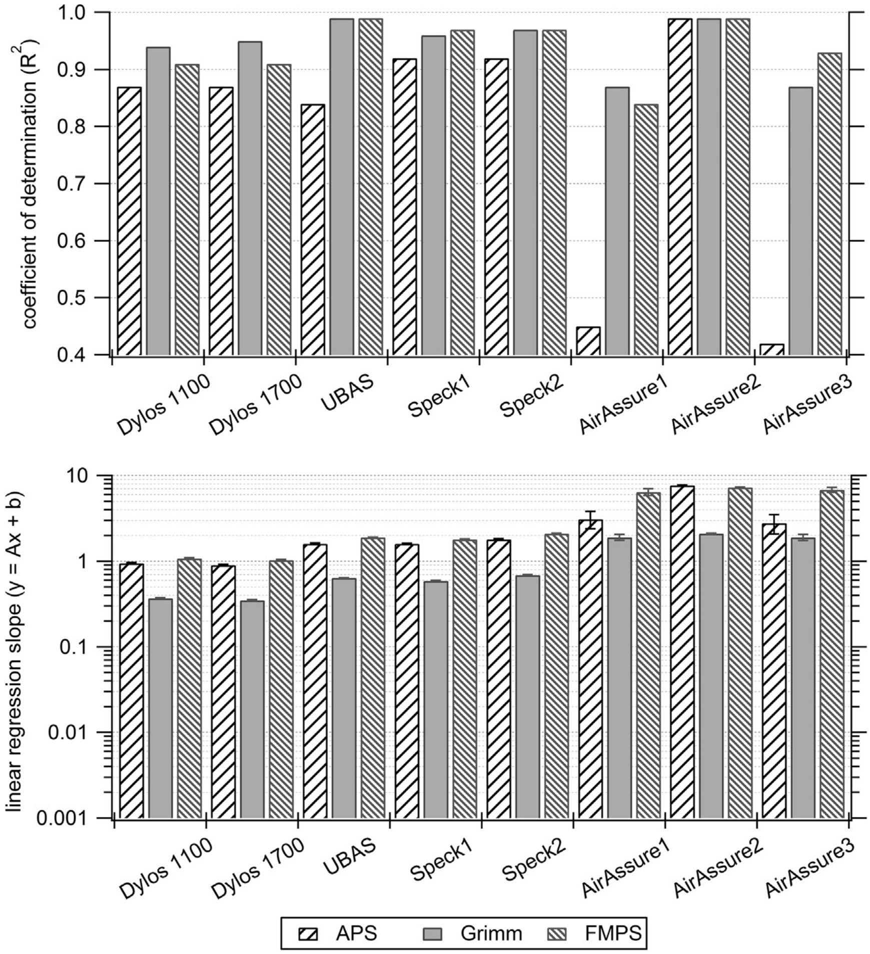

Fig. 7. Comparison of regression values from linear regression between monitors and reference instruments for cigarette smoke emissions. Error bars show standard error for the slope estimation.

Table 3 provides the summaries of correlations between the monitors and the APS 3321 for both the cigarette and ATD emissions for both particle count and estimated particle mass concentrations, when available. The Dylos monitors exhibited a non-linear relationship when compared with the reference instruments. Thus, the results for both linear and non-linear (second order polynomial) fits are also provided in Table 3.

The relative accuracy of the monitors measuring the PM types can be estimated by comparing the linear regression with the APS 3321. For the Speck monitors, the reported mass concentrations were comparable to the mass concentrations from the APS 3321 (slope = 1.6–2.3), for both PM types. The UBAS and Dylos measurements were comparable to mass concentrations measured by the APS 3321 for cigarette smoke (slope = 0.89–1.6), while the ATD concentrations from the Dylos monitors were underestimated by approximately an order of magnitude (slope = 0.10–0.11). However, when the particle number concentrations from the Dylos monitors and the APS 3321 were compared, the Dylos monitors were found to underestimate the cigarette smoke concentration by a factor of 10–20 (slope = 0.05–0.10), and the ATD concentrations by approximately a factor of two (slope = 0.41–0.44). The Speck monitors underestimated the particle number concentration for cigarette smoke by three orders of magnitude (slope = 0.0019–0.0023), while the AirAssure monitors underestimated the ATD concentrations by a factor of three (slope = 0.30–0.45). The small channel of the Dylos monitors were found to underestimate the particle number ($< 10\ \mu m$) concentrations and the PM_{10} concentrations reported by the APS 3321 (slope = 0.044–0.70). The AirAssure monitors were found to overestimate the cigarette smoke concentrations by an average of a factor of five (slope = 2.8–7.7), while the Speck monitors overestimated the ATD particle number concentration by two orders of magnitude (slope = 180–210).

Figure 7 compares the coefficient of determination and the linear regression slopes from the correlations between the low-cost PM monitors measuring cigarette smoke and the three reference instruments, the APS 3321, the Grimm 1.109 and the FMPS 3091. The Speck and the Dylos monitors show high correlations (0.87–0.97) with all the three reference instruments; while the AirAssure monitors show high correlation with the Grimm 1.109 and the FMPS 3091 (0.84–0.99),

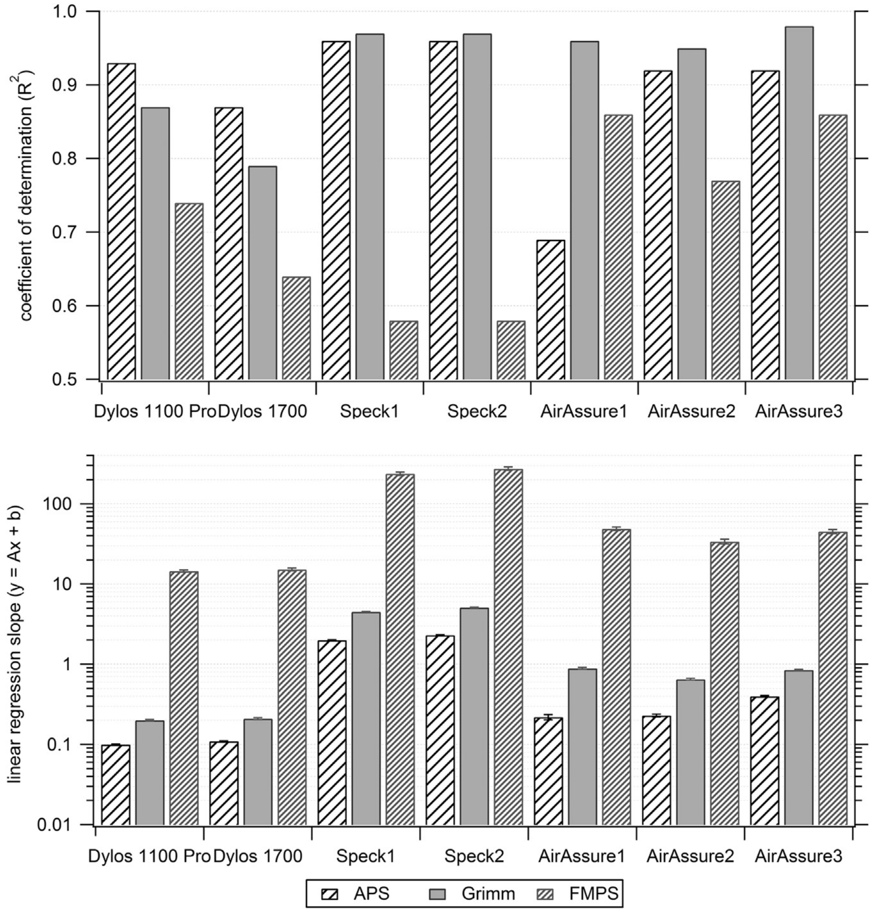

Fig. 8. Comparison of regression values from linear regression between monitors and reference instruments for ATD emissions. Error bars show standard error for the slope estimation.

correlation with the APS 3321 was moderate (<0.5 for two of the three units). The UBAS reported high correlation with all the three reference instruments, with coefficient of determination greater than 0.9.

Figure 8 compares the coefficient of determination and the linear regression slopes from the correlations between the low-cost PM monitors measuring ATD concentrations and the three reference instruments. All the monitors measuring ATD concentrations reported high correlations when compared to APS 3321 and Grimm 1.109 (mostly over 0.9), while the correlation with FMPS 3091 was low for the Specks (0.58), and moderate for the Dylos and the AirAssure monitors (>0.7). All of the monitors, with the exception of the Specks, underestimated the ATD concentrations when compared to the APS 3321 and the Grimm 1.109, with slopes between 0.1 and 0.89.

4. Discussion and conclusions

This study evaluated the precision and accuracy of four low-cost test monitors measuring two different PM types. Their response was compared to three reference instruments. The lack of precision among different monitors can be attributed to factors including the different wavelengths, orientation of the light source and the detector, the mode of particle transfer from the inlet to the sensor, and the air flow rate of the different instruments. The results may be also influenced by relatively small (1–3) number of units tested. The non-linear relationship exhibited by the Dylos monitors may be the result of the Dylos being a dual channel monitor, and the $PM_{2.5}$ particle counts were approximated by subtracting the counts reported in the >2.5 μm channel from the >0.5 μm channel.

Along with the performance of the low-cost test monitors compared to the reference instruments, other factors such as connectivity, data storage, data download, etc. can also be considered while choosing a low-cost monitor. The Speck has a large data buffer, with two years of onboard storage and unlimited online storage. It is possible to view the data in real time using the specksensor.com account. The Dylos has an onboard data storage of one week, and the data cannot be viewed in real time, while the AirAssure monitor from TSI Inc. does not have onboard storage. The data uploads directly to a web-based server, and can be viewed in real-time. The Speck, AirAssure and the Dylos monitors have a screen built-in, which provides the user with second-by-second readouts of PM levels. The Speck and the AirAssure monitors also have an air quality index (AQI) display, which changes color depending on the $PM_{2.5}$ concentrations. However, because the AQI established by the Environmental Protection Agency (EPA) for $PM_{2.5}$ is based on 24-h averaging times for measurements using FEM methods, the 1-min measurements can only be approximately compared to the AQI.

A major limitation relevant to the aim of this study is that the experiments were carried out in an indoor chamber, with relatively constant temperature and relative humidity conditions, and a single particle source at a time, representing a best case scenario. The performance of these monitors will be affected if these monitors are placed in an outdoor micro-environment, with varying temperature and relative humidity conditions. Hygroscopic growth by the particles increases their size and can cause an overestimation of the particle mass concentrations. Thus, high relative humidity may lead to biased measurements (Burkart et al., 2010; Grimm & Eatough, 2009; Wang et al., 2015). The performance and the response of the monitors also depend upon the composition of the particles. The intensity of the scattered radiation is not simply related to aerosol mass concentration, rather it is a function of the size distribution parameters, aerosol density and the index of refraction (Heintzenberg & Charlson, 1996). The response of these test monitors will also depend on the algorithms used for processing the signal from the detector or the phototransistor. The monitors also use a pre-defined algorithm to convert the particle number concentration, which is determined optically, to a mass concentration, without knowledge of the composition or density of the particles.

Based on the above results, any of the low-cost PM monitors would appear to perform with adequate precision for estimating PM exposures over time and space. Their advantage is that a sufficient number of them can be deployed to support better estimates of the variation in PM relative to a central site monitor. If properly calibrated, they could provide useful exposure estimates for health effects studies. The compact size of these monitors favor their wide application in PM field exposure studies. Other factors such as flexibility in data download, connectivity, cost, responsiveness and quality of technical support, and location of the study can be taken into consideration while choosing the test monitors for a particular application.

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Appendix A. Supplementary information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jaerosci.2016.08.010.

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