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Determining $PM_{2.5}$ calibration curves for a low-cost particle monitor: Common indoor residential aerosols

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Abstract

Real-time particle monitors are essential for accurately estimating exposure to fine particles indoors. However, many such monitors tend to be prohibitively expensive for some applications, such as a tenant or homeowner curious about the quality of the air in their home. A lower cost version (the Dylos Air Quality Monitor) has recently been introduced, but it requires appropriate calibration to reflect the mass concentration units required for exposure assessment. We conducted a total of 64 experiments with a suite of instruments including a Dylos DC1100, another real-time laser photometer (TSI SidePak^{TM} Model AM-510 Personal Aerosol Monitor), and a gravimetric sampling apparatus to estimate Dylos calibration factors for emissions from 17 different common indoor sources including cigarettes, incense, fried bacon, chicken, and hamburger. Comparison of minute-by-minute data from the Dylos with the gravimetrically calibrated SidePak yielded relationships that enable the conversion of the raw Dylos particle counts less than 2.5 µm (in #/0.01 ft^3) to estimated PM$_{2.5}$ mass concentration (e.g. µg/m^3). The relationship between the exponentially-decaying Dylos particle counts and PM$_{2.5}$ mass concentration can be described by a theoretically-derived power law with source-specific empirical parameters. A linear relationship (calibration factor) is applicable to fresh or quickly decaying emissions (i.e., before the aerosol has aged and differential decay rates introduce curvature into the relationship). The empirical parameters for the power-law relationships vary greatly both between and within source types, although linear factors appear to have lower uncertainty. The Dylos Air Quality Monitor is likely most useful for providing instantaneous feedback and context on mass particle levels in home and work situations for field-survey or personal awareness applications.

Keywords: fine particles, real-time monitoring, human exposure, calibration factors, power law relationship

Environmental Impact

Assessment of exposure to $PM_{2.5}$ is important for identifying health hazards and estimating health risk from indoor sources, due to the large proportion of time people spend indoors. Use of a low-cost, real-time particle monitor can facilitate awareness and broad characterization of instantaneous exposures to cigarettes, incense, and cooking sources such as frying chicken, bacon, and hamburger. The calibration factors presented here could enable these monitors to provide approximate peak $PM_{2.5}$ mass concentration in indoor settings where sources are well-characterized.

Introduction

Since people spend such a large proportion of their time indoors (87% for adults in the United States),[1] exposure to harmful pollutants in indoor air is cause for concern. In particular, the contribution of fine particles ($PM_{2.5}$, or particulate matter less than 2.5 μm in diameter) to illness and premature death[2] makes them a prime candidate for exposure monitoring. Additionally, the advent of a "quantified self" movement[3] in which individuals strive to monitor various aspects of their lives (e.g. activity, sleep, diet) for health and fitness purposes demonstrates a potential demand for a real-time $PM_{2.5}$ monitor that is easy to use and relatively inexpensive. Such monitors have been used to provide instantaneous feedback to change smoking behavior.[4,5,6]

Precise assessment of exposure requires real-time monitoring of $PM_{2.5}$ concentrations; pump and filter-based gravimetric measurements, while providing the most accurate measurement of $PM_{2.5}$ mass concentrations, require much longer averaging times which make it difficult to account for short-term spikes or dips in concentrations and their correlation to human presence. A number of real-time laser photometers are available that enable researchers to account for these short-term changes in concentration. However, it is essential that they be calibrated to $PM_{2.5}$ mass concentration for emissions from various types of sources based on the optical characteristics of the particulate matter.[7]

One example is the SidePak™ AM510 Personal Aerosol Monitor (TSI Inc., Shoreview, MN, USA). Several studies have collocated the SidePak with gravimetric instruments to determine a calibration factor that can be used to adjust the measurements to specific emissions.[8-12] Likewise, the DustTrak™ (TSI Inc., Shoreview, MN, USA) is another real-time laser photometer that can be calibrated to specific emissions in a variety of indoor and outdoor settings using gravimetric data.[13-18] However, many such instruments tend to be expensive (>$3000 U.S.D.), which could be a potential issue in larger studies that require the contemporaneous use of many instruments in unsecured settings. In addition, this high-end cost may prevent individuals simply interested in the quality of the air they breathe from being able to actively monitor it as part of the aforementioned “quantified self” movement.

The Dylos DC1100 Air Quality Monitor (Dylos Corporation, Riverside, CA) is a laser particle counter designed to be simple to use and inexpensive ($200-$400). However, factory models do not provide the mass concentration units necessary for exposure assessment, but instead record particle counts in two size bins – one counting all particles greater than 0.5 µm (its lower limit), and another counting only coarse particles greater than 2.5 µm. By subtracting the coarse particles from the overall number counted, one can arrive at an estimate for total number of particles less than 2.5 µm (but not including particles with diameters less than 0.5 µm, which tend to contribute little mass). Comparing this Dylos $PM_{2.5}$ data with measurements from a collocated and calibrated $PM_{2.5}$ instrument enables one to determine a calibration relationship similar in nature to those for the SidePak and DustTrak instruments mentioned above. This relationship would enable conversion between these particle counts and $PM_{2.5}$ mass concentration for specific types of indoor source emissions, and would make the Dylos a viable low-cost candidate for $PM_{2.5}$ exposure assessment.

To date, only four other studies have attempted to determine an empirical relationship between Dylos particle counts and $PM_{2.5}$ mass concentration. Northcross, et al[19] demonstrated that the relationship between Dylos counts and $PM_{2.5}$ mass concentration as measured by a calibrated DustTrak was generally linear over the range investigated, and varied by source (wood smoke, ammonium sulfate, and polystyrene latex spheres). In addition, they used a theoretical particle density and volume approach to convert Dylos counts to mass concentration in a study of ambient air.

Semple, et al (2013)[4] conducted two studies: a set of chamber experiments, and a field study (2015).[5] In the former, they burned cigarettes in a small (3.63 m^3) chamber containing both a Dylos DC1700 (similar to the DC1100, but with a battery) and a SidePak AM510, set to a previously determined calibration factor for secondhand smoke (SHS) of 0.295.[11] In all, the 13 chamber experiments yielded 591 data points at 1-minute intervals for SHS concentrations ranging from 0-1000 µg/m^3. In the field study (2015),[5] they monitored 34 homes (half including a smoker, and half without) for approximately 24 hours each with both a Dylos DC1700 and a SidePak AM510, collecting over 50,000 data pairs. They assumed that the primary emissions source in all homes was cigarette smoke, and thus used a SidePak gravimetric calibration factor of 0.295 for this study as well. In both studies, Semple, et al derived a second order polynomial relationship between Dylos and $PM_{2.5}$.

Klepeis, et al[6] derived a linear relationship between $PM_{2.5}$ mass concentration and Dylos response for SHS in a controlled laboratory setting. The study used a DustTrak aerosol monitor collocated with the Dylos in a small bench-top chamber. The DustTrak in turn was calibrated to mass concentration data from a Tapered Element Oscillating Microbalance (TEOM, Thermoelectron, USA). The linear relationship was reasonably consistent across $PM_{2.5}$ concentrations ranging from 0-150 $\mu g/m^3$ (Dylos responses from 0-25,000 counts/0.01 ft^3) among the six different Dylos instruments tested. However, the study did not investigate how this response varied for other sources, for higher concentrations of $PM_{2.5}$, or for aged (vs freshly emitted) aerosols.

We hypothesize that specific source types influence the relationship between Dylos counts less than 2.5 µm and $PM_{2.5}$ mass concentration. Time-varying instrument responses with strict first-order decay are expected to have well-defined, theoretical power-law relationships that depend on decay rates and initial values as measured by the individual instruments. As source emissions and decay rates vary between individual experiments due to changes in source conditions, deposition, and other removal processes, the parameters of the power law curve are expected to change as well – both between and within source type. The relationship for fresh or quickly decaying emissions can be drawn from the ratio of initial values.

Methods

Experimental Settings

In this study, we compared the data from a Dylos DC1100 to that of a collocated and gravimetrically calibrated SidePak AM510 to determine the relationship between the Dylos response and $PM_{2.5}$ mass concentration. We conducted a total of 73 experiments in four different locations: (a) a 47 m^3 room in a small modular building on the Stanford Campus; (b) the 60 m^3 kitchen/living area of a one-bedroom apartment in Menlo Park, CA; (c) a 1-story house in Los Altos, CA (in both the 138 m^3 living/dining room, and separately in the 44 m^3 kitchen); and (d) in a motel room in Redwood City, California. Of the 73 experiments, we initially excluded data from nine: five in which we did not use the gravimetric sampler (and had no previously determined SidePak calibration factor to employ), two in which particle concentrations were high enough to exceed the Dylos monitor's upper count limit (65,536), and two in which the air exchange rate was too high to provide a useful emissions decay period. This left 64 experiments with useful minute-by-minute Dylos and SidePak data, and a gravimetrically determined SidePak calibration factor. These experiments included a total of 17 different sources (including some mixed source experiments).

For a complete description of the experimental settings, the protocol, the instruments, and the sources, see Dacunto et al 2013[12] and 2014.[20] In general, we began collecting background data for at least 10 minutes prior to the beginning of the source emission period (e.g., burning incense, frying bacon, etc.), and then continued typically through the well-mixed decay period; experiments ranged in length from 47-1352 minutes (mean of 171 minutes). In most of the experiments, two Dylos and two SidePak instruments were collocated, though in several experiments toward the end of the study there was only a single one of the instruments in place in the "source" room (because the other was in an adjacent "receptor" room for purposes of another study). Instruments were prepared by synchronizing their internal clocks, and setting logging intervals to 1 minute. SidePaks were zero calibrated using a manufacturer-provided HEPA filter, and employed an impactor with a 2.5 µm cut point with a flowrate at 1.7 LPM to measure only the fraction of particles less than 2.5 µm. In this analysis, we averaged the results of collocated instruments, and we used only concentration data from the source room to ensure that there were no changes to the emissions as they moved from room to room that might affect the instruments' response. SidePak responses were calibrated to gravimetric units using data from a collocated gravimetric sampler; see Dacunto et al[12] for a complete description of the methods used and some of the calibration factors determined. Relative humidity varied from 30-64%, indicating a minimal impact on monitor response, according to Jiang (2010) who showed that SidePak calibration factors were only marginally affected at relative humidity levels below 70%.[21]

As discussed in Dacunto, et al[12], gravimetric analysis was performed on a Mettler-Toledo M3 Microbalance (Columbus, OH, USA) with readability of 1 µg after equilibration for 24 hours at controlled temperature and relative humidity. Samples were collected on PTFE filters (Pall Corp., Ann Arbor, MI, USA), via an apparatus consisting of an electric pump connected to a cyclone with 2.5 µm size cut. Flowrates were approximately 11 LPM as measured by a Gilibrator 2 primary flow calibrator (Sensidyne Corp., Clearwater, FL, USA). Gravimetric sampling times ranged from as low as 12 minutes (for very high concentrations) up to 146 minutes; accumulated masses ranged from 16-2934 µg. We utilized both lab blanks and travel blanks as controls.

Raw Data Processing

In comparing Dylos and SidePak data, we first subtracted background concentrations from the well-mixed decay period of each set of raw data. We then modified the Dylos data to reflect only those particles less than 2.5 µm by subtracting the counts in the >2.5 µm bin from those counted overall (>0.5 µm). Next, we adjusted the SidePak data by multiplying the results by the gravimetric calibration factor following the method in Dacunto et al.[12] Therefore, each experiment-minute had one Dylos response (particle counts less than 2.5 µm per 0.01 ft^3) and one SidePak response (calibrated $PM_{2.5}$ µg/m^3) associated with it. In all, we had 11,048 matched Dylos-SidePak data pairs from the 64 experiments.

Calibration equation form

We took a theoretical approach to determine the best form of the equation with which to relate the Dylos and the SidePak data, both of which were expected to exhibit first-order (exponential) decay. Hence, we compared one exponentially decaying variable (the Dylos response) to another exponentially decaying variable (the SidePak response). Each variable has two parameters: the initial value, and the decay rate. Thus, assuming first-order decay, the parametric form of the Dylos "calibration curve" is:

$$x = Ae^{at} \qquad \text{(Equation 1)}$$

$$y = Be^{bt} \qquad \text{(Equation 2)}$$

where

x = Dylos $PM_{2.5}$ response *[#/0.01 ft^3]*

y = SidePak calibrated $PM_{2.5}$ response *[$\mu g/m^3$]*

A,a = initial value and decay rate parameters for Dylos *[#/0.01 ft^3, min^{-1}]*

B,b = initial value and decay rate parameters for SidePak *[$\mu g/m^3$, min^{-1}]*

t = time *[min]*

Converting to Cartesian coordinates (solving for t and replacing), we have:

$$y = BA^{-b/a}x^{b/a} \qquad \text{(Equation 3)}$$

Equation (3) can be written in terms of the initial Dylos/PM$_{2.5}$ ratio [B/A], so that this value can be easily substituted in:

$$y = (\tfrac{B}{A}A\,)A^{-b/a}x^{b/a} \qquad \text{(Equation 4)}$$

or, more simply:

$$y = mx^{n} \qquad \text{(Equation 5)}$$

where

x = Dylos PM$_{2.5}$ response *[#/0.01 ft^3]*

y = SidePak calibrated PM$_{2.5}$ response *[µg/m^3]*

m = calibration curve parameter *[(µg/m^3)/(#/0.01 ft^3)]*

n = calibration curve parameter *[-]*

Data Analysis

For analysis purposes, we divided the 64 experiments into eight groups. Five groups corresponded to the unique sources for which we had the most data (a minimum of 650 matched pairs each): cigarette, stick incense, fried bacon, fried chicken, and fried hamburger. The remaining three groups included the remainder of the 17 sources categorized into "other combustion sources" (cone incense, candles, wood and synthetic log smoke), "other cooking sources" (toast, fried pork chops, fried sausage, microwave popcorn, and burned oven drippings), and "mixed sources" (cigarette smoke mixed with various cooking or incense emissions).

Since each experiment represented a unique situation with varying source and environmental conditions (source type, source strength, air exchange rate, etc.), we did not attempt to fit a single calibration curve of the form explained above to all data from one type of source or source group together. Instead, we determined power law calibration curves (Equation 5) for each experiment individually, subsequently plotting them all together by source group. Doing so enabled us to show the range of possibilities for the calibration curves associated with each unique source or source grouping.

To obtain the parameters m and n for the calibration curve (Equation 5), we first linearized Equations 1 and 2 by taking the natural logarithm of the response, plotting it versus time, and then fitting a line by linear regression. The slope of this line was the decay rate (a or b), and the intercept was the natural log of the initial value (A or B). Examining the R^2 of the fitted lines enabled us to evaluate how well each instrument's response adhered to the assumption of exponential decay. Next, using equations (4) and (5), we could then calculate the power law parameters m and n for each individual experiment. Data analysis and plots were accomplished using R software.[22]

Results and Discussion

Plots of power law calibration curves (generated from the empirical parameters from each experiment) for each of the eight source groupings are in Figure 1. Since we wanted to show the curves over a wide range of Dylos concentrations, we do not present them for nine experiments which had peak Dylos responses less than 15,000/0.01 ft^3, since these would have required excessive extrapolation to reach even moderate Dylos responses of 20,000 counts/0.01 ft^3. In addition, we identified eight experiments with anomalous discontinuities or irregular background during our analysis, and do not include the results here (though they are included in the supplementary material). Thus, Figure 1 includes power law curves for a total of 47 experiments from the eight source groups.

Figure 1

We present mean parameters (decay rate, initial value, etc.) from the linear regression of each instrument's decay plots in Table 1 by source group. Substituting these mean values into Equation (5) gives the "average" power law parameters m and n in Table 1, which, when inserted into the power-law equation, provide an approximate central-tendency calibration curve. The assumption of first-order decay for these 47 experiments appears well-founded, with R^2 for the best-fit lines of the linear regressions for each instrument's decay plots all greater than or equal to 0.90. While we present only average values here, the supplemental material contains these parameters and the R^2 for all 47 experiments of the eight source groups, as well as for the 17 experiments with low emissions or other anomalies which are not included in Figure 1 or Table 1.

Table 1

While the high R^2 values shown in Table 1 indicate consistent first-order decay within individual experiments, the variability of the power law parameters even within a source group due to differences in experimental conditions can produce a wide range of results for a given Dylos concentration. Table 2 shows an example this, displaying of the mean and range of $PM_{2.5}$ concentrations possible for given Dylos particle counts less than 2.5 μm for specified source groups. There is significant variation both within and between source groups, particularly for higher concentrations. Depending on the level and source type, our fitted data show that uncertainties for predicted mass concentrations at typical Dylos readings for indoor sources can be 10's or even 100's of μg/m^3. Note that these uncertainties reflect considerable aging of the aerosol. While these uncertainties appear to reduce the utility of accurate estimates of $PM_{2.5}$, the Dylos responses may be more useful in providing an estimate of $PM_{2.5}$ concentrations for fresh aerosol when the source of the emissions is known (see below).

Table 2

All 47 power law curves from the eight source groups are plotted in Figure 2. Since the calibration curve polynomial from Semple, et al (2015)[5] was derived from a variety of indoor sources in a field study, we have also included it here. Note that the general shape and values of the line from Semple, et al (2015)[5] fall reasonably within the range of results in this study.

Figure 2

Each of the 47 power law curves in Figure 2 displays a concave upward shape to some degree. While the instrument responses are related linearly at the beginning of the well-mixed decay period in the ratio of [*B/A*], the curvature arises because the instrument responses decay at different rates. Indeed, for all source groups the ratio *b/a* >1, indicating that the SidePak response is decaying faster than the Dylos. This leads to continuous changes in the inter-instrument ratio and results in a power law curve, versus a simple line. As time passes, the impact of the difference in decay rates becomes more pronounced, and the lines exhibit more curvature; in other words, aerosol aging leads to the relationship's curvature.

Thus, it is possible to estimate fresh (vs. aged) emissions by using a linear relationship in the form of the initial instrument ratio [*B/A*], similar to the relationships presented by Klepeis et al.[6] Linear relationships are also expected to be useful for emissions which are quickly decaying, where there is not enough time for the differences in decay rates as measured by the instruments to be significant. These linear "calibration factors" have the advantage of being simpler to use; we present them in Table 3 for the eight source groups as the actual observed initial instrument ratio, since using a ratio of the fitted initial values would introduce some error. The calibration factors *(z)* can be employed in the following manner:

$$y = zx \qquad \text{(Equation 6)}$$

where

x = Dylos $PM_{2.5}$ response $[\#/0.01\ ft^3]$

y = SidePak calibrated $PM_{2.5}$ response $[\mu g/m^3]$

z = calibration factor = $B/A\ [(\mu g/m^3)/(\#/0.01\ ft^3)]$

Table 3

Since SHS emissions were common to this study and two of those previously mentioned (Semple, et al. 2013[4], and Klepeis, et al.[6]), we compare results from all four studies in Figure 3 and Table 4. The Semple, et al. (2013) calibration curve in Figure 3 appears to be similar in shape and magnitude to those of the present study, though those derived from an analysis of the data from Klepeis, et al. appear in a cluster above the others; the conditions of the Klepeis et al. experiments led to faster decay rates that made the shape of the power law calibration curves more linear. The same trend is evident in Table 4; while the Semple, et al. (2013) results provide $PM_{2.5}$ concentrations roughly similar to those calculated from our power law curves at a range of

Dylos responses, the Klepeis results are significantly higher and more indicative of fresher emissions (younger aerosol)

However, the linear relationships for fresh or quickly decaying emissions from Klepeis, et al. and this study (Table 4) are quite similar. In addition, the relationships found by Northcross, et al[19] for fresh wood smoke, ammonium sulfate, and polystyrene latex spheres are linear. This indicates that while environmental and source-emissions conditions can cause unpredictable changes to calibration relationships over time, the linear relationships for fresh emissions are more apt to be useful regardless of conditions.

Figure 3

Table 4

While the similarity of some of this study's results to previous ones for specific sources and fresh emissions is encouraging, there remain limitations with them that indicate they should be applied carefully. Instrument response varies widely between sources; thus, investigators should be extremely cautious about applying a generic Dylos to $PM_{2.5}$ relationship to an aerosol whose source is unknown. The relationship varies if the emissions are fresh vs. aged, or slowly vs. quickly decaying. Finally, our results indicate that the relationship between Dylos and $PM_{2.5}$ mass concentration varies widely even for the same source, depending upon the specific experimental conditions. We varied the location, air exchange rate, and combustion conditions among experiments to mimic the range of settings that may be encountered in the field, which had an apparent impact on the calibration relationships.

Despite these limitations, our results indicate that it is possible to use the Dylos to measure $PM_{2.5}$ mass concentration if the calibration relationship (relative decay rates) is known.

Unfortunately, this is not expected to be the case for most applications, since decay rates vary widely under different conditions. In the absence of known decay rates, the utility of the Dylos is considerably increased (uncertainty decreased) when used for fresh or quickly-decaying emissions of a known source. The Dylos might be employed effectively as a field-survey instrument to provide qualitative measure of near-instantaneous $PM_{2.5}$ concentration, indicating whether it is generally in a “high,” “medium,” or “low” category. Investigators could employ the appropriate Dylos-$PM_{2.5}$ linear relationship to determine a rough estimate for observed sources, taking advantage of the convenience, real-time nature, and affordability (e.g., for large-scale deployments) of the Dylos. If more investigation is needed in some cases, a more accurate instrument could be subsequently deployed. In addition, the Dylos could be useful for individuals interested in the relative quality of the air in their home or workplace for known and observed sources, i.e., to report the presence of generally-elevated levels when a given source is active.

Conclusion

We have presented calibration relationships that enable the conversion of raw particle counts less than 2.5 μm from the Dylos Air Quality Monitor to mass concentration units for specific known sources. While the overall time-varying relationship between the Dylos and $PM_{2.5}$ mass concentration is best fit with a power law due to differences in the decay rates measured by each instrument, a linear relationship can be applied to fresh or quickly-decaying emissions.

The Dylos can be used to broadly evaluate $PM_{2.5}$ mass concentration. For aged aerosol, the uncertainties are quite large even if the if the source-type is known, with predicted mass levels at typical Dylos counts of 5000, 15000, or 30000 ranging over 10's or 100's of μg/m^3. Uncertainty may be reduced if the emissions from a known source are fresh. For the best results when estimating mass levels, we recommend that the Dylos be used to measure fresh emissions for well-defined sources.

Further studies to validate and refine the source-specific relationships presented here and investigate calibration curves for additional source types would be very useful, especially targeted at fresh emissions. By examining fresh emissions alone, investigators may perform a large number of short experiments without having to measure throughout long decay periods. In addition to source-specific studies, investigations into the impact of averaging time, relative humidity, or temperature on the Dylos would be welcome. We intend that our results provide a model to evaluate other low-cost real-time particle sensors for their utility in estimating standard particle-mass concentrations. Although they may be of limited use in measuring precise mass concentrations in formal exposure assessment, these kinds of instruments provide a viable option for individuals to broadly sense and contextualize immediate, real-time particle levels for visibly active sources in their environment.

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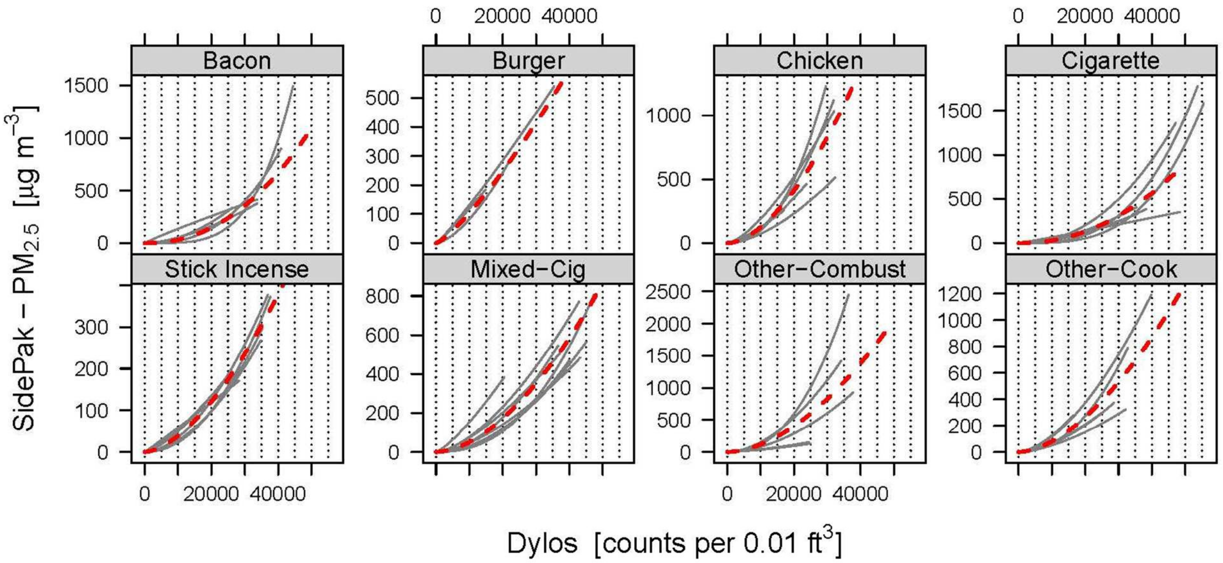

Fig. 1 Plots of power law calibration curves for each of the eight source groups, to include five pure sources, “mixed sources” (SHS mixed with other cooking or incense sources), “other combustion sources” (cone incense, candles, wood and synthetic log smoke), and “other cooking sources” (toast, fried pork chops, fried sausage, microwave popcorn, burned oven drippings). Individual curves are plotted up to the empirical maximum concentration for each of 47 different experiments to show the range of results possible. The dashed line on each plot is the mean power law curve for each source group.

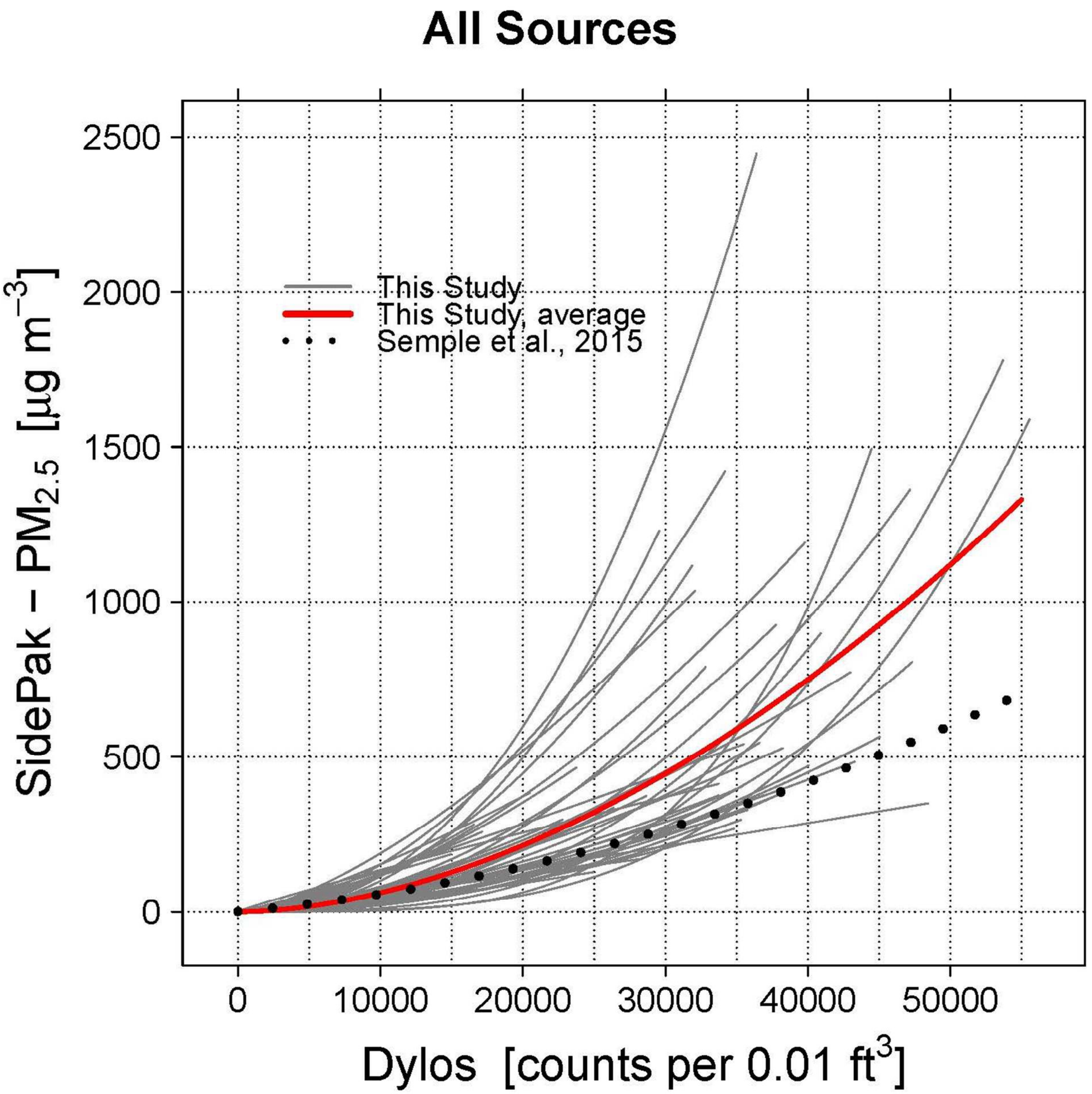

Fig. 2 Plot of power law calibration curves to the empirical maximum concentration for all 47 experiments involving a variety of sources or source mixtures, and the overall average power law curve. Also plotted is the 2nd-order polynomial from Semple, et al (2015),[17] which was derived from a field study of indoor air in 34 homes involving a variety of types of emissions, including SHS.

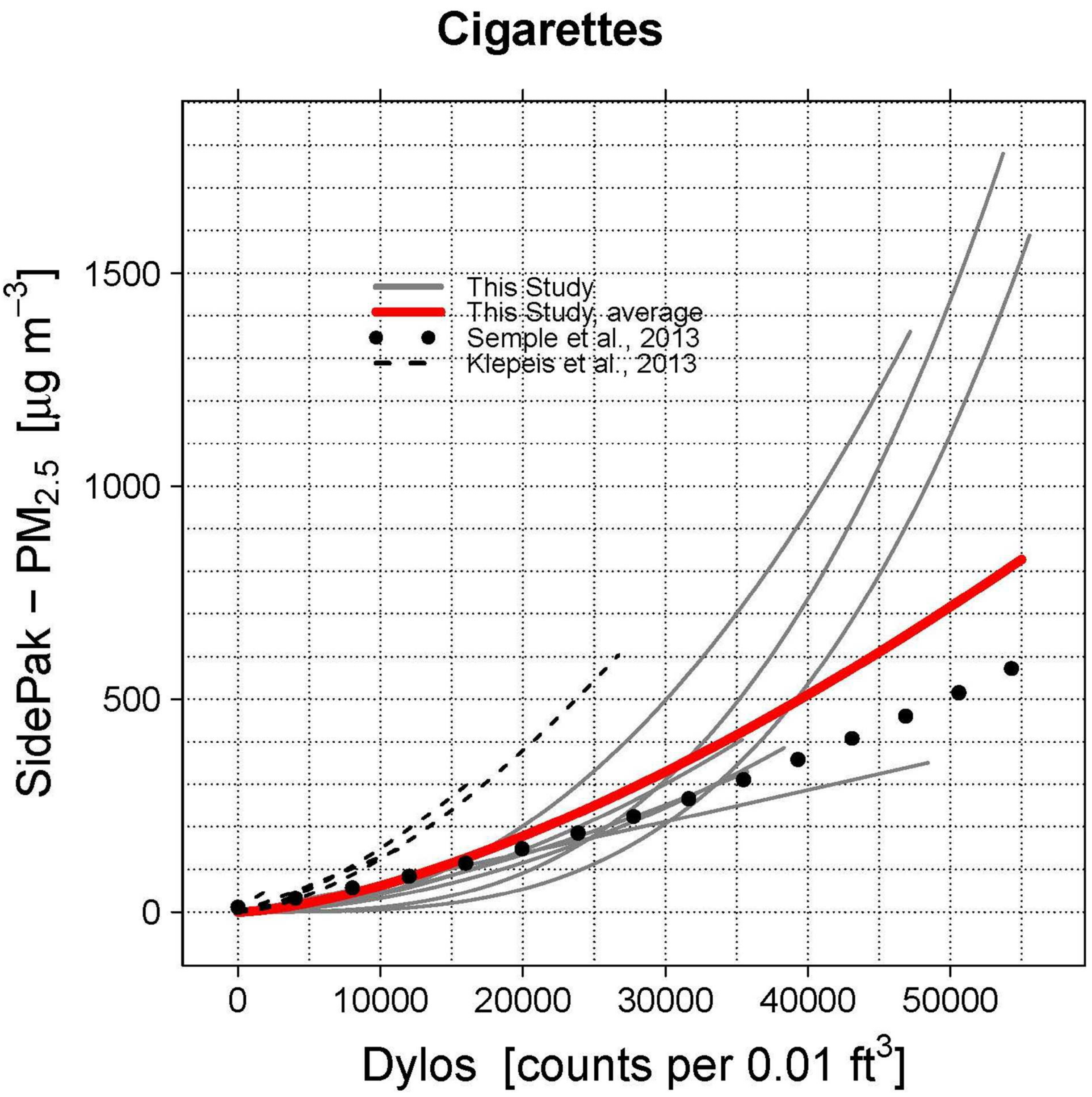

Fig. 3 Plots of theoretical power law calibration curves for seven experiments of this study involving pure secondhand smoke (SHS), along with the "average" curve created using the mean parameters for SHS from Table 1. Also plotted is the second-order polynomial relationship from Semple, et al (2013),[15] and theoretical power law curves created using the data from Klepeis, et al.[17] (excluding experiment #4 due to poor linear regression R^2). Curves from this study as well as from Klepeis, et al. are plotted up to the empirical maximum concentration of each experiment.

Table 1 Mean decay and power law parameters for 8 source groups (see equations (4) and (5) in the text). The "mean" power law parameters were calculated using the mean regression coefficients as listed in the table.

source group	#exp	a	b	A	B/A[a]	m	$n = b/a$[a]	R^2[b]
		[min^{-1}]	[min^{-1}]	[#/0.01 ft^3]	[(µg/m^3)/(#/0.01 ft^3)]		[-]	
Bacon	5	0.0159	0.0211	44468	0.0190	5.02E-08	2.200	≥0.90
Burger	3	0.0149	0.0178	37233	0.0146	8.81E-04	1.267	≥0.96
Chicken	6	0.0080	0.0137	30321	0.0279	1.53E-05	1.727	≥0.95
Cigarette	7	0.0053	0.0103	51195	0.0186	1.09E-07	2.111	≥0.92
Stick Incense	7	0.0076	0.0121	31596	0.0081	1.07E-05	1.640	≥0.98
Mixed-Cig[c]	8	0.0062	0.0106	42377	0.0153	4.59E-06	1.761	≥0.94
Other-Comb[d]	5	0.0074	0.0124	31778	0.0289	8.76E-06	1.782	≥0.98
Other-Cook[e]	6	0.0124	0.0215	31504	0.0183	1.08E-05	1.718	≥0.96
All	47	0.0090	0.0143	37924	0.0185	3.91E-06	1.803	≥0.90

[a] Mean of the ratios, not the mean of one parameter divided by the mean of the other. [b] Range of R^2 values for linear regressions of the natural log of the SidePak and Dylos response vs time. [c] Includes SHS mixed with bacon, chicken, toast, and stick incense emissions. [d] Includes candles, synthetic log, wood smoke, and cone incense. [e] Includes pork chops, microwave popcorn, toast, burned oven drippings, and sausage.

Table 2 Mean and range of $PM_{2.5}$ concentrations [µg/m^3] resulting from source-specific power law curves for “low,” “medium,” and “high” Dylos $PM_{2.5}$ counts. Power law curves were plotted up to the empirical maximum of each experiment; only those experiments which reached the specified Dylos concentration were included in the calculation of mean, minimum, and maximum. “Mean” values were obtained by averaging the power law $PM_{2.5}$ results from all the applicable experiments in that source group; overall mean value is an average of the power law $PM_{2.5}$ results from all experiments.

source group	Dylos[a] = 5000			Dylos[a] = 15000			Dylos[a] = 30000		
	mean	min	max	mean	min	max	mean	min	max
	$PM_{2.5}$ [µg/m^3]			*$PM_{2.5}$ [µg/m^3]*			*$PM_{2.5}$ [µg/m^3]*		
Bacon	22	0	72	100	20	197	349	311	399
Burger	48	28	60	183	155	206	448	448	448
Chicken	38	20	69	239	143	342	795	454	991
Cigarette	11	1	32	73	21	106	289	207	497
Stick Incense	14	5	28	73	54	92	228	205	259
Mixed-Cig[b]	20	4	63	115	54	258	322	260	438
Other-Combust[c]	23	13	44	186	62	319	1094	607	1553
Other-Cook[d]	25	14	41	162	95	240	561	290	740
Overall[e]	23	0	72	134	20	342	449	205	1553

[a] Dylos $PM_{2.5}$ counts in [#/0.01 ft^3]. [b] Includes SHS mixed with bacon, chicken, toast, and stick incense emissions. [c] Includes candles, synthetic log, wood smoke, and cone incense. [d] Includes pork chops, microwave popcorn, toast, burned oven drippings, and sausage. [e] Overall min and max are the extremes of the values for each of the 8 source groups.

Table 3 Mean and range of empirical linear calibration factors (z) for conversion of Dylos $PM_{2.5}$ counts [#/0.01 ft^3] to $PM_{2.5}$ mass concentration [$\mu g/m^3$], applicable to fresh or quickly decaying emissions. These are calculated from observed initial values of Dylos and SidePak responses; the initial ratios *B/A* in Table 1 were calculated from fitted initial values.

source group	z_{mean}[a,b]	z_{lower}[a]	z_{upper}[a]
bacon	0.022	0.014	0.034
burger	0.020	0.014	0.030
chicken	0.031	0.016	0.044
cigarette	0.021	0.010	0.035
stick incense	0.017	0.012	0.026
mixed-cigarette[c]	0.031	0.006	0.068
other-combustion[d]	0.020	0.014	0.033
other-cooking[e]	0.009	0.007	0.011
overall	0.021	0.006	0.068

[a] Units of linear calibration factor z are [($\mu g/m^3$)/ (#/0.01 ft^3)]. [b] Arithmetic mean of linear calibration factors for all experiments of that source group. [c] Includes SHS mixed with bacon, chicken, toast, and stick incense emissions. [d] Includes candles, synthetic log, wood smoke, and cone incense. [e] Includes pork chops, microwave popcorn, toast, burned oven drippings, and sausage.

Table 4 Comparison of Dylos $PM_{2.5}$ calibration results for SHS from various studies.

			$PM_{2.5}$ [µg/m^3] for Dylos response of:		
Study	calibration relationship form[a]	parameter values	5000[b]	15000[b]	45000[b]
Semple, et al (2013)[15]	$y = a_0 + a_1x + a_2x^2$	a_0 = 11.7	41	130	637
		a_1 = 0.0049			
		a_2 = 2E-07			
Klepeis, et al[17]	$y = zx$ [c]	z = 0.0186[d]	93	279	837
	$y=mx^n$	m = 2.30E-03[d]	77	297	1140
		n = 1.224[d]			
Dacunto, et al	$y = zx$ [c]	z = 0.0186[e]	93	279	838
(present study)	$y = mx^n$	m = 1.09E-07[e]	7	71	726
		n = 2.111[e]			

[a] In each calibration relationship, $y = PM_{2.5}$ [µg/m^3] and x = Dylos $PM_{2.5}$ response [#/0.01 ft^3]. [b] Units are [#/0.01 ft^3] for particles less than 2.5 µm. [c] Initial ratio approach, for fresh or quickly decaying emissions only. [d] Mean parameter values from reanalyzed data, excluding experiment #4 due to poor linear regression R^2. [e] Mean parameter value, from Table 1.

Environmental Impact

Assessment of exposure to $PM_{2.5}$ is important for identifying health hazards and estimating health risk from indoor sources, due to the large proportion of time people spend indoors. Use of a low-cost, real-time particle monitor can facilitate awareness and broad characterization of instantaneous exposures to cigarettes, incense, and cooking sources such as frying chicken, bacon, and hamburger. The calibration factors presented here could enable these monitors to provide approximate peak $PM_{2.5}$ mass concentration in indoor settings where sources are well-characterized.