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Comparison of Fine Particle Measurements from a Direct-Reading Instrument and a Gravimetric Sampling Method

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Particulate air pollution, specifically the fine particle fraction ($PM_{2.5}$), has been associated with increased cardiopulmonary morbidity and mortality in general population studies. Occupational exposure to fine particulate matter can exceed ambient levels by a large factor. Due to increased interest in the health effects of particulate matter, many particle sampling methods have been developed. In this study, two such measurement methods were used simultaneously and compared. $PM_{2.5}$ was sampled using a filter-based gravimetric sampling method and a direct-reading instrument, the TSI Inc. model 8520 DUSTTRAK aerosol monitor. Both sampling methods were used to determine the $PM_{2.5}$ exposure in a group of boilermakers exposed to welding fumes and residual fuel oil ash. The geometric mean $PM_{2.5}$ concentration was 0.30 mg/m^3 (GSD 3.25) and 0.31 mg/m^3 (GSD 2.90) from the DUSTTRAK and gravimetric method, respectively. The Spearman rank correlation coefficient for the gravimetric and DUSTTRAK $PM_{2.5}$ concentrations was 0.68. Linear regression models indicated that $\log_e$ DUSTTRAK $PM_{2.5}$ concentrations significantly predicted $\log_e$ gravimetric $PM_{2.5}$ concentrations ($p < 0.01$). The association between $\log_e$ DUSTTRAK and $\log_e$ gravimetric $PM_{2.5}$ concentrations was found to be modified by surrogate measures for seasonal variation and type of aerosol. $PM_{2.5}$ measurements from the DUSTTRAK are well correlated and highly predictive of measurements from the gravimetric sampling method for the aerosols in these work environments. However, results from this study suggest that aerosol particle characteristics may affect the relationship between the gravimetric and DUSTTRAK $PM_{2.5}$ measurements. Recalibration of the DUSTTRAK for the specific aerosol, as recommended by the manufacturer, may be necessary to produce valid measures of airborne particulate matter.

Keywords aerosol sampling methods, DUSTTRAK aerosol monitor, fine particulate matter ($PM_{2.5}$), occupational exposure

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Epidemiologic studies have associated increased cardiopulmonary morbidity and mortality with exposure to particulate air pollution, specifically the fine fraction of particulate matter.(1−3) Fine particulate matter, defined as particulate matter with an aerodynamic mass median diameter less than or equal to a nominal 2.5 μm ($PM_{2.5}$), has been found to have high penetration and retention in the alveolar region of the lungs. The increased concern regarding fine particulate matter in the ambient environment prompted the United States Environmental Protection Agency (US EPA) to adopt new National Ambient Air Quality Standards for $PM_{2.5}$ in 1997.(4)

Although there are no regulatory standards for occupational $PM_{2.5}$ exposure, the Occupational Safety and Health Administration has established a permissible exposure limit of 5 mg/m^3, 8-hour time-weighted average (TWA), for the respirable fraction of particulate matter (aerodynamic mass median diameter less than or equal to a nominal 4 μm).(5) Recognizing the importance of particle size on the deposition site of the respiratory tract and the resulting health effects, the American Conference of Governmental Industrial Hygienists (ACGIH®) has established a particle size-selective sampling criteria for airborne particulate matter. For respirable particulate matter, ACGIH has a more stringent threshold limit value of 3 mg/m^3, 8-hour TWA.(6) The National Institute for Occupational Safety and Health (NIOSH) does not support a recommended exposure limit for respirable particle exposures.(7)

The new standards increased interest in particle measurement methods and stimulated the commercial development of various particle sampling instruments. This study compares two $PM_{2.5}$ samplers—a gravimetric sampler and a direct-reading instrument. For the gravimetric sampling method, the ambient particle sample is collected on a polytetrafluoroethylene (PTFE) filter during the monitoring period. The filter is weighed before and after sampling to determine the particle mass concentration. The gravimetric sampling method has been found to be accurate, sensitive, and robust. The US EPA has established the gravimetric sampling method as the reference method for the determination of $PM_{2.5}$ in ambient air.[4] The reference method for respirable particle sampling in the *NIOSH Manual of Analytical Methods* also is a gravimetric method, with the sampling device consisting of a cyclone with a filter.[8] Another benefit of the gravimetric sampling method is that the air sample collected on the filters can be analyzed to determine the chemical composition of the aerosol. However, the filter-based gravimetric sampling method also has disadvantages that limit its usefulness.

The necessary preparation and analysis of filters may result in a significant time lag before the $PM_{2.5}$ data is available. In addition, the time-integrated sampling methods do not provide information on the temporal pattern of the exposures. Collecting measurements continuously over a short period of time, such as 1- to 10-min intervals, is impractical when using a gravimetric method because of the difficulty of preparing and exchanging a new filter for each interval of sampling. In addition, the amount of sample collected on the filter over such a short interval of time would most likely be below the limit of detection.

Direct-reading instruments frequently have been used in exposure assessment studies because of their many benefits.[9–15] A direct-reading instrument can provide real-time measurements at various specified time intervals while performing continuous monitoring for long periods of time. The ease of using a direct-reading instrument is one of its major advantages; no additional analyses are required to obtain the particle concentrations, and the measurements can be recorded in a practical database format. However, direct-reading instruments also have limitations. Unlike the gravimetric sampling method, the aerosol is not collected onto a filter, eliminating the possibility of performing chemical analyses on the aerosol sample. More importantly, due to the relative novelty and variety of such instruments, the accuracy and reliability of certain continuous real-time samplers have yet to be determined.

While comparisons of these two types of samplers have been described previously,[16–20] few studies have investigated their use in an occupational environment. A direct-reading instrument commonly used in research studies is the model 8520 DUSTTRAK aerosol monitor (TSI Inc., Shoreview, Minn.). Previous studies conducted in the general ambient environment have shown that while DUSTTRAK and gravimetric $PM_{2.5}$ concentrations are highly correlated, DUSTTRAK measurements tend to overestimate by a factor of two to three.[16,18,20] In an occupational setting, the exposure to $PM_{2.5}$ can be 20- to 30-fold greater compared with the general ambient environment, allowing a comparison between both samplers at a wider range of particle concentrations. In addition, aerosols with various particle characteristics can be studied in an occupational environment.

The objective of this study was to determine the association between $PM_{2.5}$ measurements from a gravimetric sampler and a direct-reading instrument in a work environment with exposures to residual oil fly ash and welding fume. The benefits of using each sampler are distinct; therefore, one sampler may be preferred over another depending on the needs for the exposure assessment. This study sought to determine potential factors such as type of aerosol and seasonal variations that may affect the relationship between the $PM_{2.5}$ measurements from a gravimetric sampler and a direct-reading instrument.

METHODS AND MATERIALS

Study Design

The study was approved by the Institutional Review Board of the Harvard School of Public Health. Written informed consent was obtained from each study subject prior to sampling. Personal $PM_{2.5}$ sampling was conducted on subjects recruited from the International Brotherhood of Boilermakers, Iron Shipbuilders, Blacksmiths, Forgers, and Helpers of Local No. 29. The $PM_{2.5}$ exposure assessment was conducted as part of a comprehensive epidemiologic study investigating the cardiopulmonary health effects of particulate matter in boilermakers. The $PM_{2.5}$ exposure was measured at two different work sites in the New England area—the Local No. 29 apprentice welding school and a power plant overhaul site. Sampling was conducted between October 1999 and December 1999 at the apprentice welding school where subjects were exposed primarily to particulate matter resulting from welding, grinding, and cutting operations. Sampling at the power plant overhaul site was conducted in June and July 1999, and additional sampling was performed in October 2000. At the power plant overhaul site, subjects removed and replaced panels of the interior wall and water-circulating tubing of residual oil-fired boilers and repaired the ash pit. Subjects at the overhaul site were exposed to particles from the residual oil fly ash and from typical boilermaking operations, including welding. Area samples also were collected at the two work sites.

$PM_{2.5}$ measurements were collected using both a direct-reading instrument and the gravimetric sampling method simultaneously on the same subject. The aerosol inlets of both samplers were positioned near the breathing zone of the subjects. For area samples, the samplers were placed near the work area of the boilermakers. The air monitors were checked periodically to ensure that they were properly functioning and remained in the correct positions. Air samples were collected during the entire work shift, typically 4 to 6 hours at the apprentice welding school and 8 to 10 hours at the power plant overhaul sites. Detailed industrial hygiene logs were completed to track the equipment and note any problems that arose during sampling.

Direct-Reading Instrument

The direct-reading instrument used in this study was a TSI Inc. model 8520 DUSTTRAK aerosol monitor, which is a light-scattering laser photometer with a laser diode directed at a continuous aerosol stream. The real-time particle mass concentration is determined by the intensity of the light scattered by the particles in the aerosol stream. The particle size range of the DUSTTRAK is from 0.1 to 10 μm, with a detection range from 0.001 to 100 mg/m^3.[21] The DUSTTRAK was factory-calibrated to the respirable fraction of the International Organization for Standardization (ISO) 12103-1, A1 Arizona test dust.[22] Arizona test dust is a polydispersed test aerosol commonly used because it is representative of a wide variety of ambient aerosols. A 2.5-micron cutsize impactor was attached to the inlet. The air sample was drawn through a 1.2-m long Tygon® tube into the impaction inlet at a flow rate of 1.7 L/min. $PM_{2.5}$ concentrations were logged every minute, an average of a series of measurements taken every 10 sec. The time-integrated measurement was calculated by averaging the minute-interval concentrations over the sampling duration. Eight calibrated DUSTTRAK aerosol monitors were used in this study. The recommended operating temperature range for the DUSTTRAK is 32°F to 120°F (0°C to 50°C). The National Weather Service, Boston Weather Forecast Office (Taunton, Mass.) indicated that the ambient temperature in Boston ranged from 41°F to 97°F at the power plant and apprentice school during the sampling campaign.

Gravimetric Sampling Method

A model 200 Personal Exposure Monitor (PEM) (MSP Corp., Minneapolis, Minn.) with a 2.5-micron cutsize was used to collect the gravimetric sample. A constant airflow of 4 L/min was maintained using a Gilian GilAir5 Air Sampling Pump (Sensidyne Inc., Clearwater, Fla.) in line with the PEM. The airflow was set using a calibrated flowmeter from Matheson Instruments (Montgomeryville, Pa.). A 37 mm diameter PTFE membrane filter with a 2-micron pore size (Gelman Laboratories, Ann Arbor, Mich.) was placed under the impactor ring of the PEM to collect the sample. The filters were weighed pre- and post-sampling to determine the $PM_{2.5}$ mass collected. Prior to weighing, the filters were equilibrated for a minimum of 24 hours pre-sampling and 48 hours post-sampling in a temperature (68.0°F to 73.4°F) and humidity (35% to 45%) controlled room. After equilibration, the filters were weighed on a MT-5 microbalance (Mettler-Toledo Inc., Columbus, Ohio). The sample weight was used in conjunction with the airflow measurement to calculate the integrated gravimetric $PM_{2.5}$ concentration.

Quality Assurance and Quality Control

Procedures to ensure the quality of the $PM_{2.5}$ measurements were performed. The DUSTTRAKS and PEMs were thoroughly cleaned and prepared prior to sampling each day. The flow rates were checked pre- and post-sampling to ensure that the target flow was being maintained. The DUSTTRAKS were zero-calibrated each day prior to sampling using a high-efficiency particulate air (HEPA) filter. HEPA filters are 99.97% efficient in removing particles with an aerodynamic mass median diameter of 0.3 μm. Duplicate samples were collected to assess the reproducibility of the DUSTTRAK and gravimetric measurements. Filter blanks prepared in the field and test blanks prepared in the weighing room were used to monitor potential contamination and the stability of the mass measurements.

Statistical Analysis

Statistical analyses were performed using SAS version 6.12 (SAS Institute Inc., Cary, N.C.). The effects of seasonal variation, type of aerosol, and motion on the association between DUSTTRAK and gravimetric $PM_{2.5}$ concentrations were studied. Sampling period was used to study the effect of seasonal variation. Sampling period was stratified into two categories, summer (June and July) and fall/winter (October to December). Sampling site, categorized as apprentice school or power plant, was used to study the effect of the type of aerosol. As an additional indicator of type of aerosol, dichotomized cigarette smoking status (yes/no) was used. The effect of motion was studied using sample type, categorized as area or personal samples. Area samples were stationary, whereas personal samples were worn by the subjects during the workday.

The DUSTTRAK and gravimetric $PM_{2.5}$ concentrations were positively skewed. Since the data were not normally distributed, nonparametric methods were used to investigate the agreement between the two measurements. The Wilcoxon signed-rank test initially was performed to compare the DUSTTRAK $PM_{2.5}$ concentrations to the gravimetric $PM_{2.5}$ concentrations. The Spearman rank correlation coefficient was used to determine the strength of the association between the gravimetric $PM_{2.5}$ concentrations and the DUSTTRAK $PM_{2.5}$ concentrations.

As a measure of the agreement between the gravimetric and DUSTTRAK $PM_{2.5}$ measurements, the absolute relative error between the two measurements was used. The absolute relative error was calculated as the following:

$$\left|\frac{(\text{DUSTTRAK PM}_{2.5}\text{ concentration} - \text{gravimetric PM}_{2.5}\text{ concentration})}{\text{gravimetric PM}_{2.5}\text{ concentration}}\right| \quad \textbf{(1)}$$

Wilcoxon rank-sum tests were performed to compare the absolute relative error by category for each variable of interest.

Linear regression models were constructed to examine the effect of the variables of interest on the association between gravimetric $PM_{2.5}$ concentration and DUSTTRAK $PM_{2.5}$ concentrations. Gravimetric and DUSTTRAK $PM_{2.5}$ concentrations were log-transformed to improve normality and stabilize the variance. The $\log_e$ gravimetric $PM_{2.5}$ concentrations were regressed on $\log_e$ DUSTTRAK $PM_{2.5}$ concentrations. Interaction terms were included to study the effect of individual variables on the association between $\log_e$ gravimetric and $\log_e$ DUSTTRAK $PM_{2.5}$ concentrations. For example, the linear model investigating the effect of sampling period on the association between $\log_e$ gravimetric and $\log_e$ DUSTTRAK $PM_{2.5}$ concentrations was the following:

$$\begin{aligned}\log_e[\text{gravimetric PM}_{2.5}] = \beta_0 &+ \beta_1(\log_e[\text{DUSTTRAK PM}_{2.5}]) \\ &+ \beta_2(\text{sampling period}) \\ &+ \beta_3(\log_e[\text{DUSTTRAK PM}_{2.5}] \\ &\times \text{sampling period}) + e\end{aligned} \quad \textbf{(2)}$$

The level of statistical significance for all analyses was set at 0.05.

RESULTS

Comparison of $PM_{2.5}$ Measurements

Sixty-eight pairs of DUSTTRAK and gravimetric $PM_{2.5}$ samples were collected at the apprentice welding school and power plant overhaul site. The occupational $PM_{2.5}$ concentrations measured using a DUSTTRAK and gravimetric monitor are summarized in Table I.

The DUSTTRAK and gravimetric $PM_{2.5}$ concentrations were log-normally distributed. The geometric means of the DUSTTRAK and gravimetric $PM_{2.5}$ concentrations were 0.30 mg/m^3 (GSD [geometric standard deviation] 3.25) and 0.31 mg/m^3 (GSD 2.90), respectively. The relationship between gravimetric $PM_{2.5}$ concentrations and DUSTTRAK $PM_{2.5}$ concentrations is shown in Figure 1. To control for potential outliers, nonparametric statistical methods were used to analyze the association between the DUSTTRAK and gravimetric $PM_{2.5}$ concentrations. The Wilcoxon signed-rank test indicated that there was no difference between the DUSTTRAK $PM_{2.5}$ concentrations and gravimetric $PM_{2.5}$ concentrations ($p = 0.64$). The Spearman rank correlation coefficient for the gravimetric and DUSTTRAK $PM_{2.5}$ concentrations was 0.68 (95% CI [confidence interval]: 0.53, 0.79), indicating a moderate to high positive association between the two measurements.

Summary of Variables of Interest

A summary of the variables is shown in Table II. Sampling was conducted at the apprentice welding school during the fall/winter ($n = 19$ pairs), and at the power plant overhaul site during the summer ($n = 29$ pairs) and fall ($n = 20$ pairs). Approximately one-half of the samples collected were personal samples, of which 51.3% were from cigarette smokers.

Analysis of Absolute Relative Error

The distribution of the absolute relative errors was found to be lognormal, thus geometric means and standard deviations are presented. The geometric mean absolute relative error for all 68 samples was 0.40 (GSD 2.96), as shown in Table III. Comparison of the absolute relative errors by category for each variable of interest indicated that the absolute relative errors were significantly different by sampling period ($p < 0.01$) and sampling site ($p < 0.05$). The absolute relative error between gravimetric and DUSTTRAK $PM_{2.5}$ concentrations was found to be greater during the summer (0.59, GSD 3.38) compared to the fall/winter (0.29, GSD 2.40). In addition, the absolute relative error was found to be greater in samples from the power plant (0.45, GSD 3.24) compared to the apprentice school (0.29, GSD 2.09). The absolute relative error of the gravimetric and DUSTTRAK $PM_{2.5}$ concentrations was not significantly different by smoking status or sample type ($p > 0.2$).

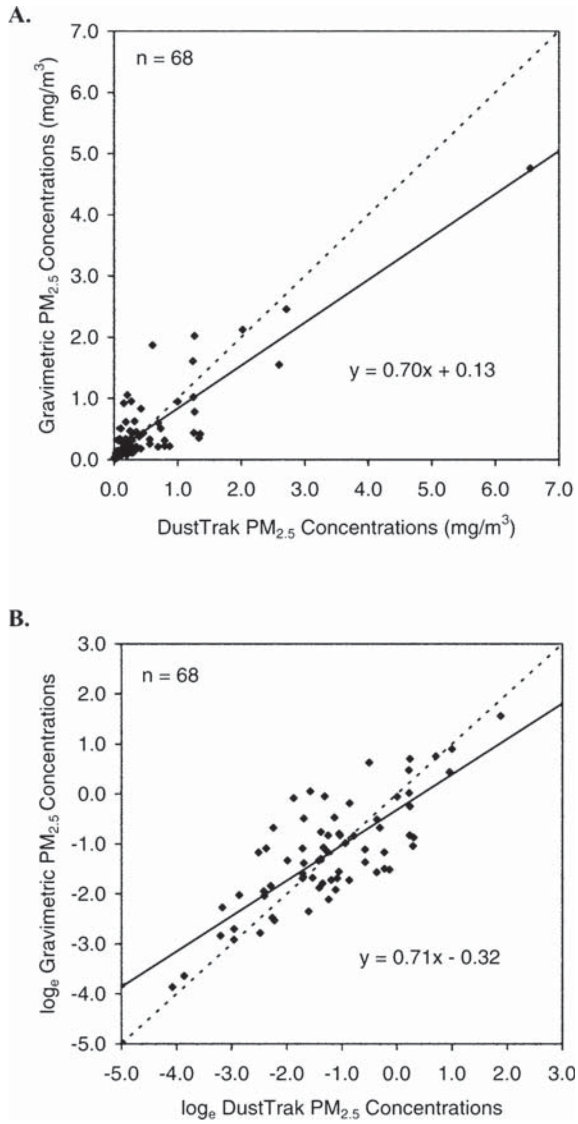

FIGURE 1. Relationship between gravimetric and DUSTTRAK $PM_{2.5}$ concentrations (A) and log-transformed gravimetric and DUSTTRAK $PM_{2.5}$ concentrations (B). The dotted reference line in both plots represent a 1:1 ratio.

TABLE I. Summary of DUSTTRAK and Gravimetric $PM_{2.5}$ Concentrations

	DUSTTRAK (mg/m^3)	Gravimetric Monitor (mg/m^3)
Arithmetic mean^A	0.58 (0.93)	0.54 (0.74)
Geometric mean^B	0.30 (3.25)	0.31 (2.90)
Median	0.29	0.31
Range	0.02–6.55	0.02–4.76

^{A}Standard deviation shown in parenthesis.
^{B}Geometric standard deviation shown in parenthesis.

Linear Regression Analysis

Linear regression models were constructed to investigate the effect of the variables of interest on the association between log-transformed gravimetric and DUSTTRAK $PM_{2.5}$

TABLE II. Properties of the Variables of Interest for 68 Total Pairs of Samples

Variable of Interest		Number of Sample Pairs (%)
Sampling period	Summer	29 (42.6)
	Fall/winter	39 (57.4)
Sampling site	Apprentice school	19 (27.9)
	Power plant	49 (72.1)
Smoking status[A]	Smoker	19 (48.7)
	Nonsmoker	20 (51.3)
Sample type	Personal	39 (57.4)
	Area	29 (42.6)

[A]Smoking status samples restricted to personal samples (n = 39).

concentrations. The regression coefficients and 95% confidence intervals for $\log_e$ gravimetric $PM_{2.5}$ concentrations regressed on $\log_e$ DUSTTRAK $PM_{2.5}$ concentrations are shown in Table IV. The simple linear model resulted in a significant regression coefficient of 0.71 (95% CI: 0.57, 0.85), thus the $\log_e$ DUSTTRAK $PM_{2.5}$ concentration was a statistically significant predictor of $\log_e$ gravimetric $PM_{2.5}$ concentration.

The effect of the variables of interest on the association between $\log_e$ gravimetric $PM_{2.5}$ concentrations and $\log_e$ DUSTTRAK $PM_{2.5}$ concentrations was examined by including interaction terms into the regression models. Smoking status and sample type were not found to influence the association between $\log_e$ gravimetric and $\log_e$ DUSTTRAK $PM_{2.5}$ concentrations ($p > 0.5$).

TABLE III. Summary of Absolute Relative Errors by Category for Each Variable of Interest

Variable of Interest	Number of Paired Samples	Geometric Mean (GSD)
All samples	68	0.40 (2.96)
Sampling period[A]		
Summer	29	0.59 (3.38)
Fall/winter	39	0.29 (2.40)
Sampling site[A]		
Apprentice school	19	0.29 (2.09)
Power plant	49	0.45 (3.24)
Smoking status[B]		
Smokers	19	0.50 (2.39)
Nonsmokers	20	0.34 (2.56)
Sample type		
Personal	39	0.41 (2.50)
Area	29	0.38 (3.63)

Note: (GSD) = geometric standard deviation.
[A]$p < 0.05$.
[B]Smoking status model also is adjusted for sample type.

TABLE IV. Linear Regression Model Results for $\log_e$ Gravimetric $PM_{2.5}$ Concentrations Regressed on $\log_e$ DUSTTRAK $PM_{2.5}$ Concentrations

Categories	Regression Coefficient (95% CI)	Intercept
All samples	0.71 (0.57, 0.85)	−0.32
Sampling period[A]		
Summer	0.49 (0.27, 0.72)	−0.91
Fall/winter	0.85 (0.72, 0.99)	0.16
Sampling site[A]		
Apprentice school	0.89 (0.68, 1.10)	0.001
Power plant	0.55 (0.37, 0.72)	−0.60
Sample type		
Personal samples	0.63 (0.42, 0.84)	−0.28
Area samples	0.72 (0.53, 0.91)	−0.46
Smoking status[B]		
Smokers	0.82 (0.52, 1.12)	−0.29
Nonsmokers	0.66 (0.50, 0.82)	−0.10

Note: CI = confidence interval.
[A]$p < 0.05$.
[B]Smoking status model also is adjusted for sample type.

The $\log_e$ DUSTTRAK $PM_{2.5}$ concentration was found to be a significant predictor of $\log_e$ gravimetric $PM_{2.5}$ concentration during both sampling periods. However, the significant interaction term indicated that the relationship between $\log_e$ DUSTTRAK and gravimetric $PM_{2.5}$ concentrations differed by season ($p < 0.01$). The regression coefficients for $\log_e$ gravimetric $PM_{2.5}$ concentrations regressed on $\log_e$ DUSTTRAK $PM_{2.5}$ concentrations were 0.49 (95% CI: 0.27, 0.72) for samples collected during the summer and 0.85 (95% CI: 0.72, 0.99) for the fall/winter (Figure 2).

The effect of sampling site also was investigated in the regression model. The interaction term for the effect of sampling site was found to be statistically significant ($p = 0.01$). The regression coefficients for $\log_e$ gravimetric $PM_{2.5}$ concentrations regressed on $\log_e$ DUSTTRAK $PM_{2.5}$ concentrations were 0.89 (95% CI: 0.68, 1.10) for the apprentice welding school, 0.55 (95% CI: 0.37, 0.72) for the power plant (Figure 3).

A regression model investigating the effect of both sampling period and sampling site could not be performed due to the similarity in the data structure of the two variables. The summer sampling period only contained samples from the power plant. All the apprentice welding school samples were collected during the fall and winter period.

DISCUSSION

The results from this study indicate that $PM_{2.5}$ concentrations measured using a direct-reading instrument were, in general, well-correlated and highly predictive of those from a filter-based gravimetric sampling method. The geometric mean absolute relative error between the DUSTTRAK and gravimetric

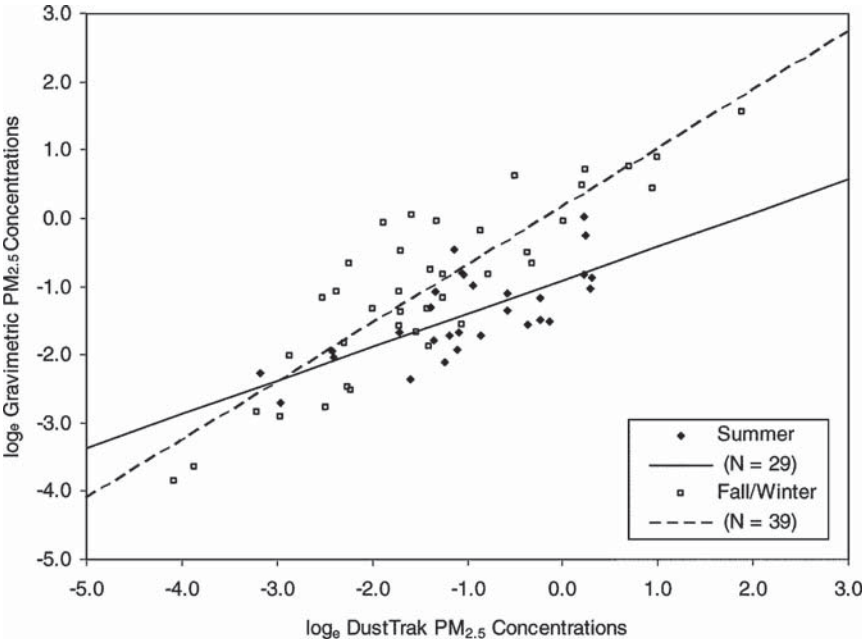

FIGURE 2. Log_e gravimetric $PM_{2.5}$ concentrations regressed on $\log_e$ DUSTTRAK $PM_{2.5}$ concentrations by sampling period. The regression coefficient for summer is significantly different than that for fall/winter ($p < 0.01$).

$PM_{2.5}$ measurements was 0.40 (GSD 2.96) for the 68 paired samples. No statistically significant differences were found between the paired DUSTTRAK and gravimetric $PM_{2.5}$ concentrations ($p = 0.64$). The $PM_{2.5}$ measurements from the DUSTTRAK and gravimetric method also were found to be moderately to highly correlated ($r = 0.68$). The linear regression model constructed using log-transformed DUSTTRAK and gravimetric $PM_{2.5}$ concentrations indicated a significant predictive relationship. Each unit of increase in $\log_e$ DUSTTRAK $PM_{2.5}$ concentrations was associated with an increase of 0.71 (95%

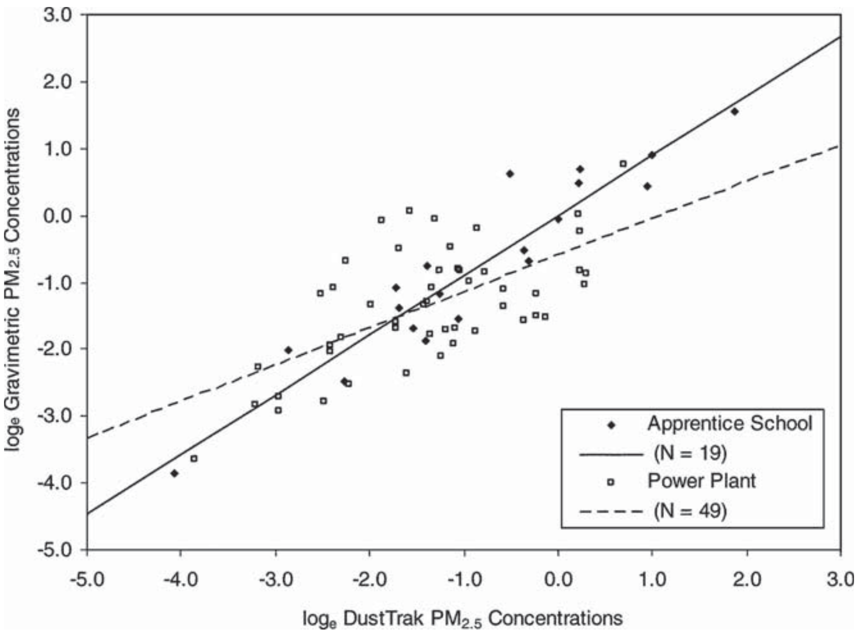

FIGURE 3. Log_e gravimetric $PM_{2.5}$ concentrations regressed on $\log_e$ DUSTTRAK $PM_{2.5}$ concentrations by sampling site. The regression coefficient for the apprentice school is significantly different than that for the power plant ($p = 0.01$).

CI: 0.57, 0.85) in $\log_e$ gravimetric $PM_{2.5}$ levels. From the regression model, the geometric mean DUSTTRAK $PM_{2.5}$ value of 0.30 mg/m^3 predicted a nearly identical gravimetric $PM_{2.5}$ concentration of 0.31 mg/m^3.

The influence of the variables on the relationship between the $PM_{2.5}$ concentrations from the DUSTTRAK and gravimetric sampling method also was investigated in this study. The type of sample, as categorized by personal or area samples, was used to examine the effect of motion. The area samples were stationary, whereas the personal samples were worn by the boilermakers while they performed their various work tasks. The geometric mean absolute relative errors were very similar for the area samples (0.38, GSD 3.63) and personal samples (0.41, GSD 2.50). In addition, the interaction term for sample type was not found to be significant in the linear regression models, indicating that movement did not significantly affect the association between the DUSTTRAK and gravimetric $PM_{2.5}$ concentrations.

Sampling period was selected to study the influence of seasonal variations on the association between gravimetric and DUSTTRAK $PM_{2.5}$ concentrations. Sampling period was found to affect significantly the association between the DUSTTRAK and gravimetric $PM_{2.5}$ measurements. The absolute relative errors were significantly higher during the summer (0.59, GSD 3.38) compared to the fall/winter (0.29, GSD 2.40). In addition, the regression coefficients for $\log_e$ gravimetric $PM_{2.5}$ regressed on $\log_e$ DUSTTRAK $PM_{2.5}$ were statistically different by sampling period. A one unit increase in $\log_e$ DUSTTRAK $PM_{2.5}$ concentrations was associated with an increase in $\log_e$ gravimetric $PM_{2.5}$ levels of 0.49 (95% CI: 0.27, 0.72) in the summer and 0.85 (95% CI: 0.72, 0.99) in the fall/winter. A DUSTTRAK $PM_{2.5}$ value of 0.30 mg/m^3 predicted a gravimetric $PM_{2.5}$ concentration of 0.22 mg/m^3 in the summer and 0.42 mg/m^3 in the fall/winter. Although all measurements were collected indoors, seasonal variations may have contributed to differences in environmental conditions, such as relative humidity. High relative humidity may influence particle behavior or size characteristics that, in turn, may modify the association between DUSTTRAK and gravimetric $PM_{2.5}$ concentrations. A study by Chang and colleagues also found that the association between $PM_{2.5}$ concentrations from a DUSTTRAK and gravimetric method slightly differed when sampling ambient air in the summer compared to the winter.[16]

Sampling site and smoking status were used as surrogate measures for the type of aerosol. The absolute relative errors between the nonsmoker samples and smoker samples were not found to be significantly different ($p = 0.19$), suggesting that the $PM_{2.5}$ exposure from cigarette smoke was minor compared to the workplace exposure. In contrast, the absolute relative errors for the apprentice school samples were found to be significantly different than the absolute relative errors for the power plant samples ($p = 0.05$). The apprentice school samples had a geometric mean absolute relative error of 0.29 (GSD 2.09), whereas the power plant samples had a significantly higher geometric mean absolute relative error of 0.45 (GSD 3.24). The significant interaction term for sampling site in the linear regression models confirmed that sampling site, or the type of particles produced at each site, affected the relationship between DUSTTRAK and gravimetric $PM_{2.5}$ concentrations ($p = 0.01$). At the apprentice school, a unit increase in $\log_e$ DUSTTRAK $PM_{2.5}$ concentrations was associated with an increase of 0.89 (95% CI: 0.68, 1.10) in $\log_e$ gravimetric $PM_{2.5}$ levels. In contrast, at the power plant, each unit increase in $\log_e$ DUSTTRAK $PM_{2.5}$ concentrations resulted in a significantly different increase of 0.55 (95% CI: 0.37, 0.72) in $\log_e$ gravimetric $PM_{2.5}$ levels. The geometric mean DUSTTRAK $PM_{2.5}$ value of 0.30 mg/m^3 predicted a gravimetric $PM_{2.5}$ concentration of 0.28 mg/m^3 at the apprentice school and 0.34 mg/m^3 at the power plant. Evaluating the effect of the type of aerosol after adjusting for seasonal conditions was difficult because there was significant overlap between the sampling period and sampling site variables.

The primary exposure at the power plant overhaul site was residual oil fly ash resulting from the combustion of fuel oil, although welding fume from the boilermaking operations also was present in the atmosphere. As welding fume and residual oil fly ash are chemically complex and dynamic aerosols, quantifying their specific particle distribution and composition is difficult. Depending on the type of boiler used for combustion and the efficiency of the burn, 40 to 100% of the residual oil fly ash particles have aerodynamic diameters less than 2.5 μm.[23] The fine and ultrafine particle fraction of residual oil fly ash contains a significant component of water-soluble metal sulfates.[23]

At the apprentice school, welding fume was the main source of particle exposure. Welding generates metal fume that is mostly composed of particles in the ultrafine and fine fraction—90% of welding fume particles have aerodynamic diameters less than 1 μm, 50% have less than 0.05 μm.[24,25] The principal component of metal fume generated from welding mild steel is iron oxide.[25]

The response of the DUSTTRAK would be affected by the differences in the aerosols as the principle of light scattering depends on the particle size distribution, refractive index, and particle light absorption.[25] The DUSTTRAK was calibrated to the respirable fraction of standard ISO 12103-1, A1 test dust during all sampling periods. Accuracy of the DUSTTRAK $PM_{2.5}$ measurements when compared to the gravimetric $PM_{2.5}$ measurements might have improved if the calibration factor of the DUSTTRAK was adjusted to account for the different response characteristics of each aerosol.

Other studies have shown that although the DUSTTRAK and gravimetric $PM_{2.5}$ concentrations are well-correlated, the DUSTTRAK measurements overestimate $PM_{2.5}$ concentrations compared to gravimetric concentrations.[16,18,20] In a study sampling ambient air in Baltimore, Maryland, Chang et al. found that the DUSTTRAK $PM_{2.5}$ concentrations were approximately two-fold greater than the gravimetric $PM_{2.5}$ concentrations.[16] Similarly, ambient aerosol studies by Ramachandran et al. in Minneapolis, Minnesota, and Yanosky et al. in Athens, Georgia, have shown that the DUSTTRAK consistently overestimated the gravimetric $PM_{2.5}$ concentrations by a factor of two to three.[18,20] Our results were inconsistent with these studies as we found that the DUSTTRAK and gravimetric $PM_{2.5}$ concentrations, in general, were similar to each other. One of the reasons for this discrepancy could be the difference in the concentration ranges that each study observed. The study by Chang et al. had an average DUSTTRAK $PM_{2.5}$ concentration of 53 $\mu g/m^3$ in the summer and 22 $\mu g/m^3$ in the winter.[16] These values were approximately 1/10 of the geometric mean concentration (300 $\mu g/m^3$) observed in our study. The detection range of the DUSTTRAK is from 1 $\mu g/m^3$ to 100 mg/m^3. At the higher concentration ranges typical in an occupational setting, the DUSTTRAK $PM_{2.5}$ concentrations may be more comparable to the gravimetric $PM_{2.5}$ concentrations.

A more likely reason for the different relationship between the $PM_{2.5}$ measurements from the DUSTTRAK and gravimetric method could be that the type of aerosol in each study was different. The environmental studies monitored ambient air; our study was conducted in an occupational environment, with the primary particle exposure resulting from welding fume and residual oil fly ash. The results of this study show that particles from welding fume affect the DUSTTRAK $PM_{2.5}$ measurements differently compared to particles from residual oil fly ash, indicating that the response of the DUSTTRAK is affected by the distinct characteristics of the particles. The characteristics of the particles in ambient air are likely to be even more dissimilar than that of the particles in both welding fume and residual oil fly ash.

Our results indicate that the particle size distribution and composition of the A1 test dust used to calibrate the DUSTTRAK might be more similar to that of welding fume and residual oil fly ash compared to the particle characteristics of general ambient air. The particles sampled in our study might have had a similar refractive index or density as the particles in the A1 test dust, or the differences in the particle properties were balanced so that the $PM_{2.5}$ concentrations from the DUSTTRAK were comparable to those from the gravimetric method.

CONCLUSIONS

A comparison of two particle samplers, a gravimetric sampler and a direct-reading instrument, was performed in an occupational setting. $PM_{2.5}$ measurements from a DUSTTRAK, the direct-reading instrument, were well-correlated and highly predictive of gravimetric $PM_{2.5}$ concentrations when sampling welding fume and residual oil fly ash.

The results from this study further suggest that the association between gravimetric and DUSTTRAK $PM_{2.5}$ measurements may depend on other factors. Seasonal variations and type of aerosol may affect the relationship between the $PM_{2.5}$ measurements from the two sampling methods. Therefore, proper calibration of the DUSTTRAK for the specific sampling environment may be necessary prior to use in order to be a reliable alternative to the reference method. Accuracy of the DUSTTRAK $PM_{2.5}$ measurement may improve with greater knowledge of the specific aerosol characteristics, including the particle size distribution, light absorption, and index of refraction.

RECOMMENDATIONS

The manufacturer of the DUSTTRAK aerosol monitor recommends performing custom calibrations if the particle distribution and type of the aerosol of interest differs significantly from the ISO 12103-1, A1 Arizona test dust. Due to the different response characteristics of the DUSTTRAK to various aerosols, recalibrating the DUSTTRAK for the specific aerosol may be necessary to improve accuracy of the particle measurements.

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