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ORIGINAL ARTICLE

Correction Factors for Outdoor Concentrations of $PM_{2.5}$ Measured with Portable Real-time Monitors Compared with Gravimetric Methods: Results from South Korea

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Abstract

This study investigated the association between $PM_{2.5}$ concentrations obtained with portable real-time monitors and those obtained with gravimetric methods in national urban air-quality monitoring sites in Seoul, South Korea. We used the SidePak AM510 Personal Aerosol Monitor (TSI Inc., 500 Cardigan Road Shoreview, MN) and DustTrak DRX 8533 (TSI Inc., 500 Cardigan Road Shoreview, MN) as portable real-time monitors for measuring $PM_{2.5}$ concentrations and compared these values with those measured with the PMS-103 or SEQ 47/50 models operated by Federal Reference Method (FRM) or the European Committee for Standardization(ECS), respectively, in national urban air-quality monitoring sites in Seoul. Measurements were conducted every other day in the winter and spring seasons of 2014. The estimated daily mean concentrations of $PM_{2.5}$ ranged between 13.4 and 161.9 $\mu g/m^3$ using AM 510 and between 22.0 and 156.0 $\mu g/m^3$ using DustTrak. The Spearman correlation coefficient for $PM_{2.5}$ concentrations between AM 510 and gravimetric results was 0.99, and the correlation between DustTrak and gravimetric results was 0.87. The correction factor suggested was 0.42 and 0.29 for AM 510 and DustTrak, respectively. We found that $PM_{2.5}$ concentrations measured with real-time monitors could overestimate true $PM_{2.5}$ concentrations and therefore the application of a correction factor (0.43) is strongly suggested for quantification when Real-time monitors were operated of $PM_{2.5}$ levels at urban atmospheric environment of South Korea.

Key words : $PM_{2.5}$, Federal Reference Method (FRM), Real-time monitor, Correction factor

1. Introduction

On October 2013, the International Agency for Research on Cancer (IARC), a specialized cancer agency of the World Health Organization (WHO), reported that outdoor air pollution is carcinogenic to humans (Group 1) and concluded that there is sufficient evidence that exposure to outdoor air pollution causes lung cancer. According to a separate evaluation, particulate matter, a major component of outdoor air pollution, is also considered carcinogenic to humans (Group 1) (IARC, 2015). Owing to the harmful effects of exposure to outdoor particulate matters, especially $PM_{2.5}$, the government of South

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Korea implemented a new national exposure guidelines (50 μg/m^3: 24 hour, 25 μg/m^3: 1 year) in January 2015 as the WHO guidelines established in 2005 (Korea Ministry of Government Legislation, 2015; WHO., 2005).

In several epidemiologic studies (Gehring et al., 2002; Morgenstern et al., 2008; Zanobetti et al., 2009), the associations between exposure to air pollution and health effects were evaluated using air pollution data obtained from national stationary monitoring sites operated with filter-based standard gravimetric (G) methods i.e., using the Federal Reference Method (FRM) of U.S.A. or the European Committee for Standardization (CEN) in cases where the personal exposure levels to $PM_{2.5}$ were not available.

As an alternative to traditional filter-based G methods for determining the personal exposure levels to air pollutants, several studies have measured personal exposure levels to $PM_{2.5}$ using real-time (RT) continuous monitors (Both et al., 2011; Morabia et al., 2009; Padró-Martíneza et al., 2012; Steinle et al., 2015; Vallejo et al., 2004; Van Vlient et al., 2013; Wheeler et al., 2011) with the advantage that these devices can detect temporal changes of concentration values and identify nearby sources to susceptible population. Several studies validated the results of RT monitors in the U.S.A. and Canada (Chung et al., 2001; Wallace et al., 2011).

However, information on validation of the results obtained with portable RT monitors compared with those obtained with FRM or CEN is still insufficient in South Korea where speciation of particles may be different from those U.S.A or Canada. $PM_{2.5}$ monitors use light scattering technology to determine mass concentration of particles scattering light in the sensing changer in a continuous sampling stream of monitor. The lack of validation limits their applicability in South Korea. This study provided quantitative evidence supporting application of correction factors for $PM_{2.5}$ real time monitors by investigating the association of the $PM_{2.5}$ concentrations obtained with portable RT monitors and G methods in national urban air-quality monitoring sites located in metropolitan cities in South Korea.

2. Material and methods

2.1. $PM_{2.5}$ measurement devices

In this study, we used two RT monitors including SidePak AM 510 (TSI Inc., 500 Cardigan Road Shoreview, MN) and DustTrak DRX 8533 (TSI Inc., 500 Cardigan Road Shoreview, MN). Comparative measurements of $PM_{2.5}$ concentrations using RT monitors were conducted between September 2013 and March 2014 in three national monitoring sites located in Seoul Incheon and Bucheon, South Korea, where the G instruments are located (PMS-103, APM Engineering Co., Technopark, Bucheon, South Korea; or SEQ 47/50, Leckel GmbH, Berlin, Germany), according to standard operation procedures established by the FRM and CEN (Allegrini et al., 2015; U.S. EPA, 2014).

2.2. Measurement of $PM_{2.5}$ concentrations

$PM_{2.5}$ concentration data were collected from the two RT monitors every minute followed by the calculation of 24-hour average values. Corresponding daily $PM_{2.5}$ concentrations were obtained with G methods at the same sampling points. The flow rates for AM510 and DustTrak were 1.7 L/min and 3.0 L/min, respectively. We used TrakPro software (Version 4.5.1.0) to obtain log data from RT monitors. G data on the sampling sites, for the sampling period, were provided by an agent of the national air pollution monitoring sites upon request. Considering that each national monitoring site has equipment operated by either FRM or CEN, we compared the RT results with those obtained with one G method but not with both G methods. During the fall season (September 2013) at Bucheon city and during the early spring season

(March 2013) at Incheon, the RT-AM510, RT-DustTrak and G-PMS-103 equipment were operated but only the RT-AM510 and G-SEQ equipment located in Seoul were used during the winter season (February 2014). RT-DustTrak could not be used during this period because of hardware malfunction. After repair, it was used for monitoring of following the spring season.

2.3. Data analysis

The SPSS statistical package (version 21.0) was used for statistical analyses. The Spearman correlation test was used to evaluate the associations among the $PM_{2.5}$ concentrations for three sampling seasons using different devices, considering that variables were not normally distributed.

Then, we compared the distribution of $PM_{2.5}$ con-centration ratios obtained by comparative measure-ments of RT monitors with a G equipment using the Wilcoxon's rank sum test because the ratio distribu-tion was not normally distributed. Furthermore, we evaluated the associations of the daily mean concen-trations (n=24) from RT monitors with those obtained with G methods using multivariate linear regression models (Tabachnick et al., 2001). We used the daily mean concentration values obtained with G methods as dependent variables and those obtained with RT monitors as independent variables. The daily mean temperature and relative humidity data for each sampling date, obtained from the nearest national meteorological monitoring sites, were used to adjust the effects on the association between RT and G outcomes. The distribution of the daily mean concentration values using G methods was normal (p=0.20). A sensitivity test was conducted by analyzing FRM results separately from CEN results. Corresponding correction factors for each RT monitor were also provided.

3. Results and Discussions

3.1. $PM_{2.5}$ concentration levels

The distribution of daily mean $PM_{2.5}$ concentra-tions is shown in Figure 1. The medians (interquartile range [IQR]) of $PM_{2.5}$ concentrations measured using G and RT (RT-AM510) methods for the entire sampling period were 22.5 (13.0~35.8) μg/m^3 and 43.8 (24.0~84.1) μg/m^3, respectively. The medians (IQR) for the fall (September 2013) and early spring (March 2014) seasons using G and RT-AM510 methods were 9.7 (7.0~11.0) μg/m^3 and 21.0 (21.0~25.0) μg/m^3, and 23.0 (18.0~30.0) μg/m^3 and 49.8 (35.0~74.6) μg/m^3, respectively. The medians (IQR) obtained with the RT-DustTrak monitor were 41.0 (24.3~81.8) μg/m^3 in the fall and 56.0 (45.0~95.0) μg/m^3 in the spring period (Figure 1).

The medians (IQRs) of temperature and relative humidity for the entire sampling period were 1.9℃ (0.0~3.6℃) and 51.5% (48.0~68.0%). The IQRs of these two variables for the fall and spring seasons were 21.7℃ (20.8~22.5℃) and 75.0% (71.0~97.5%), and 1.0℃ (0.9~2.2℃) and 58.5% (49.9~68.9%) respectively. The medians of these variables obtained during the winter season were 0.7℃ (-0.7~2.2℃) and 49.0% (41.6~51.5%). The details of the meteoro-logical conditions by sampling season are summa-rized in Figure 1.

Despite the growing public and political interest in reducing the personal exposure levels to $PM_{2.5}$ in South Korea RT $PM_{2.5}$ monitoring still faces challenges in providing real time concentration information. In addition, although the number of national $PM_{2.5}$ G monitoring sites in South Korea increased from 8 in 2011 to 104 in 2014 (National Institute of Environmental Research, 2011, 2014), additional RT monitors are required because they can detect continuous temporal variations each minute and identify nearby exposure sources on a RT basis in micro environment of hotspots. However, this study

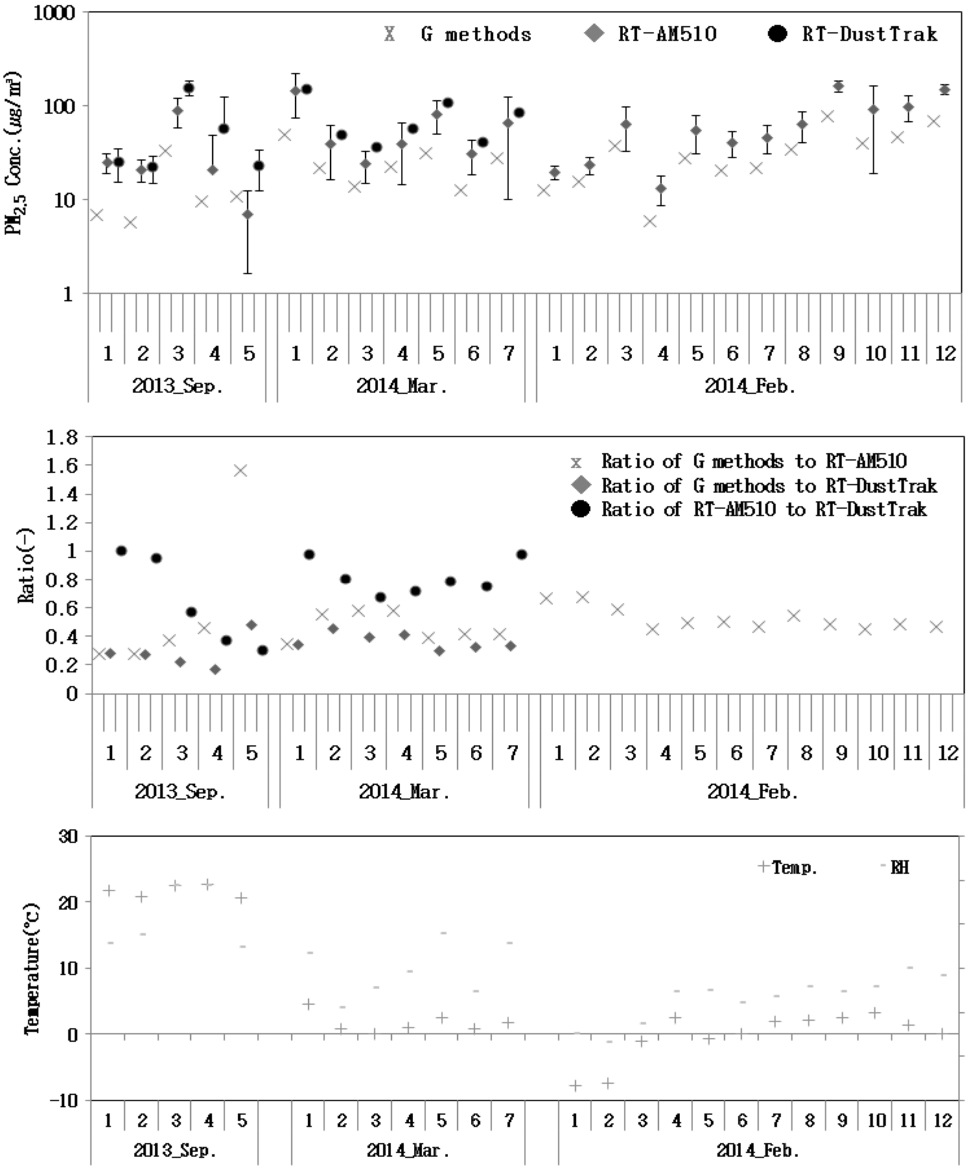

Fig. 1. Distributions of $PM_{2.5}$ concentrations, ratios of gravimetric (G) to real-time (RT) methods and meteorological conditions.

found that $PM_{2.5}$ concentrations measured with commonly used RT monitors overestimate true $PM_{2.5}$ concentrations 2- to 3-fold, depending on the instrument used. Therefore, the application of a correction factor is strongly suggested for RT monitoring of $PM_{2.5}$ concentrations.

3.2. Ratio of $PM_{2.5}$ concentrations by RT to G (RT/G) methods

The median (IQR) of the RT-AM510/G ratio of the $PM_{2.5}$ concentration for the entire sampling period was 0.48 (0.42~0.57) and the medians (IRQs) in the fall, early spring, and winter seasons were 0.38 (0.28~0.46), 0.42 (0.40~0.57), and 0.50 (0.47~0.56), respectively. The IQRs of RT-DustTrak/G ratio in the fall and early spring seasons were 0.27 (0.22~0.28) and 0.34 (0.33~0.40), respectively. According to the results of Kruskal-Wallis test, the ratios by sampling season (n=5, 7, and 12 in the fall, early spring, and winter seasons) were not statistically different (p=0.16 for RT-AM510/G and p=0.09 for RT-Dust Trak/G) (Figure 1).

3.3. Correction factors for $PM_{2.5}$ for RT monitors

The results of the Spearman test showed that the $PM_{2.5}$ concentrations using RT monitors were strongly associated with those obtained with G methods (r=0.95, n=24, $p \leq 0.01$ between RT-AM510 and G, and r=0.87, n=12, $p \leq 0.01$ between RT-DustTrak and G) (Table 1) whereas $PM_{2.5}$ concentrations using RT or G methods had no significant association with temperature or relative humidity (Table 1).

Subsequently, correction factors were obtained from single linear regression models for RT monitors (0.42 for RT-AM510 and 0.29 for RT_DustTrak, $p<0.01$) for measurement of $PM_{2.5}$ at urban atmospheric environment of South Korea. After adjusting for temperature and relative humidity, the results were unchanged (0.42 for RT-AM510, n=24, and 0.29 for RT-DustTrak, n=12, $p<0.01$) (Table 2).

Further analyses validated the correction factor for RT-AM510 to G. Our results indicated that the correction factor was not affected by the G instruments, i.e., FRM, or CEN; the distributions of the two ratios (RT-AM510/G-FRM and RT-AM510/ G-CEN) were not significantly different (p=0.219) according to Wilcoxon's rank sum test (Figure 2).

Several previous studies provided a correction factor for AM510 RT monitors: 0.77 in Northern California, U.S.A. (ambient air), 0.43 or 0.52 in Italy (ambient air at urban or rural areas), and 0.42 in Italy (indoor-outdoor mixed environment) (Borgini et al., 2011; Jiang et al., 2011; Karagulian et al., 2012) which were somewhat similar to our results.

Similarly, our correction factor for DustTrak was consistent with results reported by Chung et al.(2001) (0.33), Ramachandran et al. (2000) (0.33), and Wallace et al. (2011) (0.38), who conducted their studies on atmospheric environments. Also a previous Korean studies provided 0.57 as a correction factor for DustTrak (Kim et al., 2014). This study obtained correction factor of 0.78 for RT-AM510, compared to values of RT-DustTrak (Data not shown). According to Zhang et al., the correction factor for AM510 to DustTrak, obtained from Oxford Street of U.K. was also similar (0.92) to our study. We acknowledge that

Table 1. Spearman correlation coefficients obtained among gravimetric, real-time $PM_{2.5}$ concentrations, temperature, and relative humidity

	G methods (㎍/㎥)	RT-AM510 (㎍/㎥)	RT-DustTrak (㎍/㎥)	Temp. (℃)	RH (%)
G methods (㎍/㎥)	1.00				
RT-AM510(㎍/㎥)	0.95**	1.00			
RT-DustTrak(㎍/㎥)	0.87**	0.85**	1.00		
Temp. (℃)	-0.13	0.02	0.12	1.00	
RH (%)	-0.01	0.15	0.34	0.76**	1.00

**: p<0.01

Table 2. Associations of real-time $PM_{2.5}$ concentrations with gravimetric values after adjusting for levels of humidity and temperature

	Model 1 (n=24, R^2 = 0.93)		Model 2 (n=24, R^2 = 0.94)		Model 3 (n=24, R^2 = 0.94)	
	Coef.	SE	Coef.	SE	Coef.	SE
Intercept	2.87	1.82	3.36	1.80	4.42*	1.90
RT-AM 510(㎍/㎥)	0.42**	0.03	0.43**	0.02	0.42**	0.03
RH (%)			-0.01	0.01	-0.00	0.01
Temp. (℃)					-0.19	0.13
	Model 1 (n=12, R^2 = 0.81)		Model 2 (n=12, R^2 = 0.93)		Model 3 (n=12, R^2 = 0.92)	
	Coef.	SE	Coef.	SE	Coef.	SE
Intercept	3.39	3.01	20.03**	4.51	18.10*	6.69
RT-DustTrak(㎍/㎥)	0.26**	0.04	0.30**	0.03	0.29**	0.04
RH (%)			-0.28**	0.07	-0.23	0.14
Temp. (℃)					-0.09	0.22

*: p<0.05., **: p<0.01

sources of outdoor $PM_{2.5}$ can vary and include the industrial sector and cooking activities, as well as motor vehicles and seasonality (Zhu et al., 2012). A lack of quantitative information on the speciation of particles, traffic volume, type of vehicle, or difference of sampling time or season limits further exploration of the basis for the differences in the correction factors between these studies and ours.

The RT monitors were well adapted to monitor $PM_{2.5}$ levels in South Korea. The median $PM_{2.5}$ concentrations in the fall, early spring, and winter seasons include the daily mean concentration range obtained from corresponding national monitoring sites between 2013 and 2014 (Personal Communication) indicating that our correction factors can be applied to calculate individuals' exposure levels to ordinary $PM_{2.5}$ levels in South Korea.

However, this study has some limitations, including the relatively small sample size. Nevertheless, we randomly obtained 24 data sets at various concent -ration levels to ensure that the concentration distributions would not be systematically biased as indicated earlier with the normality test outcome (p=0.20). Conducting future studies with larger sample sizes will help estimate the correction factors considering the spatial and temporal variations of $PM_{2.5}$ concentrations. Second, Our $PM_{2.5}$ concent -rations might not be representative of each sampling season or area due to spatial-temporal variations (Contini et al., 2014; Enftens et al., 2012; Puustinen et al., 2007). However, the purpose of this study was to provide general correction factors for $PM_{2.5}$ monitoring. Therefore, we achieved our goal by monitoring different $PM_{2.5}$ concentration levels in three different sites over 24 days through different seasons. If measurements were made in longer sampling periods for each season and location, our results would be more representative. Furthermore, we could not measure wind speed or wind directions owing to the limited study period and funding limitations. Although most of matched $PM_{2.5}$ concentration values, between RT and G methods, agreed well (R^2 = 0.92 or higher, after controlling for temperature and relative humidity), measurements

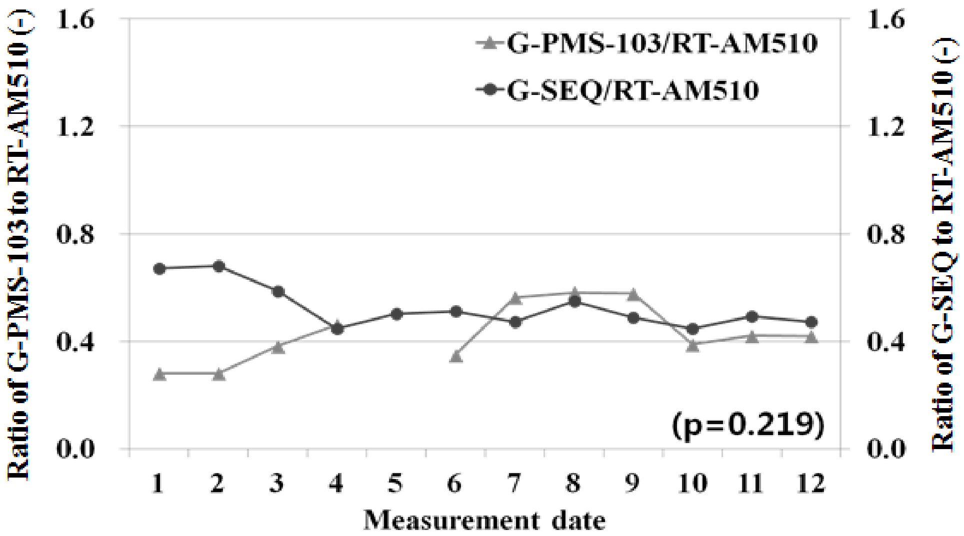

Fig. 2. Ratios of $PM_{2.5}$ concentrations measured by FRM or CEN to the values measured by the real-time method.

conducted in our early experiment period were likely to be affected by other factors, probably wind. In future studies, measurements of the wind direction and wind speed will provide improved correction factors between the RT and G methods. Also future studies may be necessarily conducted to obtain site specific correction factors including construction fields or rural areas.

4. Conclusions

We found that $PM_{2.5}$ concentrations measured with real-time monitors could overestimate true $PM_{2.5}$ concentrations and therefore the application of a correction factor (0.43) is strongly suggested for quantification when Real-time monitors were operated of $PM_{2.5}$ levels at urban atmospheric environment of South Korea. Our study provides compelling evidence supporting the application of correction factors for RT $PM_{2.5}$ monitors aimed at decreasing measurement biases for RT exposure levels in urban atmospheric hotspots.

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