Performance characterization of the portable miniVOL particulate matter sampler

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Abstract

This paper describes the performance of the portable miniVOL sampler during a one year study conducted in the United States from April, 1999 to March, 2000. The reliability, precision, and relative accuracy of the miniVOL sampler are assessed. Sampler precision was evaluated from co-located measurements. Comparative measurements with a dichotomous and a TEOM sampler were also made to determine the miniVOL’s accuracy relative to two internationally accepted monitoring techniques. Results indicate that the miniVOL operates reliably and yields statistically similar concentration measurements when co-located. Thus, the characterization of spatial distributions and exposures to PM_{10} and PM_{2.5} mass concentrations with the miniVOL can be accomplished with confidence. The miniVOL also produced statistically comparable results with a time-averaged dichotomous and a continuous TEOM sampling system for PM_{10} and PM_{2.5} mass concentration measurements. However, the data indicate that measurement accuracy relative to these systems can be a function of environmental conditions. The study results will assist regulatory agencies and epidemiologists to better assess spatial distributions and human exposures to ambient particulate matter concentrations.

Introduction

The miniVOL portable particulate matter sampler possesses many attributes beneficial for conducting ambient air quality investigations for inhalable and respirable particulate matter. The samplers are portable, lightweight, inexpensive, easy to use, and do not require an external power source at the monitoring site.
Because of these attributes, the miniVOL sampler has been utilized in several studies to assess particulate matter less than 10 µm (PM$_{10}$) and particulate matter less than 2.5 µm (PM$_{2.5}$) mass concentration distributions. [1],[2],[3],[4],[5],[6] The samplers can provide better spatial representation and improved human exposure assessments than traditional, fixed site samplers.[7]

Although miniVOL samplers have been used extensively, few published data exist on the performance of these samplers. To evaluate the performance of the miniVOL, co-located monitoring sites were established. These sites allowed for comparisons of miniVOL PM$_{10}$ and PM$_{2.5}$ measurements with internationally accepted sampling methods during typical ambient exposures.

**Sampler description**

The miniVOL particulate matter sampler [8] was jointly patented by the U.S. Environmental Protection Agency (USEPA) and the Lane, Oregon Regional Air Pollution Authority (Figure 1). The miniVOL is approximately 1 meter in height and weighs less than 10 kilograms. The sampler collects at a flow rate of 5 liters per minute, and is equipped with a programmable timer. The sampler can operate from either AC or DC power sources. A battery pack powers the sampler for a 24 hour sampling period.

The miniVOL is equipped with a size selective inlet for particulate matter sampling. A single stage inertial impactor with a 10 µm cutpoint is used for PM$_{10}$ sampling. The PM$_{10}$ impactor is used in series with a 2.5 µm cutpoint single stage inertial impactor for PM$_{2.5}$ monitoring. The miniVOL has not been designated as a reference or equivalent method sampler for PM$_{10}$ or PM$_{2.5}$ by the USEPA.

**Experimental method**

From March 1999 to March 2000, University of Kansas (KU) personnel collected ambient particulate matter mass concentration measurements at twenty-one sites using miniVOL samplers to assess regional-scale, particulate matter distributions in Southeast Kansas, as part of the Southeast Kansas Health Assessment Study. PM$_{10}$ data were collected at all twenty-one sites while PM$_{2.5}$ data were collected at nine of the sites. In total, thirty-two miniVOLs collected PM$_{10}$ or PM$_{2.5}$ mass measurements on a six day schedule. Monitoring sites were located in urban and rural areas. Urban areas consisted of light and heavy industrial uses, while rural areas were undeveloped or supported agricultural activities. Because many of the sampling locations were in areas with limited access to electrical power, the miniVOL was an ideal choice for assessing spatial distributions of the particulate matter mass concentrations.

For the assessment, several sampling sites were established to obtain information on the performance of the miniVOL Sampler. A co-located set of PM$_{10}$ and PM$_{2.5}$ samplers were established at separate sites to assess the precision
of the miniVOL. Both PM$_{10}$ and PM$_{2.5}$ samplers were programmed to operate during the same time period, and collect samples on the same filter media. Inlet spacing between the co-located samplers was approximately 0.5 meters. The miniVOLs were rotated throughout the study to prevent potential sampling bias.

MiniVOL samplers were also co-located with a PM$_{10}$/PM$_{2.5}$ dichotomous Versatile Air Pollutant Sampler (VAPS, University Research Glass, Chapel Hill, North Carolina, USA), and a continuous PM$_{10}$ Tapered Element Oscillating Microbalance (TEOM) monitor (Model 1100A, Rupprecht and Patashnick, Albany, New York, USA). All samplers were evaluated over the same time period. Mass loadings from the miniVOL samplers were collected on 47mm teflon-coated, glass fiber filter media (Pall Corporation, #T60A20, Ann Arbor, Michigan, USA), and measured using a Cahn Model C-33 Microbalance (Orion Research Inc., Boston, Massachusetts, USA). Mass loadings from the VAPS were collected on 47 mm teflon membrane filters (1μm pore size, #R2PL047, Pall Corporation, Ann Arbor, Michigan, USA), and also measured with the Cahn Microbalance. All analyzed filters were equilibrated before initial and final weighing for a minimum 24-hour period in a chamber controlled to 20° C and forty percent relative humidity. Reported mass concentrations were not corrected to standard temperature and pressure. Inlet spacing between the miniVOL and VAPS sampler was approximately 2 meters, while spacing between the miniVOL and TEOM was approximately 1.5 meters. MiniVOL samplers were also rotated among the monitoring sites.

Laboratory, transport, and field blanks were evaluated during each sample day to identify potential contamination during the filter analysis, handling, or static exposure to atmospheric particulate matter between sampling days. Each control blank had an initial and final weighing in conjunction with all of the thirty-two sample filters. The laboratory blanks were stored in the temperature and humidity controlled chamber between analyses. Transport blanks were loaded into miniVOL inlets and taken to the field between analyses. Two laboratory and two transport blanks were evaluated for each set of thirty-two samples. Field blanks were obtained when a miniVOL did not operate at all on a sampling day due to mechanical failure or operator error. Thus, these field blanks were installed into the miniVOL inlets, set in a sampler, and exposed to the ambient air during the five day static period between sampling events.

Operation and maintenance procedures utilized during the study conformed to the guidelines recommended by the manufacturer.[8] Sampler impactor stages were cleaned and greased after every seventh sampling event. Flowrates were checked and set to 5 lpm during sample collection days. Differences in temperature and pressure from the flowrate set date to the sampling event date were deemed negligible during a three month pilot study. All miniVOL inlets were placed in clean plastic bags for transport to the field.
Results and discussion

Performance reliability

An evaluation of invalid data due to operational failures by the miniVOL during the field assessment was conducted. A potential of 1,600 miniVOL sampling events occurred during the study period. However, on twenty-six occasions, a monitoring site was inaccessible due to a building closure or inclement weather conditions. Of the remaining 1,574 potential sampling events, sixty-eight miniVOL mechanical failures occurred; nineteen of these occurred during the first three sample days when ambient temperatures at start-up were below 0°C. Failures likely occurred from freezing of the sampling pumps. Dessicant packs (Impak Corp, Pasadena, California, USA) added to the miniVOL casing reduced the occurrence of pump freezing during the remainder of the study. An additional thirty-nine samples were invalidated due to filter contamination from insects which penetrated the inlet, and nine samples were invalidated due to operator error. The total sample collection success rate for the miniVOLs during the one year study period was ninety-three percent. The miniVOL samplers successfully operated during ninety-six percent of potential sampling events.

The error associated with sample analysis was evaluated through the control filter blanks. During the field assessments, the average laboratory blank difference was 0.2±0.7 μg with a standard deviation of 6.9 μg (n=100). The average transport blank different was +5.7±1.6 μg with a standard deviation of 12.8 μg (n=64). The average reported field blank difference value for the miniVOL PM$_{10}$ inlets was +11.6±2.3 μg with a 12.1 μg standard deviation (n=28). For the miniVOL PM$_{2.5}$ inlets, the average reported field blank difference value was +6.9±1.9 μg with a ±8.9 μg standard deviation (n=23). Results indicate that passive collection of particles occur during static sampler conditions, especially with the PM$_{10}$ inlet.

Precision assessment

The precision of the MiniVOL sampler was determined based on comparisons of co-located samplers for both PM$_{10}$ and PM$_{2.5}$ mass measurements. Reported filter mass loadings were not corrected for laboratory, transport or field blank values. Normality of all data presented in this paper were verified by normal scores plots (p-values greater than 0.1). Figure 2 shows a scatterplot of the results of the PM$_{10}$ precision analysis. The average difference between co-located PM$_{10}$ samplers was 0.29±0.30 μg/m$^3$ with a standard deviation of 2.35 μg/m$^3$ and a coefficient of variation (COV) of 8.6 percent. The maximum difference between co-located sampler concentration measurements was 7.38 μg/m$^3$ while the second largest difference was 5.28 μg/m$^3$.

Results of the ambient PM$_{2.5}$ analysis are shown on Figure 3. The average
difference between co-located PM$_{2.5}$ samplers was $0.12 \pm 0.25$ µg/m$^3$ with a standard deviation of 1.57 µg/m$^3$ and a COV of 12.7 percent. The maximum difference between co-located PM$_{2.5}$ samplers was 4.17 µg/m$^3$ while the second largest difference was 3.45 µg/m$^3$.

**Relative accuracy assessment**

One PM$_{10}$ and two PM$_{2.5}$ miniVOL samplers were co-located with the VAPS to estimate the relative accuracy of the miniVOL compared with a commonly used, time-averaged measurement technique. Figure 4 shows a scatterplot of the average PM$_{10}$ actual concentration measurements from the VAPS sampler against the miniVOL actual concentration measurements. The average difference between the VAPS and miniVOL 24-hour average concentration measurements was $0.69 \pm 0.92$ µg/m$^3$ (VAPS higher) with a standard deviation of 4.79 µg/m$^3$ and a COV of 18.8 percent (average measurement = 25.5 µg/m$^3$, n=27). The maximum difference between the co-located VAPS and miniVOL samplers was +13.06 µg/m$^3$ while the second largest difference was -10.81 µg/m$^3$.

Figure 5 shows a scatterplot of the average PM$_{2.5}$ actual concentration measurements from the VAPS sampler against the miniVOL actual concentration measurements. The average difference between the VAPS and miniVOL 24-hour average concentration measurements was $1.07 \pm 0.45$ µg/m$^3$ (miniVOL higher) with a standard deviation of 2.68 µg/m$^3$ and a COV of 24.1 percent (average measurement = 11.1 µg/m$^3$, n=36). The maximum difference between the co-located VAPS and miniVOL samplers was -7.74 µg/m$^3$ while the second largest difference was +5.89 µg/m$^3$.

Two PM$_{10}$ miniVOL samplers were co-located with a continuous TEOM Sampler to estimate the relative accuracy of the miniVOL compared with a well defined, real-time measurement technique. Figure 6 shows a scatterplot of the average miniVOL actual concentration measurements against the co-located TEOM actual concentration measurement. The average difference between the TEOM and miniVOL 24-hour average concentration measurements was $2.21 \pm 0.61$ µg/m$^3$ (TEOM higher) with a standard deviation of 4.00 µg/m$^3$ and a COV of 16.2 percent (average measurement = 24.7µg/m$^3$, n=43). The maximum difference between the co-located TEOM and miniVOL samplers was +10.88 µg/m$^3$ while the second largest difference was +10.73 µg/m$^3$.

Environmental factors which may have contributed to measurement difference between the miniVOL and the VAPS and TEOM, respectively, were examined. These factors included the daily average ambient PM$_{10}$ concentration (from the VAPS or TEOM), maximum 1-hour PM$_{10}$ concentration (TEOM), average wind speed, maximum 2-minute wind speed, maximum 5-second wind speed, average wind direction, minimum temperature, maximum temperature,
average temperature, and absolute humidity experienced during the sample period at the monitoring site. A principle components analysis (PCA) was conducted on the correlation matrix to determine independent environmental factors. Results of the PCA indicated that independent environmental components could be categorized as ambient PM concentration (average and maximum 1-hour), wind speed (average, 2-minute maximum, and 5-second maximum), wind direction, and temperature (maximum, minimum, average, and absolute humidity) based on the evaluation of measurements collected during the study period.

A multiple regression analysis was conducted for the independent variables to determine the relative influence of these factors on the measurement difference between the sampling systems. The combination of independent variables which explained the maximum amount of variance in the data are reported. Wind direction was not included since this factor could not be quantified with respect to the other parameters.

The regression equation describing the relationship between VAPS and miniVOL measurement differences for PM$_{10}$ suggest that the ambient concentration, the maximum 2-minute wind speed, and the absolute humidity effect the samplers’ performance characteristics. The equation suggests that the miniVOL exhibits a low sampling bias relative to the VAPS as ambient concentration, wind speed, and the absolute humidity increase.

Several factors related to the operational characteristics of the VAPS and miniVOL samplers may explain the influence of environmental factors on measurement differences. The miniVOL utilizes a small inertial impactor with a round jet and a greased flat or cupped impaction plate for particle size separation. The VAPS uses a large impactor for PM$_{10}$ removal followed by a circular virtual impactor to separate PM$_{10}$ and PM$_{2.5}$ size fractions. During sampling days with large mass loadings, the small miniVOL impaction plate may become overloaded and decrease sampling efficiency. Since the impactor is relatively small in size, minimal changes in particle loadings on the impaction plate may result in a decreased channel depth, thus lowering the actual cutpoint of the inlet.

The collection efficiency of the miniVOL inlet will also be influenced by wind speed. As shown on Figure 7, the inlet is not isokinetically designed. Air flow around the inlet’s raincap requires two 90° turns. As wind speeds increase, particle momentum increases and the cutpoint of the miniVOL inlet will decrease.

Effects of absolute humidity on concentration measurement differences may be a function of particle charging. As the atmospheric water vapor content decreases, particle charging will increase. The multiple regression equation indicates that the miniVOL inlet may be susceptible to particle charging effects; however, no tests were conducted to verify this theory. Particle charging may result in removal of the particles in the inlet or an increase build up of charged particles on the impaction plate. Either mechanism will result in a lowered inlet cutpoint, and a corresponding decrease sample measurement from the miniVOL.

A multiple regression analysis comparing the VAPS and miniVOL samplers for PM$_{2.5}$ also suggests that ambient concentration, wind speed, and absolute humidity effect measurement differences. However, the sensitivity to these
factors is less than for PM$_{10}$ sampling. A review of the co-located VAPS and miniVOL measurements shown in Figure 5 reveals that the miniVOL has a potential positive sampling bias. A static chamber analysis of the PM$_{2.5}$ impactor found a cutpoint of approximately 2.7 μm.[9] The elevated cutpoint may result in a positive sampling bias for the PM$_{2.5}$ miniVOL.

The relationship between temperature and the TEOM-miniVOL difference is likely a function of the TEOM's operating characteristics. Reports from several studies show that PM$_{10}$ mass concentration measurements from the TEOM are negatively biased on low temperature days.[1], [10],[11],[12] These studies noted that volatilization of some organic component of the PM occurs as a result of conditioning of the sample air. The TEOM inlet and sampling chamber air are maintained at 50°C to prevent precision loss due to thermal expansion or contraction of the tapered element during temperature changes.[7] The regression equation shows that the measurement difference between the TEOM and the miniVOL decreases as temperature decreases.

Conclusions

The reliability, precision and relative accuracy of the portable miniVOL PM sampler during typical ambient exposures have been assessed. Results indicate that the miniVOL (a) operates reliably and (b) yields statistically similar concentration measurements when co-located. Thus, the characterization of spatial distributions of PM$_{10}$ and PM$_{2.5}$ mass concentrations with the miniVOL can be accomplished with a high level of confidence.

The miniVOL also produced statistically comparable results when co-located with the VAPS for PM$_{10}$ and PM$_{2.5}$ and the TEOM sampling system for PM$_{10}$. However, environmental factors such as ambient concentration, wind speed, temperature, and humidity influence the relative measurement comparability between these sampling systems. Results also indicate that passive airborne particulate matter collection can occur at the miniVOL inlet during non-sampling conditions.

References

[5] Lin, Y.J.; Kasprak, A. portable PM$_{10}$ monitoring for a large roadway tunnel


Figure 1. Diagrams of (a) a miniVOL particulate matter sampler equipped with a PM$_{10}$ size selective inlet, (b) the sampler operating board, and (c) an air flow schematic.
Figure 2. Comparison of co-located PM$_{10}$ miniVOL Samplers.

Figure 3. Comparison of co-located PM$_{2.5}$ miniVOL Samplers.
Figure 4. Comparison of co-located PM$_{10}$ miniVOL Sampler and corresponding PM$_{10}$ VAPS Sampler concentration measurements.

Figure 5. Comparison of co-located PM$_{2.5}$ miniVOL and VAPS Sampler concentration measurements.
Figure 6. Comparison of co-located PM$_{10}$ miniVOL Samplers and corresponding 24-hour average TEOM concentration measurements.