Determining the Spatial Variability of Personal Sampler Inlet Locations

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This article examines the spatial variability of dust concentrations within a coal miner's breathing zone and the impact of sampling location at the cap lamp, nose, and lapel. Tests were conducted in the National Institute for Safety and Health Pittsburgh Research Laboratory full-scale, continuous miner gallery using three prototype personal dust monitors (PDM). The dust masses detected by the PDMs were used to calculate the percentage difference of dust mass between the cap lamp and the nose and between the lapel and the nose. The calculated percentage differences of the masses ranged from plus 12% to minus 25%. Breathing zone tests were also conducted in four underground coal mines using the torso of a mannequin to simulate a miner. Coal mine dust was sampled with multi-cyclone sampling cans mounted directly in front of the mannequin near the cap lamp, nose, and lapel. These four coal mine tests found that the spatial variability of dust levels and imprecision of the current personal sampler is a greater influence than the sampler location within the breathing zone. However, a one-sample t-test of this data did find that the overall mean value of the cap lamp/nose ratio was not significantly different than 1 (p-value = 0.21). However, when applied to the overall mean value of the lapel/nose ratio there was a significant difference from 1 (p-value < .0001). This finding is important because the lapel has always been the sampling location for coal mine dust samples. But these results suggest that the cap location is slightly more indicative of what is breathed through the nose area.

Keywords dust samplers, inlet location, respirable dust

BACKGROUND

Monitoring of personal respirable dust exposure is an important step in eliminating many dust-related occupational illness and diseases. The Federal Coal Mine Health and Safety Act of 1969, the predecessor for the Federal Mine Safety and Health Act of 1977, mandates that coal mine dust levels be monitored and controlled to below 2 mg/m^3 for a working shift. To date, this monitoring process has relied on a coal mine dust personal sampler unit to collect a filter sample in the mine environment. The filter is then sent to a laboratory for analysis and the results returned to the miners days or weeks after the actual sample was taken. Current methods do not provide timely feedback to detect or correct excessively dusty conditions. In the *Report of the Secretary of Labor's Advisory Committee on the Elimination of Pneumoconiosis Among Coal Mine Workers*,(1) several recommendations call for the development of continuous respirable dust monitors to help protect workers' health.

To address these recommendations, the National Institute of Occupational Safety and Health (NIOSH) Pittsburgh Research Laboratory along with the Mine Safety and Health Administration (MSHA) issued a development contract to Rupprecht & Patashnick Co., Inc. (R&P, now the Thermo Fisher Scientific) to develop a one-piece, person wearable, respirable dust monitor. This unit is referred to as the Tapered Element Oscillating Microbalance (TEOM) Series 3600 Personal Dust Monitor, or PDM. The PDM is essentially a miniaturized TEOM that is based on proven technology of the TEOM Series 1400a Ambient Particulate Monitor used worldwide by air monitoring organizations.

The complete unit incorporates both the dust monitor and a miner's cap lamp. Coal dust is drawn into the PDM through a brass inlet attached to the cap lamp (which mounts to the bill of the hard hat) and through a section of conductive tubing that is connected to the dust monitoring section of the PDM. The PDM then monitors respirable dust concentrations in near real-time with TEOM technology. Locating the PDM sampler inlet at the cap lamp raised questions about the loss of dust through the tubing and whether the cap lamp location is equally representative of a miners' respirable dust exposure in comparison with the traditional lapel location. Previous work demonstrated that less than 2% of the respirable dust will be lost in the tube from the cap lamp to the PDM.(2) This work investigates the impact of inlet location.

Industrial hygiene practice requires that personal exposure to atmospheric contaminants be measured in a worker's personal breathing zone. The breathing zone has been variously identified as close to a person's nose and mouth, within 30 cm

(1 ft) of a person's nose and mouth, or simply representative of the person's exposure. MSHA currently defines acceptable sampling locations to be within 1 m (36 in) of the miner.(3) It is possible that the cap lamp location may be less indicative of exposure if dust generation occurs more in front of and below the worker's shoulders. In fact, Guffey et. al.(4) suggest that when a gas emission source is at waist level, the lapel samples are greater than those at the nose or ear locations. Alternatively, in mining, it is also possible that bumping the roof with the cap lamp or liberating dust at the roof during roof supporting operations may cause more dust to be sampled at the cap lamp than at the lapel location.

Cohen et al.(5) studied inlet location on a mannequin in a laboratory dust room exposed to three test aerosols: a radon aerosol (activity mean diameter of 0.15 μm), a magnetite aerosol (mass median aerodynamic diameter [MMAD] = 1.6 μm), and an Arizona Road Dust aerosol (MMAD = 7.5 μm). Analysis of the average mean ratio of concentration at the lapel compared with that at the nose for all three aerosols was 0.98 ± 0.01 and for the forehead the nose ratio was 1.01 ± 0.02. These findings showed that for uniformly dispersed aerosols, the bias is essentially equivalent for any of these sampling locations.

Cohen et al.(5) further developed a field method to analyze for sampling location bias using three continuous reading, light-scattering aerosol monitors. Dust levels were recorded from positions at the forehead, nose, and lapel in a beryllium casting operation. Results were highly variable, and additional data were needed to apportion the source of the variability. This high variability is consistent with large spatial variability of dust concentrations found in mining and summarized by Kissell and Sacks.(6)

The current study was conducted to better define the influence of sample inlet location in the underground coal mine environment.

METHODS

Two methods were used to examine dust concentrations within the miner's breathing zone. The first method used NIOSH's PRL full-scale continuous miner gallery(7) and three prototype PDMs,(8) which were mounted onto a modified backpack frame, and the inlets were then positioned at the miner's cap lamp, nose, and lapel. The test gallery was filled with coal dust at typical mine levels, and airflows were generated to simulate a continuous miner section. The researcher carried the PDMs and continuously walked in the mine gallery where miners would typically work.

The second method used to examine the dust concentrations within the miner's breathing zone, involved collecting gravimetric dust samples at the cap lamp, nose, and lapel in the working sections of four underground coal mines. The head and torso of a full-scale mannequin was used in place of a coal miner. The mannequin was mounted on a metal base that had a vertical shaft the same height as the mannequin mounted directly in front of the mannequin (Figure 1).

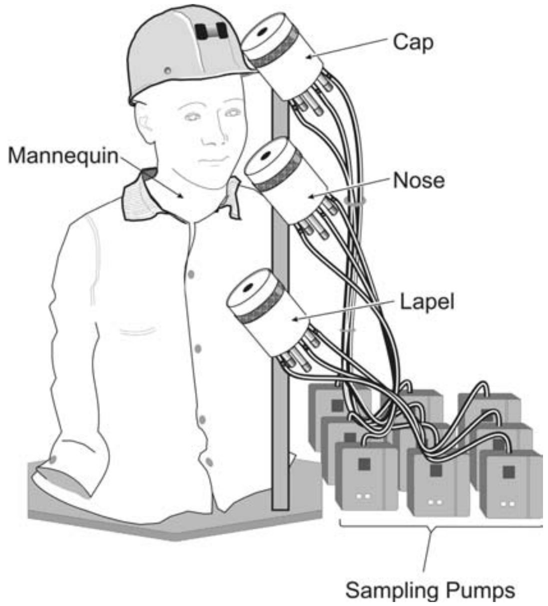

FIGURE 1. Mannequin and multicyclone can setup used in coal mine tests

Three multi-cyclone sampling cans were mounted on the vertical shaft at the cap lamp, nose, and lapel of the mannequin. Each multi-cyclone sampler is made up of a metal can 10.8 cm in diameter and 12.7 cm high with a lid having a 1.9 cm diameter hole in its center. Each can contains cyclones and filter cassettes of three coal mine dust personal sampling units (CMDPSU) (Figure 2). A CMDPSU is made up of a 10-mm

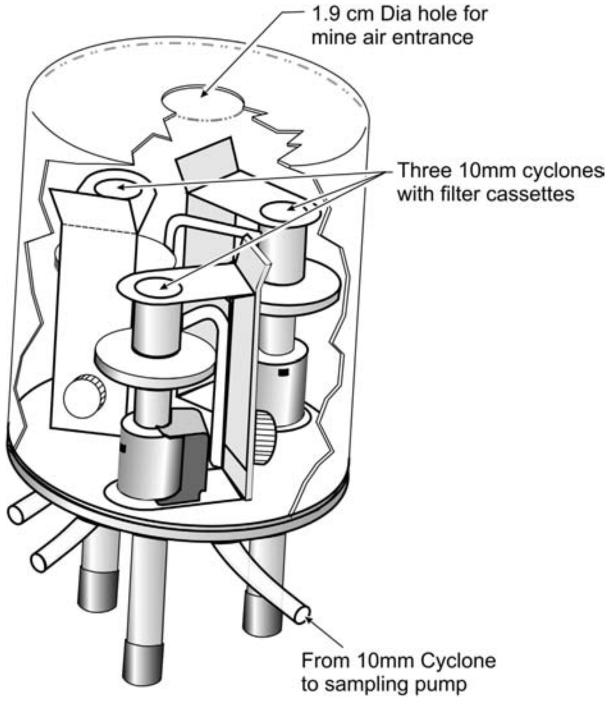

FIGURE 2. Cutaway view of multicyclone sampling can

nylon cyclone with a preweighed filter cassette connected to an MSA Elf Escort pump with a section of 0.64-cm flexible tubing. The flexible tubing passes through three holes in the bottom of the multi-cyclone sampler connecting the cyclones to MSA Elf Escort pumps. The MSA Elf Escort pumps were calibrated with a Gilibrator (Sensidyne Inc., Clearwater, Fla.) primary standard flow meter to 2.0 ± 1% L/min. Dust samples were collected on preweighed 37 mm diameter MSA filter cassettes, which are similar to the cassettes used for the federal dust sampling program.

A single gravimetric personal sampler is not a precise sampling device when it is necessary to sample small differences between multiple samplers. To ensure that multiple samplers measure the *same* dust environment requires the canister approach to minimize the spatial variability between sampling inlets. The purpose of this work was to examine the spatial variability of dust concentrations within the miner's breathing zone. The actual respirable dust concentration in the mine air is not of primary importance here. What is essential is that the three cyclones in each canister are sampling the same dust concentration. Each sampling canister acts as a miniature aerosol chamber.

Placing three cyclones in the canister significantly reduced spatial sampling variability between the cyclones. Although the location and size of the canisters may have influenced the dust concentrations, the primary concern was the relative concentrations at each canister inlet.

TEST PROCEDURE

Full-Scale Gallery

The full-scale surface test gallery simulates a continuous miner working section with the face 12.2 m deep, 5.5 m wide, and roughly 2.0 m high. The gallery contains a full-scale mockup of a continuous mining machine with a 0.9 m diameter cutting drum rotating at 50 rpm. The machine was positioned at the face. Exhaust curtain (set back 9.1 m from the face) ventilation was created in the laboratory by drawing air via a gallery fan through a curtain positioned on the left side of the test gallery. The machine used a water spray system consisting of 24 hollow cone sprays positioned above, below, and along the sides of the cutting head.

Coal dust was introduced into the gallery at the miner's cutting head via a compressed air/eductor system. The eductors mixed the coal dust with the compressed air to deliver the dust to the cutting head. One eductor discharged along the left front side of the cutting drum, while the other discharged along the right front of the drum. The rotating cutting drum mixed the dust with the ventilation airflow.

Two series of six tests each were run in the mine gallery. The three PDMs were programmed to run throughout each test series and store dust mass and concentration sampling data every minute. Each test ran 30 min. Between the tests, air filters were inserted into the PDM sampling inlets for at least 5 min. With the filters on the inlets, the PDMs recorded zero increase in dust mass that, in addition to the time, gave a marker to the file that separated each set of stored PDM test data.

Between each test, the PDM inlet locations were switched so that each of the three PDMs sampled at the three sampling locations. This was done to minimize any effect caused by difference in response between the PDMs. Two series of 6 tests were conducted for a total of 12 tests. This meant that each PDM sampled at each sampling location for four of the tests. After each test series, the PDM files were downloaded into an Excel 2003 workbook for analysis.

In both series of the gallery tests, PDM #3 gave a high response to the dust mass even though its inlet location was changed for each test. To improve the inter-sample precision of the PDM to detect smaller differences, data were normalized with a correction factor. The correction was applied to the PDM #3 data to match the response of the other two PDMs. Theoretically, by rotating each PDM equally to each sample location, the ratio between any pair of PDMs should be 1. This was not true for PDM #3 and, consequently, a correction factor was derived. This correction is the ratio of the PDM #3 slope to the average of the slopes of PDMs #1 and #2. For Series One tests the ratio was 0.881; and for Series Two tests the ratio was 0.781. The responses of PDM #3 were multiplied by these ratios for their respective test series. The corrected response curves of PDM #3 and the responses of PDMs #1 and #2 were then used to find the dust masses that each PDM recorded for each test in both series. This was done for each test by simply taking the total mass reading at the beginning of a test and subtracting it from the total mass reading at the end of the same test. The resulting dust masses for each PDM at each location for every test are listed in Table I. This data was then used to calculate the differences in collected dust masses between the cap lamp and the nose and also between the lapel and nose.

Four Coal Mines

The mannequin/multi-cyclone sampling system was used to collect samples in two longwall sections on the downwind side of the machine called the tailgate return, on the back right side of a continuous mining machine, and on the front of a twin boom roof bolting machine.

The NIOSH researchers together with mine personnel determined the actual placement of the sampling system to protect the equipment and to give a representative indication of a miner's location. After the mannequin/multi-cyclone sampling system was secured to the mining equipment, the sampling pumps were turned on and the sampling time noted. The test time to collect an adequate dust sample was estimated by the researchers based on previous experience or, in some cases, use of a light scattering dust monitor to obtain sufficient mass of dust for analysis. At the end of the test, the time was noted and the sampling pumps turned off. The 37-mm filters with the collected dust masses were removed from their cyclones and stored. If time allowed, a new set of 37-mm filters was installed along with clean 10-mm cyclones, and another test conducted.

TABLE I. PDM Responses for Each Gallery Test

Test #	Cap (mg)	Nose (mg)	Lapel (mg)	Ratio Cap/Nose	Ratio Lapel/Nose
			Test Series One		
1	0.429	0.469	0.444	0.916	0.948
2	0.329	0.404	0.392	0.816	0.971
3	0.198	0.263	0.274	0.754	1.043
4	0.346	0.431	0.421	0.802	0.976
5	0.334	0.423	0.457	0.789	1.079
6	0.296	0.383	0.429	0.772	1.120
			avg	0.808	1.023
			std	0.057	0.068
			rsd	0.071	0.067
			Test Series Two		
1	0.360	0.386	0.406	0.933	1.053
2	0.328	0.318	0.355	1.031	1.116
3	0.390	0.421	0.398	0.926	0.944
4	0.319	0.293	0.301	1.089	1.030
5	0.302	0.314	0.293	0.962	0.933
6	0.202	0.197	0.189	1.029	0.963
			avg	0.995	1.007
			std	0.065	0.072
			rsd	0.065	0.072

The 37-mm filters were pre- and postweighed (along with three control filters) in the NIOSH PRL filter weighing room. The pre- and post filter weights, along with the sampling times, sampling pump flow rates, and control filter weights were input into an Excel 2003 workbook that calculated the average concentration, standard deviation, and relative standard deviation of the triplicate dust samples in the multi-cyclone sampling cans. The average concentrations from each multi-cyclone sampling can was then used to calculate the concentration differences and ratios between the cap lamp and the nose and also between the lapel and nose.

RESULTS AND DISCUSSION

Full-Scale Gallery

In the NIOSH PRL test gallery, two series of six tests each were run. Differences between the two series include the use of different researchers wearing the apparatus and, in the second series, a longer length of time elapse between the initial dust generation and the test start time.

The respirable masses in milligrams detected by each PDM at the cap, nose, and lapel are listed in Table I. The table also lists the mass ratios between the cap and nose and between the lapel and nose. The average standard deviation and the relative standard deviation (RSD) are listed at the bottom of each test series.

We subjected the RSDs to the methodology developed by Kissell and Sacks.(6) They examined dust concentration ratios developed by dividing dust concentrations taken at fixed locations by dust concentrations taken on mining machine operators. They were looking for a possible correlation between the two sampling locations. This was similar to our objective. They used NIOSH's accuracy criterion, which requires "that a method will give a result that is within ±25% of the true concentration with a probability of 0.95 for an individual observation."(6, p.35)

Ideally, if there is no difference in the nose or lapel sampling locations, all of the ratios in Table I have a numerical value of one. Applying NIOSH's criteria, the ratios must be within 1.25 and 0.75. For the measurements to fall within the range 95% of the time, the measurements must fall within 1.96s where s is the standard deviation. When the mean value of the ratios is 1 and the standard deviation is 0.25, the maximum RSD is 0.217. All of the RSDs in Table I are less than 0.217, which means that both the cap and lapel sampling locations meet NIOSH's sampling method criteria. Therefore, either the cap or lapel are valid sampling locations with respect to the nose area.

Four Coal Mines

The mannequin dust sampling system was used to collect 297 dust samples from four coal mines. Twelve of the 297 samples were rejected leaving 285 dust samples for analysis. Of the 12 samples that were rejected, the breakdown is as follows: The tubing was pulled off the sampling pump of two samples, the sampler pump battery was dead for three of the samples, a pre-weigh error was recorded on one of the samples, and six of the samples were deemed outliers by Grubb's test,(9) which is a statistical procedure for detecting outlying observations.

The valid dust samples were used to produce 33 breathing zone test comparisons. The mean gravimetric dust concentrations at each location and summary statistics by mine and overall are shown in Table II. In all cases of in-mine testing, the mean lapel concentration was lowest. The highest mean concentration varied between the nose and cap lamp location. Included in this table are the upper and lower 95% confidence limits of the mean concentrations and ratios. A histogram in Figure 3 shows the mean concentrations along with standard error bars. For the overall ratio data set with 33 samples, the cap lamp location was about 1.1% higher than the nose location, and the lapel location was about 5% less than the nose.

A paired t-test was used to determine whether a difference existed between the cap/nose and lapel/nose ratios. One of the assumptions of this test is that the difference values (cap/nose minus lapel/nose) are normally distributed. The entire data set of 33 observations was evaluated for normality with the Shapiro-Wilk test. This test did not reject the null hypothesis that the distribution was normally distributed ($p\text{-value} = 0.1120$); thus, the parametric t-test for related samples was used. Because multiple t-tests were employed, the level that was used to determine statistical significance was adjusted from .05 to .01 using a Bonferroni correction(10) (.05 divided by the number of comparisons). This correction was applied to control the probability of finding a significant difference when one does not really exist (Type I error). The results

TABLE II. Summary Statistics of Four Coal Mine Studies

Mine	Variable	Mean	Std. Error	95%Cl For Mean
Longwall (A) (n=8)	Cap Lamp^A	1.804	0.208	[1.312, 2.296]
	Nose^A	1.852	0.214	[1.346, 2.357]
	Lapel^A	1.705	0.185	[1.266, 2.143]
	Cap lamp/Nose	0.972	0.010	[0.948, 0.996]
	Lapel/Nose	0.930	0.020	[0.883, 0.977]
	Ratio Diff	0.042	0.019	[−0.004, 0.088]
Continuous miner (n=7)	Cap Lamp^A	1.142	0.109	[0.876, 1.408]
	Nose^A	1.169	0.113	[0.893, 1.445]
	Lapel^A	1.109	0.116	[0.825, 1.393]
	Cap Lamp/Nose	0.979	0.015	[0.943, 1.016]
	Lapel/Nose	0.942	0.014	[0.907, 0.977]
	Ratio Diff	0.038	0.024	[−0.022, 0.097]
Bolter (n=9)	Cap Lamp^A	1.573	0.369	[0.722, 2.425]
	Nose^A	1.483	0.318	[0.750, 2.217]
	Lapel^A	1.411	0.267	[0.796, 2.027]
	Cap Lamp/Nose	1.047	0.019	[1.003, 1.092]
	Lapel/Nose	0.976	0.019	[0.932, 0.020]
	Ratio Diff	0.071	0.030	[0.001, 0.141]
Longwall (B) (n=9)	Cap Lamp^A	7.475	0.861	[5.491, 9.460]
	Nose^A	7.219	0.835	[5.294, 9.143]
	Lapel^A	6.834	0.794	[5.002, 8.665]
	Cap Lamp/Nose	1.035	0.005	[1.023, 1.048]
	Lapel/Nose	0.947	0.012	[0.919, 0.975]
	Ratio Diff	0.088	0.012	[0.060, 0.117]
Overall n=33	Cap Lamp^A	3.147	0.533	[2.063, 4.232]
	Nose^A	3.070	0.511	[2.030, 4.110]
	Lapel^A	2.897	0.483	[1.914, 3.881]
	Cap Lamp/Nose	1.011	0.009	[0.993, 1.029]
	Lapel/Nose	0.950	0.009	[0.932, 0.967]
	Ratio Diff	0.062	0.011	[0.038, 0.085]

^{A}mg/m^3.

of the paired t-tests are presented in Table III. The longwall (B) had a mean difference value (.088) that was significantly different from zero.

The cap lamp location will measure dust concentrations that are closer to what the nose position measures than the dust concentrations measured at the lapel location. This finding was supported by a one-sample t-test that was compared with the overall mean ratios to 1 (see overall values at the bottom of Table II). This test showed that the overall mean value of the cap lamp/nose ratio (1.011) was not significantly different

TABLE III. Results of Hypothesis Tests of Sampling Locations (tests conducted at four coal mines)

		Hypothesis: Mean Difference of Ratios = 0			
Mine	Count	Mean Difference (Cap/Nose-Lapel/Nose)	t-Value (Paired t-test)	95% CI For Mean	p-Value
Longwall (A)	8	0.042	2.17	[−0.004, 0.0876]	0.07
Continuous miner	7	0.038	1.53	[−0.022, 0.0972]	0.18
Bolter	9	0.071	2.34	[0.0011, 0.1414]	0.047
Longwall (B)	9	0.088	7.17	[0.0599, 0.1168]	<.0001
Total	33	0.062	5.39	[0.0383, 0.0849]	<.0001

Note: Tests conducted at four coal mines.

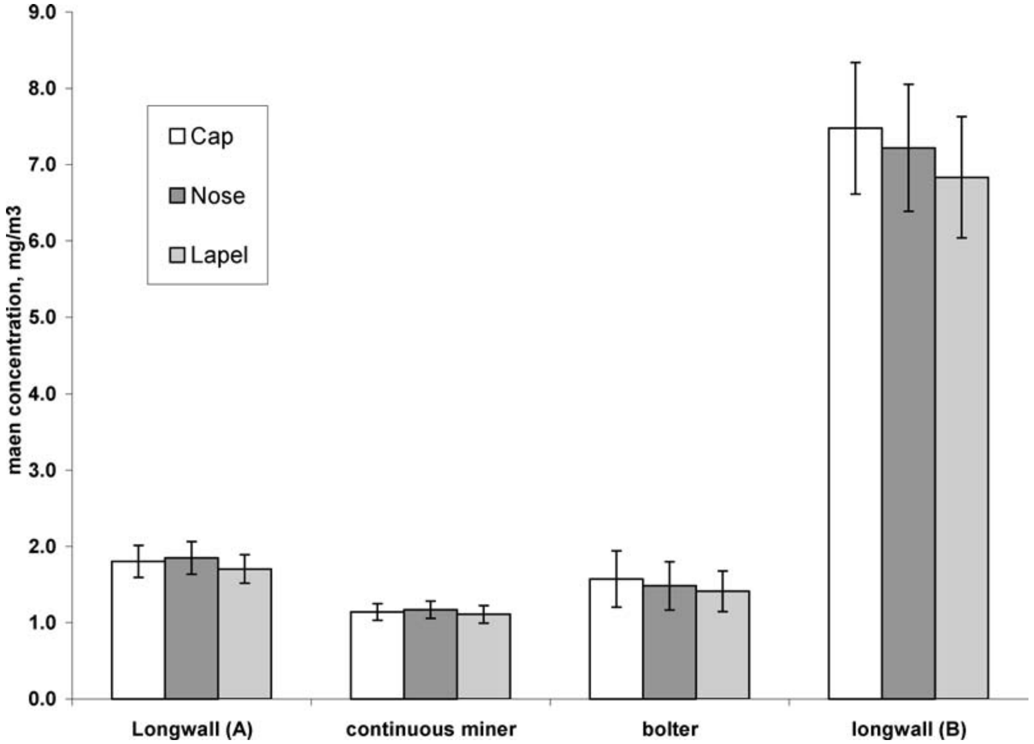

FIGURE 3. Histograms of mean value dust concentrations with standard error bars for fourcoal mine tests

than 1 (p-value = 0.21). However, for overall mean value of the lapel/nose ratio (0.950), there was a significant difference from 1 (p-value $<.0001$). Thus, in this study, the lapel sampled less dust than the nose position.

Individual mine section results (Table II) showed that the roof bolter and longwall (B) sections had higher dust concentrations at the cap lamp location compared with the lapel location. The other two sections showed a somewhat smaller difference, but when all of the data were examined together (see Overall values in Table II), the cap lamp sampling location was about 2.5% higher than the nose sample location, and the lapel sample was about 5.6% low compared with the nose location. These differences are in the range of individual sampler precision of 5.1% determined by Kogut.(11) Because individual sampler precision and the differences measured in these mine studies are within the same range, historic dust exposure data taken at the lapel should be comparable to dust exposure data sampled at the cap lamp location.

CONCLUSIONS

The gallery testing of dust mass loadings at the cap lamp, nose, and lapel indicated that little difference in inlet locations could be determined beyond the spatial variability of the gallery. The calculated percentage differences of the masses differed at each location, but the percentage difference was less than plus or minus 25%. In field sampling situations, the spatial variability of dust levels and imprecision of the current personal sampler in taking an individual measurement is, in general, a greater influence than the change in breathing zone sampler location from lapel to cap lamp. The four coal mine studies and the mannequin/multi-cyclone system indicate that sampling at the cap lamp is a slightly better indicator of the dust concentration at the nose level than at the lapel. A sample inlet adjacent to the cap lamp is within the accepted definitions of the breathing zone. The gallery data did not clearly indicate a difference between positions. The mine data shows that there is no difference between the nose and cap lamp location, but that there is a difference between the cap lamp location and the lapel. The effect is small and within the precision of the CMPDSU.

REFERENCES

1. **U.S. Department of Labor (DOL):** *Report of the Secretary of Labor's Advisory Committee on the Elimination of Pneumoconiosis Among coal Mine Workers*. Arlington, Va.: DOL, Mine Safety and Health Administration, 1996.
2. **Peters, T.M., and J.C. Volkwein:** Analysis of sampling line bias on respirable mass measurement. *Appl. Occup. Environ. Hyg. 18*:458–465 (2003).
3. "Mandatory Health Standards–Underground Coal Mines," *Code of Federal Regulations Title 30,* Part 70.207e. 2006.
4. **Guffey, S.E., M.E. Flanagan, and G. VanBelle:** Air sampling at the chest and ear as representative of the breathing zone. *AIHAJ 62*:416–427 (2001).
5. **Cohen, B.S., H.H. Harley, C.A. Martinelli, and M. Lippmann:** Sampling artifacts in the breathing zone. In *Aerosols in the Mining and*

Industrial Work Environments, Vol. 1. V.A. Marple and B.Y.H. Liu (eds.). Ann Arbor, Mich.: Ann Arbor Science, 1983. pp. 347–360.

6. **Kissell, F.N., and H.K. Sacks:** Inaccuracy of area sampling for measuring the dust exposure of mining machine operators in coal mines. *Mining Engineering 54(2)*:33–38 (2002).
7. **Goodman, G.V.R., and D.E. Pollock:** Use of a directional spray system design to control respirable dust and face gas concentrations around a continuous mining machine. *J. Occup. Environ. Hyg. 1*:806–815 (2004).
8. **National Institute of Occupational Safety and Health (NIOSH):** *Performance of a New Personal Respirable Dust Monitor for Mine Use*, by J.C. Volkwein, R.P. Vinson, L.J. McWilliams, D.P. Tuchman, and S.E. Mischler (Pub. No. 2004-151). Pittsburgh, Pa.: Department of Health and Human Services, Centers for Disease Control and Prevention, NIOSH, 2004.
9. **Grubbs, F.E.:** Procedures for detecting outlying observations in samples. *Technometrics 11(1)*:1–21 (1969).
10. **Maxwell, S.E., and H.D. Delaney:** *Designing Experiments and Analyzing Data: A Model Comparison Perspective*. Belmont, Calif.: Wadsworth, 2000. pp. 171–174.
11. **Kogut, J., T.F. Tomb, P.S. Parobeck, A.J. Gero, and K.L. Suppers:** Measurement precision with coal mine dust personal sampler. *Appl. Occup. Environ. Hyg. 12*:999–1006 (1997).