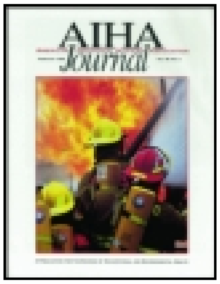

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This study estimated the ratio of the tracheo-bronchial dust fraction to the fraction collected by a respirable dust sampler for a variety of job classifications found in conventional, continuous, and longwall coal mining sections. The ratios could then be applied in epidemiologic studies to existing respirable dust measurements to estimate thoracic mass concentrations for evaluation of the relative importance of the respirable and thoracic dust fractions to obstructive lung disease. Data collected include particle size distributions from four U.S. underground coal mines using eight-stage personal cascade impactors. A total of 180 samples were examined by mine, occupation and occupations grouped by proximity to the mine face, and by mining technology. Several fractions—that collected by the 10-mm nylon cyclone, the American Conference of Governmental Industrial Hygienists respirable and thoracic particulate mass fractions, and the estimated alveolar and tracheo-bronchial deposition fractions—were estimated. These were not significantly different when grouped by occupation, by proximity of work to the mine face, or by the type of mining technology in use. Distributions from one mine varied from the others, perhaps because it used diesel equipment in the haulage ways, which contributed to the fine aerosol fractions. Results suggest that although the tracheo-bronchial dust fraction may contribute to the development of obstructive lung disease, occupation-specific tracheo-bronchial dust fractions are not likely to produce stronger exposure-response estimates than the historically collected respirable dust concentrations.

The primary basis for dust exposure evaluation in underground coal mines is measurement of exposure to respirable coal mine dust.[1] The rationale for controlling exposure is the importance of coal workers' pneumoconiosis (CWP) as a disabling lung disease.[2-4] Because CWP is a disease of the deep lung tissues, control of dust reaching this anatomical region is likely to help prevent its occurrence. In recent years several studies have demonstrated an association between dust exposure in coal mines and chronic obstructive pulmonary disease (COPD), including emphysema and chronic bronchitis.[5-8] Because COPD may involve changes in the larger airways, respirable dust might be an inappropriate target for measurement and control. Rather, dust depositing in the airways (i.e., the tracheo-bronchial fraction) might be more suited to the evaluation of risk of bronchitis from coal dust exposure. Although the theoretical advantage of using this measure has been cited repeatedly in the epidemiologic literature concerning bronchitis in miners, no epidemiologic studies apply estimates of tracheo-bronchial dust to respiratory outcomes in coal miners owing to the lack of such historical measurements. In addition, any suggestion that a standard for coal dust exposure be written for prevention of diseases of the airways would have to ensure adequate protection against risks of pneumoconiosis.

Although the toxicologically relevant fraction of inhaled dust is that which penetrates to specific functional regions of the respiratory tract and is actually deposited on the surface of the airways or lungs, practical measurement devices have until now reflected models of respiratory tract penetration but not deposition. For instance, respirable dust generally is defined as the fraction of dust penetrating beyond the reach of the mucociliary transport system to the gas exchange region (GER) of the lungs.[9-11] However, deposition in the respiratory region may differ substantially from penetration, especially at submicron particle sizes, and evidence has begun to accumulate to suggest that modeling dose on the basis of deposition could significantly improve risk assessments.[12-14] In this article, the authors refer to aerosol fractions penetrating to the GER as the respirable fraction, while aerosols penetrating and depositing in the GER are referred to as the alveolar deposition fraction (DE_a). Similarly, aerosols penetrating beyond the larynx and into the tracheo-bronchial region (TBR) (or GER) are referred to as the thoracic fraction, whereas those particles penetrating to and depositing in the TBR are referred to as the tracheo-bronchial (DE_b) or thoracic (DE_{ba}) deposition fractions.

In Britain, respirable dust typically has been measured with a horizontal elutriator and in the United States with a 10-mm cyclone. The two instruments measure closely related dust fractions designed to approximate the dust penetrating to the

TABLE I. Marple 298 Personal Impactor Characteristics with Particle Size Fraction Definitions

	Stage								
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*Filter*
Cut Point (microns)	21.10	15.00	9.8	6.00	3.50	1.54	0.91	0.53	<0.53
Correction Factor[A]	0.26	0.70	0.82	0.90	0.94	0.97	0.98	0.99	0.99
Mass Fractions[B]									
Cyclone (Cyc)	0.000	0.000	0.000	0.002	0.180	0.921	1.000	1.000	1.000
ACGIH Respirable (RPM)	0.000	0.000	0.002	0.034	0.268	0.807	0.994	1.000	1.000
ACGIH Thoracic (TPM)	0.008	0.084	0.325	0.731	0.964	0.999	1.000	1.000	1.000
Alveolar Deposition (DE_a)	0.000	0.000	0.003	0.064	0.286	0.393	0.277	0.179	0.130
TB Deposition (DE_b)	0.006	0.031	0.110	0.285	0.314	0.138	0.040	0.020	0.022
Alv. + TB Deposition (DE_{ba})	0.006	0.031	0.113	0.349	0.600	0.531	0.317	0.199	0.152

[A] Calculated using the inlet efficiency and internal loss functions developed by Rader et al.[16]

[B] Fraction definitions are: Cyc, mass fraction collected by the 10-mm nylon cyclone at 2.0 L/min; RPM, respirable particulate mass by ACGIH definition; TPM, thoracic particulate mass by ACGIH definition; DE_a, alveolar deposition fraction; DE_b, tracheo-bronchial deposition fraction; DE_{ba}, alveolar plus tracheo-bronchial deposition fraction. See text for further explanation.

GER.[15] However, if the whole particle-size distribution is available, deposition models can be used to estimate exposure to the various regions of the respiratory tract. In this article the authors use particle-size distributions to estimate thoracic and respirable penetration fractions according to the U.S. definition,[10] and respirable, tracheo-bronchial, and thoracic dust deposition fractions according to a current aerosol deposition model.[9]

Two studies in U.S. underground mines have observed substantial differences in particle size distributions between specific areas of mines and between longwall and continuous mining technologies.[16,17] On the basis of these observations Potts et al.[16] suggested that controlling respirable dust may be inadequate for control of hazards related to dust depositing in the thoracic region. The potential importance of these observations lead to this effort to better characterize the personal particle-size distributions of exposures received by underground coal miners, and if possible, to test the hypothesis that tracheo-bronchial exposures might be specifically associated with the development of chronic obstructive lung disease in miners.

Since almost all historical exposure measurements have been made as respirable concentrations, a method to estimate job-specific tracheo-bronchial exposures from the respirable dust concentrations would be required to conduct such an investigation using the existing historical data. The current study was designed to determine the relationship between tracheo-bronchial and respirable dust exposures in coal miners. To accomplish this goal, particle size distributions in underground mining jobs at four coal mines were assessed so that the job-specific respirable and tracheo-bronchial dust fractions could be estimated and used to convert the historical respirable dust measurements into estimates of tracheo-bronchial dust exposures. The intention was to then examine the relationship between newly estimated tracheo-bronchial dust exposures and respiratory outcomes in coal miners to see whether predictive power was increased over models using only respirable dust estimates.

MATERIALS AND METHODS

Surveys were undertaken at four bituminous mines in Western Pennsylvania, Kentucky, and Maryland that volunteered to participate. Three of the four (A, B, and C) were in reasonable proximity to the National Institute for Occupational Safety and Health (NIOSH) laboratory in Morgantown and used both continuous and longwall mining technology. The fourth mine (D) utilized conventional drilling and blasting techniques. One of the mines (C) used diesel equipment for transporting personnel and equipment, while the others used only electric machinery. Surveys were conducted at each site for three or four days. The occupations targeted for evaluation were those highly represented in the work history data of the epidemiologic cohort that was intended to be used for this project.[8] Miners in the selected job titles, on both face jobs (in areas in which coal is actively being extracted) and nonface occupations (i.e., jobs away from the face, including transportation and mine maintenance activities) were identified before entering the mine. For nonface occupations, in which the total dust concentrations were expected to be relatively low, miners donned the sampler at the portal and returned with it at the end of the day. For face occupations, in which dust concentrations are higher and sampler overloading could occur, the samplers were carried into the mine by the investigators, donned by the miners, and worn for a variable period, depending on the expected dust loading.

Particulate samples were collected with an eight-stage personal cascade impactor (Andersen Samplers, Atlanta, Ga.; henceforth designated M298) using a flow rate of 2 L/min.[18] The nominal cutoff diameters and sampler efficiency correction factors for the stages are given in Table I. These values are refinements of the manufacturer's suggested numbers, as developed by Rader et al.[19] using the data generated by Rubow et al.[18] with both solid and liquid aerosols in a quiescent environment. For calculation of the first and last stage interval width, the lower cutoff for the filter (0.26 μm) was adopted by convention as one-half the lower cut point for the last stage,[20] and the upper cutoff for the first stage (42 μm) was chosen because the inlet efficiency curve for the impactor approaches zero at this point. It is noted, however, that particles larger than about 22 microns aerodynamic diameter are poorly characterized by the M298.[19]

The fractions of airborne dust collected on each impactor stage that would be expected to deposit in the respiratory tract according to specified definitions (penetration or deposition factors), or to be collected by a nylon cyclone, also are given in Table I. These factors were calculated by dividing the stage interval, expressed in log units, into 20 equal segments; calculating the expected fraction at each endpoint of each segment (using the functions that define each of the inhalation fraction definitions); integrating across the stage interval width with the trapezoidal rule; and then dividing by the interval width.

Each impaction plate held a Mylar® substrate prepared using a spray application of Apiezon grease (Apiezon Products Limited, London), equilibrated for at least 24 hours to control for weight changes due to off-gassing, and then weighed. After sampling, the impactors were disassembled and the impaction plates reweighed. Any sample with visibly loose dust was rejected on the basis of unknown particulate loss. Further, any sample with weight losses greater than 0.02 mg on any one stage was rejected.

The filter weight change was first corrected for internal losses by dividing the observed weight change by the correction factors given in Table I. The size-specific mass fractions were calculated by multiplying the mass fraction on each stage times the appropriate factor specified in Table I (for each type of dust fraction) and summing across the eight impaction stages and the final filter:[20]

$$MF(X)_j = \sum_{i=1}^{9} MF(X)_i \times MF_{ij}$$

where $MF(X)_j$ is the mass fraction according to size definition X measured on sample j; $MF(X)_i$ is the factor for stage i (see Table I), calculated using one of the size-specific definitions described below; and MF_{ij} is the mass fraction measured on stage i for sample j corrected for the sampler efficiency for that stage.

The size definitions (X, above) used to estimate the penetration and deposition fractions from the impactor-derived particle-size distributions were:

(1) 10-mm nylon cyclone (Cyc): This quantity estimates the dust fraction sampled by the cyclone operated at 2.0 L/min, which has been determined empirically.[21] This apparatus and flow rate is mandated by the Mine Safety and Health Administration (MSHA) sampling program[1] to sample dust in close conformance to the American Conference of Governmental Industrial Hygienists' (ACGIH) respirable particulate mass criteria, and is the basis of the respirable dust estimates used for previous analyses.[22] Those data represent the concentration of dust measured by the cyclone and multiplied by 1.38 to convert to a British Medical Research Council (MRE) equivalent concentration.

(2) ACGIH respirable (RPM) and thoracic (TPM) penetration: These factors estimate the fractions of airborne dust on each impactor stage that will penetrate to, but not necessarily deposit in, the GER (respirable) and beyond the larynx (thoracic). They are defined by the ACGIH as a cumulative lognormal curve with geometric mean of 3.5 (respirable) or 10 (thoracic) microns and geometric standard deviations of 1.5.[10] Changes in these definitions were adopted in 1993 to bring the American and European definitions into concordance.[23] The most significant change in the new definitions is that the 50% cut diameter for the respirable dust fraction is 4.0 microns instead of 3.5, as used in this analysis and historically for analyses in the United States.

(3) Stahlhofen alveolar (DE_a), tracheo-bronchial (DE_b), and thoracic (DE_{ba}) deposition: These factors estimate the fraction of inhaled dust that will penetrate to and deposit in the GER (alveolar), airways (tracheobronchial), and thoracic (sum of tracheobronchial and alveolar) regions using a lung deposition model reported by Stahlofen.[9] The Stahlhofen factors given in Table I represent the stage-specific fractions according to the models, multiplied by the fraction of total particulate that is inhalable according to the ACGIH inhalable (formerly inspirable) particulate curve.[10] This step was necessary only for the Stahlhofen deposition fractions, since they are defined on the basis of inhalable particulate rather than total airborne particulate.

To convert the historically collected respirable exposure data (collected with the cyclone) to estimates of historical thoracic or tracheo-bronchial dust exposures, the ratios of the ACGIH and Stahlhofen mass fractions to the fraction represented by the cyclone were calculated. Only the mass fraction that would be collected by a cyclone (Cyc) is given in Tables II through IV. The mass fractions by the ACGIH or Stahlhofen definitions can be easily derived by multiplying the cyclone mass fraction by the ratio given in the tables.

After calculation of the mass fractions and their ratios, the data were compared by stratifying by mine and occupation. Both individual occupations and grouped occupations were considered. Occupation groups were defined by proximity to the face (face and nonface jobs) and by mining technology (jobs specific to continuous, longwall, and conventional mining technologies). Differences between these categories were tested with a t-test (face vs. nonface jobs) or one-way analysis of variance (ANOVA) (mining technologies) using PROC TTEST and PROC GLM (SAS Institute, Cary, N.C.), respectively. Two-way ANOVA also was conducted to consider differences between mines and proximity to the face simultaneously. Histogram particle size distributions averaged across the various strata were constructed using a log scale for the aerodynamic diameter and the mass fraction divided by the log interval of each stage for the bar heights.[20]

RESULTS

Of the 208 samples collected, 28 were rejected because of overloading or negative weights, yielding a total of 180 samples available for analysis. Of these, 142 were from face occupations and 38 from nonface jobs. The calculated cyclone-collected mass fraction and ratios of the other fractions (specified above) to the cyclone fraction are given in Table II. As expected, the ratio of the mass fraction representing the ACGIH respirable dust definition to the mass fraction collected by the cyclone was very close to unity. The comparable ratio for the Stahlhofen respirable fraction ratio was lower, as a result of the low deposition predicted at very small particle sizes compared to the fraction collected by the cyclone. The tracheo-bronchial deposition fractions were greater than the alveolar fractions in all cases.

TABLE II. Average (Standard Deviation) Cyclone Mass Fractions and Dust Fraction Ratios for All Samples and By Proximity to the Face and Mining Method

	n	*Cyc*[A]	*RPM/Cyc*[B]	*TPM/Cyc*[B]	DE_a/Cyc[B]	DE_b/Cyc[B]	DE_{ba}/Cyc[B]
All	180	0.07 ± 0.04	1.07 ± 0.06	3.84 ± 1.46	0.63 ± 0.17	1.18 ± 0.58	1.81 ± 0.73
By Location[D]							
Face	145	0.07 ± 0.04	1.06 ± 0.05	3.84 ± 1.33	0.63 ± 0.15	1.18 ± 0.53	1.81 ± 0.67
Nonface	35	0.07 ± 0.04	1.07 ± 0.08	3.84 ± 1.93	0.62 ± 0.22	1.18 ± 0.75	1.80 ± 0.96
By Mining Method[D]							
Continuous	54[C]	0.07 ± 0.05	1.07 ± 0.05	3.90 ± 1.55	0.63 ± 0.18	1.21 ± 0.62	1.83 ± 0.79
Longwall	48	0.06 ± 0.03	1.06 ± 0.04	3.86 ± 1.19	0.64 ± 0.13	1.19 ± 0.47	1.84 ± 0.58
Conventional	19	0.08 ± 0.04	1.06 ± 0.05	3.62 ± 1.02	0.60 ± 0.11	1.09 ± 0.40	1.69 ± 0.50

[A] Mass fraction collected by the 10 mm-nylon cyclone at 2.0 L/min. See text for further definition.
[B] Ratio of the mass fraction according to the specified definition to the mass fraction collected by the cyclone. Fraction definitions are: RPM, respirable particulate mass by ACGIH definition; TPM, thoracic particulate mass by ACGIH definition; DE_a, alveolar deposition fraction; DE_b, tracheo-bronchial deposition fraction; DE_{ba}, alveolar plus tracheo-bronchial deposition fraction. See text for further explanation.
[C] The number of samples by mining method do not sum to 180 because some occupations sampled are not unique to a particular method.
[D] Differences were not statistically significant by t-test (Face vs. Nonface) or one-way Analysis of Variance (Mining Method).

No substantial (or statistically significant) differences between face and nonface distributions (Figure 1) or their mass fraction ratios (Table II) were observed. Grouping of face occupations by the type of coal mining technology used (Table II and Figure 2), similarly indicated no statistically significant differences between technologies.

When the data were further stratified by mine (Table III and Figure 3), some statistically significant ($p<0.05$) differences were observed between face and nonface jobs, particularly in Mine C. Larger proportions of the dust from Mine C were observed at lower particle sizes, yielding consistently higher cyclone mass fractions and lower ratios on both face and nonface jobs compared to the other mines. However, there was no consistent pattern between face or nonface jobs across mines. For instance, the ACGIH thoracic to cyclone ratio (RPM/Cyc) was higher for face jobs in Mine A and lower for face jobs in Mines B and C, giving rise to the lack of significance between these categories across mines. Distributions for a few selected face and nonface occupations for which there were at least 10 samples (Table IV) show little variability.

The simultaneous effects of occupation and mine were considered in ANOVA models using the cyclone mass fraction or the various fraction ratios as the dependent variable and mine and occupation, or occupation groups, as the independent variables. The results of the model using the ratio of the Stahlhofen tracheo-bronchial fraction to the cyclone fraction (DE_b/Cyc) as a function of mine and proximity to the face are given in Table V. The model was highly significant ($p<0.0001$) with a model r^2 of 0.317. No significant differences were observed between face and nonface occupations although mine was a highly significant ($p<0.0001$) predictor of the ratio. Similar results were obtained for the other fractions or fraction ratios, indicating consistent differences between the mines but little effect of particular occupations or technologies.

DISCUSSION

A useful exposure assessment for occupational epidemiology or risk evaluation requires that the measured quantity is an accurate

TABLE III. Average (Standard Deviation) Cyclone Mass Fractions and Dust Fraction Ratios by Mine and Location

	n	*Cyc*[A]	*RPM/Cyc*[B]	*TPM/Cyc*[B]	DE_a/Cyc[B]	DE_b/Cyc[B]	DE_{ba}/Cyc[B]
Mine A							
Face	41	0.06 ± 0.03	1.07 ± 0.05	4.04 ± 1.05	0.68 ± 0.12	1.26 ± 0.41	1.94 ± 0.52
Nonface	9	0.05 ± 0.03	1.14 ± 0.12	5.61 ± 2.31	0.83 ± 0.20	1.86 ± 0.87	2.66 ± 1.03
Mine B							
Face	43	0.04 ± 0.02*[C]	1.09 ± 0.05	4.76 ± 1.46	0.72 ± 0.15	1.55 ± 0.58	2.28 ± 0.72
Nonface	13	0.06 ± 0.02	1.07 ± 0.06	4.15 ± 1.39	0.69 ± 0.17	1.31 ± 0.56	2.01 ± 0.74
Mine C							
Face	42	0.09 ± 0.05*	1.03 ± 0.03*	2.81 ± 0.64*	0.50 ± 0.10**	0.77 ± 0.26*	1.27 ± 0.36*
Nonface	13	0.10 ± 0.03	1.02 ± 0.01	2.32 ± 0.40	0.41 ± 0.07	0.57 ± 0.17	0.99 ± 0.23
Mine D							
Face	19	0.08 ± 0.04	1.06 ± 0.05	3.62 ± 1.02	0.60 ± 0.11	1.09 ± 0.40	1.69 ± 0.50

[A] Mass fraction collected by the 10 mm-nylon cyclone at 2.0 L/min. See text for further definition.
[B] Ratio of the mass fraction according to the specified definition to the mass fraction collected by the cyclone. Fraction definitions are: RPM, respirable particulate mass by ACGIH definition; TPM, thoracic particulate mass by ACGIH definition; DE_a, alveolar deposition fraction; DE_b, tracheo-bronchial deposition fraction; DE_{ba}, alveolar plus tracheo-bronchial deposition fraction. See text for further explanation.
[C] Differences between Face and Nonface were statistically significant by t-test at the $p < 0.05$ level (*) or $p < 0.01$ (**).

TABLE IV. Average (Standard Deviation) Cyclone Mass Fractions and Dust Fraction Ratios for Selected Occupations

	n	*Cyc*[A]	*RPM/Cyc*[B]	*TPM/Cyc*[B]	DE_a/Cyc[B]	DE_b/Cyc[B]	DE_{ba}/Cyc[B]
Continuous Miner Operator	22	0.07 ± 0.05	1.07 ± 0.05	3.86 ± 1.16	0.64 ± 0.15	1.19 ± 0.46	1.84 ± 0.61
Roof Bolter	22	0.06 ± 0.04	1.07 ± 0.06	3.97 ± 1.73	0.63 ± 0.19	1.23 ± 0.69	1.86 ± 0.87
Long Wall Jacksetter	16	0.06 ± 0.03	1.06 ± 0.04	3.82 ± 1.23	0.63 ± 0.13	1.17 ± 0.48	1.80 ± 0.61
Long Wall Operator	28	0.06 ± 0.02	1.06 ± 0.04	3.77 ± 0.85	0.65 ± 0.11	1.16 ± 0.34	1.81 ± 0.43
Beltman	10	0.06 ± 0.02	1.07 ± 0.04	3.99 ± 1.09	0.67 ± 0.15	1.24 ± 0.43	1.90 ± 0.56

[A] Mass fraction collected by the 10-mm nylon cyclone at 2.0 L/min. See text for further definition.
[B] Ratio of the mass fraction according to the specified definition to the mass fraction collected by the cyclone. Fraction definitions are: RPM, respirable particulate mass by ACGIH definition; TPM, thoracic particulate mass by ACGIH definition; DE_a, alveolar deposition fraction; DE_b, tracheo-bronchial deposition fraction; DE_{ba}, alveolar plus tracheo-bronchial deposition fraction. See text for further explanation.

predictor of the relevant dose to the target organ for the specific outcome being considered.[24] For the case of particulate exposures and respiratory disease, particle size-specific sampling should help make the measured quantity specific to the underlying disease process being studied.[25] Respirable dust exposure estimates for the epidemiology of diseases of the lung, especially the pneumoconioses, have worked well. However, for diseases of the airways, especially chronic bronchitis, it would appear that the fraction of dust depositing in the large airways would be a more specific measure.

Because the existing historical data for exposure assessment in coal mines were based on respirable dust fractions, a research program to assess the impact of tracheobronchial dust fractions on disease would require the conversion of the respirable dust concentrations to tracheo-bronchial concentrations. This conversion would be conducted using the ratio of the tracheo-bronchial to cyclone fractions by specific identifiable categories of mine work. Note that if using the existing MSHA exposure data, one would first divide the MSHA concentrations (or the ratios) by 1.38 to obtain the specified fraction concentrations, accounting for the conversion of the cyclone-collected dust to the MRE-equivalent respirable dust concentration.[1]

However, in order for conversion of respirable dust concentrations to tracheo-bronchial dust concentrations to be achievable and worthwhile, three conditions must be met. First, there would have to be significant variation in the dust mass size distributions across specific occupations, or alternatively, groups of occupations assigned on the basis of their proximity to different dust-generating activities or control technologies. In this analysis groups were formed on an *a priori* basis to examine differences between face vs. nonface occupations, and between face occupations that were specific to mining technologies. The current data showed no statistically significant differences in the ratio of cyclone to tracheo-bronchial deposition fractions for specific occupations or the selected occupation groups. As a result these data do not support the ability to distinguish these fractions between categories of mining jobs. It is possible that given a significantly larger data set, some differences in the mass fraction ratios between occupations or technologies would begin to appear. However, even if such differences occur, the current data would indicate that those differences would be small relative to the range of exposure levels found in the mining environment.

Second, there would have to be no significant differences in the distributions between mines, while adjusting for the technology, occupation, or other easily measured parameters. Specifically, the variability in the ratio would have to be greater between job, location, or mining method than between mines. The data presented here suggest that some significant differences occur between mines with significantly smaller aerodynamic diameter particulate, found in Mine C as compared to the other three mines. It is suspected that this difference may be due to the use of diesel equipment to haul personnel and supplies to the working

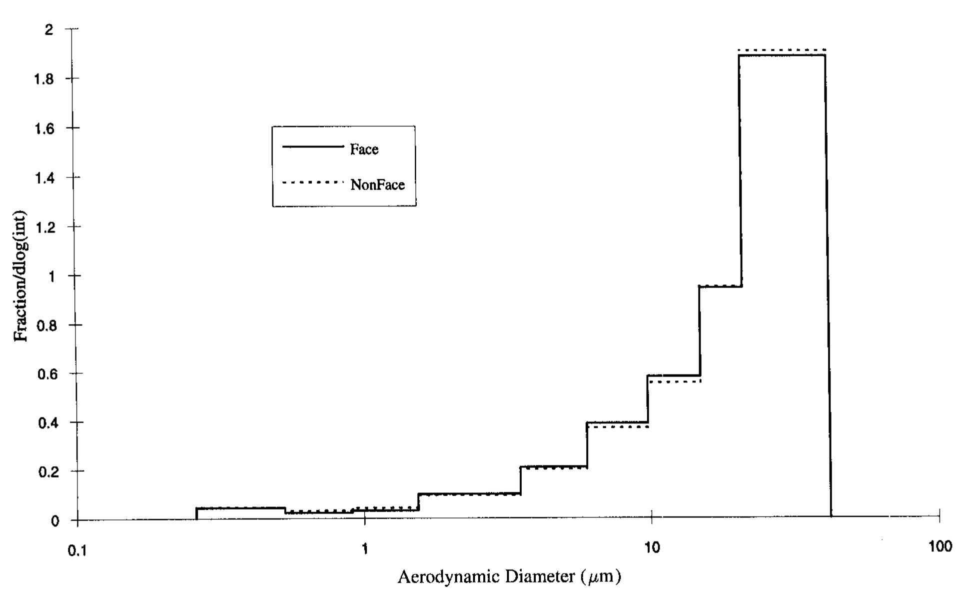

FIGURE 1. Histograms representing the average particle-size distribution for face (n=145) and nonface (n=35) personal cascade samples

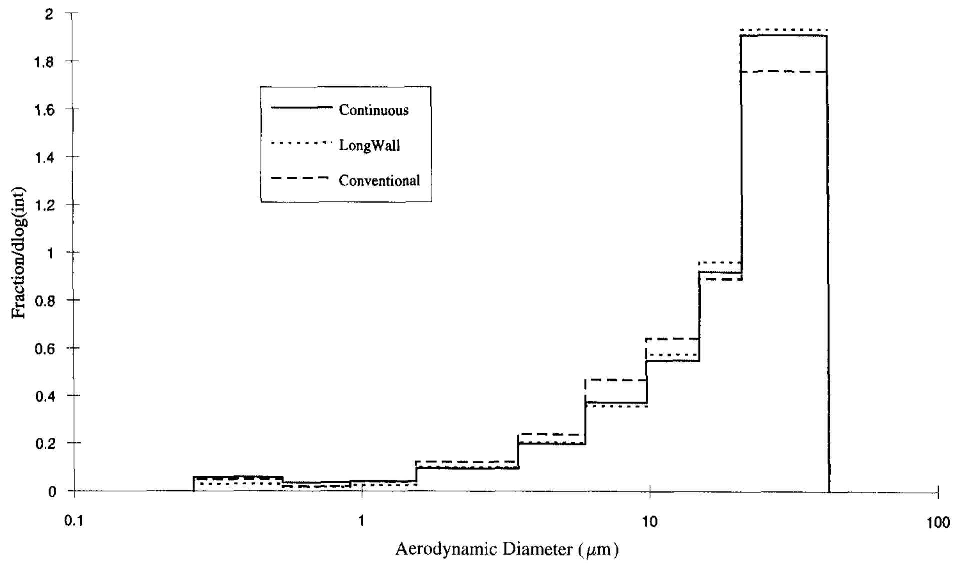

FIGURE 2. Histograms representing the average particle-size distribution for face occupations specific to continuous (n=52), longwall (n=48), and conventional (n=19) mining technologies

sections in Mine C. However, because only four mines were included in this sample, it would be premature to suggest modeling the distributions on the basis of use of diesel equipment. A much larger study comparing diesel to electric equipment in mines would be required to allow such a conclusion.

Finally, particle size distributions would have to be invariant across time. Because historical particulate distribution data are unavailable, it is impossible to determine this with any certainty. However, it appears that this may be a reasonable assumption given the relative lack of change of technology (within continuous, longwall, or conventional techniques) over the past 20 years.

These findings appear to be in contrast to earlier reports of particle-size distributions in mines.(16,17,26,27) These earlier reports found some differences in particle size distributions in longwall compared to continuous mining and between locations in different proximity to the mining machines within a particular technology. However, most of these reports are limited by the use of static (area) samplers rather than the personal samplers used in the current research.

Potts et al. found ratios of thoracic to respirable dust (using ACGIH definitions) ranging from 1.8 in the intake airway to 6.7 downwind of support movement in longwall operations, and 1.5 in the intake airway to 4.1 on a continuous mining machine.(16) He concluded that control of respirable dust would not equally limit the exposures of miners to thoracic fraction dust. The measurements were made by sampling at locations defined by their proximity to the dust generating machinery. Particle size distributions reported for longwall shearer and downwind of roof support movement (their Figure 3), and for a continuous mine roof bolter (his Figure 6) are in general agreement with the distributions observed by the current authors. The extreme values obtained by Potts et al. in intake air (small particle sizes) and downwind of support movement (large particle sizes) do not reflect personal exposures. It is not surprising that intake air, being made up primarily of suspended fine particles, had a very low thoracic to respirable ratio. However, when a miner works in intake air, he would be expected to reintrain settled dust by his activities and thus raise the thoracic to respirable ratio. Dust sampled just downwind of support movement would similarly be unlikely to reflect true exposure distributions since miners would only spend a fraction of their time in this location.

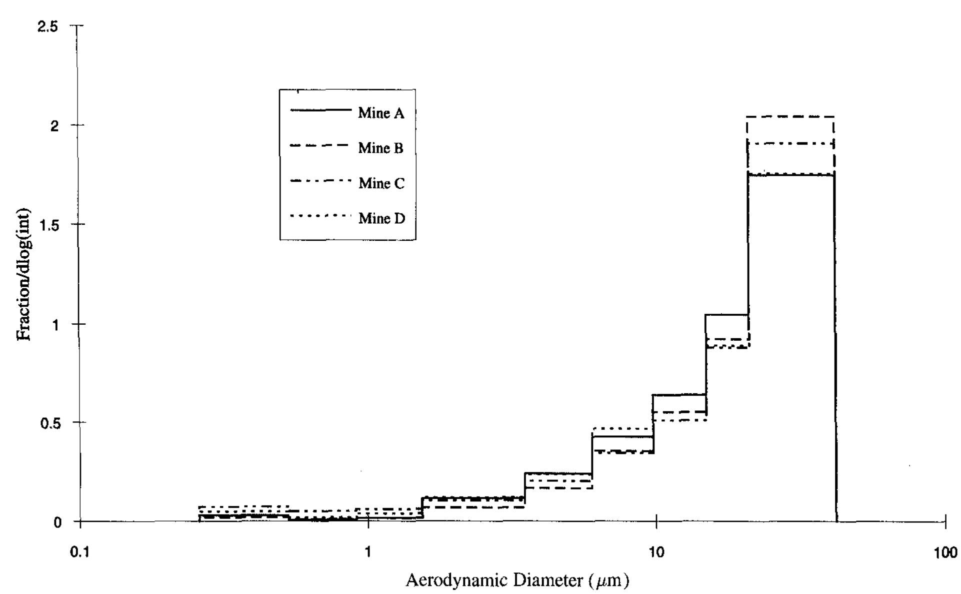

FIGURE 3. Histograms representing the average particle-size distribution for face occupations only from Mine A (n=41), Mine B (n=43), Mine C (n=42), and Mine D (n=19)

Burkhardt et al. presented particle size distributions for a continuous miner, on a haulage road, and at the feeder/breaker (their Figures

TABLE V. ANOVA Table for Differences in Ratio of Tracheo-Bronchial to Cyclone Mass Fractions (DE_b/Cyc) by Mine and Proximity to the Face[A]

	Degrees of Freedom	Sum of Squares	Mean Square	F	P
Source					
Model	4	18.79	4.70	20.32	<0.0001
Error	175	40.46	0.23		
Total	179	59.25			
Variable					
Mine	3	18.79	6.26	27.09	0.0001
Face/Nonface	1	0.0001	0.0001	0.00	0.9832
Model r^2 = 0.317					

[A] Refer to text for definition of terms

3, 4, and 5, respectively) that were very similar to those observed here.[17] Rubow and Marple examined underground coal dust particle size distributions using the Microorifice uniform deposit impactor (MOUDI).[26] In their study the samplers were located several blocks distant from the coal-cutting operations (a block is a unit of coal-cutting operations and is generally about 40 feet long). As a result of the sampler locations the larger particles would have had sufficient time to settle before reaching the sampler, and the particle size distributions are therefore probably unrepresentative of personal exposures to mining equipment operators.

Mark et al. developed particle-size fraction estimates using an improved personal cascade impactor, the personal inspirable dust spectrometer, and compared inhalable dust concentrations with respirable and tracheo-bronchial subfraction concentrations in three British coal mines.[27] This study found a high correlation between the various subfraction concentrations. However, the relationships between the fractions (e.g., respirable to inspirable ratios) varied across job groups. Nevertheless, on the basis of the high correlations between respirable and other particulate subfractions of dust exposures, the report concluded that respirable dust estimates should be equally predictive of obstructive lung disease as other fractions.

It is not possible to compare directly the current results to those of Mark et al.[27] since theirs were reported as the ratio of the various subfractions to inspirable mass fraction instead of the cyclone-collected fraction, as provided here. Since the current authors' data were obtained with the M298, it is not possible to calculate the inspirable fraction for reasons discussed below. However, an approximate thoracic to respirable fraction ratio can be derived from the data of Mark et al. (as reported in their Table 20). The results suggest that there is little difference between these fractions across the job groups considered (range 2.0 to 3.4) and support the current authors' observation that there is little substantial difference in the particle size distributions between coal mining job categories, at least in the thoracic and respirable particle size range.

Despite the fact that miners are assigned relatively specific occupations, they frequently trade-off jobs or help each other conduct specific tasks. For instance, the continuous miner operator and helper generally share the tasks of operating the machinery and doing the support work for about equal time. Utility or general laborers frequently help operate machinery when needed. Thus, Thus, these findings, which show little variation in particle size distributions across jobs, may be a result of the averaging of activity-specific size distributions across various types of activities in which miners are engaged over the work day.

In this analysis samples collected both historically and for this analysis have been referred to as "personal." In industrial hygiene parlance, a personal sample means that the sampling apparatus was worn by the individual during all work tasks. However, MSHA uses the term "occupational" sample to distinguish this type of sample from an area sample. For certain occupations—for instance, the continuous miner operator—MSHA defines an occupational sample as being placed on the machine within 36 inches inby (toward the coal-cutting face) the operator.[1] When not operating the machinery, or for miners in more mobile occupations, the sampler would be worn by the miner. Therefore the samples were not all strictly "personal," but would be highly representative of the individual miner's dust distribution.

The definitions for ACGIH respirable and thoracic dust fractions used in this analysis refer to the long-standing definitions that have recently been changed.[23] The most significant change in definitions was the increase in the 50% collection efficiency size for respirable aerosols from 3.5 to 4.0 microns. This change would make relatively little difference to most measured concentrations,[28] and would make almost no difference in the ability to distinguish the ratios of various fractions as was done for this analysis.

The particle-size distributions measured by the M298 sampler may not accurately reflect the inhaled dust as a result of the poor inlet collection efficiency and internal losses prior to entering the orifices of the upper stage. The inlet efficiency of the M298 falls off rapidly for particle sizes greater than about 15 μm.[18,19] The accuracy of the correction factors used for the first two stages are therefore particularly crucial for estimating the true particle size distribution. While this problem makes the observed distributions inaccurate—and the calculation of the inhalable fraction, mean aerodynamic diameter, and geometric standard deviation impossible—it should not greatly affect calculation of ratios of respirable or tracheo-bronchial mass fractions to cyclone mass fractions. Less than 1% of the dust deposited on the first stage and about 8% deposited on the second contribute to the ACGIH thoracic fraction. The percentages for the other fractions on the first two stages are even lower. Thus, large diameter dust makes very little contribution to these calculated fractions.

CONCLUSIONS

In summary, these results indicate that it is not possible to distinguish the particle size distributions between specific occupations or groups of occupations, and it appears that the variability in distributions may be greater between mines than between occupations. The cause of this cross-mine variability cannot be assessed with the current limited data. Therefore, even assuming that the particle-size distributions were invariant over time, it does not appear possible to reconstruct historical particle size-specific distributions for a large cohort of miners, including work in multiple mines, without extremely extensive particulate distribution sampling in these mines. It should be noted, however, that because conversion of historically collected respirable dust measurements to estimates of thoracic exposures is infeasible, this does not mean that measurement of thoracic fraction exposures is equivalent to respirable measurements and is without merit. Therefore, unless these four mines prove to be quite unrepresentative, the authors conclude that occupation-specific tracheo-bronchial dust exposures would be highly correlated with historically collected respirable exposures, and exposure-response analyses using the two measures would be similar.

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REFERENCES

1. "Mineral resources." *Code of Federal Regulations*, Title 30, Part 70, Subpart C—Sampling Procedures, 446–451 (1985).
2. **Jacobsen, M.:** The relation between pneumoconiosis and dust-exposure in British coal mines. In *Inhaled Particles III*, W.H. Walton, ed. Old Woking, Surrey: Unwin Bros., 1971. pp. 903–919.
3. **Attfield, M.D. and K. Morring:** An investigation into the relationship between coal workers' pneumoconiosis and dust exposure in U.S. coal miners. *Am. Ind. Hyg. Assoc. J. 53*:486–492 (1992).
4. **Attfield, M.D. and N.S. Seixas:** Prevalence of pneumoconiosis and its relationship to dust exposure in a cohort of U.S. coal miners and ex-miners. *Am. J. Ind. Med. 27*(1):137–151 (1995).
5. **Rogan, J.M., M.D. Attfield, M. Jacobsen, et al.:** Role of dust in the working environment in development of chronic bronchitis in British coalminers. *Br. J. Ind. Med. 30*:217–226 (1973).
6. **Soutar, C.A. and J.F. Hurley:** Relation between dust exposure and lung function in miners and ex-miners. *Br. J. Ind. Med. 43*:307–320 (1986).
7. **Marine, W.M., D. Gurr, and M. Jacobsen:** Clinically important respiratory effects of dust exposure and smoking in British coal miners. *Am. Rev. Respir. Dis. 137*:106–112 (1988).
8. **Seixas, N.S., T.G. Robins, M.D. Attfield, and L.H. Moulton:** Exposure-response relationships for coal mine dust and obstructive lung disease following enactment of the federal Coal Mine Health and Safety Act of 1969. *Am. J. Ind. Med. 21*:715–734 (1992).
9. **Stahlhofen, W., G. Rudolf, and A.C. James:** Intercomparison of experimental aerosol deposition data. *J. Aerosol. Med.* 2:285–308 (1989).
10. **American Conference of Governmental Industrial Hygienists (ACGIH):** Particle Size-Selective Sampling in the Workplace; Report of the ACGIH Technical Committee on Air Sampling Procedures. Cincinnati, OH : ACGIH, 1985.
11. **Lippman, M.:** Size-selective health hazard sampling. In *Air Sampling Instruments for Evaluation of Atmospheric Contaminants*, S.V. Hering, ed. Cincinnati, OH: American Conference of Governmental Industrial Hygienists, 1989. pp.163–198.
12. **McCawley, M.A.** Should dust samplers mimic human lung deposition? *Appl. Occup. Environ. Hyg. 5*:829–835 (1990).
13. **Hewett, P.:** Limitations in the use of particle size-selective sampling criteria in occupational epidemiology. *Appl. Occup. Environ. Hyg. 6*:290–300 (1991).
14. **Hodgkins, D., T.G. Robins, D.L. Hinkamp, et al.:** The effect of airborne lead particle size on worker blood-lead levels: an empirical study of battery workers. *J. Occup. Med. 33*:1265–1273 (1991).
15. **Treaftis, H.N., A.J. Gero, P.M. Kacsmar, and T.F. Tomb:** Comparison of mass concentrations determined with personal respirable coal mine dust samplers operating at 1.2 liters per minute and the Casella 113A gravimetric sampler (MRE). *Am. Ind. Hyg. Assoc. J. 45*:826–832 (1984).
16. **Potts, J.W., M.A. McCawley, and R.A. Jankowski: Thoracic dust exposures on longwall and continuous mining sections.** *Appl. Occup. Environ. Hyg. 5*:440–447 (1990).
17. **Burkhart, J.E., M.A. McCawley, and R.W. Wheeler:** Particle size distributions in underground coal mines. *Am. Ind. Hyg. Assoc. J. 48*:122–126 (1987).
18. **Rubow, K.L., V.A. Marple, J. Olin, and M.A. McCawley:** A personal cascade impactor: design, evaluation and calibration. *Am. Ind. Hyg. Assoc. J. 48*:532–538 (1987).
19. **Rader, D.J., L.A. Mondy, J.E. Brockmann, et al.:** Stage response calibration of the Mark III and Marple Personal Cascade Impactors. *Aerosol Sci. Technol. 14*:365–379 (1991).
20. **Hinds, W.C.:** Data analysis. In *Cascade Impactor Sampling and Data Analysis*, J.P. Lodge and T.G. Chan, eds. Akron, OH: American Industrial Hygiene Association, 1986. pp. 45–78.
21. **Caplan, K.J., L.J. Doemeny, and S.D. Sorenson:** Performance characteristics of the 10 mm cyclone respirable mass sampler: part 1—monodisperse studies. *Am. Ind. Hyg. Assoc. J. 38*:83–95 (1977).
22. **Seixas, N.S., L.H. Moulton, T.G. Robins, et al.:** Estimation of cumulative exposures for the National Study of Coal Workers' Pneumoconiosis. *Appl. Occup. Environ. Hyg. 6*:1032–1041 (1991).
23. **American Conference of Governmental Industrial Hygienists (ACGIH):** *Annual Reports of the Committees on Threshold Limit Values and Biological Exposure Indices.* Akron, Ohio: ACGIH, 1993.
24. **Smith, T.J.:** Exposure assessment for occupational epidemiology. *Am. J. Ind. Med. 12*:249–268 (1987).
25. **Vincent, J.H. and D. Mark:** The measurement of aerosols in relation to risk assessment. In *Exposure Assessment for Epidemiology and Hazard Control*, S.M. Rappaport and T.J. Smith, eds. Chelsea, U.K.: Lewis Publishers, 1991. pp. 41–52.
26. **Rubow, K.L. and V.A. Marple:** Determining the size distribution of coal/diesel aerosol mixtures with the microorifice uniform deposit impactor. In *Respirable Dust in the Mineral Industries*, R. Frantz and R. Ramani, eds. Akron, OH: American Conference of Governmental Industrial Hygienists, 1988.
27. **Mark, D., H. Cowie, J.H. Vincent, et al.:** *The Variability of Exposure of Coalminers to Inspirable Dust.* [Report no. TM/88/02] Edinburgh, U.K.: Institute of Occupational Medicine, 1988.
28. **Solderhom S.C.:** Why change ACGIH's definition of respirable dust? *Appl. Occup. Environ. Hyg. 6*:248–250 (1991).