AMERICAN JOURNAL OF INDUSTRIAL MEDICINE 51:231–245 (2008)

Mortality Among U.S. Underground Coal Miners: A 23-Year Follow-Up

M.D. Attfield, PhD[1]* and E.D. Kuempel, PhD[2]

Background *The mortality experience over 22–24 years of 8,899 working coal miners initially medically examined in 1969–1971 at 31 U.S. coal mines was evaluated.*
Methods *A cohort life-table analysis was undertaken on underlying causes of death, and proportional hazards models were fitted to both underlying, and underlying and contributing causes of death.*
Results *Elevated mortality from nonviolent causes, nonmalignant respiratory disease (NMRD), and accidents was observed, but lung cancer and stomach cancer mortality were not elevated. Smoking, pneumoconiosis, coal rank region, and cumulative coal mine dust exposure were all predictors of mortality from nonviolent causes and NMRD. Mortality from nonviolent causes and NMRD was related to dust exposure within the complete cohort and also for the never smoker subgroup. Dust exposure relative risks for mortality were similar for pneumoconiosis, NMRD, and chronic airways obstruction.*
Conclusions *The findings confirm and enlarge upon previous results showing that exposure to coal mine dust leads to increased mortality, even in the absence of smoking.*
Am. J. Ind. Med. 51:231–245, 2008. © *2008 Wiley-Liss, Inc.*

KEY WORDS: coal; mortality; pneumoconiosis; dust; exposure-response

INTRODUCTION

The mortality of underground coal miners has been studied intensively. Over 25 studies worldwide have been undertaken, starting in 1936 [Merchant et al., 1986]. In the main, these analyses examined standard mortality ratios by occupation, tenure, and health status, without the benefit of measured assessments of dust exposure. The principal finding from these studies was excess all-cause mortality associated with radiographic evidence of complicated coal workers' pneumoconiosis (also known as progressive massive fibrosis, or PMF). Certain causes of death were elevated in most studies, these mainly being mortality from coal workers' pneumoconiosis (CWP), tuberculosis, nonmalignant respiratory disease (NMRD), and accidents. In contrast, deaths from malignancies were not typically elevated, apart from occasional elevations of lung cancer and stomach cancer.

Only two mortality studies have included measured dust exposures in their analyses. The first [Miller and Jacobsen, 1985], a 22-year follow-up of a cohort of British underground coal miners, found that age-adjusted mortality from all nonviolent causes rose systematically with increasing cumulative dust exposure experienced before the start of follow-up. This increase was mostly accounted for by excesses in deaths from pneumoconiosis and from bronchitis and emphysema. There was an indication that stomach cancer deaths were related to dust exposure, but no such elevations were found for lung cancer. The second study involved a 9-year follow-up until 1979 of a cohort of U.S. underground coal miners [Kuempel et al., 1995, 1996]. This study was the first to examine contributing causes of death among coal miners in addition to underlying causes. The

[1]Division of Respiratory Disease Studies, National Institute for Occupational Safety and Health (NIOSH), Morgantown, West Virginia
[2]Education and Information Division, National Institute for Occupational Safety and Health (NIOSH), Cincinnati, Ohio
The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.
*Correspondence to: Dr. M.D. Attfield, Division of Respiratory Disease Studies, NIOSH, 1095 Willowdale Road, Morgantown, WV, 26505. E-mail: mdal@cdc.gov

Accepted 11 December 2007
DOI 10.1002/ajim.20560. Published online in Wiley InterScience (www.interscience.wiley.com)

study showed statistically significant relationships between cumulative exposure to respirable coal mine dust (prior to start of follow-up) and mortality either from pneumoconiosis or from bronchitis or emphysema, after controlling for age, smoking, and coal rank. A relationship was also observed between increasing radiographic category of simple CWP and mortality from pneumoconiosis as an underlying or contributing cause of death.

The study reported here is an extension of the U.S. coal miner cohort, with the follow-up for the same cohort of miners extended to an average of 23 years. The larger number of deaths in the study provides the ability to enhance the reliability of the earlier findings as well as to explore aspects of interest not possible before because of small numbers. In particular, this report contains new information on the relationship between respirable coal mine dust exposure and chronic obstructive airways disease mortality.

METHODS

Study Cohort

The initial cohort included 9,078 working coal miners who participated in medical examinations undertaken 1969–1971 at 31 nationally distributed mines [Attfield and Castellan, 1992]. About 90% of the eligible miners participated in the medical surveys, which included a chest X-ray, a symptoms, demographic, smoking and work history questionnaire, and pulmonary function testing. The mines were located in every major coalfield, from Alabama in the south, to Pennsylvania in the north, and to Utah in the west. Apart from mortality follow-up and dust measurement data used to compute the cumulative dust exposures, all data employed in this analysis come from the 1969 to 1971 surveys. Appropriate institutional review board clearance was obtained.

After deletion of records with missing data, 8,899 observations remained for analysis (Table I). The 179 records with missing data included those without smoking (n = 81), dust exposure (n = 24), or radiographic data (n = 31), while 41 records were omitted for those lost to follow-up. Two records of known or suspected deaths (0.06% of all deaths) were omitted from cause-of-death-based analyses because no death certificate could be found. Unlike the 9-year follow-up of these data [Kuempel et al., 1995] we did not exclude working miners who were aged 65 or older. In that study, it was done a priori to avoid potential selection bias arising from including miners who were working beyond retirement age. However, whether or not the older miners were included in analyses did not alter the original findings [Kuempel et al., 1996], and so these miners were retained in this analysis.

TABLE I. Mortality Follow-Up Status*

Category	n (%)
Original cohort	9,078
Rejected because of missing data	136 (1.5)
Lost to follow-up	41 (0.5)
Deceased with no death certificate located	2 (0.02)
Study cohort	8,899 (98.0)

*Percentages based on original cohort of 9,078.

Vital Status and Cause of Death

Vital status of the 8,899 miners was determined by comparison with various sources: Social Security Administration death data, Internal Revenue Service records, the National Death Index database, files of the United Mine Workers of America (UMWA) Welfare and Retirement Fund, national telephone listings stored on CD-ROM, postmasters, local funeral directors, and through use of a tracing agency. Miners were considered alive if two reliable sources could be identified to support this (e.g., IRS tax filing, receiving UMWA pension). Miners not located from these sources were considered lost to follow-up.

Death certificates for deceased miners were obtained from the appropriate State Department of Vital Statistics. A professional nosologist classified the underlying and contributing causes of death using either the 8th or 9th revision of the International Classification of Diseases (ICD) depending on the date of death of the miner as recorded on the death certificate. The causes of death examined include all causes, nonviolent causes, heart and circulatory diseases, malignant neoplasms, and NMRD (Fig. 1). Nonviolent

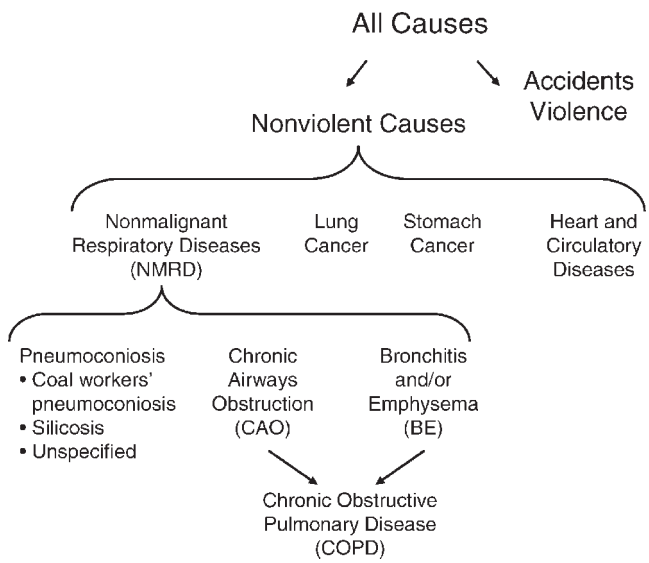

FIGURE 1. Causes of death examined in 23-year mortality follow-up of U.S. coal miners. (PMF: progressive massive fibrosis, or complicated CWP). Number of deaths by underlying cause are provided in Table III except for CAO, BE, and COPD, which were 90, 38, and 128 respectively.

causes of death include all deaths except those due to accidents or violence (i.e., includes 8th or 9th ICD codes 000-799). The term ''nonviolent'' is used here for consistency with the previous coal miner mortality studies [Miller and Jacobsen, 1985; Kuempel et al., 1995]. Deaths due to accidents include 8th or 9th ICD codes E800-E949 (violence and suicide include 8th or 9th ICD codes E950-E9878). Various subcategories of NMRD were examined separately. These included pneumoconiosis (8th revision ICD code 515.0, 515.1, and 515.9, as well as 9th revision codes 500, 502, and 505), chronic airways obstruction (CAO) (ICD code 519.3 (8th revision) or 496 (9th revision)), and bronchitis and/or emphysema (CBE) (ICD codes 490-492) (8th or 9th revision) (there were too few cases to examine bronchitis and emphysema separately). CAO and CBE were also combined into a single category representing chronic obstructive pulmonary disease (COPD).

Radiographic Status

This study used X-ray readings taken during the first round of a national coal miners' medical survey [Attfield and Castellan, 1992]. The readings were made using the UICC/Cincinnati classification of the pneumoconioses [Bohlig et al., 1970] and are tabulated here by major category (0–3) of small opacities of simple CWP and of PMF (category A, B, or C), where the presence of PMF takes precedence over small opacity profusion category.

Cumulative Exposure Estimates

Estimates of cumulative exposure to respirable coal mine dust were computed for each individual from starting work in coal mining until the time of medical examination in 1969–1971 [Attfield and Morring, 1992b]. Briefly, each miner's cumulative dust exposure was estimated by summing the products of the intensity of exposure (mean airborne dust concentration) for a given job and the duration of exposure (tenure) in that job derived from work histories collected from each miner in 1969–1971. The job-specific exposure intensity estimates were based on data collected from 1970 to 1972 by mine operators. These were adjusted to past conditions using approximately 4,300 gravimetric samples of airborne respirable dust concentrations collected by the U.S. Bureau of Mines (BOM) during 1968 and 1969 in 29 underground coal mines across the U.S. [Jacobson, 1971]. In this, an average ratio of the 1968–1969 dust levels to the 1970–1972 levels (i.e., pre- and post-compliance air concentration measurements across all underground jobs) was derived and applied to the 1970–1972 levels. The use of an average ratio for all jobs was justified through examination of the data and because the reduction of dust exposures at the source (primarily, the coal face) would be expected to affect all other jobs proportionately [Attfield and Morring, 1992b]. Seventeen of the 29 mines were later included in the National Study of Coal Workers' Pneumoconiosis (NSCWP) medical surveys. Exposures that occurred during the 22–24 years of follow-up were not determined because work history information was not available after 1969–1971 for most of the miners. Since exposure levels were substantially reduced after 1970 following the imposition of federal regulations, the omission of the post-1970 exposure component is not considered to have drastically influenced the analysis of exposure-response (see Discussion Section).

SMRs were computed for six cumulative exposure strata (measurements in milligram-years per cubic meter, mg-year/m^3): (I) 0.1–48.9, (II) 49.0–69.3, (III) 69.4–88.3, (IV) 88.4–107.0, (V) 107.1–127.0, (VI) 127.1–234. These ranges were used in the earlier published mortality study and were derived on the basis of approximately equal number of deaths in each group [Kuempel et al., 1995] (approximately 132 originally, but now 541 on average here, and still approximately equal across exposure groups).

Coal rank was also employed as an exposure variable in the analysis. Coal rank is defined by the percentage of carbon in the coal, and is correlated with the age and hardness of coal. Anthracite coal, which is found almost exclusively in eastern Pennsylvania (PA), has the highest percentage carbon and the greatest propensity to cause pneumoconiosis [Attfield and Morring, 1992a]. In this analysis, coal rank was defined by geographic region as follows (from high to low): the anthracite region (eastern PA), East Appalachia (central and west PA, West Virginia, Ohio, Virginia, eastern Kentucky, Tennessee, and Alabama), West Appalachia (western Kentucky), Midwest (Illinois and Indiana), and West (Colorado and Utah).

Modified Life Table Analysis

Analyses of underlying causes of death were done using the National Institute for Occupational Safety and Health (NIOSH) Life Table Analysis System (LTAS) mortality program [Steenland et al., 1995], which uses a modified life table procedure. Person-days were calculated from the date of examination (1969–1971) until date of death or December 31, 1993 (end of follow-up). Expected deaths for each cause of death category were calculated by applying the age-, race-, and calendar year-specific mortality rates (SMRs) for all males in the U.S. population to the corresponding person-years in each cumulative exposure stratum of the study population. In addition to the SMRs, standardized rate ratios (SRRs) were computed for certain causes of death, using the approach of [Rothman, 1986] to undertake trend tests of the SRRs.

Proportional Hazards Analysis

Cox proportional hazard models (PROC PHREG of the SAS® System [SAS, 1991]) were employed to investigate

the effects of smoking, chest radiographic category (simple CWP or PMF), coal rank region, and cumulative dust exposure on underlying cause mortality from nonviolent causes or from NMRD. Underlying and contributing causes of death were examined for specific NMRD causes (i.e., CAO, CBE, COPD, pneumoconiosis).

An exponential (log-linear) model form was fitted to the data. Smoking was studied using dummy variables to distinguish between never, ex-, and current smokers, with the inclusion of pack-years as a continuous variable (zero for never smokers). Dummy variables were also used to represent coal rank regions and cumulative dust exposure categories. Cumulative dust exposure was also modeled using a continuous variable. The time dimension used in these models was time in study, that is, from start of follow-up until date of death or censoring, with age at start of follow-up being included as a covariate in the models. The validity of the assumption that the hazard ratio does not change with time for the comparison groups was tested using a time-dependent explanatory variable representing the interaction between time since start of follow-up and cumulative exposure to respirable coal mine dust.

RESULTS

Descriptive Statistics

Of the 8,899 in the study cohort, 3,213 had died by December 31, 1993. Table II gives some basic demographic information for the 8,899 miners. The cohort was all male and 95% white, with a mean age of 44 years at start of follow-up. The majority (54%) were smokers with only 20% having never smoked. The largest group of coal miners came from West Appalachia, making up just over half of the cohort. The smallest group came from the anthracite area and made up only 6% of the group. The average tenure in coal mining up to the 1969–1971 medical surveys was 21 years for the overall cohort, with the average time at the coal face being 9 years. The mean cumulative coal mine dust exposure prior to follow-up was 64 mg-year/m^3.

Life Table Analysis

All-cause, nonviolent cause, and selected cause-specific SMRs and confidence intervals for the study cohort (n = 8899) are shown in Table III. The overall SMR for all causes of death was 103 and was not significantly elevated above 100. However, this lack of elevation concealed a rising trend of mortality relative to the U.S. population with length of follow-up (Fig. 2). In the first 5-year follow-up period the overall SMR was 81. This increased to 95 in the second follow-up period and had reached 113 by end of follow-up. This trend was even more pronounced when nonviolent causes were considered (Fig. 2). In the rest of this

TABLE II. Basic Demographic Information*

Number of miners	8,899
Race (%)	
White	95.1
Other	4.9
Smoking (%)	
Smokers	54.0
Never smokers	20.5
Ex-smokers	25.5
Region (%)	
Anthracite	5.6
East Appalachia	15.2
West Appalachia	54.9
Mid-west	13.6
West	10.7
Age (years) at start of follow-up (mean, SD)	44.5 (11.9)
Tenure (mean, SD)	
Years coal mining	20.7 (13.2)
Years underground	17.5 (13.7)
Years at the coalface	8.7 (11.1)
Cumulative dust exposure (mg-year/m^3) prior to follow-up (mean, SD)	64.4 (46.4)

*Based on analysis subset (n = 8,899); presented as % or mean (SD).

TABLE III. Standardized Mortality Ratios (SMRs) for Selected Underlying Cause Mortality in the Complete Cohort

Cause of death	Observed	SMR	95% CI
All-cause	3,213	103	99–106
Nonviolent cause	2,988	102	98–105
Tuberculosis	5	114	37–265
Malignant neoplasms			
All cancers	790	95	88–101
Stomach	21	75	46–114
Respiratory system	340	105	94–116
Bronchus, trachea, and lung	331	107	95–119
Nonmalignant respiratory disease			
All	474	195[a]	178–214
Pneumonia	51	75[b]	56–99
Bronchitis	5	69	22–161
Emphysema	33	89	61–125
Pneumoconiosis and other respiratory disease	383	308[a]	278–341
Heart and circulatory diseases			
All	1,194	99	94–105
Ischemic	949	99	93–106
Cerebrovascular	125	78[a]	65–93
Accidents	148	129[a]	109–151

95% CI, 95% confidence interval.
[a]Significant at 1%.
[b]Significant at 5%.

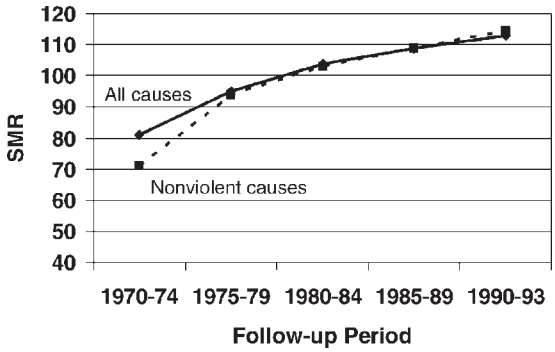

FIGURE 2. Underlying all-cause and nonviolent cause standard mortality ratios (SMRs) by follow-up period.

analysis, nonviolent cause mortality is favored over all-cause mortality because, as discussed later, there was a clear and significant *negative* trend of mortality from accidents with increasing age and cumulative exposure. That is, retention of accidental deaths would have interfered with the assessment of the predictors of occupational respiratory disease mortality.

With respect to specific causes, the overall cohort demonstrated a statistically significant twofold increase in all NMRD (SMR = 195, CI = 178–214), and particularly from pneumoconiosis and other respiratory diseases (SMR = 308, CI = 278–341). On the other hand, significant elevations in overall mortality from cancer of the respiratory system or stomach cancer were not observed (SMR = 105, CI = 94–116; and 75, CI = 46–114). Mortality from heart and circulatory diseases was not elevated, with cerebrovascular mortality showing a significant deficit (SMR = 78, CI = 65–93).

We observed the expected deficit in mortality from respiratory tract cancer among never smokers and an excess among current smokers, reflecting the effects of both smoking status and comparison with national rates derived across all smoking groups (Table IV). A similar trend was observed for heart disease. In contrast, mortality attributed to NMRD was statistically significantly elevated in all three smoking groups, including never smokers (SMR = 136, CI = 107–170).

Tables V–VII provide SMRs for selected underlying causes of death—stratified by either radiographic status for CWP or PMF at the start of follow-up (Table V), coal rank region in which miners worked (Table VI), or cumulative dust exposure groups (Table VII). Each of these Tables includes the percentage of ever smokers and the mean cumulative coal mine dust exposure in each stratum.

Mortality by radiographic status at start of follow-up (defined by small opacity profusion category of simple CWP and PMF) is shown in Table V. Significant elevations in SMRs are seen for nonviolent cause mortality for simple CWP category 3 and PMF. The SMRs for NMRD are

TABLE IV. Standardized Mortality Ratios (SMRs) for Selected Underlying Causes of Death, by Smoking Status at Start of Follow-Up

	Never smoker		Ex-smoker		Current smoker	
Cause of death	**Obs.**	**SMR**	**Obs.**	**SMR**	**Obs.**	**SMR**
Nonviolent cause	478	73[a]	789	82[a]	1,721	130[a]
Heart diseases						
All	206	76[a]	318	80[a]	674	124[a]
Malignant neoplasms						
All cancers	95	52[a]	202	75[a]	493	130[a]
Respiratory system	5	7[a]	68	65[a]	267	179[a]
Nonmalignant respiratory disease						
All	76	136[b]	128	153[a]	270	262[a]
Pneumoconiosis and other respiratory disease	63	220[a]	103	241[a]	217	412[a]

Obs., observed.
[a]Significant at 1%.
[b]Significant at 5%.

elevated in all radiographic categories, including category 0, and show a trend with increasing radiographic abnormality (SMR = 152–872). SRRs (not shown in tables) for NMRD were 1.03, 1.22, 1.75, and 1.22 for increasing radiographic abnormality relative to the category 0, with statistically significant trend ($P < 0.01$). This effect was even more pronounced among never smokers (SRRs = 1.20, 1.06, 1.62, 1.58, and 1.33; $P < 0.001$). There is a suggestion of an increasing trend for stomach cancer with radiographic category (although observed numbers are small) and an inverse trend for lung cancer, with a statistically elevated SMR for lung cancer for category 0 (Table V). The average percentage of ever smokers is similar across the small opacity profusion groups, with no evidence of any trend in smoking with increasing radiographic category. As would be expected, cumulative dust exposure increases with increasing radiographic category. Not shown in Table V is respiratory tuberculosis mortality which was statistically elevated among those with PMF (SMR = 1,591, CI = 193–5,746).

We examined mortality by coal rank group (as defined by geographic region). Nonviolent cause mortality death rates increased with increasing coal rank (from 71 for the West region to SMR = 133 for Anthracite), with significant elevations for the Anthracite and East Appalachian regions (Table VI). For NMRD, we saw statistically increased SMRs ranging from 126 in West Appalachia to 787 in the Anthracite region. No region showed an increase in stomach cancer, and there was no trend in lung cancer with coal rank, although lung cancer SMRs were elevated for West Appalachia and the Mid-west and trended somewhat with the percentage of ever smokers. Cumulative dust exposures were greater for the

TABLE V. Standardized Mortality Ratios (SMRs) for Selected Underlying Causes of Death, Percentage of Ever Smokers,* and Mean Cumulative Dust Exposure—by Radiographic Status at Start of Follow-Up

	Category 0		Category 1		Category 2		Category 3		PMF	
Cause of death	**Obs.**	**SMR**	**Obs.**	**SMR**	**Obs.**	**SMR**	**Obs.**	**SMR**	**Obs.**	**SMR**
Nonviolent cause	2,451	100	248	100	108	99	44	150[a]	137	137[a]
Malignant neoplasms										
Stomach cancer	16	68	1	44	1	96	2	714	1	104
Lung cancer	294	113[b]	23	89	6	53	1	33	7	69
Nonmalignant respiratory disease										
All	304	152[a]	39	182[a]	36	379[a]	19	764[a]	76	872[a]
Pneumoconiosis and other respiratory disease	229	223[a]	33	299[a]	35	714[a]	19	1,504[a]	67	1,523[a]
% ever smoked	80		79		75		79		81	
Mean cumulative exposure (mg-year/m^3)	59.3		94.8		106.6		121.3		116.4	

Obs., observed.
*Smoking status at start of mortality follow-up.
[a]Significant at 1%.
[b]Significant at 5%.

Anthracite region (probably a function of the older age of the miners there), but differed little among the other regions.

Nonviolent cause mortality increased slightly with increasing exposure, with the highest exposure category having a statistically significant elevation, and the lowest, a significant decrement, while the SRRs demonstrated a trend with increasing dust exposure ($P < 0.05$; Table VII). A generally decreasing trend in mortality from accidents with cumulative exposure was observed, with a significant excess in mortality in the lowest exposure group. NMRD showed a marked trend from a low of 115 for the first category of exposure to a high of 280 in the highest exposure category. All NMRD SMRs were significantly elevated except for those for the first two exposure categories. SRRs for NMRD were 1.00, 1.37, 1.74, 1.63, and 2.17 for each exposure group relative to the lowest dust exposure category, with statistically significant trend ($P < 0.001$). Similar findings were obtained for pneumoconiosis as the underlying cause of death. No clear trends in mortality from stomach or lung cancer were seen (Table VII).

Overall, there was little indication that smoking was a confounder for dust exposure, the percentage of ever smokers being similar in the lowest and highest exposure groups. This supposition was confirmed by the finding that nonviolent

TABLE VI. Standardized Mortality Ratios (SMRs) for Selected Underlying Causes of Death, Percentage of Ever Smokers,* and Mean Cumulative Dust Exposure—by Coal Rank Region

	Anthracite		East Appalachia		West Appalachia		Mid-west		West	
Cause of death	**Obs.**	**SMR**	**Obs.**	**SMR**	**Obs.**	**SMR**	**Obs.**	**SMR**	**Obs.**	**SMR**
Nonviolent cause	294	133[a]	460	111[b]	1,607	102	379	100	248	71[a]
Malignant neoplasms										
Stomach cancer	0	0	5	121	12	79	1	29	3	96
Lung cancer	18	80	43	96	195	117[b]	58	145[a]	17	47[a]
NMRD										
All	152	787[a]	69	213[a]	162	126[a]	41	129	50	163[a]
Pneumoconiosis and other respiratory diseases	146	1,491[a]	61	370[a]	114	174[a]	25	152	37	233[a]
% ever smoked	78		79		79		83		78	
Mean cumulative exposure (mg-year/m^3)	92.0		62.7		65.1		56.7		58.8	

Obs., observed.
*Smoking status at start of mortality follow-up.
[a]Significant at 1%.
[b]Significant at 5%.

TABLE VII. Standardized Mortality Ratios (SMRs) for Selected Underlying Causes of Death, Percentage of Ever Smokers,* and Mean Cumulative Dust Exposure—by Cumulative Coal Mine Dust Exposure Category

	0.1–48.9		49.0–69.3		69.4–88.3		88.4–107.0		107.1–127.0		127.1–234.0	
Cause of death	**Obs.**	**SMR**	**Obs.**	**SMR**	**Obs.**	**SMR**	**Obs.**	**SMR**	**Obs.**	**SMR**	**Obs.**	**SMR**
Nonviolent causes	430	87[a]	484	104	536	96	527	105	450	108	561	111[b]
Accidents	75	171[a]	25	153	12	70	10	70	17	154	9	73
Malignant neoplasms												
Respiratory system	51	94	64	122	71	119	53	99	49	116	43	89
Stomach cancer	3	64	2	45	3	56	6	125	2	51	5	104
NMRD												
All	38	115	46	124	84	181[a]	95	220[a]	81	221[a]	130	280[a]
Pneumoconiosis and other respiratory disease	27	162[b]	37	191[a]	68	284[a]	72	332[a]	68	365[a]	109	470[a]
% ever smoked	79		81		80		83		77		77	
Mean cumulative exposure (mg-year/m^3)	17.5		59.7		79.0		97.5		116.4		150.0	

Obs, observed.
*Smoking status at start of mortality follow-up.
[a]Significant at 1%.
[b]Significant at 5%.

cause of death exposure-response was apparent in the never smoker subgroup, the SRRs being 1.48, 1.06, 1.46, 1.83, and 1.83 relative to the lowest exposure category ($P < 0.05$ for trend). For NMRD, there was a clearer trend with cumulative dust exposure in the never smoker group than overall, the SRRs being 0.75, 1.26, 1.53, 2.30, and 3.02 relative to the lowest exposure group ($P < 0.001$).

Proportional Hazards Analysis

Tables VIII and IX provide the mortality hazard ratios (an approximation of relative risk (RR)) for underlying causes of death, including nonviolent causes (Table VIII) and NMRD (Table IX). For nonviolent causes (2,988 deaths), mortality increased from west to east; deaths were greater among smokers compared to never smokers and among those who smoked more (greater pack-years); and deaths increased with increasing cumulative exposure (Table VIII). There was clear evidence of a linear exposure-response with cumulative exposure to respirable coal mine dust (RR = 1.0022 per mg-year/m^3; CI = 1.0011–1.0032). Inclusion of a quadratic term in the model led to a marginally significant dust exposure-squared coefficient, but no major change in the estimated RRs (Fig. 3). Analysis of the never smokers alone (i.e., eliminating any smoking effect), allowing for age and coal rank region, gave rise to a RR for cumulative dust exposure of 1.0040 per mg-year/m^3 (CI = 1.0015–1.0066) in the linear model—somewhat greater than seen for the complete cohort.

Similar models applied to NMRD mortality (474 deaths) showed that mortality in the anthracite region was greatly elevated over that in West, but was somewhat lower in West Appalachia compared to the West (Table IX). Only the term for current smokers demonstrated statistical significance, no obvious relationship being seen with pack-years of smoking. In contrast, clear elevations in mortality risk were seen with increasing cumulative dust exposure. The linear model was found to be sufficient, giving rise to a RR of 1.0071 per mg-year/m^3 (CI = 1.0046–1.0096). The RR for

TABLE VIII. Hazard Ratios (RRs) for Underlying Nonviolent Cause Mortality, Estimated for Predictor Variables in Multivariate Proportional Hazards Model

Variable	**RR**	**95% CI**
Region[a]		
Anthracite	1.75	1.48–2.08
East Appalachia	1.57	1.34–1.83
West Appalachia	1.39	1.21–1.59
Mid-west	1.34	1.14–1.57
Age (year)	1.10	1.09–1.10
Smoking[a]		
Ex-	0.95	0.83–1.08
Current	1.54	1.36–1.73
Pack-years	1.007	1.01–1.01
Cumulative coal mine dust exposure category (mg-year/m^3)		
II: 49.0–69.3	1.29	1.13–1.48
III: 69.4–88.3	1.17	1.02–1.35
IV: 88.4–107.0	1.26	1.09–1.45
V: 107.1–127.0	1.37	1.18–1.59
VI: 127.1–234.0	1.38	1.19–1.60

95% CI, 95% confidence interval.
[a]Regional coefficients relative to West region, and smoking status relative to never smokers.

TABLE IX. Hazard Ratios (RRs) for Mortality Due to Nonmalignant Respiratory Diseases (NMRD) as An Underlying Cause of Death, Estimated for Predictor Variables in Multivariate Proportional Hazards Model

Variable	RR	95% CI
Region[a]		
Anthracite	4.41	3.08–5.92
East Appalachia	1.21	0.84–1.75
West Appalachia	0.71	0.50–0.95
Mid-west	0.74	0.49–1.12
Age (year)	1.11	1.10–1.13
Smoking[a]		
Ex-	1.11	0.80–1.54
Current	1.93	1.41–2.61
Pack-years	1.00	1.00–1.01
Cumulative coal mine dust exposure category (mg-year/m^3)		
II. 49.0–69.3	1.21	0.78–1.89
III: 69.4–88.3	1.67	1.11–2.52
IV: 88.4–107.0	1.99	1.32–2.99
V: 107.1–127.0	2.02	1.32–3.09
VI: 127.1–234.0	2.68	1.77–4.06

95% CI, 95% confidence interval.
[a]Regional coefficients relative to West region, and smoking status relative to never smokers.

cumulative dust exposure derived from modeling of NMRD on the never smoker subgroup was also somewhat greater than that seen for the complete cohort: 1.0130 per mg-year/m^3 (CI = 1.0076–1.0183) after allowance for age and coal rank region.

The modeling results for NMRD using cumulative dust exposure as a continuous variable (Table X) are similar to those using cumulative exposure as a categorical variable (Table IX). RRs calculated from the NMRD model in Table X using the midpoint of each exposure category range, after division by the RR for the lowest exposure category, are 1.27, 1.47, 1.67, 1.92, and 3.03, are similar to those shown in Table IX.

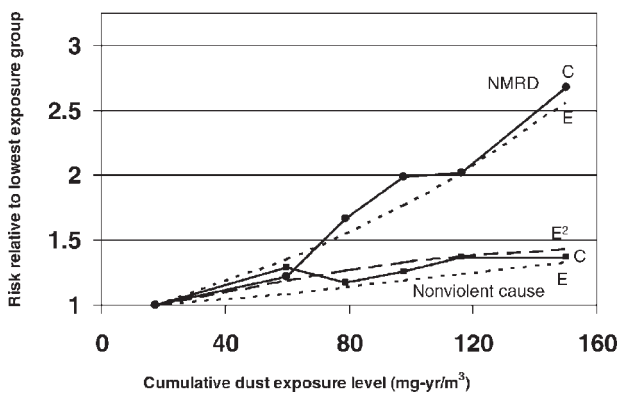

FIGURE 3. Relative risks for nonviolent and nonmalignant respiratory disease (NMRD) underlying causes of death by cumulative dust exposure based on categorical cumulative dust exposure groups (C), linear continuous exposure (E), and quadratic continuous exposure (E^2). All results relative to lowest exposure group (range = 0.1–48.9, mean = 17.53 mg-year/m^3) and plotted at mean level of each exposure group.

Dust exposure as a continuous variable

Results from employing models on selected underlying causes using continuous cumulative dust exposure terms rather than exposure categories are shown in Table X. Only the models using linear cumulative dust exposure are shown, not only for ease of comparison but also because the quadratic terms demonstrated only borderline significance. Coefficients for cumulative coal mine dust exposure are similar across the models of NMRD, pneumoconiosis, and CAO. For NMRD, the dust exposure RR was 1.0071 (CI = 1.0045–1.0096), and 1.0087 per mg-year/m^3 (CI = 1.0054–1.0121) for pneumoconiosis. There were sufficient deaths from CAO (90 deaths) to permit exposure-response modeling, which was not possible in the previous analysis of this cohort [Kuempel et al., 1995], and the RR for cumulative dust exposure was 1.0081 per mg-year/m^3 (CI = 1.0025–1.0138). As in the previously published analysis, CBE as an underlying cause (38 deaths), did not show significantly elevated RRs for any exposure group nor demonstrate a relationship with cumulative dust exposure. Combining the CBE deaths with the CAO deaths to form a COPD category led to findings similar to those for CAO alone, although the RR for dust exposure was somewhat lower at 1.0065 per mg-year/m^3 (CI = 1.0017–1.0054).

Radiographic category

A significant trend in NMRD (as the underlying cause of death) was seen with increasing severity of pneumoconiosis at start of follow-up (based on chest X-ray data), after accounting for age, coal rank region, and smoking. The RRs were: 1.10 (CI = 0.79–1.55); 1.87 (CI = 1.31–2.67); 2.62 (CI = 1.62–4.25); 3.44 (2.61–4.55), respectively for simple CWP category 1, 2, 3, or PMF (relative to category 0). The addition of a cumulative dust exposure term to this model led to a slight reduction in the RRs (1.05, 1.68, 2.25, and 3.09, respectively), but the RR for cumulative coal mine dust exposure (1.0053 per mg-year/m^3; CI = 1.0026–1.0079) was similar to that obtained when radiographic status was not in the model—implying that dust exposure plays a role in mortality among coal miners independent of pneumoconiosis.

DISCUSSION

This 23-year mortality follow-up study confirms previous findings on the underlying and contributing causes of

TABLE X. Coefficients of Proportional Hazards Models on Selected Underlying Causes of Death Based on Use of Linear Cumulative Dust Exposure

	Coefficients			
Variable	**Nonviolent**	**NMRD**	**Pneumoconiosis**	**CAO**
Region[a]				
Anthracite	0.5602	1.4844	2.2580	−2.2756
East Appalachia	0.4531	0.2187	0.4108	0.4516
West Appalachia	0.3252	−0.3477	−0.5770	−0.4667
Mid-west	0.2886	−0.2870	−1.2156	−0.0758
Age at start of follow-up (year)	0.0932	0.1079	0.1005	0.1138
Smoking[a]				
Current	−0.0554	0.1097	0.2102	−0.1191
Ex-	0.4298	0.6577	0.5216	1.0093
Pack-years	0.00678	0.00262	−0.00022	0.0126
Cumulative coal mine dust exposure (mg-year/m^3)	0.00215	0.00709	0.00870	0.00811

NMRD, nonmalignant respiratory disease; CAO, chronic airways obstruction.
All exposure coefficients are statistically significant ($P < 0.005$).
[a]Regional coefficients relative to West region, and smoming status relative to never smokers.

death in U.S. coal miners and provides additional insight on the relationship between specific causes of death and cumulative exposure to respirable coal mine dust and other factors. The longer follow-up period in this analysis enables more reliable estimates of mortality rates and predictors than was possible in the earlier 9-year follow-up. Both lifetable and proportional hazards modeling methods were employed here, as in the earlier study. Lifetable methods provide external comparisons with general U.S. population underlying cause mortality rates. Proportional hazards models provide internal comparisons of the exposure-response relationships (i.e., hazard rates are compared within the coal miner cohort), which minimizes any potential bias from use of general U.S. population rates. The models based on both underlying and contributing causes provide a greater number of outcome observations and more reliable estimates of certain causes of death with few underlying cases (CBE with or without pneumoconiosis).

All-Cause and Nonviolent Cause Mortality

The all-cause and nonviolent cause mortality rates in this cohort were near 100 and were not statistically significantly elevated, although evidence of a healthy worker survival effect (which could obscure the true exposure-response relationship) was observed. That is, Figure 2 shows that the SMRs for either all-cause or nonviolent causes were considerably lower in the first 5 years of follow-up (at the beginning of which all of the miners were sufficiently healthy to be currently employed) compared to later follow-up periods, when occupational disease was more obviously being manifested. The effect of increasing age was not likely a factor since the SMRs are matched on age and gender in the general U.S. population. It might be thought that state-specific mortality rates would be preferable to national rate since regional differences in mortality from specific causes are known to occur in the general population. However, we chose to use the national rates in the lifetable analyses because the use of state-specific rates (given that coal mining is a predominant occupation in some states, e.g., West Virginia) could lead to the attenuation of true effects, leading to bias in the results.

Nonmalignant Respiratory Diseases

With regard to specific causes of death, we found a marked elevation in mortality from NMRD (SMR = 193), a disease category that includes death ascribed to pneumoconiosis as well as chronic obstructive pulmonary diseases. While smokers, as expected, had the highest SMR from NMRD, it was noticeable that both ex- and never-smokers showed significant elevations as well. There was also a marked, statistically significant, trend in mortality from NMRD with increasing dust exposure and with increasing radiographic category of simple CWP or PMF. The latter finding, which confirms that observed for pneumoconiosis both as an underlying, and as an underlying or contributing, cause of death in the 9-year follow-up of these data [Kuempel et al., 1995], has not been seen in other cohorts so clearly. Miller and Jacobsen [1985] observed higher death rates among miners with complicated pneumoconiosis (PMF), but did not detect any clear trend with increasing small opacity profusion category (simple CWP). Note that miners in the

category 0 group had elevated NMRD mortality (SMR = 152, $P < 0.01$) despite the fact that their mean cumulative dust exposure (59.3 mg-year/m^3) was less than would be expected after a 40-year working life at the current federal regulatory limit of 2 mg/m^3 (30 USC 801-962; 30 CFR 70.101 and 71.101).[1]

Smoking did not appear to be a confounding factor in the current findings for NMRD mortality because the prevalence of smoking did not vary systematically with mortality among miners across the pneumoconiosis or cumulative dust exposure groups. Moreover, NMRD relationships with both dust exposure and pneumoconiosis were both evident and more pronounced in the never smoker group. Furthermore, the effect of both pneumoconiosis category and dust exposure remained clearly evident in the proportional hazards models after adjustment for smoking status and amount smoked.

Pneumoconiosis

The proportional hazards modeling results for pneumoconiosis were similar whether based on underlying causes alone or both underlying and contributing causes. Both showed clear trends across cumulative dust exposure groups, and the RRs for dust exposure as a continuous linear variable were almost identical in the two analyses, that is, underlying alone or underlying and contributing causes. The RRs for on underlying and contributing causes in this 23-year follow-up analysis were somewhat lower across cumulative dust exposure categories (2.0, 2.2, 2.8, 3.2, 3.2) (all $P < 0.01$) than those presented in the 9-year follow-up (2.6, 2.8, 3.8, 5.2, 3.8) (all $P < 0.05$) [Kuempel et al., 1995], although the current results show a more consistent trend with increasing cumulative dust exposure category. The exposure-response relationship for pneumoconiosis (as an underlying or contributing cause) based on cumulative dust exposure as a continuous variable was also similar and somewhat lower in this 23-year follow-up compared to the 9-year follow-up study (see Appendix).

Chronic airways obstruction

Mortality from CAO was also clearly related to cumulative dust exposure, in proportional hazards models using either underlying causes of death or underlying and contributing causes. This finding is consistent with the many epidemiological morbidity studies that have demonstrated reduced pulmonary function with increasing cumulative coal mine dust exposures, after accounting for smoking and other factors [Rogan et al., 1973; Love and Miller, 1982; Attfield, 1985; Hurley and Soutar, 1986; Soutar and Hurley, 1986; Gauld et al., 1988; Marine et al., 1988; Attfield and Hodous, 1992; Wang et al., 1999]. The RRs for the categorical exposure groups were slightly higher using underlying and contributing causes, but the trend across the groups was more uniform using underlying causes alone (results not shown) As occurred with NMRD, the RRs for dust exposure as a continuous linear variable on CAO were almost identical using underlying causes of death or underlying and contributing causes. It is noteworthy that the continuous cumulative dust exposure RR for CAO (1.0067) was almost identical to that for mortality from pneumoconiosis (1.0066), indicating similar exposure-response relationships. Smoking was not a confounder as it was accounted for in the model. Importantly, the relationship between dust exposure and CAO persisted among miners with no mention of mortality from pneumoconiosis. In the previous analysis of this cohort [Kuempel et al., 1995], CAO was not studied separately from NMRD and so no direct comparison is possible.

Chronic bronchitis and emphysema

For CBE, an exposure-response relationship was not observed using underlying causes but, as in the earlier study [Kuempel et al., 1995], significant exposure-response was observed for underlying and contributing causes when a quadratic term for exposure was included. A new finding in the current study is the relationship between mortality from CBE and pneumoconiosis. Among the 226 who died with CBE as an underlying or contributing cause, 147 were said also to have pneumoconiosis, while 79 did not. The RRs for cumulative dust exposure among miners with mention of both CBE and pneumoconiosis on the death certificate (RRs: 4-8 across exposure category) were about twice the magnitude of those with mention of pneumoconiosis only (RRs: 2-3 across exposure category); furthermore, the relationship between cumulative dust exposure and CBE mortality (RRs: 1-2 across exposure category) disappeared when those with mention of pneumoconiosis were omitted. Therefore, it appears that CBE plays a role in mortality associated with respirable coal mine dust exposure, especially in association with pneumoconiosis. This finding supports results from epidemiological study of respiratory symptoms and their relationship to cumulative exposure to coal mine dust [Rae et al., 1971].

Chronic obstructive pulmonary diseases

Mortality from COPD, defined as deaths with mention of CBE or CAO, was related to cumulative dust exposure. However, the relationship was weaker than that seen for CAO alone, as expected. This probably arose because of the tenuous relationship observed for CBE and cumulative dust

[1] USC. United States Code. Washington, DC: U.S. Government Printing Office. CFR. Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

exposure. In this analysis, these outcomes formed the minority compared with those from CAO.

Lung Cancer

Some elevation in lung cancer mortality rates might have been expected in this cohort, based on known exposure to silica in coal mines and known potential for silica to cause lung cancer. However, this study, in common with most other mortality investigations of coal miners, did not show any convincing excess of lung cancer deaths. Although the numbers of deaths are few and do not demonstrate statistical significance, there is an interesting negative trend in lung cancer mortality with increasing category of pneumoconiosis. It is unclear what might have led to the pattern of lung cancer mortality observed in this study, but one might speculate that it could arise from difficulties in detection and diagnosis of lung cancer among those with advanced pneumoconiosis. It is also possible that workers with the highest exposures and severity of pneumoconiosis (who may also have been at highest risk for lung cancer) died before lung cancer was detected (i.e., competing risks effect). The negative finding for lung cancer in this study is contrary to that observed in a study of German coal miners, where the risk of lung cancer appeared elevated in those with pneumoconiosis [Morfeld et al., 2002].

Stomach Cancer

Mechanisms for stomach cancer have been proposed (e.g., dust cleared from the lungs is swallowed, and thereby has potential for carcinogenesis [Swaen et al., 1995]). A relationship of stomach cancer with dust exposure has been noted in one major investigation [Miller et al., 1986] while a meta-analysis has shown evidence of an effect across 17 cohort and case-control studies [Morfeld et al., 1997]. In the present study, the findings for stomach cancer were mixed, with overall low mortality (SMR = 75), but some evidence of a trend in stomach cancer with increasing cumulative dust exposure (the SMRs for two of the three higher exposure groups are larger than those for the three lower groups) (Table VII). However, the number of cases overall is too low for formal analysis.

Predictors of Mortality

Cumulative exposure to respirable coal mine dust, coal rank region, presence of simple pneumoconiosis, smoking, and age at start of follow-up were all predictors of mortality from nonviolent causes and nonmalignant respiratory diseases. These factors were taken into account to some extent in the lifetable analyses by computing SMRs within strata and evaluating mean values for the other terms within these strata. In the Cox proportional hazards models, these predictors were explicitly accounted for by inclusion as covariates in the model.

Coal rank, as defined by geographic region, was associated with the mortality patterns, particularly from nonviolent causes and NMRD (Table VI). This trend is probably a reflection of the greater fibrogenicity of higher rank coals, as evidenced by trends in CWP prevalence with coal rank observed in the U.S. after adjustment for cumulative dust exposure [Attfield and Morring, 1992a]. Other outcomes, such as the excess in lung cancer deaths in the West Appalachia and Mid-west coalfields, the low cancer death rates in the West, and the elevation of deaths from NMRD in Western miners are less easy to explain, however. It should be noted that any variations in lifestyle, health care, and non-coalmine exposures across geographical regions are also confounded with coal rank in this comparison.

Healthy Worker Survival Effect

Evidence of a healthy worker survival effect (HWSE) was observed in the cohort (Fig. 2). That is, the overall and nonviolent cause SMRs increased with length of follow-up, being less than national rates early on and greater than expected later. This phenomenon was confirmed in the proportional hazards modeling for nonviolent causes, following the addition of time-dependent variables for cumulative dust exposure to the model (test of the proportionality assumption). These terms attained statistical significance ($P < 0.05$), and the effect was to increase the RR at long follow-up times and reduce it at shorter periods, which is consistent with the retention of healthier workers among those with higher cumulative dust exposure. For example, for nonviolent causes, the RR was reduced from 1.38 for the highest exposure group to 1.33 at 3,492 days of follow-up (10th percentile of follow-up time). In contrast, at 8,689 days of follow-up (90th percentile), the RR increased from 1.38 to 1.57. As might be expected, the RR from the model without a time-dependent exposure variable tended to underestimate the risk for about half the range of follow-up, but in doing so impacted the RR for the majority of workers. Similar models for other mortality outcomes demonstrated consistent findings, although only those for nonviolent causes and pneumoconiosis were statistically significant. Notably, there was no indication of time dependence for age, suggesting that worker selection is largely based on factors associated with better health at greater cumulative dust exposures.

Potential for Misclassification

Exposure estimates

This study, like its two major predecessors [Miller and Jacobsen, 1985; Kuempel et al., 1995], employed cumulative dust exposures for exposure-response investigation, and in all

three studies the exposures were censored at start of follow-up date. That is, exposures experienced after the start of follow-up were not included in the miners' total cumulative exposure estimate. Data on retirement date from coal mining were not available for most miners in this cohort, and so it was not possible to estimate exposures after the start of follow-up. If the cohort had been limited to miners with sufficient data to estimate exposures during follow-up, bias would likely have been introduced due to selection of those who had continued to work and had received further medical examinations after the start of follow-up. For the two previous studies these intervals are about 9 years [Kuempel et al., 1995] and 22 years [Miller and Jacobsen, 1985]. In the case of this study, with its follow-up of 23 years on average, it is possible that up to 23 years of exposure may have been omitted from a miner's exposure. Hence, as in the previous studies, there is the potential for exposure misclassification, with possible attenuation of the exposure-response relationship.

A closer look, however, reveals that the potential effect of exposure misclassification may not be as great as might be first suspected. First, dust exposure levels in U.S. mines were mandated to be much lower after 1969 (i.e., around the time of start of follow-up) than previously. Data on dust concentrations indicates that levels had dropped by 1975 to about one-third to one-quarter of pre-1969 levels, with most of the drop happening in the period 1970–1972 [Attfield and Morring, 1992b]. Also, this drop tended to happen across all jobs, suggesting that all exposures dropped proportionately regardless of job. Hence, the contribution of a miner's post-1969 to his total exposure was considerably less than for pre-1969 work. Second, the workforce had an average age of 45 at the s start of follow-up, meaning that many of the group would likely retire early in the follow-up period, again limiting the potential for misclassification. Third, although younger miners have the most potential for misclassification in their exposures since their tenure during follow-up may have been as long, or longer than, their pre-follow-up tenure, very few deaths from causes of interest to this study (e.g., NMRD) occurred in younger miners. A tabulation of deaths from NMRD showed that only 6% of the total deaths occurred in miners who were younger than 45 years of age at start of follow-up, while just 19% occurred in miners who were younger than age 50. The impact of exposure misclassification during follow-up was assessed by restricting the analysis to miners aged 50 years or older at time of start of follow-up. Use of the proportional hazards model on NMRD on this subgroup gave rise to a RR of 1.006 per mg-year/m^3 ($P < 0.0001$), which is similar, but slightly smaller than that for all workers (RR = 1.007). Although these findings clearly do not absolve the results from the effects of exposure misclassification, they do indicate that any effect is limited and much less than might be suggested by first appearances.

In addition, a potential for bias in the cumulative exposure estimates exists to the extent that airborne dust concentrations within a given job category may have varied systematically by region or mine. It was not possible to account for any mine- or region-specific differences in the development of the cumulative dust exposure estimates [Attfield and Morring, 1992b]. Systematic differences by region could have contributed to the observed coal rank effect on mortality, while systematic differences by mine would have increased the variability of the exposure-response relationship.

Thus, while there is potential for exposure misclassification in this cohort to influence the analyses, it did not obscure the observation of a statistically significant relationship between cumulative exposure to respirable coal mine dust and mortality from specific causes of death. More apparent is the influence of a HWE on the RR for cumulative dust exposure in the whole cohort, as discussed above.

Cause of death

Misclassification on death certificates is a problem intrinsic to cohort mortality studies [Selikoff, 1992]. As was noted in the earlier study, this potential factor is mitigated when, as here, internal analyses are conducted. Overall, the results from the internal analyses support those obtained using the life-table approach, suggesting that bias was not a concern. Because the hazards of coal mining are well established, it seems unlikely that under-reporting of disease is an issue with these data. Rather bias in cause of death may be more of a concern, given the traditional focus on pneumoconiotic causes, with only more recent acceptance that other pulmonary diseases also commonly result from coal mine dust exposure. It is clear, though, that if such a bias exists, it did not prevent detection and quantification of exposure-response.

Survival Predictions

Figure 4 shows the projected 24-year survival for nonviolent causes of death for miners with certain criteria (i.e., age 58 years at start of follow-up, never smoker, west Appalachian coal rank region – with specified cumulative dust exposure and radiographic category). Twenty-four years was selected because it was the longest survival observed in this cohort. The five groups shown in Figure 4 include four having no radiographic evidence of CWP and 40 years of exposure to either 0, 1, 2, and 3.7 mg/m^3 of coal mine dust, and one group with 40 years of exposure to 3.7 mg/m^3 and PMF. These values were selected as 40 years is considered to be a typical working lifetime, and 3.75 mg/m^3 for 40 years translates to approximately 150 mg-year/m^3, which is the mean value for the highest exposure group in this analysis.

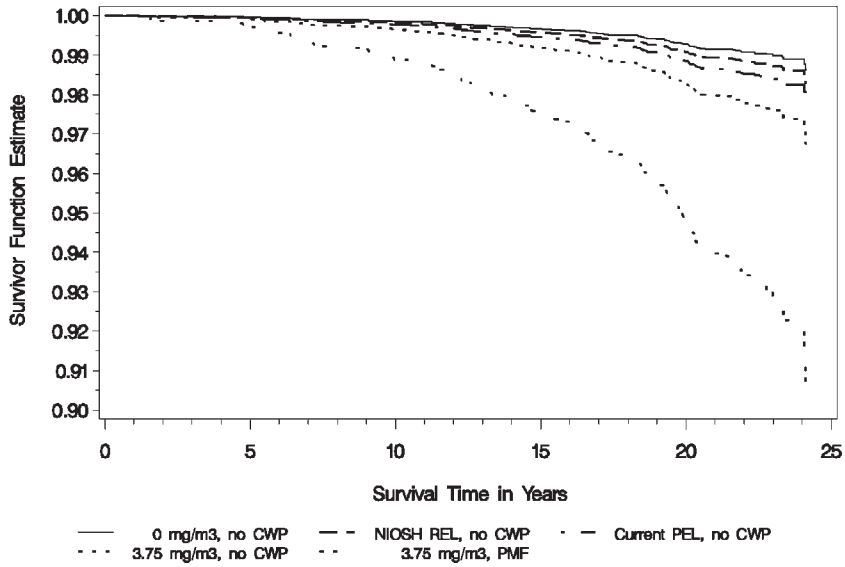

FIGURE 4. Predicted 24-year nonviolent cause survival for nonsmoking, west Appalachian miners, aged 58 at start of follow-up for those with: no dust exposure; 40 prior years of exposure to respirable coal mine dust at 1 mg/m^3 [National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit (REL) [National Institute for Occupational Safety and Health, 1995]]; 40 prior years of exposure to 2 mg/m^3 [Mine Safety and Health Administration (MSHA) permissible exposure limit (PEL) (30 CFR 70.101 and 71.101; 30 USC 801-962)]; 40 years at 3.75 mg/m^3 (mean concentration for highest dust exposure group in this study); and 40 years at 3.75 mg/m^3 with progressive massive fibrosis (PMF) at the start of follow-up. All groups but the latter are assumed to have no coal workers' pneumoconiosis (CWP).

These projections are based on the proportional hazard model on underlying nonviolent cause mortality (Table A.I), with cumulative dust exposure as a continuous variable and covariates for coal rank region, age, smoking.

The results show that reduction in the dust concentration has an important impact on survival. Compared to nonsmoking individuals from the same region, of same age, and without dust exposure, miners exposed to respirable coal mine dust at a mean concentration of 2 mg/m^3 over a 40-year working lifetime are predicted to have a 58% increase in mortality (8/1,000 additional deaths). Survival is predicted to be more than doubled among miners with exposure at half the dust concentration, or 1 mg/m^3 over 40 years (3.5/1,000 additional deaths than in comparison group). In the U.S., the federal regulatory limit [Mine Safety and Health Administration (MSHA) permissible exposure limit (PEL)] for respirable coal mine dust is 2 mg/m^3 (30 USC 801-962; 30 CFR 70.101 and 71.101), and the NIOSH recommended exposure limit (REL) is 1 mg/m^3 [NIOSH, 1995]. Among miners with the highest dust exposure in this study (mean concentration of 3.75 mg/m^3 over 40 years), a 136% increase in mortality is predicted (19/1,000 additional deaths than in comparison group). Figure 4 also shows, as is well known, that the development of PMF reduces survival. Among miners with the highest dust exposure who had developed PMF by age 58, a nearly 700% increase in mortality is predicted (82/1,000 additional deaths than in comparison group). Previous studies have shown that higher dust exposures increase miners' risk of developing PMF [Attfield and Seixas, 1995; National Institute for Occupational Safety and Health, 1995]. We can therefore conclude that lowering dust exposure brings about benefits in at least two ways: (1) it increases survival among those who do not develop PMF; (2) it reduces the risk of PMF development and thus eliminates the loss in survival from that cause. There is recent evidence that PMF is still occurring [Antao et al., 2006].

In conclusion, the findings from this study show elevations in nonviolent cause and NMRD mortality overall and in association with dust exposure, after allowance for age, smoking, and coal rank region. Little definitive evidence was found, however, for any increase in deaths from lung cancer or stomach cancer. A large healthy worker effect appeared to be present, and may have had the effect of attenuating the exposure-response relationships. Mortality was increased with severity of pneumoconiosis as ascertained at start of follow-up. Regional effects, probably associated with coal rank, were very obvious. The results in this study provide additional evidence that exposure to coal mine dust leads to lung diseases other than pneumoconiosis. In particular, the analysis of underlying, and of underlying plus contributing, mortality from chronic airways obstruction shows not only that obstructive airways disease is elevated in coal miners, but also that (1) the risk increases

with increasing dust exposure, and (2) manifestation of the disease can occur independently of pneumoconiosis.

REFERENCES

Antao VC, Petsonk EL, Attfield MD. 2006. Advanced cases of coal workers' pneumoconiosis—Two counties, Virginia, 2006. Morb Mortal Wkly Rep 55:909–913.

Attfield MD. 1985. Longitudinal decline in FEV_1 in United States coalminers. Thorax 40:132–137.

Attfield MD, Castellan RM. 1992. Epidemiological data on US coal miners' pneumoconiosis, 1960–1988. Am J Public Health 82: 964–970.

Attfield MD, Hodous TK. 1992. Pulmonary function of U.S. coal miners related to dust exposure estimates. Am Rev Respir Dis 14:605–609.

Attfield MD, Morring K. 1992a. 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.

Attfield MD, Morring K. 1992b. The derivation of estimated dust exposures for U.S. coal miners working before 1970. Am Ind Hyg Assoc J 53:248–255.

Attfield MD, Seixas NS. 1995. Prevalence of pneumoconiosis and its relationship to dust exposure in a cohort of U.S. bituminous coal miners and ex-miners. Am J Ind Med 27:137–151.

Bohlig H, Bristol LJ, Cartier PH, Felson B, Gilson JC, Grainger TR, Jacobson G, Kiviluoto R, Lainhart WS, McDonald JC, Pendergrass EP, Rossiter CE, Selikoff IJ, Sluis-Cremer GK, Wright GW. 1970. UICC/ Cincinnati classification of the radiographic appearances of pneumoconiosis. Chest 58:57–67.

Gauld SJ, Hurley JF, Miller BG. 1988. Differences between long-term participants and non-responders in a study of coalminers' respiratory health and exposure to dust. Ann Occup Hyg 32:545–551.

Hurley JF, Soutar CA. 1986. Can exposure to coalmine dust cause a severe impairment of lung function? Br J Ind Med 43:150–157.

Jacobson M. 1971. Respirable dust in bituminous coal mines in the U.S. In: Walton WH, editor. Inhaled Particles III. OId Woking. England: Unwin Brothers. pp. 903–917.

Kuempel ED, Stayner LT, Attfield MD, Buncher CR. 1995. Exposure-response analysis of mortality among coal miners in the United States. Am J Ind Med 28:167–184.

Kuempel ED, Stayner LT, Attfield MD, Buncher CR. 1996. Possible misclassification did not obscure detection of exposure-response. Am J Ind Med 30:643–644.

Love RG, Miller BG. 1982. Longitudinal study of lung function in coal miners. Thorax 37:193–197.

Marine WM, Gurr D, Jacobsen M. 1988. Clinically important respiratory effects of dust exposure and smoking in British coal miners. Am Rev Respir Dis 137:106–112.

Merchant JA, Taylor G, Hodous TK. 1986. Coal workers' pneumoconiosis and exposure to other carbonaceous dusts. In: Merchant JA, editor. Occupational respiratory diseases. Washington, DC: USDHHS. pp. 329–400.

Miller BG, Jacobsen M. 1985. Dust exposure, pneumoconiosis, and mortality of coal miners. Br J Ind Med 42:723–733.

Miller A, Thornton JC, Warshaw R, Bernstein J, Selikoff IJ, Teirstein AS. 1986. Mean and instantaneous expiratory flows, FVC and FE V_1: Prediction equations from a probability sample of Michigan, a large industrial state. Bull Eur Physiopathol Respir 22: 589–597.

Morfeld P, Lampert K, Ziegler H, Stegmeier C, Dhom G, Piekarski C. 1997. Overall mortality and cancer mortality of coal miners: Attempts to adjust for healthy worker selection effects. Ann Occup Hyg 41(Suppl. 1):346–351.

Morfeld P, Lampert K, Emmerich M, Reischig HL, Klinkner H-G, Bauer H-D, Stegmeier C, Ziegler H, Dhom G, Piekarski C. 2002. Dust exposure, pneumoconiosis and lung cancer: An epidemiological study in the Saar hard coal mining. Zbl Arbeitsmed 52:382–397.

National Institute for Occupational Safety and Health. 1995. Criteria for a recommended standard: Occupational exposure to coal mine dust. DHHS (NIOSH) Publication No. 95-106. Washington, DC, National Institute for Occupational Safety and Health.

Rae S, Walker DD, Attfield MD. 1971. Chronic bronchitis and dust exposure in British coalminers. In: Walton WH, editor. Inhaled particles III. Old Woking, Surrey. England: Unwin Brothers. pp. 883–896.

Rogan JM, Attfield MD, Jacobsen M, Rae S, Walker DD, Walton WH. 1973. Role of dust in the working environment in development of chronic bronchitis in British coal miners. Br J Ind Med 30:216–217.

Rothman KJ. 1986. Modern epidemiology. Boston, MA: Little, Brown, and Co. 341 p.

SAS. 1991. SAS Technical Report P-217, SAS/STAT Software: The PHREG Procedure, Version 6. Cary, North Carolina: SAS Institute, Inc.

Selikoff IJ. 1992. Use of death certificates in epidemiological studies including occupational hazards: Discordance with clinical and autopsy findings. Am J Ind Med 22:469–480.

Soutar CA, Hurley JF. 1986. Relation between dust exposure and lung function in miners and ex-miners. Br J Ind Med 43:307–320.

Stayner L, Steenland K, Dosemeci M, Hertz-Picciotto I. 2003. Attenuation of exposure-response curves in occupational cohort studies at high exposure levels. Scand J Work Environ Health 4:317–324.

Steenland K, Beaumont J, Spaeth S, Brown D, Okun A, Jurcenko L, Ryan B, Phillips S, Roscoe A, Stayner L, Morris J. 1995. New developments in the life table analysis system of the national institute for occupational safety and health. J Occup Med 32:1091–1098.

Swaen GMH, Meijers JMM, Slangen JJM. 1995. Risk of gastric cancer in pneumoconiotic coal miners and the effect of respiratory impairment. Occup Environ Med 52:606–610.

Wang ML, Petsonk EL, Beeckman LF, Wagner GR. 1999. Clinically important FEV_1 declines among coal miners: An exploration of previously unrecognized determinants. Occup Environ Med 56:837–844.

APPENDIX: UNDERLYING AND CONTRIBUTING CAUSES OF DEATH

The addition of contributing to underlying deaths for specific causes brings about greater numbers of outcome observations and thus permits the analysis, or facilitates the more reliable analysis, of those causes. Overall, 226 deaths had CBE listed as an underlying or contributing cause, while there were 418 deaths associated with CAO, and 791 associated with pneumoconiosis. These numbers can

TABLE A.I. Cumulative Dust Exposure Coefficients for Proportional Hazards Models on Underlying and Contributing Mortality from Selected Causes of Death*

Outcome	Model	Term	Coefficient	*P*
Bronchitis and/or emphysema (deaths = 226)	Linear only	Exposure	0.00294	NS
	Quadratic	Exposure	0.0186	0.017
		$Exposure^2$	−0.0000753	0.039
Chronic airways obstruction (deaths = 418)	Linear only[a]	Exposure	0.00667	<0.0001
Pneumoconiosis (deaths = 791)	Linear only	Exposure	0.00656	<0.0001
	Quadratic	Exposure	0.02573	<0.0001
		$Exposure^2$	−0.0000890	<0.0001

*Models include covariates for age at start of follow-up, smoking status and pack-years, and coal rank region (see text for discussion of statistical significance of covariates for selected causes of death).
[a]The quadratic exposure term for chronic airways obstruction was not statistically significant and therefore that model was omitted from the table.

be compared to the 38, 90, and 268 reported solely as underlying.

Proportional hazards models for some underlying and contributing causes of death included a statistically significant (negative) quadratic term for cumulative exposure (Table A.I), unlike models for underlying causes only (Table X). A comparison of the exposure-response relationships from the 9-year and 23-year follow-up analyses for pneumoconiosis shows similar-estimated coefficients for cumulative exposure (and cumulative exposure squared); these were 0.030 (−0.00012) in the 9-year follow-up analysis [Kuempel et al., 1995] and 0.026 (−0.000089) in this 23-year follow-up analysis (Table A.I). For chronic bronchitis or emphysema as an underlying or contributing cause of death, the coefficients for cumulative dust exposure (both linear and quadratic terms) are about half those observed in the 9-year follow-up study; the number of deaths attributed to these causes increased from 76 [Kuempel et al., 1995] to 226 (Table A.I).

Within this 23-year follow-up study, the findings for underlying and contributing causes for CAO and pneumoconiosis were very similar to those for underlying causes, with a RR of 1.0067 per mg-year/m^3 (CI = 1.0040–1.0094) for CAO, and a RR of 1.0066 per mg-year/m^3 (CI = 1.0046–1.0086) for pneumoconiosis. Among the subset of those who were reported to have CAO but not pneumoconiosis (n = 257), the RR was 1.0044 per mg-year/m^3 (CI = 1.0010–1.0079), demonstrating the presence of exposure-response with cumulative dust exposure in the absence of reported mortality from pneumoconiosis.

For CBE there was evidence of elevated RRs among the five cumulative coal mine dust exposure categories compared to the first exposure category (RRs of 1.4, 2.0, 2.0, 1.7, and 2.1) but little evidence of a trend with increasing exposure. There was a suggestion of curvilinear exposure-response with cumulative dust exposure (linear RR = 1.019, CI = 1.003–1.034; quadratic RR = 0.9999, CI = 0.9999–1.0000) but no linear exposure-response for CBE was detected. This relationship disappeared when miners reported to also have pneumoconiosis were removed. In contrast, analysis of the 147 with both CBE *and* pneumoconiosis showed sharply elevated RRs across the dust exposure groups (RRs = 4.1, 5.1, 5.5, 5.6, 7.9). These compare to RRs of 2.0, 2.2, 2.8, 3.2, and 3.2 seen for pneumoconiosis when analyzed without regard to other diseases. As with underlying causes only, combination of CAO and CBE to form COPD led to exposure-response somewhat attenuated from that for CAO alone. In this case the RR was 1.0052 (CI = 1.0030–1.0074).

In summary, the results of underlying and contributing causes are generally consistent with those seen for underlying causes only. In addition, models of CBE (which had sufficient number of outcome observations to analyze only as an underlying or contributing cause) provided some evidence of a curvilinear relationship with cumulative coal mine dust exposure, but only when miners who also had pneumoconiosis as a listed cause were included. The findings with respect to cumulative dust exposure were similar whether obtained from the SMR analysis or from the Cox models, in that the most striking effect was a difference in mortality between the lowest exposure group and the other groups, although there was some evidence of a trend across the other exposure groups. The proportional hazards modeling revealed a marginally significant *negative* exposure-squared term, which is consistent with findings in other occupational cohorts [Stayner et al., 2003], and may be due to several factors including bias from the healthy worker survivor effect.