RESPIRABLE DUST IN THE MINERAL INDUSTRIES: HEALTH EFFECTS, CHARACTERIZATION AND CONTROL

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Noninvasive Magnetopneumographic Studies of Lung Dust Retention and Clearance in Coal Miners

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Coal mine dust has ferrimagnetic properties. In 2289 samples of respirable coal mine dust, we found a concentration of ferrimagnetic mineral (FM) equivalent to 0.45 percent (σ_g = 1.1) magnetite.

Magnetopneumography (MPG), a noninvasive technique for determining the amount and distribution of ferrimagnetic mineral dust in the lungs, was used to study 53 recently retired underground coal workers. No correlation of lung dust with years underground was found, though we did find an inverse relationship of lung dust burden to smoking history, suggesting reduced alveolar deposition in cigarette smokers.

Twenty-six retired miners were restudied at an interval of one year and 13 measured again at two years. At one year, seven showed no clearance of FM lung dust. The clearance T 1/2 for 19 others was 63 +/- 66 months (range 9 - 134). There was no correlation of T 1/2 with work history, time retired, age, pulmonary function, or degree of X-ray abnormality. Those with cough, phlegm or dyspnea had slowing of clearance of mine dust from deeper lung regions. At two years, seven miners had no detectable clearance, and T 1/2 for six others was 115 +/- 93 months (range 45 - 262 months). These values are similar to animal and autopsy human studies and may suggest a cytotoxic role of coal mine dust in slowing alveolar clearance.

Introduction

Magnetopneumography (MPG) noninvasively measures the relatively small net remanent magnetic field due to the alignment of the individual dipolar magnetic moments of ferrimagnetic particles by a brief DC magnetization.[1] Magnetite (FeO Fe_2O_3) and maghaemite (γ -Fe_2O_3) are thought to be the predominant ferrimagnetic minerals (FM) present in coal mine dust.[2] None of the body's endogenous organic iron compounds has ferrimagnetic properties. Therefore, it is safe to assume that all measured FM in the body originates from exogenous sources, primarily inhalation of environmental dust particles. Total lung dust content can be derived from measurements of ferrimagnetic dust, when the average fraction of magnetic mineral in the respirable dust of a given occupation is known.

The retention of large amounts of mineral dust in the lung may be associated with lung disease, termed pneumoconiosis. Although lung damage can be medically assessed, actual lung dust content could not be noninvasively measured before the advent of MPG. MPG has been used for assessing the retention of occupationally acquired lung dust in welders, coal miners, foundry workers, and others.[3,4] MPG assessment of asbestos accumulation in the lung has met with variable success.[4-6] Additionally, MPG has been used to estimate the clearance half time of welding fume from cross sectional human studies and to directly measure it in a rat model.[7,8]

Our initial MPG studies found 3 of 14 active bituminous underground coal miners and 11 of 21 retired disabled miners to have elevation of FM compared to 20 rural control subjects.[9] We were also able to discern the accumulation of dust present in the central lymphatic structures. A second cross sectional study showed that 17 of 71 underground bituminous miners (60 active and 11 retired) had FM levels in the lungs greater than 22 of 23 control subjects.[4] No correlation with years mining underground, job category or cigarette smoking history was found. Few of the miners had X-ray changes of pneumoconiosis. Also, there is no way of quantitating their past dust exposure.

We now report measurement of the thoracic burden of FM and its clearance in a larger group of retired coal miners. Analysis of the FM contribution to coal mine dust will also be presented.

Methods

Coal Mine Dust

Two thousand, two hundred and eighty nine (2289) coal mine respirable dust filter samples weighing over 0.5 mg were randomly chosen from all dust samples collected by the Mining Safety and Health Administration over a one-month period in Pennsylvania and West Virginia. The dust laden filter was dissected out and mounted on a nonmagnetic medium. Measurement of FM was carried out on these samples and on similar samples with known concentrations of magnetite. Results were expressed as percent equivalent magnetite. Comparison of groups was performed with a two-tailed test of significance.

Retired Underground Coal Miners

Coal miners were screened to eliminate those with significant exposure to welding fume or other ferrimagnetic dusts. A detailed occupational and smoking history as well as an informed consent were obtained from each subject.

The 53 recently retired miners had a 33 +/- 9 years underground work history and had been retired for an average of 6 +/- 4 months. Although 30 had some degree of pneumoconiotic abnormality, only five were greater than category 1. Their smoking history averaged 14 +/- 25-pack years. Spearman's rank correlation and Student's t test were used to assess statistical significance of observation.

Magnetopneumographic Measurements

MPG measurements were made over the posterior chest on a grid of 3 x 3 points using a 7 cm grid interval. The spinous process of the 7th cervical vertebra was used as a fixed anatomic reference for the scan. A localized-field MPG technique previously described was employed.[10,11] The remanent magnetic field was measured using a 4.4 cm diameter second order SQUID gradiometer of 8 cm baseline. The SQUID, in conjunction with an 11.2 cm diameter water-cooled electromagnet generating 135 milliTesla DC at the skin, had a measured sensitivity of 713 picoTesla/mg/liter. This was based on phantom lung and chest wall models. Partial magnetic erasures were employed to ascertain the distribution of ferrimagnetic mineral within the lung and thereby permit distinction between superficial and deeper concentrations. The values for remanent magnetic field of the nine locations were used to derive mean values for total lung and the contributions of outer, middle and deep lung compartments.

Clearance Calculation

For purposes of clearance calculation, day zero was considered to be the day of retirement. The second measurement of total lung FM was performed either 390 or 430 days after the first and the third measurement was performed 820 days after the first. Twenty six of the 53 initial subjects had a second measurement and 13 had a third measurement performed.

Results

Coal Mine Dust

As can be seen from Figure 1, 2289 coal mine respirable dust samples had a mean FM content expressed as equivalent magnetite of 0.45% +/- 0.90% (mean +/- s.d.). Geometric mean of FM content was 0.22 percent with the geometric standard deviation of 1.20. No significant difference was seen in FM content between Pennsylvania and West Virginia samples.

There was a significant difference in FM content when classified according to job category, as could be seen in Table I. Percent equivalent magnetite of dust breathed by underground face workers was 0.29 percent, of underground nonface workers was 0.71 percent, of transportation workers was 2.31 percent, and of surface occupations was 0.83 percent. A similar distribution was seen when analyzed by sample type with percent magnetite of high risk samples 0.24 percent, of intake air 0.61 percent, of face 0.36 percent, of nonface 0.98 percent, and of surface air 0.82 percent. Mechanics, track men and motormen have the highest percent FM in surrounding air, but these are workers likely to be exposed to welding fumes which are highly ferrimagnetic.

Magnetopneumographic Measurements

The mean value of the remanent field ranged from 9 to 279 picoTesla (pT) with a mean of 48 +/- 53 pT. This is much

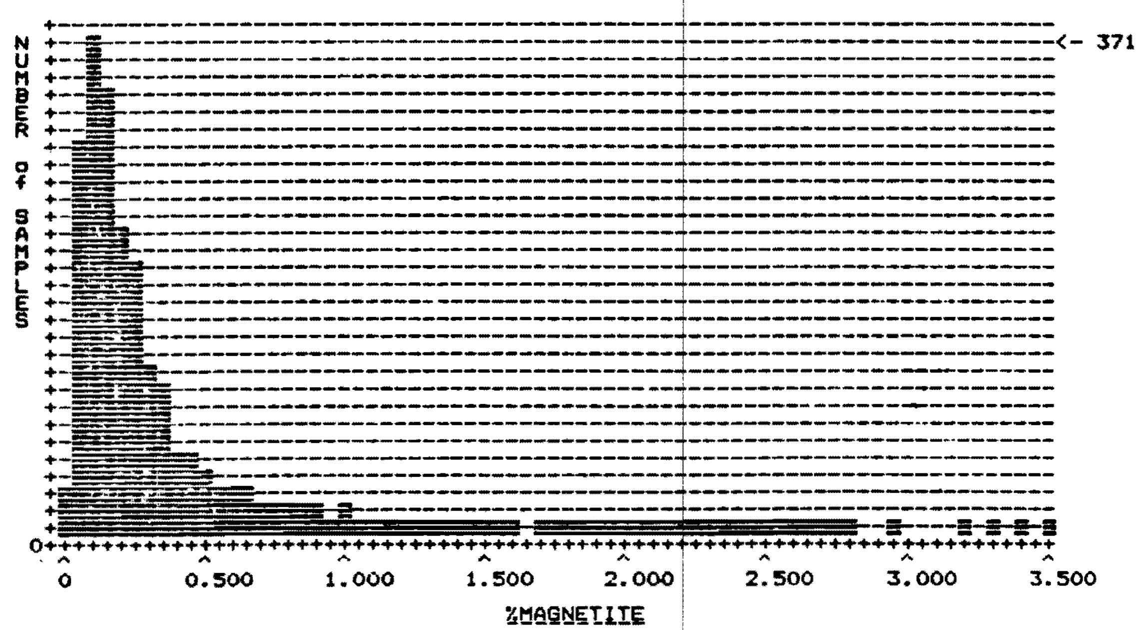

FIGURE 1. Frequency distribution of percent equivalent magnetite in 2289 respirable coal mine dust samples from underground mine in Pennsylvania and West Virginia. Mean, 0.455; Standard deviation, 0.899; Standard mean error, 197.736; Geometric mean, 0.215; and Geometric deviation, 1.199.

higher than the 20 +/- 19 pT obtained from similar measurements of 28 urban dwellers studied by us.

No correlation was found with years underground mining history, despite an attempt to correct MPG measurements for clearance during time retired using mean clearance half time for the group studied serially. A negative correlation was found with pack-years (the product of average packs per day smoked multiplied by years smoking history) of $p < 0.01$. There was no correlation with cigarettes smoked per day or with total years of cigarette smoking. There was no correlation of remanent field measurements with symptoms of cough, sputum production, wheezing or shortness of breath. However, there was a significant negative correlation ($p < 0.05$) with symptoms of sinus disease.

There was a positive correlation between the forced vital capacity expressed as a percent of predicted and the remanent field measurements reaching a significance of $p < 0.05$. No correlation was seen with the forced expiratory volume in one second expressed as a percentage of the forced vital capacity or with the maximal voluntary ventilation. There was no correlation of the remanent field measurements with pneumoconiotic category of the chest X-ray (Table II).

Clearance Calculations

Of the 26 retired miners restudied at an interval of one year, seven showed no clearance of lung dust. The clearance T 1/2 for 19 others was 63 +/- 66 months (range 9 to 134). There was no correlation of T 1/2 with work history, time retired, age, pulmonary function or degree of X-ray abnormality. As can be seen in Table III, the clearance tended to be slower from both superficial and deep lung regions than for the mid lung regions. The T 1/2 from the deep lung was significantly correlated with degree of wheezing.

At two years, 13 miners were measured again and seven miners showed no detectable clearance. The T 1/2 for the six others was 115 +/- 93 months (range 45 to 262).

Discussion

Coal Mine Dust

Since MPG measures the FM fraction of lung dust, extrapolation of MPG measurements to quantitation of total lung dust requires accurate knowledge of lung dust composition. From Table I, it is evident that the FM fraction of respirable coal mine dust is fairly constant within job categories. In a monitoring program, sampling of the dust in the working environment would ideally proceed in tandem with MPG measurements of the worker.

The higher ferrimagnetic activity of dust from nonface sites and the further increase at transportation sites probably reflects contamination with rock strata and welding fume. Since welding fume may contain up to 30 percent FM, its presence in the lung will overshadow the contribution to FM of coal mine dust.[7] Additionally, workers may be exposed to pure magnetite at tipple sites using magnetite for gradient separation of coal.

A final consideration is the *in vivo* stability of the FM fraction of coal mine dust. Though iron oxides are relatively insoluble,[12] there is inferential data suggesting its slow solubilization.[13] Unpublished data from our laboratory regarding measurements on dust extracted from autopsied coal workers' lungs suggest that the contribution of FM may decline with time.

Magnetopneumographic Measurements of Lung FM

Approximately 25 percent of the retired underground coal miners had FM levels outside the 95 percent confidence

TABLE I

Ferrimagnetic Mineral Content by Job Classification

		% Magnetite	S.D	Geom. Mean	Geom. S.D.
All Samples	(2289)	0.46	0.90	0.22	1.22
West VA	(1673)	0.44	0.91	0.20	1.20
Pennsylvania	(616)	0.49	0.87	0.25	1.10
Face Workers	(1707)	0.29	0.39	0.18	0.91
Non-Face	(329)	0.71	1.15	0.33	1.32
Transport	(73)	2.31	2.46	0.61	2.85
Surface	(139)	0.83	1.52	0.26	1.84
Supervisory	(40)	0.80	1.29	0.43	1.05
High Risk	(978)	0.24	0.28	0.16	0.89
Intake Air	(16)	0.61	0.98	0.28	1.26
Face	(711)	0.36	0.48	0.23	0.88
Non-Face	(424)	0.98	1.59	0.37	1.64
Surface	(141)	0.82	1.51	0.26	1.83

It can be seen that the magnetite content of respirable coal mine dust is lowest at the face and highest in transportation, with non-face and surface locations having intermediate magnetite levels. Because of the non-gaussian distribution of the data, the geometric S.D. is the best measure of the constancy of magnetite within dust samples from a given job category within the mine.

TABLE II

Retiring Bituminous Coal Miners Study

Code Name	Remanent Field	Years Under	Time Retired	Chest X-Ray**	Smoking Pack-Years
Delbow	279 pT	16	6 Mths	1	0
Xirhen	235	33	9 Mths	2	0
Rayjoh	169	24	3 Mths	2	2
Ewagle	143	39	11 Mths	3	0
Waltyoul	108	36	6 Mths	2	0
Josbaluh	102	29	6 Mths	0	0
Wilshare	88	35	13 Mths	8	3
Samyoul	82	42	6 Mths	0	0
Gerray	74	42	3 Mths	3	5
Fierorga	64	0	5 Mths	1	0
Orlafava	62	40	1 Mth	5	15
Morgeo	55		4 Mths	3	2
Juljesso	54	42	3 Mths	1	1
Jogorohy	52	33	21 Mths	1	2
Mazjoh	51	26	8 Mths	2	0
Robkrich	48	44	6 Mths	3	23
Mikmcke	48	42	9 Mths		0
Paulpetr	48	10	0 Mths	1	1
Henrknig	40	47	3 Mths	3	0
Noacha	40	33	0 Mths	4	6
Jamdevin	39	29	1 Mth	8	0
Koplou	39	41	7 Mths	1	17
Rudmilov	38	44	6 Mths	1	10
Stebasey	37	38	1 Mth	2	10
Frangord	36	35	9 Mths	2	46
Bormik	30	49	2 Mths	6	0
Donashou	29	28	8 Mths	3	0
Vancross	28	13	12 Mths	0	24
Charstre	27	33	6 Mths		11
Simmic	26	42		4	0
Charburk	26	21	3 Mths	1	0
Framayan	25	11	17 Mths		0
Blyken	24	21	0 Mths	2	105
Robcarls	22	15	6 Mths	3	132
Shifor	22	37	3 Mths	5	23
Hajmik	22	32	1 Mth	3	28
Benmik	22	38	7 Mths	2	8
Mckjoh	21	30	7 Mths	0	4
Stevepov	21	41	1 Mth	3	19
Mongeo	21	40	5 Mths	0	28
Donatch	20	40	5 Mths	3	45
Strsta	19	25	7 Mths	2	0
Sharus	17	26	7 Mths	0	13
Richmoro	17	42	0 Mths	2	12
Meageo	16	5	7 Mths	0	9
Giopet	16	32	8 Mths	0	3
Sheste	15	34	7 Mths	2	0
Robebrod	15	31	4 Mths	3	0
Elliharr	12	33	6 Mths	1	10
Chersene	11	36	6 Mths	0	49
Rotjac	10	38	7 Mths	2	11
Andrmcke	9	37	5 Mths	0	9
Johnshab	9	35	2 Mths		26

* Urban control subjects were 20 +/- 19 pT; n = 28.

** Based on a scale of ILO category 1/1 = 3.

interval for urban controls. This is similar to two previously reported groups of workers that we have studied.[4,9] This may be a falsely low prevalence of elevated thoracic FM, as rural dwellers would probably have less FM in their lungs than our urban controls.

The failure of lung FM to be predicted by years underground mining is not surprising. Not only do coal miners have a wide range of past dust exposure levels, but there are individual differences in deposition efficiency and dust clearance kinetics.[11,14,15]

The lack of correlation of lung FM with ILO category of pneumoconiosis is unexpected in view of reported autopsy studies.[16] However, only five of the miners in our study had greater than category 1 abnormality, so the spectrum of coal workers' pneumoconiosis is not adequately represented.

The marked inverse relationship of lung FM to smoking history is most interesting. Decreased alveolar deposition of dust in bronchitic subjects is well known and is thought to be due to airway narrowing and consequent increased deposition in the bronchial tree proximal to the alveoli.[17] This would then represent a sign of airway damage from cigarette smoking, though indices of airway obstruction (FEV_1/FVC% and maximal voluntary ventilation) were not related to lung FM. There was also no relationship seen of lung FM to subjective symptoms of cough, sputum production or wheezing, though there was correlation with the presence of symptoms of paranasal sinus disease.

Finally, pulmonary function tests were not predictive of FM in the lung, except for the correlation of FM with forced vital capacity as a percent of predicted. The reason for this is unclear, though it may relate to reduction in deposition efficiency of dust in damaged lungs.

Clearance of Lung FM

Lung FM clearance T 1/2 over the first year of observation was 63 +/- 66 months in 19 miners, with seven others having no discernible clearance. This is longer than values from human studies after a single exposure to dust, but we are looking at the final steps of alveolar clearance for dust acquired during the years before retirement.[11,18,19] Our data are consistent with calculations based on autopsy studies,[20,21] and animal data on coal dust clearance.[22] Morrow raised the question of coal mine dust being cytotoxic and impairing its own clearance, but our data in a rat model do not bear this out.[23]

The lung FM clearance T 1/2 based on two years of observation was 115 +/- 93 months in six miners, with seven others having no discernible clearance. This apparent slowing of clearance fits the hypothesized very long phases of alveolar clearance.[15] The lack of correlation of clearance T 1/2 with work history and X-ray abnormality is not unexpected, as there is little physiologic derangement in simple coal workers' pneumoconiosis.[24] Its lack of correlation with cigarette smoking history, respiratory symptoms and pulmonary function tests does not fit with the reported effect of airway obstruction causing slowing alveolar clearance.[4,18,19,25]

Compartmental Analysis of FM Clearance

As can be seen in Table III, clearance from superficial and deep lung regions was slower than from the middle of the lung. This is consistent with the known pattern of dust clearance to subpleural and central lymphatic tissue and was seen in our laboratory studies of magnetite clearance.[11]

Conclusions

1. FM is consistently present in coal mine dust and its concentration is predictable within job categroies.
2. MPG is capable of noninvasively measuring accumulation of lung FM in coal miners, many of whom have higher levels than control subjects.
3. MPG is capable of measuring the clearance of lung FM from coal workers.
4. MPG is therefore suitable for the noninvasive monitoring of coal mine dust accumulation of the lung and its clearance.

TABLE III

Compartmental Clearance at 1 Year

Superficial Lung	43 +/- 43 months (n = 12)
Middle Lung	23 +/- 9 months (n = 8)
Deep Lung	44 +/- 39 months (n = 13)

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