11.9

Coal Workers' Pneumoconiosis and Other Coal-Related Lung Disease*

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HISTORY

Coal Production

The growth in coal mining is virtually coincident with the Industrial Revolution. Although shallow mining of coal seam outcrops is reported to have occurred since the 9th century, the 18th century brought increased demand for coal as well as the technology to pursue the mining of seams well below the earth's surface. By the early 1800s coal mining had become an important industry in the United States. Employment in coal mining peaked about 100 years later in 1923, when over 800,000 coal miners were working. From that point, although production and consumption of coal continued to increase, mechanization progressively reduced the size of the workforce. In 1990, a total of 126,642 coal miners were at work in the United States, of whom almost half were employed on surface operations.

The principal coal deposits in the United States are shown in Figure 37. The majority of coal production is still based in the eastern Appalachian coal fields. However, western states account for an increasing proportion of coal output.

Health Effects

In Europe, recognition of the adverse health consequences of coal mining followed the marked increase in the population of miners. Ramazzini cites Wedel, who in 1672 wrote of miner's asthma, but was probably referring to hard rock miners. According to Kerr, the term was first applied to coal miners in 1822. Laennec described the black pigment in the lungs of coal miners as melanosis in 1806 and, by 1819,

Coal Deposits in the United States

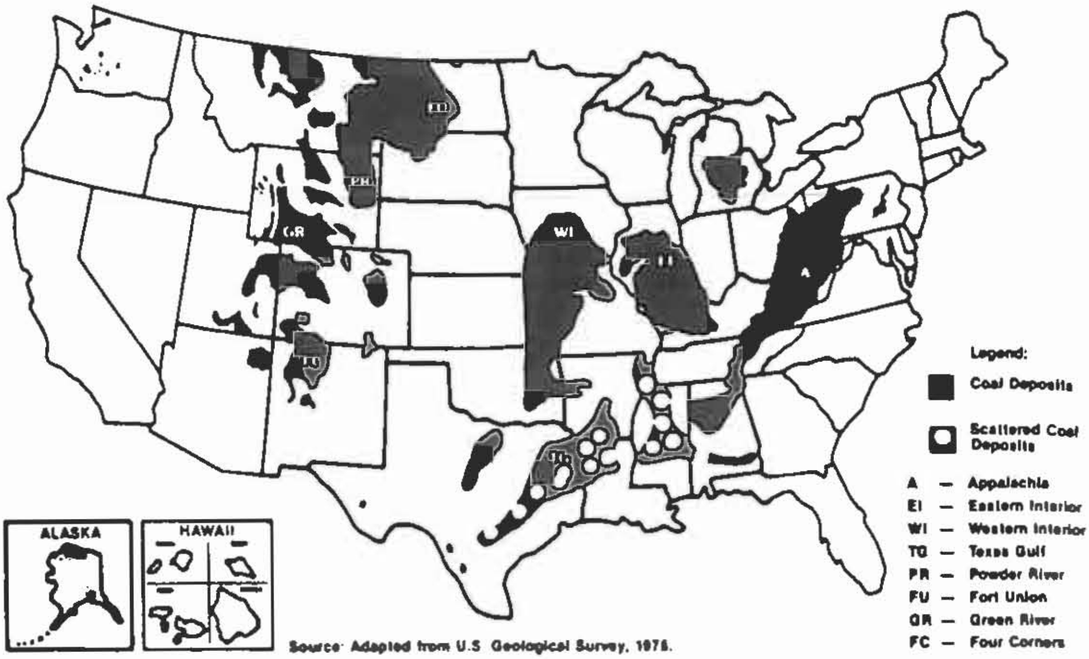

FIGURE 37 Map of United States coal deposits.

clearly differentiated the condition from malignant melanoma. Several years later, the term miners' black lung was used to describe the disease in Scotland. In 1919, silicosis became a certifiable disease in the United Kingdom, and British miners with coal workers' pneumoconiosis (CWP) became eligible for certain benefits. Based on studies of British coal miners, CWP was differentiated from silicosis in the early 1940s.

Unfortunately, this awareness of CWP failed to cross the Atlantic. A mine explosion in Farmington, West Virginia, on November 20, 1968, was widely reported on television and graphically illustrated to the nation the plight of coal miners in the United States. This tragedy added momentum to the movement to improve coal mine health and safety conditions. Black Lung Associations were organized in the coal fields. A 3-week-long strike in the West Virginia coal mines, one of the largest and longest strikes ever called on the single issue of occupational health, ended when the state legislature passed a bill in 1969 making CWP a compensable disease. By the end of 1969, the Federal Coal Mine Health and Safety Act (FCMHSA) had been passed into law. Dust control and safe practices in coal mines were mandated and backed up by fines or closures and the right of the miners' representatives to participate in inspections.

MINING JOBS

An understanding of mining techniques is useful in the evaluation of respiratory diseases of miners because different activities involve exposures to different degrees of risk. Activities in coal mines generally are classified into face, nonface, and surface work. By virtue of multiple activities, some workers spend portions of their workday in two or more of these mine locations.

Face Workers

Miners working at the edge of the unmined coal seam, or coal face, are engaged in the actual removal of coal from the working section of the mine. Face miners generally are exposed to the highest concentrations of respirable airborne dusts, particularly carbon, but may also be exposed to silica dust when the cutting bits strike silica-bearing rock immediately adjacent to or within the coal seams. There are three primary methods of mining coal underground that have been employed in the United States: (1) continuous mining, (2) longwall mining, and (3) conventional mining.

Continuous Mining

Room and pillar mining with continuous mining machines is the most commonly used coal mining technique in the United States today. *Continuous miner operators* and their helpers direct the rotating bits on the machine into the coal seam to rip out the coal. The loosened coal is pushed to the back of the machine, where a *loading machine operator* and helpers use a large scoop to load the coal into a rubber-tired buggy or directly onto a conveyor line.

Pillars of unmined coal are left at the sides of the advancing tunnel to help support the roof. As the continuous mining machine advances, *roof bolters* and their helpers install steel plates to strengthen the unsupported roof of the tunnel. Holes are drilled into the hard rock above the coal seam, and long steel bolts are inserted along with glues to anchor these plates. Silica exposure is common in roof bolting, and there also may be exposure to resins and plasticizers in glues. *Timber men* install wooden pillars to stabilize further the roof of the tunnel. *Brattice men* install curtains or tubing to direct the flow of ventilation at the working face.

Shuttle car ('buggy') operators transport newly mined coal in rubber-tired vehicles. *Scoop car operators* run battery operated vehicles throughout the mine, transporting coal or mining supplies. *Mobile bridge operators* operate portable conveyor lines to move coal away from the face. *Section maintenance* workers repair and maintain the underground heavy equipment at the face in all mining methods.

Longwall Mining

Longwall mining is the most cost-efficient method of mining and results in the highest rate of production. Production using this technique is increasing as an alternative to room and pillar mining. The longwall machine spans several hundred to a thousand feet along the active coal face. A rotating drum (shear) or a plow moves back and forth along the face, breaking coal loose from the seam and allowing it to fall onto a conveyor line. A series of hydraulic jacks support the roof along the face, and are advanced as the coal is removed. Behind the longwall device, the unsupported roof is simply allowed to fall. This minimizes the loss of the coal in pillars and eliminates the need for roof support activities, as in room and pillar mining. To develop the mining section in advance of the longwall machine, one or two continuous miner crews are generally operated. However, to run the longwall section itself, a smaller crew of *longwall operators, mechanics, headgate operators,* and *jack setters* are required.

Respirable dust exposures in longwall mining have been difficult to control. In recent years, nearly 40% of reported dust measurements on longwall sections have been over the 2 mg/m^3 respirable dust standard, compared with 10% to 15% in continuous mining sections.

Conventional Mining

Little coal is mined in the United States today using the conventional mining technique, although many current miners have used this method in prior jobs. In this system, *cutting machine operators* and helpers make a deep cut in the coal face at the bottom of the seam. *Shot firers* drill deep holes in the area of the cut and place explosive charges to blast the coal free. *Hand loaders,* or loading machine operators, shovel the coal into vehicles, which then transport it away from the face. In addition to dusts, important exposure to nitrogen oxides from the explosives may occur by using this technique.

Nonface Workers

Several underground mining activities relate to reducing dust or methane gas hazards. *Masons* construct plastic, cloth, or block barriers to keep the flow of air directed across the working face. *Rock dusters* scatter hygroscopic powdered limestone along the cut faces of the mine tunnels to moisten and trap loose dusts and reduce the danger of explosion. Although this job may involve considerable visible dust and irritation, the lung toxicity of the limestone is considered to be lower than the other mine dusts. *Electricians, mechanics,* and *welders* may work on equipment throughout the mine.

Workers on nonface transportation have several types of exposure. The coal is loaded at the working face (see earlier) and is transported to the main haulageways, where it is dumped into train cars or a conveyor belt and taken out of the mine. *Motormen* operate the train locomotives. To improve traction on the steel rails, motormen drop sand or other abrasives on the rails. The materials are fragmented into respirable particles and resuspended by passing trains, creating a mixed-dust or silica exposure hazard. *Belt men* patrol the conveyor belts, ensuring the continued movement of coal, and shovelling up spilled coal. In some mines, diesel exhaust exposure may be present from diesel-powered vehicles.

Surface Workers

With a few important exceptions, surface workers generally are exposed to lower levels of respirable dust. *Surface maintenance* workers frequently perform welding and cutting on equipment, and they may be exposed to welding fumes as well as asbestos shields and gloves. *Tipple operators* and *preparation plant workers* are exposed to dusts during the cleaning, processing, and loading of the coal. *Lampmen* and others at the mine portal often have little dust exposure.

Surface coal mine equipment operatives, particularly *high wall drillers* and their helpers, and to a lesser extent *bulldozer operators,* may experience important silica exposures while drilling and removing overburden.

In summary, modern mining techniques bear little resemblance to the pick-and-shovel techniques of the early 1900s. Highly mechanized equipment allows mining more coal with far fewer miners. Unfortunately, the high production intrinsic to these operations may lead to dust levels that are difficult to control, and strict attention to industrial hygiene is necessary to avoid unhealthy conditions.

DEFINITIONS

Overview

When dealing with respiratory diseases of coal miners, it is important to be familiar with disease definitions. Differing terms and different definitions have been used for clinical, epidemiologic, pathologic, and legal or legislative purposes.

In the clinical arena, use of the term pneumoconiosis tends to be restricted to the radiologic or pathologic appearances relating to the accumulation of dust deposits in the lungs and the associated tissue reactions. This usage generally does not include other lung abnormalities, such as those associated with bronchitis or emphysema. Although distinguishing between the differing disease processes facilitates the diagnosis, treatment, and study of disease, it has tended to lead to fragmented understanding and assessment of the totality of lung disease associated with exposure to coal mine dust. This distinction also is not entirely accurate, because focal emphysema, as discussed later, is considered an integral part of the pathologic lesion of CWP.

Generic definitions of pneumoconiosis that include all dust-related effects on the lung also are widely used. Some of these definitions are employed more often in the nonclinical sphere, particularly with regard to legal and legislative activities, and include dust-related effects that may not be radiographically apparent, such as dust-induced chronic airflow obstruction. The lay term black lung is a generic term used by miners for lung disorders associated with their work.

Because the radiographic pattern of CWP may be distinctive, pneumoconiosis in coal miners often has been defined based on a radiographic change. For example, in research publications, confirmation of CWP may require that several readers concur in the finding of a certain shape and profusion on a chest film (for example 1/0, rounded opacities using the ILO system of classification of radiographs for pneumoconiosis). (For more detail, see the introduction to this chapter.) Although this approach increases precision, it may reduce sensitivity for several reasons: (1) it is recognized that readings of 0/1 rounded opacities also correlate with mine dust exposures; (2) the profusion of *irregular* as well as rounded opacities seen on the chest radiograph also increases with increasing mining exposures, (3) the routine chest radiograph may be normal in the presence of clinically important and pathologically identifiable interstitial lung disease, and (4) several dust-related diseases may not be apparent radiographically. Chronic bronchitis and emphysema may arise from coal-mine exposures. If dust deposition is identifiable in the lung parenchyma, these conditions also would appear to meet the definition of pneumoconiosis of the Fourth International Pneumoconiosis Conference and the Federal Coal Mine Health and Safety Act of 1969.

In summary, for clinical purposes, coal miners with typical radiographic or pathologic findings of pneumoconiosis are properly identified as having CWP. For legal and compensation purposes, a broader definition of pneumoconiosis is used, which includes dust-related effects that may not be radiographically apparent.

Specific Medical Terms Relating to Respiratory Diseases in Coal Miners

Simple CWP—This lesion usually is defined clinically in miners showing multiple radiographic shadows up to 10 mm in diameter. These dust-related shadows usually are rounded, although irregular shadows also may be noted in combination with rounded opacities or occasionally alone. The pathologic correlates of the chest radiograph are discussed in the text.

Complicated CWP—This lesion also is defined clinically based on a chest radiograph showing a dust lesion or lesions over 10 mm in diameter. Complicated CWP is found most often on a background of smaller rounded opacities, with the risk increasing with increasing profusion. Progressive massive fibrosis (PMF) is a term sometimes used interchangeably with complicated CWP, although not all of the larger rounded shadows seen in coal miners progress with time. In pathologic specimens, PMF lesions with a diameter of greater than 20 mm are more closely correlated with chest radiographic findings.

Silicosis—This is the chronic interstitial lung disorder caused by the inhalation of crystalline silica. Radiographically, silicosis is also characterized by small rounded opacities, which may coalesce to form shadows larger than 10 mm (complicated silicosis or PMF). Although silicosis is pathologically distinct from CWP, the two disorders often cannot be distinguished clinically. The lungs of coal miners frequently show lesions consistent with both disorders.

Bronchitis—Sometimes referred to as industrial bronchitis, this dust-related disorder is characterized by excessive cough and sputum production. Sputum production is deemed excessive when it occurs on most days for at least three months a year for two or more years. The pathology of this disorder has been less well studied.

LUNG PATHOLOGY

Pathologic Classification of Dust-Induced Changes

PIGMENTED LESIONS:
- Coal macule, nodule, PMF
- Silicotic nodule

EMPHYSEMA

BRONCHITIS

RHEUMATOID PNEUMOCONIOSIS

Pigmented Lesions

The most characteristic and striking pathologic changes in the respiratory system of coal miners are associated with the deposition of dark pigment, primarily located in lung macrophages. Localized *dust macules* are considered pathognomonic of CWP. They are located at the level of the respiratory bronchioles and are associated with deposition of reticulin and destruction of adjacent alveolar walls (focal emphysema), but they produce only minimal collagenous scarring (Fig. 38). With increasing dust deposition, the pigmented macule progressively enlarges, becoming solid and palpable. Adjoining macules may coalesce. At this stage, the lesions show clear collagen deposition and are labeled *nodular lesions.* Destructive vascular lesions are commonly associated with nodules. With further progression of the disorder, coalescence of nodules can result. The massive lesions of complicated CWP (PMF) also may appear. These lesions are greater than 1 to 2 cm in diameter and usually are seen in upper lobes or superior segments of lower lobes of lungs

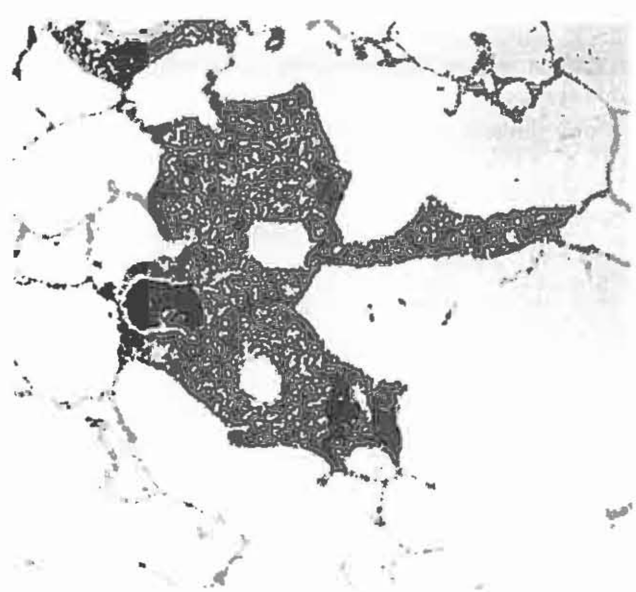

FIGURE 38 Coal dust macule.

with extensive pigment deposition (Fig. 39). PMF lesions may be unilateral, bilateral, and multiple and have shown cavities containing black liquid. The lungs of miners with complicated CWP usually also show pathologic changes of bronchitis and extensive emphysema. Cardiovascular changes consistent with cor pulmonale also are seen. Right ventricular hypertrophy has been correlated with the thickening of vessel walls seen in association with increasing severity of CWP, as well as the emphysematous changes in miners' lungs.

Factors facilitating progression to complicated CWP are not entirely understood. Excessive lung dust deposition clearly is the basis for the condition. The greatest risk factor for subsequent development of complicated CWP is the miner's radiographic category of simple CWP. In the past, mycobacterial infection was frequently associated with complicated CWP and was considered a precursor to development of PMF. It is now accepted that the lesions often develop in the absence of infection. The role of excessive silica exposure is still debated, although PMF clearly can develop in workers with scant silica exposure, and recent studies indicate a reduced prevalence of PMF in coal miners with silica exposure. Miners, particularly those with simple or complicated CWP have an increased frequency of autoantibodies and other serologic abnormalities. The significance of these findings is not known.

Although it is rarely reported in the United States, a small group of dust-exposed miners with rheumatoid arthritis may develop a syndrome known as rheumatoid pneumoconiosis, or Caplan's syndrome. Features include multiple large (up to 5 cm) lung nodules developing rapidly, often over several months, with little or no background profusion of simple pneumoconiosis. The pulmonary lesions may cavitate and occasionally precede the onset of the joint disorder. Pathologically, the lesions are distinct from the typical lesion of PMF and are similar to rheumatoid nodules.

Typical lesions of silicosis are described elsewhere (see Chapter 11.8). They appear to be fairly common in the lungs of coal miners. Overall, classic silicotic nodules have been reported at autopsy in 12.5% of miners. Higher prevalences are observed in certain jobs, such as motormen (25%) and in miners with complicated CWP (over 50%).

Even in nonminers, the extent of pigment in the lungs generally increases with age. It also is greater in smokers than in nonsmokers. However, without occupational exposure, it is very rare that the deposition of pigment will be sufficient to form macular lesions.

Emphysema

Localized emphysema is considered an integral component of the dust macule, the pathognomonic lesion of CWP. Cigarette smoking also may result in emphysema of the centrilobular type, which differs from the emphysema due to coal dust only in the extent of lung involvement and in nonminers, the absence of associated dust pigment. Generalized emphysema also can be seen in the lungs of both smoking and nonsmoking coal miners, and after taking tobacco use into account, the extent of emphysema correlates with the amount of mine dust exposure as well as lung dust deposition. Opinions differ among pathologists as to whether or not the emphysema associated with the dust macule is different in any way from that related to tobacco use. However, the severity of airflow obstruction measured during life correlates significantly with the extent of pathologic emphysema in the coal miners' lungs at autopsy, suggesting an important functional effect.

Bronchitis

The prevalence of chronic cough with sputum production is elevated in miners, increasing with mine dust exposure. It is generally accepted that coal mine dust deposition in the airways over prolonged periods of time leads to mucous gland enlargement and proliferation of goblet cells. However, few investigations have been performed regarding the histology of the airways and mucous glands in coal miners. The lungs of miners with complicated CWP frequently show the changes of chronic bronchitis. Some autopsy studies of miners also have shown a significant correlation between prior coal mine dust exposure and the proportion of mucous glands in the bronchial walls (the Reid index). This is considered evidence that dust exposure contributes to the pathologic

FIGURE 39 Gross pathology of complicated coal workers' pneumoconiosis.

changes as well as the clinical symptoms of chronic bronchitis. No significant relationship was found between airway mucous gland changes and the severity of pneumoconiosis in the lungs, indicating that there may be different mechanisms for these responses.

Mycobacterial Infection

Tuberculosis and nontuberculous mycobacterial infections are seen in coal miners. The risk of these infections generally is considered to be somewhat increased, particularly in miners with PMF. Miners also develop lesions of silicosis, which represents a greater risk factor than CWP alone for these infections. As in the general population, patients' responses to appropriate chemotherapy usually are satisfactory for tuberculous infections and unsatisfactory for most atypical mycobacterial disease. Tuberculosis was at one time considered an important factor in the development of massive lesions in the lungs of coal miners. This concept has been convincingly disproved.

Several pathologic lesions have been identified in the lungs and airways of coal miners. Some are rarely seen in the absence of extensive inhalation of coal mine dusts and, therefore, are accepted as generally related to occupational exposure. Some lesions have been correlated with the appearance of characteristic changes of CWP on the chest radiograph. Other lesions, although similar to those found in the general population, are seen with greater frequency in workers exposed to coal mine dusts. In the lungs of underground coal miners, macules, massive lesions (as well as the emphysema associated with these lesions), and silicotic nodules are accepted as almost uniformly related to mine dust exposures. In contrast, overall emphysema scores, carbon pigmentation, and possibly Reid indices are increased in miners' lungs in relation to their mine exposures, but other inhaled agents may also contribute, depending on the relative exposures to mine dusts and other materials such as tobacco smoke.

RADIOLOGY

Radiographic Changes in Coal Miners

Several patterns of abnormality on routine posteroanterior chest radiographs have been related to coal mine dust exposure. Most commonly, fairly discrete small nodular radiographic shadows are seen in the lung fields. These densities usually are rounded in shape and are seen in greater numbers in the upper and middle lung zones rather than the lower lung zones. However, prominent lower zone involvement occasionally is seen. Typically, the largest diameter of the small nodules is 3 mm or less but may be up to 10 mm. The condition is categorized as simple CWP. With increasing lung dust deposition, the number of opacities observed in a lung zone (profusion) increases. The normal vascular shadows of the lung become obscured. Further progression may be indicated by a coalescence of the small opacities into a combined density, which may be homogeneous. By convention, if a dust-related radiographic shadow is larger than 10 mm, it is categorized as complicated CWP, or PMF. Complicated shadows frequently are bilateral, occurring in the upper and mid-lung zones. As they enlarge, they may migrate toward the hilum, forming a sharp lateral margin delineated by a zone of emphysematous lung. Often, the lesions are parallel to the chest wall and have a greater diameter on the posteroanterior film than on the lateral view. If ischemic necrosis of the lesion occurs, a central cavitation or lucency may be noted.

Small irregularly shaped radiographic shadows also are observed in the lungs of miners. The finding of irregular densities, in contrast to small, rounded densities, frequently has been associated with a reduction in gas transfer, ventilatory lung function, or both. The tissue pathology associated with these radiographic shadows is unclear. These shadows have been correlated with increasing dust exposure, increasing age, and cigarette smoking, and are thought to have multiple causes, including both pathologic emphysema and dust-induced fibrosis.

Under the ILO classification scheme, the small, rounded type of radiographic changes seen early in CWP usually are classified as p or q type opacities. The larger r type opacities are more commonly associated with silicosis. Less frequently, the irregular opacities (ILO type s, t, or u) also are noted. The typical radiographic appearance of simple CWP is shown in Figure 40. The detail shows the opacities to be less than 3 mm in diameter, and the profusion was interpreted as category 1/0.

Course and Progression

Much of the information on the course and progression of radiographic changes in coal miners has been derived from long-term epidemiologic studies of coal miners in Britain. These studies were greatly facilitated by the concurrent collection of dust exposure data. Overall, these studies have shown that the overwhelming determinant of simple pneumoconiosis is the extent of exposure to coal mine dust per se. In addition, different coals are categorized by their rank, a characteristic that appears to have some influence on development of disease. Rank is a factor that is related to the hardness and degree of metamorphosis of the coal due to heat and pressure. High-rank coals, such as anthracite, have been associated with a greater risk of CWP than lower rank and softer coals, such as bituminous coal or lignite. No other environmental factor has been shown to have a major effect. Silica does not appear to play a primary role in development of radiographic changes in underground coal miners, unless the worker has been exposed to high concentrations. Tobacco use appears to have little effect on the development of the radiographic findings of CWP.

The main recognized risk factor for development of PMF is the category of simple CWP. Hence, prevention of simple CWP must remain a priority. Recently, it has been shown that there appears to be a dose-response relationship between PMF and dust exposure in miners without radiographic evidence of simple CWP. Other factors pertinent to the development of PMF are coal rank, age of the miner, and residence time of dust in the lungs. Even though clear and consistent dose-response trends have emerged from the many studies undertaken in Britain and elsewhere, much unexplained variability remains for both simple and complicated CWP. Large variations in prevalence of disease between mines are seen that cannot be explained by recourse to available information on dust levels and composition. This finding

FIGURE 40 *A* and *B*, Chest radiographic patterns of simple coal workers' pneumoconiosis with detail (ILO 1/1).

argues for an effective surveillance program of miners in order to detect the mines where excessive disease is occurring and to advise mine operators accordingly.

The current federal dust standard in the United States is 2 mg/m^3, but the standard may be further reduced when silica levels are high. This limit was derived from early British studies that indicated that progression to category 2 or greater simple CWP would be prevented at this dust level. By this means, it was expected that further progression to PMF would be eliminated. As an additional health measure, an x-ray screening program was set up to identify miners with signs of CWP and to offer them the right to work in a reduced dust environment and have their work environment monitored more frequently. Lung functional changes due to coal mine dusts, in the absence of radiographic changes, were not considered in promulgation of the United States standard.

Unfortunately, more recent work from Britain and elsewhere suggests that the current United States disease prevention strategy may be flawed. First, the later dose-response models predict somewhat higher levels of disease than did the early studies for the same dust exposure. In particular, 2 mg/m^3 is no longer associated with a zero incidence of category 2 or greater (Fig. 41). Second, as noted earlier, it has been shown that PMF can develop when prior radiographs show no identifiable changes of simple CWP and that this development is dose related. Moreover, results from Britain have shown a substantial amount of PMF developing on a category 1 background. Therefore, although there is no doubt that the current United States strategy should lead to a greater reduction in disease levels compared with those in the past, it may be less protective than originally intended. A recent survey of retired miners in Northern France also demonstrated the onset of simple or complicated forms of CWP in 24% of miners who had normal radiographs at retirement. These reports have challenged the efficacy of radiographic surveillance in secondary prevention of dust diseases in miners and highlight the importance of dust controls in eliminating the development of complicated CWP.

Additionally, radiographic surveillance programs do not identify miners with dust-related reductions in ventilatory lung function that are not associated with radiographic changes of pneumoconiosis, as discussed later.

Contemporary Trends in Coal Workers' Pneumoconiosis

Several radiographic surveys of selected mines, performed as part of the United States National Coal Study, provide information regarding the prevalence of radiographic CWP in the United States. The prevalence of the more advanced simple CWP (category 2 or greater) in miners with over 30 years tenure declined from about 11% in the first round of radiologic studies in 1971, to 8% in 1980, and to about 2% in 1988 (Fig. 42). Some of the observed decline was found to be related to differences in the x-ray readers as well as the use of a new version of the ILO chest radiograph classification system. When miners were grouped by mining tenure and the proportion of miners with radiographic evidence of complicated CWP was analyzed, a clear decline was seen between the initial and final round of surveys. However, trends over the last decade were not as apparent.

In addition to the National Coal Study, an ongoing National Coal Workers' X-ray Surveillance Program is administered by NIOSH. Miners may participate in this program and receive chest radiographic examinations during the first 6 months and after 3 years of employment, and at approximately 3- to 5-year intervals thereafter. The diagnoses of

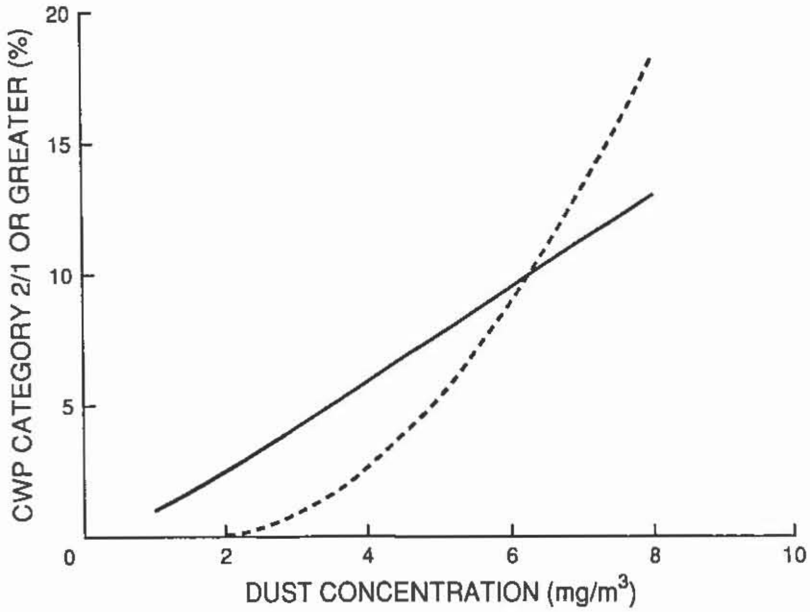

FIGURE 41 Lifetime prevalence of radiographic changes of category 2/1 or greater coal workers' pneumoconiosis by average coal mine dust exposures, based on British field research. (Dashed line, original estimate; solid line, current estimate.) (From Attfield MD, Hodous TK. Pulmonary function of U.S. coal miners related to dust exposure estimates. Am Rev Respir Dis 1992; 145:605–609.)

pneumoconiosis resulting from radiographs taken from 1970 to 1986 through this system have been analyzed. Over the course of the program, the prevalence of category 2 or greater pneumoconiosis has generally declined for miners in each tenure category (Fig. 43). Again, the proportion of participating miners with complicated CWP decreased from 1970 for all tenure groups, but the decline in this finding since 1975 is less apparent. Both of these studies document a large reduction in the prevalence of CWP in coal mines in the United States since 1970.

Participation in the first round of the National Coal Study was over 90%, but it was lower in later rounds. The National Coal Workers' X-ray Surveillance Program participation rates have been 50% or less, which somewhat reduces the confidence in the analysis of trends. Overall, it does appear that the mandated programs of environmental and medical monitoring initiated under the FCMHSA of 1969, in conjunction with transfer options and compensation of affected miners, have had an effect in reducing the prevalence and incidence of CWP in United States coal miners.

New Imaging Techniques

In the past two decades, computerized radiographic techniques, gallium lung scanning, and magnetic resonance imaging have become widely available. It has been recognized that traditional chest radiography is insensitive to early pathologic interstitial and emphysematous changes. Therefore, interest has focused on these new modalities in the nonoccupational lung disorders. Limited evaluations of the usefulness of new imaging techniques have been performed relative to pneumoconiosis. Digital image processing has shown promise in areas of display, storage, and transmission of chest images. Computer-assisted pneumoconiosis interpretation of digitized images is being evaluated at present. High-resolution CT has been reported to be a sensitive technique in identifying early interstitial fibrosis, including silicosis and asbestosis, as well as emphysema. Coalescence of pneumoconiotic nodules, as well as massive lesions, has been identified on CT scans when they were not apparent on routine radiographic evaluations. Increased activity on gallium scanning of the lungs has been noted in several types of pneumoconiosis, but this is nonspecific and may be less prominent in coal workers. Magnetic resonance imaging in the pneumoconioses has currently demonstrated utility at present. Digitized chest images will likely become widely used in the next few years. At this time, it is not clear what role, if any, the other modalities will play in the evaluation of coal miners' lung diseases.

FUNCTIONAL CONSEQUENCES

Pathogenesis

The inhalation of sufficient coal mine dust affects the function as well as the structure of the lungs. Functional consequences generally can be divided into two categories: (1) those effects related to the movement of gas into and out of the lungs (the bellows function) and (2) those effects related to the transfer of gases between the alveolar air and lung capillary blood.

Bellows Function

Resistance to airflow into and out of the lungs of coal miners may be increased by bronchitic changes in the larger airways, as well as airway distortion, and destruction of elastic lung tissue at the level of the bronchioles and alveoli. These changes reduce the rate of maximal air flow, producing an obstructive ventilatory defect, demonstrated by reductions in the $FEV_1\%$ (ratio of FEV_1/FVC) and the forced expiratory flow in the middle 50% of the vital capacity (FEF_{25-75}) (see also Introduction to Chapter 11). In contrast, dilation of small air spaces can lead to overinflation and gas trapping, whereas fibrotic lesions, particularly of the massive type, reduce the volume of air contained in the lungs (TLC). Both of these latter changes can result in a reduction of the FVC and FEV_1, producing a restrictive or mixed restrictive-obstructive pat-

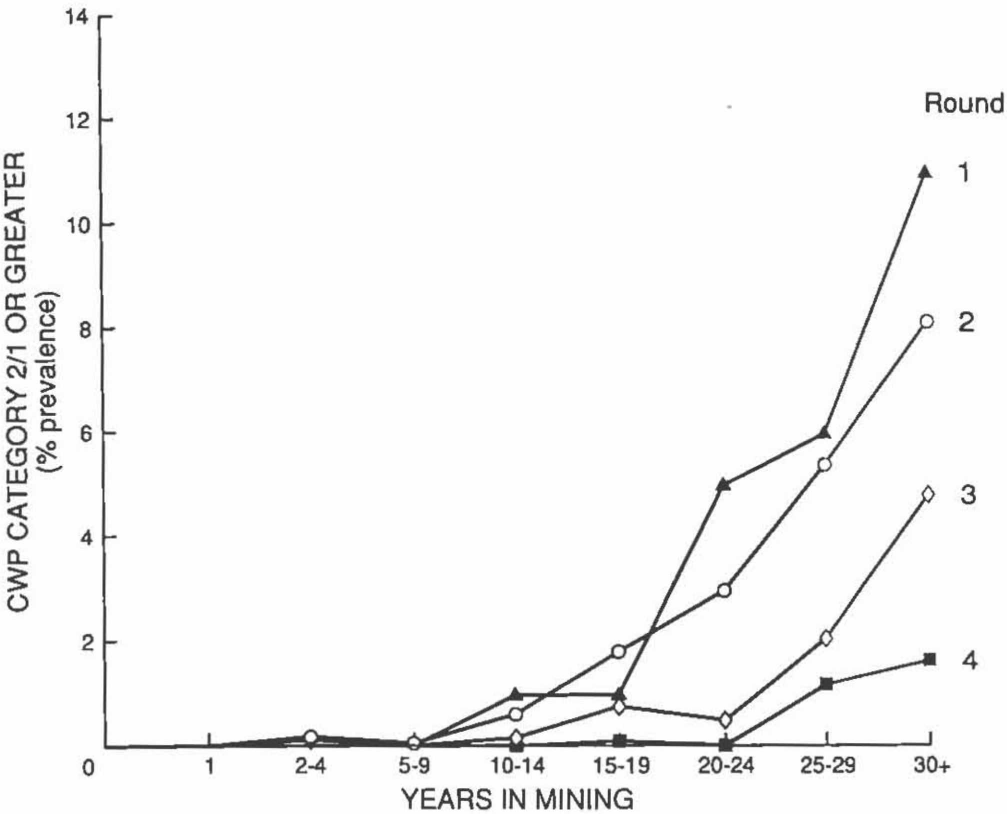

FIGURE 42 Prevalence of radiographic changes of category 2/1 or greater coal workers' pneumoconiosis by job tenure, based on the United States National Study of Coal Workers' Pneumoconiosis. (From Attfield MD, Hodous TK. Pulmonary function of U.S. coal miners related to dust exposure estimates. Am Rev Respir Dis 1992; 145:605–609.)

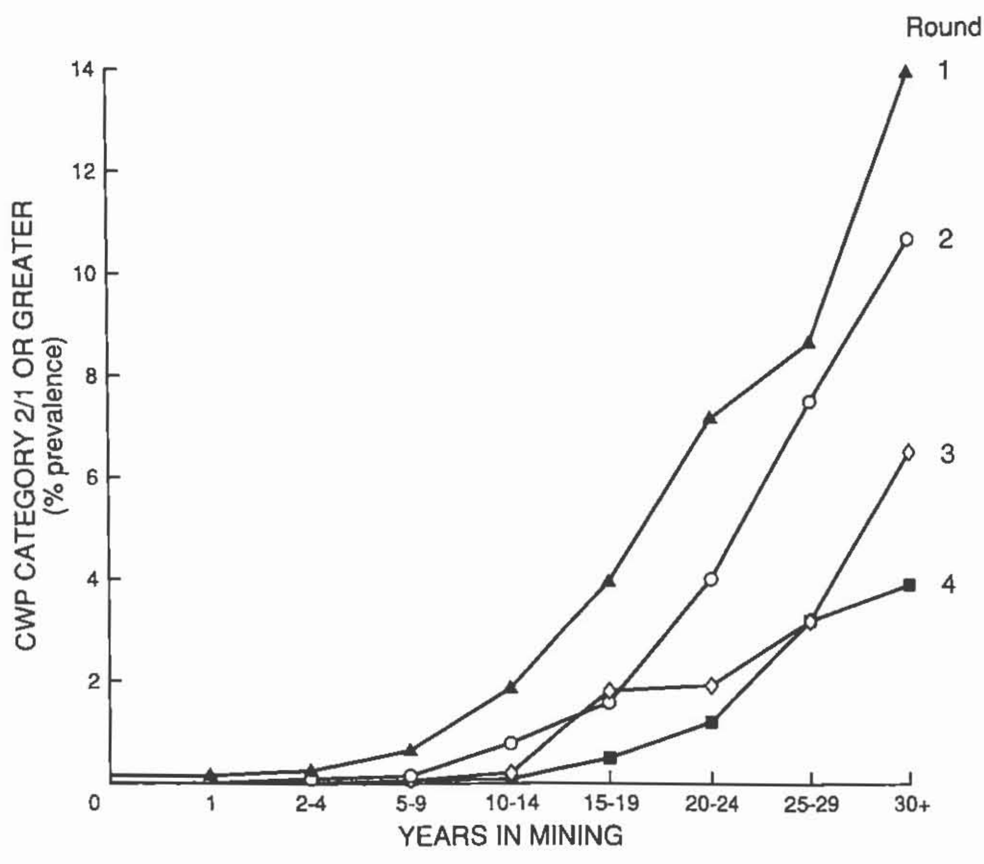

FIGURE 43 Prevalence of radiographic changes of category 2/1 or greater coal workers' pneumoconiosis with job tenure, based on the United States National Coal Workers X-ray Surveillance Program. (From Attfield MD, Hodous TK. Pulmonary function of U.S. coal miners related to dust exposure estimates. Am Rev Respir Dis 1992; 145:605–609.)

tern of abnormality on spirometry. It can be seen that, based on the predominant pathology, miners may show obstructive, restrictive, or often mixed patterns of dysfunction on spirometry related to their dust exposure.

Gas Exchange

Reduced ability to transfer gases in the lungs of miners also can result from multiple structural abnormalities. Dilation and distortion of small airways, as well as the fibrotic changes due to dusts, results in an inhomogeneous delivery of inspired air into the alveoli. Destruction of capillaries and small vessels also reduces the uniformity of lung perfusion. These effects combine to result in the mismatching of lung ventilation and perfusion as well as subsequent hypoxemia in the systemic arterial blood. The destructive loss of capillaries alone also may be sufficient to reduce the combined surface area of the alveolar-capillary membrane to an extent that gas transfer is impaired, particularly on exertion. In advanced disease, airflow obstruction may be so severe that alveolar ventilation is insufficient for metabolic demands. In this situation, hypoxia with hypercapnia results. An additional cause for hypoxia is reduced cardiac output, primarily seen in association with cor pulmonale and right ventricular dysfunction. Finally, excessive ventilation on exertion has been associated with dyspnea in the presence of normal measures of lung mechanics.

Investigations of Coal Miners

The functional consequences of the inhalation of coal mine dust have been documented through both clinical and epidemiologic studies. Most studies of large groups of miners have used routine spirometry in the evaluation of expiratory flows and FVC. Smaller groups have been studied using other techniques. Series of miners also have been reported from clinics emphasizing disability and impairment evaluations. Although disability series are of interest, the representativeness of miners in these series is undetermined, exposure information often is scant or absent, and a control group generally is lacking. Their overall usefulness in the study of the effects of coal mine dusts on lung function thus is limited.

Epidemiologic Studies

Most information regarding ventilatory effects of coal mining has been derived from large field studies of miners in the United States and the United Kingdom. Studies from other countries have been reported and show generally very similar findings. Both cross-sectional and longitudinal evaluations of the United States and British studies have been published. The lung functional findings from both countries are consistent and are summarized in the following sections.

The miners who were exposed to the dustiest environments show lower mean FEV_1 levels than those in less dusty mining jobs. More important, dose-response relationships of FEV_1 with estimated dust exposure or with exposure surrogates such as tenure underground have been reported for miners in both countries. Other ventilatory function indices, such as FVC, FEV_1/FVC ratio, and flows at both higher and lower lung volumes, also have been shown to be inversely related to estimated dust exposure. Evidence of an effect on airflow at low lung volumes implies obstruction in small airways. In addition to the cumulative effects of dust, a large but nonprogressive reduction in average lung function is seen in the group of miners who develop the symptom of a chronic productive cough.

Certain miners from both the United States and the United Kingdom were studied longitudinally over an approximately 11-year period. These studies showed that as the miners' dust exposures increased, there was a resulting progressive decrement in lung function, as measured by the FEV_1, over the period of follow-up. Differences in the effects were seen between miners at different collieries.

The effects on lung function associated with dust exposure were present after adjustment for smoking and were typically observed to occur in all three smoking groups (never smokers, ex-smokers, and current smokers). The smoking and mine dust effects appeared to be independent and additive but not synergistic. Thus, the average reduction in ventilatory function associated with exposure to mine dusts in smokers was similar to that in miners who never smoked. No disproportionate dust effects were noted in the smoking miners. In fact, the observed dust exposure effect, rather than being greater in current smokers, usually was somewhat less.

In miners who also smoke cigarettes, comparisons have been made between the excess reductions in lung function associated with mining exposures versus those associated with tobacco use. Because both effects are dose related, estimates of relative effect on lung function are related to the levels of exposure to tobacco smoke and to dust exposure chosen for the comparison. In the longitudinal study of United States miners, for example, the average tobacco consumption in the smoking miners was 14 cigarettes per day. This was observed to result in an average excess loss of FEV_1 of 96 ml over 11 years in smoking miners compared with nonsmoking miners. Eleven years of working at the coal face was associated with an average loss of FEV_1 of 84 ml in miners (nonsmoking or smoking). For all miners, including those in less dusty work (average dust concentration 1.2 mg/m^3), the mean dust-related decline in FEV_1 over 11 years was 36 ml.

It has been stated that although mean dust-related functional declines may be of similar magnitude to smoking effects, the tobacco and mining effects might be distributed differently. Under this hypothesis, tobacco effects among smokers are confined to large deficits in a small group of susceptible persons, whereas mining effects are small but occur in most miners. Based on this hypothesis, equivalence in mean values could conceal very different functional consequences. However, several recent observations tend to contradict this hypothesis. Studies of smoking and nonsmoking miners have revealed similar increases in the proportion of severe impairments from effects related to dust and smoking. Miners with severe ventilatory deficits attributed to coal mine dust also have been identified.

Miners' ventilatory lung function also has been compared with their chest radiographic changes of CWP, categorized using the ILO classification scheme. Higher categories of CWP, particularly complicated disease, generally are associated with large reductions in FEV_1 and other functional consequences, as discussed in the following section. Lower categories of simple CWP are not consistently associated with identifiable abnormalities on spirometry, after taking into account the functional losses associated with mine dust exposure, tobacco use, and the development of bronchitis. Conversely, a negative result on an x-ray study does not exclude the possibility of occupationally related lung disease.

Laboratory Studies

Lung Mechanics

Static lung compliance often is normal but may be abnormally low or high in coal miners. High compliance, suggestive of emphysema, is the most common abnormality. Miners with PMF may have marked compensatory emphysema and high lung compliance; in others with PMF, the fibrotic process appears to predominate, and stiff lungs with low static compliance are seen. Miners with pinpoint p type opacities also appear to have larger peripheral airspaces.

Gas Transfer

The transfer of gases in the lungs of coal miners has been evaluated using both the single breath and the steady state techniques to measure carbon monoxide diffusing capacity. Certain miners were found to have abnormalities on these tests. Reduced diffusing capacities are more commonly observed in miners with either pinpoint (p type) or irregular (s or t type) opacities of simple pneumoconiosis and in those with complicated CWP, when compared with those with q type opacities.

The findings related to gas exchange on exercise in coal miners are less well defined. Many authors have reported highly selected groups of miners referred for disability evaluation. Estimated dust exposures often were not determined. Diminished gas transfer or excessive ventilation on exercise has been found in some groups but not in others. Miners with PMF often have shown severe gas exchange abnormalities on exercise. Those with increasing airflow obstruction also generally have corresponding defects in gas exchange on exercise. When the functional correlates of radiographic pneumoconiosis have been carefully evaluated in miners without severe airflow obstruction, it does appear that simple pneumoconiosis, particularly categories 2 and 3, can lead to identifiable abnormalities of gas exchange on exercise. These changes have been attributed to the emphysema accompanying the radiographic changes.

Low categories of pneumoconiosis, particularly the q type of opacities, in the absence of airflow obstruction, often appear to be associated with little or no gas exchange impairment. In contrast, miners with a finding of airflow obstruction, higher category of CWP, and either irregular or pinpoint opacities may show impairment of gas exchange, particularly on exertion.

Pulmonary Hemodynamics

Increases in pulmonary artery pressure, at rest and on exercise, have been documented in some coal miners. Abnormalities are more commonly seen when the miners have measurable airflow obstruction. When the hemodynamics were compared with radiographic findings, abnormalities were most commonly seen in miners with complicated pneumoconiosis, silicosis, or pinpoint p type opacities of simple CWP. In the absence of airflow obstruction or one of these radiographic features, pulmonary hypertension appears uncommon in coal miners.

Summary of Functional Consequences

Miners may show several functional abnormalities in relation to the inhalation of coal mine dusts. Radiographic changes of PMF often are associated with multiple abnormalities. Certain patterns of simple pneumoconiosis (irregular and rounded pinpoint opacities) appear to be associated with gas exchange impairment. However, ventilatory dysfunction often is unrelated to the radiographic category of simple CWP. In contrast, deficits in expiratory volumes on spirometry appear to be related to the intensity and duration of dust exposures, independent of radiographic abnormalities. An additional reduction in ventilatory function often is seen in miners with symptoms of bronchitis. Spirometric abnormalities measured during miners' lives are correlated with pathologic changes of emphysema, which, in turn, have been correlated with measures of both dust exposure and lung dust retention. The dust effects in miners who smoke cigarettes appear to be additive to the effects of tobacco use; no disproportionate effect of smoking has been identifiable. In miners who smoke, FEV_1 reductions associated with 1 year of working at the mine face are of similar magnitude to the average smoking effect. When work at less dusty jobs is included, average dust-associated reductions in ventilatory function over 1 year appear smaller than the average effect of 1 year of smoking. In addition, evidence has been presented that dust exposure can lead to severe changes in some miners.

DIAGNOSIS

Pathologic changes of CWP may be found in the absence of radiographic evidence of pneumoconiosis. However, the radiographic picture of CWP often is sufficiently distinctive that in the presence of an adequate exposure history, a diagnosis can be made with reasonable certainty. A lung biopsy rarely is needed. The question of what constitutes an adequate exposure history is determined by the timing and characteristics of the occupational history. Underground work prior to the institution of federal dust control regulations in 1970 to 1973 likely represents a high-risk exposure. In this setting, pneumoconiosis developed in some miners with less than 5 years of exposure. Several jobs, as discussed earlier, offer recognized risks for silicosis. Recent reports have emphasized that surface coal mine drillers are at risk for accelerated and acute silicosis (see Chapter 11.8). Face work, particularly in longwall mining, is still occurring commonly with exposures over the 2 mg/m^3 respirable dust standard. In the absence of these high-risk settings, a careful work-up should be performed before diagnosing radiographic CWP in a miner with less than 5 to 10 years of coal mine exposure. Stability of the radiograph, or slow progression over a period of 2 to 5 years, is expected. More rapid change also should prompt a search for alternative processes. Hilar or mediastinal adenopathy and pleural effusion also are not likely to be due to CWP alone. For example, the appearance of bilateral small rounded radiographic opacities in low profusion and principally in the middle and upper lung zones in a coal miner with 10 or more years of underground mining experience should be accepted as diagnostic of CWP. Some miners with this presentation have complaints of cough and sputum, although basilar lung crackles usually are scant and clubbing is not present. Infectious processes, other interstitial lung disorders, and a metastatic neoplasm should be carefully considered if fever, weight loss, chest pain, or progressive dyspnea or malaise are present. A broad differential diagnosis also should be included if the initial radiograph shows unilateral disease, predominant irregular opacities, or a high profusion of small rounded densities. Finally, prominent gas exchange abnormalities also are unusual early in the course of simple CWP.

Of great diagnostic concern is the development of a large radiographic opacity in a coal miner. The differential diagnosis must include malignancies and mycobacterial or fungal infections, as well as complicated CWP. PMF typically develops on a background of simple nodular densities, often is bilateral, and appears in the upper lung zones. Stability or slow progression over several years also is more consistent with complicated CWP. If doubt exists, then an appropriate work-up should be completed before accepting the diagnosis of a dust-induced lesion. Caplan's syndrome (rheumatoid pneumoconiosis) may be exhibited as multiple larger nodules appearing without a definite background of simple CWP. The nodules may appear rapidly (over a period of weeks). A similar radiographic appearance may be seen with pulmonary metastases, but joint examination and serology almost always reveal the confirming evidence of active rheumatoid disease.

MANAGEMENT

Medical Screening

Preplacement medical testing primarily is intended to identify workers with existing medical conditions that would increase the health risk associated with employment in a coal mine. Questions arise related to the risks associated with underground coal mine employment in asymptomatic workers with abnormalities on chest films. In the absence of a definable lung impairment, minor radiographic abnormalities alone should not affect or limit work activities. The implications for preplacement testing of workers under the Americans with Disabilities Act are uncertain at this time.

Periodic medical screening may use standard chest radiography or spirometry. At present, a program offering periodic chest radiographs to all underground coal miners in the United States is mandated by federal regulations. This program serves to highlight potential areas of continuing medical and environmental problems. In addition, miners who are identified with pneumoconiosis qualify for administrative actions. They are entitled to increased frequency of personal environmental monitoring and are offered the option to work in an environment where dust is reduced. This may require job transfer with maintenance of pay. Owing to the long latency of CWP, however, it often is difficult to relate contemporary environmental exposures to the cases identified.

Periodic medical screening using spirometry is targeted toward identifying individuals with progressive airflow obstruction. To avoid the development of disabling lung impairment, workers with accelerated loss of lung function should be counseled regarding reducing current and future exposures to dust, if possible, as well as controlling other recognized risk factors (e.g., tobacco smoke).

General Medical Management

Medical management of symptomatic coal miners with pneumoconiosis, airflow obstruction, or both is similar in many ways to that of patients with nonoccupational chronic lung diseases but with emphasis on three principal areas: control of exposures, treatment of complications, and compensation for disability. These factors are discussed in the following sections.

Exposure Control

Control of symptoms in underground coal miners must address the mine environment, in addition to other potentially aggravating exposures, such as tobacco use. The miner should be encouraged to obtain and review the results of contemporary periodic air monitoring to determine the employer's compliance with respirable dust and silica regulations.

A recommendation that the miner transfer to the surface or a less dusty underground job often is the most viable option for reducing exposure to environmental dust. Miners, particularly those not close to retirement, who show identifiable airflow obstruction, accelerated longitudinal decline in lung function, or radiographic changes of pneumoconiosis should be counseled regarding transfer to a less dusty environment. Miners who develop symptomatic bronchospasm in dusty environments at times can suppress the symptoms through the use of inhaled medications and oral bronchodilators. However, transfer often is necessary in order to control symptoms without resorting to more hazardous forms of therapy, such as systemic corticosteroid therapy. Transfer rights with retention of wage rates and benefits are available only for coal miners with radiographic abnormalities identified through radiographic surveillance, under United States mining regulations at present. Radiographs may be submitted to NIOSH for an official interpretation to determine eligibility.

Recommendations for the use of respiratory protective equipment are rarely practical in underground mining. However, occasionally a miner with prominent cough or bronchospasm may be able to continue working underground while participating in a formal respiratory protection program.

Attention also should be paid to nonoccupational respiratory hazards. In miners who smoke, recommending smoking cessation is an initial step in exposure management. Referral to volunteer organizations or other formal cessation programs; prescription of nicotine delivery systems, when appropriate; and unambiguous advice from the health care provider are effective approaches.

Treatment of Complications

Dust-induced fibrosis, emphysema, and chronic airflow obstruction are irreversible changes. Interventions should be targeted toward detecting, treating, and preventing complications. Management of conditions etiologically unrelated to mine dust exposure also may be complicated by lung impairments related to dust effects.

Periodic monitoring of spirometry and chest radiographs is useful to determine the rate of progression of the disorder and to detect onset of complications. An initial electrocardiogram may be helpful for subsequent comparisons. In miners who present with symptoms and signs of illness, assessment of gas exchange may be indicated. The subsequent performance of these evaluations must be tailored to the clinical course of the individual miner. Infectious exacerbations, including bronchitis and pneumonias, may occur in affected miners. Broad-spectrum antibiotics and physical therapies are helpful in reducing symptoms during episodes of purulent sputum production. The treating clinician should take care to exclude both tuberculosis and nontuberculous mycobacterial infections. Particularly in miners with silicosis, the risk of these infections is increased and the response to chemotherapy less satisfactory (see Chapter 11.8). Tuberculin reactivity should be tested in all miners with CWP. In tuberculin-positive miners with radiographic pneumoconiosis, active disease must be carefully excluded. Once this has been accomplished, preventive therapy with isoniazid is recommended for those with positive skin tests and no contraindications or risk factors for isoniazid-resistant infection. Twelve months of daily treatment reduces the lifetime risk of developing active disease. Shorter courses of chemoprevention are not suggested for miners with abnormal chest radiographs.

Inhaled oral bronchodilator therapy should be attempted in most symptomatic miners. Prolonged courses of inhaled steroids have been shown to control symptoms and reduce nonspecific bronchial hyperresponsiveness in many patients. Short tapering courses of systemic corticosteroids may be helpful for acute exacerbations. However, it is rarely, if ever, justified to use long-term systemic steroids to allow a miner to remain working in a dusty environment.

Cor pulmonale with right-sided heart failure due to CWP is treated the same as cor pulmonale due to other etiologies.

A coordinated rehabilitation program, with attention to nutrition, reduction of emotional stress, physical therapy, and judicious exercise may improve the clinical status of the disabled miner. As in patients with other irreversible disorders, discussions regarding the use of life-support and mechanical ventilation are most appropriate in miners with severe but clinically stable lung disease.

Compensation for Disability

Miners with lung impairments may be eligible for compensation under the Federal Black Lung Benefits program, as well as through state pneumoconiosis and workers' compensation plans. In advising individual miners, the health care provider should be familiar with specific requirements of the programs. Particular note should be taken of the statute of limitations, because the date of reporting relative to the establishment of a diagnosis of work-related disease may be critical in determining eligibility for benefits. Legal counsel often is necessary in establishing eligibility (see Chapter 5.1).

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