Exercise capacity in coal workers' pneumoconiosis: an analysis using causal modelling

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Abstract

Miners disabled from black lung disease (coal workers' pneumoconiosis, CWP) are entitled to disability benefits under United States federal and state laws. The determination of disability currently involves several scientific controversies. The Federal Department of Labor states that one second forced vital capacity (FEV_1) is an important marker of disability from CWP. The Department of Labor also states that disability may occur in simple CWP, in the absence of progressive massive fibrosis (PMF). Both these contentions may reasonably be challenged. To investigate these issues, and to investigate the relation between exercise tolerance and several other variables, including age, weight, radiographic findings, and exposure to mining and smoking, we studied 690 miners. Simple correlation analysis was not helpful because many variables were correlated with each other. Linear regression analysis led to conclusions that were thought to be misleading. Causal modelling provided an analysis that appeared to be most explanatory. In the model tested years of coal mining did not affect FEV_1 ; if this conclusion is substantiated by others FEV_1 should be eliminated as an indicator of disability from CWP as it is not related to mining experience. On the other hand, the Department of Labor's position that disability may occur in simple CWP seems reasonable, as years of underground coal mining does affect forced vital capacity (FVC), which in turn impairs exercise capacity, even in the absence of PMF. FVC should be the major spirometric value used in determining disability from CWP because it alone is seen to decrease in relation to mining, and a decrease in FVC does affect exercise capacity. Thus this analysis addresses issues in determining black lung

disability and shows the value of causal modelling.

Coal workers' pneumoconiosis or black lung disease is associated with coal dust inhalation by susceptible miners and is characterised by a chronic fibrous tissue reaction in the lungs that may cause disability or death.^{1,2} Federal and state programmes provide disability compensation for miners with the disease, or for surviving dependents, provided that certain criteria are met. These criteria are intended to identify miners who, as a result of coal mining, became totally disabled. There are no scientific criteria for defining total disability from black lung disease and each case is evaluated individually after evidence is presented. Usually, the evidence is the miner's pulmonary function evaluation.

Confusion over basic issues has resulted in conflicting conclusions among scientists, federal administrators, and lawyers concerned with black lung disability. The key to understanding disability from black lung disease probably rests with understanding how the disease affects pulmonary function, but it is this area that is the most controversial. For example, black lung disease is generally accepted to be a type of occupational pneumoconiosis and is classified as an interstitial lung disease.³ On the other hand, cigarette smoking causes a chronic obstructive lung disease. These two different types of lung disease, interstitial and obstructive, are separated clinically by a laboratory test, the spirogram. Interstitial disease causes a reduced forced vital capacity (FVC) whereas obstructive disease causes a reduced one second forced expiratory volume (FEV_1). Yet the Federal Department of Labor allows a low FEV_1 (obstructive disease) and pneumoconiosis on chest radiographs to be sufficient evidence of total disability from black lung disease.⁴ This has led one textbook to conclude that "coal workers may be compensated for chronic airway obstruction due to cigarette smoking at a much higher rate than are workers in other industries."⁵ The Department of Labor's FEV_1 criteria are probably due to observations that FEV_1 is often reduced in pneumoconiosis without regard to whether the reduction in FEV_1 is due to the pneumoconiosis or to some other factor—for example, examination of 30 000 British miners found

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a significant reduction of both FVC and FEV₁ in miners with simple pneumoconiosis.⁶

Besides the issue of FEV₁ in determining disability, another controversy separates some experts from the accepted disability determination practice: does simple pneumoconiosis even cause disability at all? Pneumoconiosis is classified in two categories according to radiographic appearance: simple and complicated. Complicated pneumoconiosis is recognised as a more advanced disease and is also called progressive massive fibrosis (PMF).⁷ PMF has nodules at least 1 cm or larger on radiographs. The presence of PMF leads to the "irrebuttable presumption of total disability or death due to pneumoconiosis" according to Department of Labor regulations.⁸ In the absence of PMF total disability may still be determined when only simple pneumoconiosis and some other criteria, such as low FEV₁, are present. Again, textbook writers contradict this. Textbooks indicate that there is no impairment in simple pneumoconiosis, stating "(simple) CWP is not associated with any respiratory symptoms . . . PMF is the only disabling form of coal workers' pneumoconiosis"⁹ and "simple (pneumoconiosis) is a disease virtually without symptoms."¹⁰

These two issues may be restated. Firstly, does coal mining significantly reduce FEV₁? Secondly, is simple pneumoconiosis associated with impairment of physical activity? In general, exercise tolerance is an indicator of physical capacity or impairment. The present study was undertaken to examine the issues outlined, using exercise tolerance as a measure of disability. The study was also aimed at providing a better understanding of the relation of coal miners' exercise tolerance to other potentially related variables, including other pulmonary function values, age, weight, radiographic findings, and smoking.

Table 1 Mean values for subjects. Pulmonary function variables are expressed as per cent of predicted, except PCO₂, which is in torr. ILO rank is an indicator of radiographic findings (see text)

	Mean	Standard deviation
Age (y)	53.9	10.2
Weight (lbs)	178.1	33.7
Years smoking	16.7	14.8
ILO rank	2.6	1.1
Mining (y):		
Above ground	5.7	9.1
Below ground	16.9	13.3
FEV ₁ (%)	96.0	26.4
FVC (%)	94.7	23.1
FEF ₂₅₋₇₅ (%)	79.1	39.4
PaO ₂ (%)	94.2	10.8
PCO ₂	37.0	3.5
Exercise (min)	6.9	2.4

Methods

SUBJECTS

A respiratory disease evaluation unit was established at the University of Kentucky to examine compensation applicants under federal and state black lung programmes. Applicants are referred to the evaluation unit by state and federal departments of labor. All 1064 applicants examined at the laboratory over a two year period were entered into this study. All were miners or former miners and most were from Eastern Kentucky. The average age was 54 and the average experience in coal mining 23 years. Table 1 lists variables obtained for all subjects and includes exercise tolerance, historical and physical data, spirometric flow and volume measurements, arterial blood gases, and chest radiographs. Electrocardiograms also were obtained.

PROCEDURES

Subjects were interviewed by trained personnel who completed standard history forms. Employment and smoking history were obtained. Chest radiographs were obtained and were read independently by board certified radiologists at the University of Kentucky. The radiologists interpreted the radiographs using uniform standards, the International Labour Organisation U/C 1971 classification.^{7 11}

Expiratory spiograms were obtained using an Ohio omni-lab pulmonary function testing system. At least three trials were completed and the results were selected using standard criteria as outlined in the ATS 1979 statement.¹² All results were corrected and are expressed here as per cent of predicted, using the formulas of Knudson *et al.*¹³

Arterial blood gas samples were obtained from the radial artery at rest and were analysed immediately with a radiometer ABL 2d acid base laboratory. Arterial oxygen tension (PaO₂) was calculated and expressed here as per cent of predicted according to age.¹⁴

Both the spirometer and the blood gas analyser were standardised at least daily in accordance with the manufacturer's recommendations and federal requirements and the blood gas analyser was calibrated before and after each determination.

Subjects were exercised on a treadmill using the Bruce protocol, which increases the speed and incline of the treadmill at three minute intervals.¹⁵ The electrocardiogram was monitored with a three channel system using leads avF, V1, and V5. Subjects continued to exercise until they stopped because of dyspnoea, fatigue, pain, or until the test was terminated by the physician because of significant ECG changes. Subjects with significant ECG changes were excluded from this analysis. Therefore data on exercise tolerance in this study represent maximum symptom limited capacity.

EXCLUSIONS

Some miners had difficulty walking on the treadmill because of musculoskeletal problems, usually back-ache or old hip or leg fractures. Because stopping the exercise test in these cases was unrelated to pulmonary function, 205 subjects who stopped because of back or leg pain were eliminated from this analysis.

Because heart disease may also limit exercise tolerance, subjects with apparent heart disease were eliminated. Apparent heart disease was defined as significant ST changes on the electrocardiogram during exercise, a history of heart attack, or electrocardiographic evidence of myocardial infarction. These criteria eliminated an additional 169 subjects, leaving 690 subjects with a history of coal mining, applying for disability, able to complete the exercise test without musculoskeletal problems, and with no apparent heart disease. These miners are the subject of this report.

Analyses

The first analysis examined factors that might be related to exercise capacity. Pearson's correlation coefficients were determined among the variables. Because of the many inter-relations found among the variables, multivariate regression analysis was completed. Regression analysis attempts to find the effect of a given variable after adjusting for the effect of the other variables. The statistical analysis system (SAS) general linear model was used.¹⁶ "Years of smoking" was selected as the variable for smoking history rather than "pack-years of smoking" because the former explained slightly more variance than the latter.

To complete linear regression analyses, variables must be continuous—that is, the variables must have values that are established at equal intervals. The standard ILO chest radiographic diagnoses have progressive numerical values for extent of nodule perfusion (1/1, 1/2, etc), but the values are not at equal intervals. To use radiographic diagnosis in the regression analyses, ILO diagnoses were converted to "ILO rank" by establishing an ordinal scale for ILO rank, and matching with the rank order ILO

Table 3 Results of regression analysis. The dependent variable was minutes of exercise for maximum symptom limited treadmill exercise testing in 690 coal miners. "Estimate" is the estimated effect of the independent variable on exercise minutes, per unit of the variable

Regression results		
Dependent variable = exercise minutes		
Variable	Estimate	Significance
Age	-0.094	0.001*
Weight	-0.009	0.001*
Smoking	0.007	NS
ILO rank	-0.014	NS
Mining:		
Above ground	0.004	NS
Below ground	0.012	NS
PAO ₂ (% pred)	1.652	0.059
PCO ₂	0.076	0.004*
FEV ₁ (% pred)	0.016	0.001*
FVC (% pred)	0.014	0.001*
Flow 25-75%	0.002	NS

R² is 0.22.

NS = p > 0.05.

* = p < 0.005.

diagnoses; thus ILO 0/0 became 1, 0/1 became 2, 1/0 became 3, 1/1 became 4, 1/2 became 5, etc. This rank system was used by Outhrod *et al*, who found it correlated significantly with postmortem pneumoconiosis.¹⁷

Results

Miners in this study completed an average of 6.9 minutes of exercise. Coal mining experience averaged 22 years, of which almost 17 years was underground. Other averages are shown in table 1. The correlation analysis indicated that exercise tolerance was significantly correlated to seven variables; radiographic changes, 25-75% flow rate, FVC, FEV₁, years mining below ground, and age and weight (table 2). There were also 27 other relations identified as having significant correlations. Because of the multiple interrelations, it was not clear which variables were affecting exercise tolerance and which variables were covariables. Multivariate regression analyses reduced the number of variables affecting exercise tolerance from seven to five: arterial PCO₂, FEV₁, FVC, age, and weight (table 3). Years smoking and years mining had no direct effect on exercise

Table 2 Correlation of variables

	PAO ₂ %	Flow	FVC%	FEV ₁ %	Below	Above	Rank	Smoking	Weight	Age
Exercise (min)	NS	+0.001	+0.001	+0.001	-0.046	NS	-0.001	NS	-0.004	-0.001**
Age	+0.001	NS	NS	NS	+0.001	+0.001	+0.001	+0.001	-0.010	
Weight	-0.001	+0.001	-0.01	NS	NS	NS	NS			
Years smoking	-0.010	-0.001	NS	-0.001	NS	NS	NS	-0.001		
ILO rank	-0.001	-0.001	-0.001	-0.001	+0.001	NS				
Mining:										
Above ground	NS	NS	+0.001	NS	+0.001					
Below ground	NS	NS	-0.001	NS						
FEV ₁ , % predicted	+0.001	+0.001	+0.001							
FVC, % predicted	+0.002	+0.001								
Flow 25-75%	+0.001									

Numbers are significance (p) values. NS = Not significant at p = 0.05. Sign (+/-) = direction of correlation. ILO rank: see text. Above ground = Years coal mining above ground; below ground = years coal mining below ground.

Causal model for how smoking, years mining underground, and other factors affect exercise tolerance. All relations significant at $p < 0.001$ level.

tolerance in the regression model. This was contrary to common wisdom and was thought to be a misleading result. To explore this finding, it was postulated that smoking and mining may have an effect on PCO₂, FEV₁, or FVC, or a combination of these, and thus have an indirect effect on exercise tolerance. A "causal model" was postulated in which smoking and mining were analysed as having potential effects separately on PCO₂, FEV₁, FVC, or a combination of these.

Causal modelling is a heuristic and analytic tool in which variables are partitioned in a way that suggests a causal or sequential pathway. It is useful in various situations, including that in which variables are interrelated but the mechanisms are unclear, as was found here. To operationalise this approach, each of the variables that was significantly predictive of exercise tolerance (except age and weight) was analysed separately to determine what variables in turn predicted them. (Age and weight were not further analysed because their cause is obvious.) Regression analysis was again used. These regressions have as one model:

$FEV_1 = f(\text{years smoking, years mining, age, height, weight})$.

Similarly, FVC and PCO₂ were analysed as dependent variables with the same set of independent variables.

FEV₁ was found to be significantly related to height, weight, and smoking ($p < 0.001$) but not to mining. FVC, on the other hand, was related to height, weight, and years below ground mining ($p < 0.001$) but not to smoking or years above ground mining. PCO₂ was not related to any of the independent variables tested. Thus these data support a model that indicates that smoking decreases FEV₁, which in turn decreases exercise tolerance, whereas underground mining decreases FVC and not FEV₁ and FVC in turn also decreases exercise tolerance (figure).

Discussion

Of miners who claim disability from pneumoconiosis, about 12% receive federal disability benefits.¹⁸ Under the Kentucky state programme, the proportion of applications who receive benefits is over 50% (C Wells, 3rd Black Lung Conference, Lexington, 1985). The economic implications of disability in miners with black lung disease are significant. For the individual miner, the determination of disability from coal workers' pneumoconiosis may result in over \$100 000 in benefits.¹⁹ For the United States, the federal black lung disability programme costs over a billion dollars annually.²⁰ It is important that the disability evaluation be done fairly and scientifically; this requirement emphasises the need for an understanding of the relations among historical variables, pulmonary function parameters, and physical disability. Accurate models are essential.

Causal modelling has been used extensively in the social sciences. It has also been used in psychiatry.²¹⁻²³ It appears to be useful in situations such as described here, where there are multiple interactions and confusing correlations, as seen in table 2. Even regression analyses fail satisfactorily to sort out these important variables; left alone, the regression analysis would suggest that neither number of years of underground mining nor years smoking had any impact on exercise tolerance (table 3). These conclusions are, at a minimum, counter-intuitive. Causal modelling, in this case, sorted variables into a reasonable model.

At its most elementary level, causal modelling is a postulated arrangement among events and factors, usually represented by an arrow diagram. Causal modelling has both heuristic and analytical potential; heuristic because constructing the model may help clarify hypotheses to be tested, and analytical because if the data are available "causal" relations may be evaluated. Any proposed model is stronger if three conditions are met.²¹ The first is that there is concomitant variation between variables in the model, along the pathway outlined. In our study this condition is met, demonstrated by the regression analyses which show, for example, that a change in smoking history is accompanied by a change in FEV₁ and that a change in FEV₁ is accompanied by a change in exercise tolerance.

The second condition requires a time ordering among the variables. In the model presented here this is a reasonable assumption. Our time ordering assumption is that the miners had at least normal FEV₁, FVC, and exercise capacity when they began their careers; that a variable amount of smoking and mining intervened; and that a variable decrease in exercise tolerance occurred subsequent to the smoking or mining or both.

The third condition for a strong causal model is

that other possible causes that may be producing the observed relation are eliminated. We believe that we have considered the major candidate factors (age, height, weight, smoking, and mining history) in a population in which we attempted to exclude major cardiac and musculoskeletal disease but other confounding factors are always possible. Our model is elementary and we have not attempted to revise it by testing for omitted linkages.

The mean values for most functional variables in this study are near normal. We think this represents a typical population that may apply for disability benefits. Within the population, there are a reasonable number of claimants with clearcut disease. For example, in the population of 690 there were 111 subjects with an FEV₁ less than 70% of predicted, which would qualify them as having "Class 3" impairment according to the American Medical Association guides to the evaluation of permanent impairment.²⁴ There are also 66 subjects with FEV₁ less than 60% predicted. There were 200 subjects with an arterial PO₂ less than 70 mm Hg. Regression analysis does not require a normal distribution of values but it does depend on an adequate range of values. The range of values requirement has been satisfied with these data. These data are partially in agreement with those of Violante *et al* in that we did not find any relation between exercise capacity and radiographic changes. Their study of 45 subjects with pulmonary silicosis in Genoa also found no correlation between exercise capacity and smoking, years exposure, age, weight, or any pulmonary function result. The number of subjects they studied is considerably less than in this study and they did not attempt multivariate analysis. Their conclusion that exercise is therefore limited by factors other than ventilatory limitation was not substantiated by the current study.²⁵

The data presented here suggest that exercise capacity is affected by several variables. Age is a significant factor inversely related to exercise capacity, which is not a surprising finding; older people have less exercise capacity.¹⁵ Body weight also affects exercise capacity, which also is not surprising; heavier people also had shorter treadmill exercise tolerance. FEV₁ was related to exercise tolerance. Jones *et al* previously indicated the relation of age and FEV₁ to exercise capacity.²⁶ Their study, however, on a relatively few subjects (n = 50), was not directed at pneumoconiosis and did not include blood gas or radiographic findings. Our study supports and extends Jones's findings. FEV₁ in this study was related to cigarette smoking, an observation made frequently before.²⁷ For some miners, exposure to coal dust may be more likely to produce reduced FEV₁ rather than FVC. Hurley and Sautar reported 199 selected ex-miners who had a pronounced inverse relation between exposure to dust and FEV₁.²⁸ This relation was more pronounced among ex-smokers; however, the analysis did not otherwise

control for smoking history and the selection of a subgroup of miners for study makes generalisation difficult.

FVC also had a significant relation on exercise tolerance in this population of coal miners. The causal modelling analysis showed that FVC was in turn affected by years mining underground.

PCO₂ was related to exercise tolerance but neither smoking nor mining history were seen to affect PCO₂ in this study. Possibly PCO₂ is a non-specific indicator of cardiopulmonary function or it does not have a linear relation to other variables.

We did not find that the resting arterial oxygen level predicted exercise capacity. Maximal work rate had previously been thought to be directly proportional to arterial oxygen tension at rest.²⁹ Morgan *et al*, however, asserted that resting blood gases are not useful in assessing black lung disease.³⁰ The assertion was not based on a multivariate study and was met with dissent by others.^{31,32} The data presented here suggest that, whereas arterial oxygen level is not associated with exercise tolerance when other variables are controlled for, changes in arterial carbon dioxide, PaCO₂, may be important. The fact that the arterial oxygen level was not shown to be related to exercise tolerance raises the question of its value in the disability examination. We do not propose abandoning the arterial gas study in black lung disability examinations; on an individual case level, the best assessment probably is still based on finding a consistent pattern of results from several types of tests. Nevertheless, these data do invite consideration of how some individuals with lower resting arterial oxygen levels manage to have an exercise tolerance as good as others with higher levels.

Because reduced FEV₁ appears to result from smoking and not mining, its value in the determination of disability from CWP is questionable. If others substantiate our findings we would recommend that authorities remove FEV₁ as a possible criterion for black lung disability determination. On the other hand, FVC, which is related both to mining and to exercise impairment, should be the primary spirographic indicator of black lung impairment. Our data show that mining related changes in FVC do occur even in the absence of advanced disease or PMF, supporting the position of the United States Department of Labor.

Reports concerning coal workers' pneumoconiosis and respiratory function have many discrepancies and ambiguities, a fact substantiated by Marek who cites 95 publications in his review of this topic.³³ Marek's review suggests that major problems await clarification. Weeks and Wagner have also recently reviewed the conflicting definitions and interpretations related to black lung compensation.³⁴

One reason for ambiguity has been the use of simple correlation analysis in research. Correlation analysis does not provide an adequate understanding of pulmonary pathophysiology. This observation

was made at least ten years ago,³⁵ even though simple correlations are still reported.²⁵⁻³⁶ In the present study many significant simple correlations were observed, which is not surprising given the overlap in variables and the relatively large number of subjects. A major weakness of simple correlations analysis is that two variables may be spuriously related due to their association with a third variable. Here, exercise tolerance was related to years mining below ground and to age. When multivariate analysis was done, years mining below ground dropped out of significance, presumably because the multivariate analysis controlled for the effect of age. Historically, multivariate analysis has begun to replace simple correlation analysis.

Even multivariate analysis, however, does not account for all interactions. Typical multivariate analysis—for example, regression analysis in the present study—is a “here and now” analysis and does not provide insight into possible time sequences. Further, covariation—that is, the linkage of two or more variables—may obscure the effect of one variable. In the present study years of smoking had no effect on exercise tolerance in the regression analysis. This was probably due to its linkage with FEV₁, which did affect exercise tolerance. Multivariate analysis would miss the impact of smoking because of smoking's covariance with FEV₁. Causal analysis provides a more rational explanation of the observed data—that is, that exercise tolerance is related to FEV₁ and FEV₁ is related in turn to smoking history; thus smoking affects exercise tolerance through its impact on FEV₁.

Interpretation of causal analyses, however, also requires caution. Variables may be shown to be significantly related but that alone does not prove causality. We think it reasonable to suggest that in the population we studied there is some causal relation between underground mining and FVC, and between smoking and decreased FEV₁, and further that FVC and FEV₁ affect exercise tolerance, as the model predicts. We suggest that more use of multivariate techniques and appropriate causal modelling will enhance future studies and help bring about needed research and clarification.

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Accepted 13 March 1989