

Lung Mechanics and Frequency Dependence of Compliance in Coal Miners

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ABSTRACT The mechanical properties of the lungs were studied in two groups of coal miners. The first group consisted of miners with either simple or no pneumoconiosis and was divided into two subgroups (1A and 1B). The former (1A) consisted of 62 miners most of whom had simple pneumoconiosis but a few of whom had clear films. Although their spirometry was normal, all claimed to have respiratory symptoms. The other subgroup (1B) consisted of 25 working miners with definite radiographic evidence of simple pneumoconiosis but normal spirometric findings. The second major group consisted of 25 men with complicated pneumoconiosis.

In subjects with simple pneumoconiosis, static compliance was mostly in the normal range, whereas it was often reduced in subjects with the complicated disease. The coefficient of retraction was normal or reduced in most subjects except those with advanced complicated disease, in several of whom it was elevated. So far as simple pneumoconiosis was concerned, abnormalities, when present, reflected "emphysema" rather than fibrosis. In severe complicated pneumoconiosis, changes suggesting fibrosis tended to predominate. In the 25 working miners (subgroup 1B) dynamic compliance was measured at different respiratory rates. 17 of the subjects in this subgroup demonstrated frequency dependence of their compliance, a finding unrelated to bronchitis and suggestive of increased resistance to flow in the smallest airways.

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INTRODUCTION

Coal workers' pneumoconiosis (CWP)¹ is a condition caused by the inhalation and retention of particles of coal dust in those regions of the lung concerned with gas exchange. Over a period of years the characteristic pathological lesion of CWP, the coal macula, develops. This is characterized by the accumulation of dust around the first- and second-order respiratory bronchioles, a little surrounding fibrosis, and some dilatation of the respiratory bronchioles. The latter lesion is commonly referred to as focal emphysema (1). In about 10% of subjects with simple pneumoconiosis, the disease is complicated by the development of large aggregates of fibrous tissue, usually in the upper zones of the lung. This condition is known as complicated pneumoconiosis, or progressive massive fibrosis (PMF). When the fibrotic masses are extensive, they may lead to severe, restrictive lung disease and cor pulmonale.

Dyspnea occurs frequently in coal workers and is usually related to the presence of chronic obstructive airway disease. However, there is a poor correlation between this symptom and the radiographic category of simple, as opposed to complicated, CWP. The standard tests of ventilatory capacity, viz., spirometry and the various expiratory volume and flow measurements, are influenced mainly by airflow resistance in the larger airways and, to a much lesser extent, by the resistance of the smaller airways. Moreover, there is almost no correlation between these tests of ventilatory capacity and the radiographic category of simple pneumoconiosis (2, 3). Other

¹ *Abbreviations used in this paper:* CWP, coal workers' pneumoconiosis; FEV₁, forced expiratory volume in 1 sec; FVC, forced vital capacity; p, pinhead opacity; PMF, progressive massive fibrosis; q, micronodular opacity.

measurements of lung function in simple CWP rarely show much abnormality in the absence of demonstrable spirometric evidence of airway obstruction (4). Nevertheless, studies of gas exchange occasionally reveal significant abnormalities; and there is some evidence that an increased residual volume may commonly occur in coal workers, even in the absence of a significant reduction in forced expiratory volumes (5).

Since the pathological lesion in CWP involves only the smallest air passages, disorders of which may not be detected by standard tests of ventilatory capacity, the present study was planned to investigate the mechanical properties of the lungs of coal workers in the hope of finding abnormalities that would be likely to originate from pathological changes limited to this part of the lung. In particular, it was hoped to determine whether either the small amount of fibrosis or the focal emphysema found in the disease might alter the elastic properties of the lung. In addition, it was decided to ascertain, in a carefully selected group, whether dynamic compliance was frequency dependent, since if this were so it would be an indication of an increased resistance to airflow in the smallest airways.

METHODS*

Two groups of subjects were studied.

Group 1. This group included only subjects with simple pneumoconiosis. It was divided into two subgroups: 1A and 1B. Group 1A consisted of 62 active or retired coal miners. All had worked for a number of years in the bituminous-coal fields of either Pennsylvania or West Virginia. Some were seeking compensation for "black lung," some had been referred to the Chest Clinic, but all claimed to have respiratory symptoms, and all were volunteers. Only 11 of the subgroup failed to fulfill the criteria of the Medical Research Council for chronic bronchitis (6). Their age ranged from 35 to 71, with a mean of 54 yr. They had worked underground between 8 and 50 yr except for one man who had worked 30 yr at the surface tipple. 20 had no CWP; 23, category 1; 14, category 2; and 5, category 3 simple CWP (7). This subgroup was selected from a larger population on the basis of an absence of significant impairment of ventilatory capacity as defined by a ratio of forced expiratory volume in 1 sec to forced vital capacity, FEV₁/FVC, of not less than 70%. Thus it was assumed that these subjects might well have an increased resistance to flow in the peripheral, but not in the central, airways.

Group 1B consisted of 25 working bituminous-coal miners from northern West Virginia and southwestern Pennsylvania. All had either category 2 or 3 simple CWP of either the pinhead (p) or micronodular (q) types of opacity (7). All were either nonsmokers or had not smoked for the last 10 years. None had an FEV₁/FVC of less than 70%, although 10 of the 25 gave a history of chronic bronchitis. Their age ranged from 42 to 65, with a mean of 55 yr.

These subjects were selected from local coal miners studied in a nationwide field survey undertaken by the U. S. Public Health Service; all volunteered after having re-

ceived a full explanation of the procedures. Details of diffusing capacity in these subjects have already been reported (8).

Group 2. This group consisted of 25 coal workers with respiratory symptoms from the same states as group 1, although 6 of them were anthracite-coal miners. All had complicated CWP, stages B or C (7). In addition, many of these subjects had airway obstruction, and all save seven had chronic bronchitis. Their age ranged from 42 to 78 yr and their underground experience, from 10 to 47 yr. Some mean data on groups 1A and 2 are recorded in Tables I and IV.

Controls. A control group of six subjects in the same age range (41–61, mean 54) underwent the same tests as the subjects in group 1B. These subjects were male members of the teaching staff of the medical school. All were lifelong nonsmokers, and none suffered from any respiratory disease.

Spirometry was performed using a high-fidelity, waterless electronic spirometer (Ohio Medical Products, Madison, Wis., model No. 800). Lung volumes and airway resistance were measured in a constant volume body plethysmograph (Warren E. Collins, Inc., Braintree, Mass.) by the methods of Dubois, Botelho, Bedell, Marshall, and Comroe (9, 10). The normal values used for lung volumes were those predicted by the short formulae of Needham, Rogan, and McDonald (11).

Transpulmonary pressure was estimated by subtracting airway pressure from esophageal balloon pressure, which was measured by a 10-cm long, 3–5-cm in circumference, thin latex balloon containing approximately 0.4 ml of air. The tip of the balloon was positioned approximately 45 cm from the nares (12). Flow was measured by a heated pneumotachograph placed just distal to the mouthpiece. Volume was obtained by electronically integrating the output of the pneumotachograph. Pressure-volume curves were recorded photographically by feeding the outputs of the various transducers to an oscillographic recorder (Electronics for Medicine, White Plains, N. Y.).

Static compliance was calculated from the linear portion, just above functional residual capacity, of the expiratory limb of a static pressure-volume curve obtained over the full vital-capacity range (13). The result reported was the mean of three curves, each preceded by several full inspiratory breaths, to obtain a constant volume history. Recoil pressure at total lung capacity was also measured from this curve. The coefficient of retraction was calculated by dividing pulmonary recoil pressure at total lung capacity by the total lung capacity measured in the plethysmograph (14).

Dynamic compliance was measured in each case during quiet breathing, and in selected subjects, at approximately 30 and 60 breaths per min. Care was taken that the tidal volume remained close to that during quiet breathing and that there was no change in end expiration at the faster rates by having the subject observe his tidal volume record on an oscilloscope during this maneuver.

Transpulmonary pressure was measured by a differential pressure transducer (Statham PM131TC, Statham Instruments, Hato Rey, Puerto Rico) which had a frequency-amplitude response that was $\pm 5\%$ up to 30 Hz with a phase shift of less than 5 degrees. Volume at the mouth was obtained by electronic integration of flow measured by a Fleish No. 3 heated pneumotachograph (Instrumentation Associates Inc., New York) connected to a differential pressure transducer (Statham PM97) with a frequency-amplitude response that was $\pm 5\%$ up to 15 Hz with a phase shift of less than 5 degrees.

* Mention of commercial names and concerns does not constitute endorsement by the U. S. Public Health Service.

TABLE I
Mean Data on Subjects in Group 1A

Radiographic category	Number of subjects		Age	Time underground	Cigarettes	FEV ₁ FVC	Total lung capacity	Residual volume	RV TLC	Functional residual capacity
			<i>yr</i>	<i>yr</i>	<i>pack yr</i>	<i>%</i>	<i>% predicted</i>	<i>% predicted</i>	<i>%</i>	<i>liters</i>
0	20	Mean	51	28	19	80	117	134	43	4.8
		SD	9	11	20	7	20	56	13	1.3
1	23	Mean	58	32	15	80	112	114	41	4.1
		SD	7	9	21	5	22	43	11	1.1
2	14	Mean	55	30	18	78	112	107	37	4.2
		SD	7	10	16	5	14	34	11	0.9
3	5	Mean	53	32	11	78	115	113	38	4.8
		SD	7	13	15	4	16	50	15	0.8

Transpulmonary pressure, flow, and volume were displayed simultaneously on the oscillographic recorder operated at a fast paper speed. Dynamic compliance was calculated by dividing the change in volume by the corresponding change in transpulmonary pressure at zero flow points over at least eight respiratory cycles and taking the mean value. Oscillations in the transpulmonary pressure tracing due to cardiac impulses were smoothed out by eye where necessary before measurement.

RESULTS

Group 1A. The mean results are recorded in Tables I and II. There were no significant differences in age, years of work underground, or smoking history among the groups with no CWP and categories 1, 2, and 3 CWP. Total lung capacity and residual volume tended to be rather higher than predicted in all categories, though this may be the result of the use of the body plethysmograph, which may give higher values than equilibration techniques (15).

Airway resistance at functional residual capacity tended to be slightly elevated in all categories in spite

of normal spirometry and maximal voluntary ventilation. Also, mean static compliance and pulmonary recoil pressure at total lung capacity were normal, though individuals showed values outside the normal range. Almost equal numbers of subjects had a reduced compliance as had an increased value and the same was true of pulmonary recoil pressure (Figs. 1 and 2). There was no tendency for either abnormality to predominate in the more advanced categories of simple CWP.

Static compliance divided by functional residual capacity, in order to allow for differences in lung volumes, is illustrated in Fig. 3. Again, no trend is observed with increasing radiographic category, though several subjects in each group show a marked increase in pulmonary distensibility. Dynamic compliance tended to be somewhat lower than static compliance in all categories (Table II).

Fig. 4 illustrates the coefficient of retraction in individual subjects according to CWP category. Again, there is no significant difference among the categories, though a large number of subjects fall outside the normal

TABLE II
Mechanics—Mean Results in Group 1A Subjects

Radiographic category		Maximal voluntary ventilation	Airway resistance at FRC	Pulmonary recoil pressure at TLC	Static compliance	Dynamic compliance	Coefficient of retraction
		<i>liter/min</i>	<i>cm H₂O/liter per sec</i>	<i>cm H₂O</i>	<i>liter/cm H₂O</i>	<i>liter/cm H₂O</i>	<i>cm H₂O/liter of TLC</i>
0	Mean	117	3.2	29	0.26	0.20	4.1
	SD	38	1.4	12	0.13	0.11	1.8
1	Mean	115	2.5	27	0.25	0.16	4.2
	SD	35	0.7	8	0.11	0.08	1.3
2	Mean	114	2.9	31	0.27	0.18	4.8
	SD	28	1.0	12	0.14	0.10	2.3
3	Mean	141	2.4	27	0.26	0.24	3.9
	SD	35	1.1	6	0.07	0.07	1.0

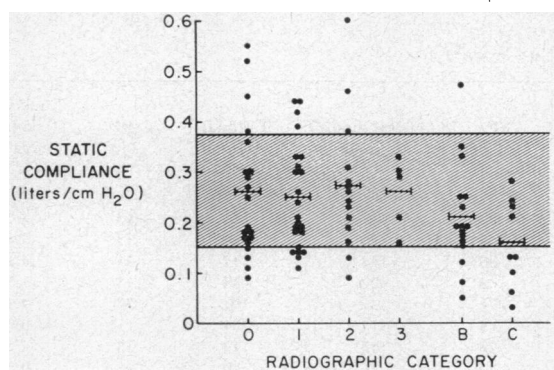


FIGURE 1 Static compliance in subjects (group 1A and group 2) with different radiographic categories of coal workers' pneumoconiosis. (Hatched area represents normal range.)

range, and most of these show values lower than normal. 37 of the subjects with simple CWP had a normal coefficient; 22 had low values, and only 3 had high values. The coefficient of retraction showed a significant negative correlation with residual volume ($r = -0.49$), residual volume divided by total lung capacity ($r = -0.44$), and functional residual capacity ($r = -0.49$).

Group 1B. All these subjects had normal spirometry and lung volumes. The mean values and standard deviations are shown in Table III. The differences between those with p and q types of radiographic opacity have been reported previously (8). Airway resistance was normal in all subjects, as was specific conductance (the reciprocal of airway resistance divided by functional residual capacity). Static compliance and pulmonary recoil pressures are shown in Figs. 5 and 6. The coefficient of retraction was reduced in nine subjects and increased in none.

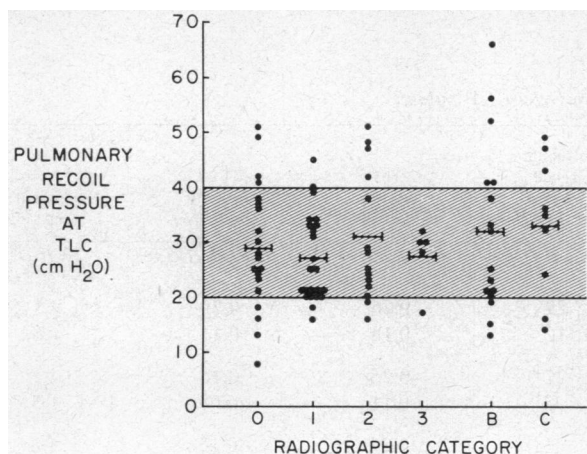


FIGURE 2 Pulmonary recoil pressure at total lung capacity in subjects (group 1A and group 2) with different radiographic categories of CWP. (Hatched area represents normal range.)

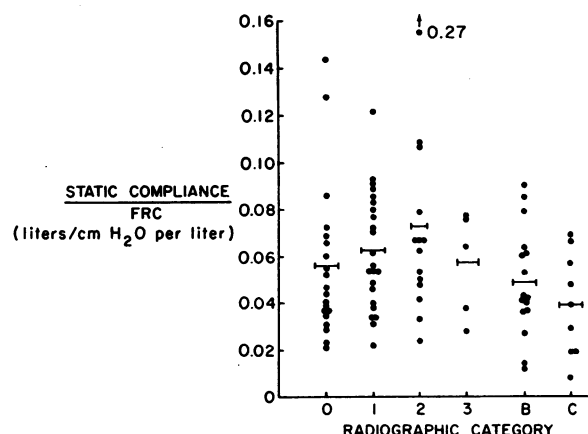


FIGURE 3 Specific compliance in subjects (group 1A and group 2) with different radiographic categories of CWP.

cient of retraction was reduced in nine subjects and increased in none.

The changes in dynamic compliance with increasing respiratory rates expressed as a percentage of dynamic compliance at the lowest frequency are illustrated in Figs. 7 and 8. Of the 10 bronchitic subjects, 6 showed a fall in compliance at rapid respiratory rates; and of these 6, 2 had a low coefficient of retraction. 11 of the 15 nonbronchitic subjects showed a fall in compliance at faster rates of respiration, 4 of these also having a low coefficient of retraction. No relationship was observed between the coefficient of retraction and a change in dynamic compliance at increased rates of respiration. These studies were repeated after inhalation of an aerosol of isoproterenol in 10 of the subjects in whom there was a fall in compliance, and in none did it alter the response.

Group 2. The mean results are recorded in Tables IV and V. These subjects were slightly older and had

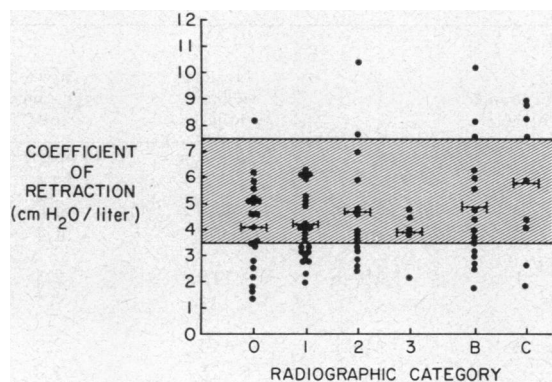


FIGURE 4 Coefficient of retraction in subjects (group 1A and group 2) with different radiographic categories of CWP. (Hatched area represents normal range.)

TABLE III
Data on Working Coal Miners and Controls

	Number of subjects		Age	FEV ₁ /FVC	Total lung capacity	Residual volume	Airway resistance at FRC	Dynamic compliance, quiet breathing
			yr	%	% predicted	% predicted	cm H ₂ O/liter per sec	liter/cm H ₂ O
Miners	25	Mean	55	76	94	76	1.7	0.24
		SD	5	6	11	23	0.6	0.07
Controls	6	Mean	54	81	99	72	1.3	0.20
		SD	7	4	11	26	0.5	0.09

worked longer underground than those in group 1. They had more airway obstruction, and had smoked more cigarettes. Their total lung capacity was somewhat greater than predicted. This was associated with a marked increase in residual volume, presumably related to the greater airway obstruction in this group. Maximal voluntary ventilation was reduced, and airway resistance was increased. Pulmonary recoil pressure at total lung capacity was slightly higher than in the subjects with simple or no CWP, and several individuals had abnormally high values (Fig. 2). Static compliance was reduced, compared with the subjects in group 1; and this was most marked in the men with advanced, stage C, complicated CWP (Fig. 1). Dynamic compliance was again lower than static compliance, as in group 1 (Table V). Static compliance divided by functional residual capacity tended to be reduced in those with both stages B and C complicated CWP (Fig. 3). Similarly, the coefficient of retraction was somewhat higher in those with the complicated disease than in those with no or simple CWP. 11 of these subjects had a normal coefficient; low values were found in 7, and high values in the remaining 7 (Fig. 4).

Normal controls. Six comparable subjects of the same age were studied. Their characteristics and lung volumes are shown in Table III. The values for their static lung compliance and elastic recoil pressure are shown in Fig. 5 and 6. One subject had a very low pulmonary recoil pressure and coefficient of retraction, a finding suggestive of loss of retractive forces in his lungs. In no case was a significant fall in the dynamic compliance found at faster rates of respiration (Fig. 9).

DISCUSSION

Studies of coal workers' pneumoconiosis are complicated by the fact that a high proportion of subjects living in mining communities have obstructive airway disease. This obstruction could originate in either the central or peripheral airways, although it is felt that the former site is the more probable. Most of these subjects give a history of chronic bronchitis; moreover, it has been demonstrated that this disease is much more important than CWP as a cause of functional abnormalities and therefore masks any changes due to simple CWP (2, 3, 16, 17). In this study the subjects with simple CWP

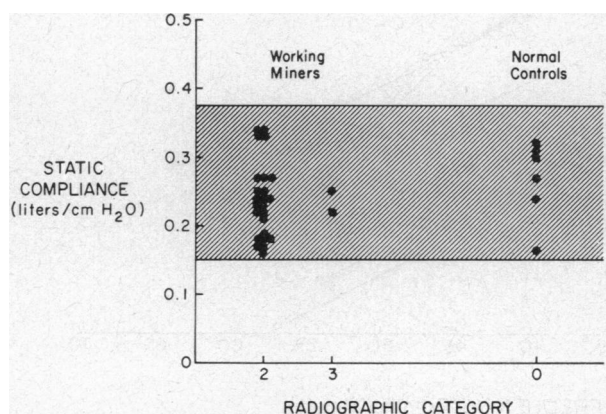


FIGURE 5 Static compliance in working miners with categories 2 and 3 (group 1B) and also in normal controls.

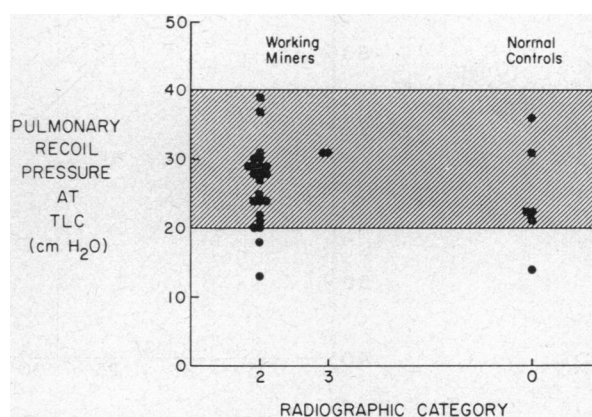


FIGURE 6 Pulmonary recoil pressure at total lung capacity in working miners with categories 2 and 3 (group 1B) and also in normal controls.

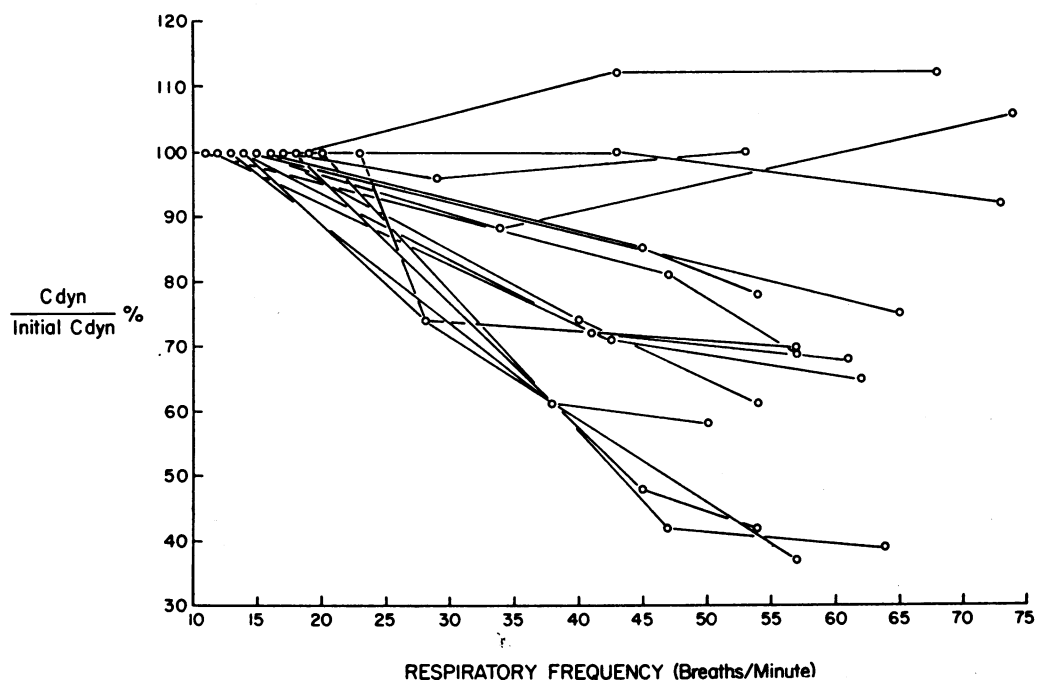


FIGURE 7 Dynamic compliance at different respiratory rates expressed as a percentage of the initial dynamic compliance (working miners, nonbronchitic).

were specifically selected on the basis of normal spirometry, thereby rendering it possible to study the effects on pulmonary function of pneumoconiosis uncomplicated by other respiratory disease.

As the essential pathological lesion of CWP is the coal macula with its attendant focal emphysema (1), the physiological abnormalities detectable might be expected to be of the sort associated with emphysema. These

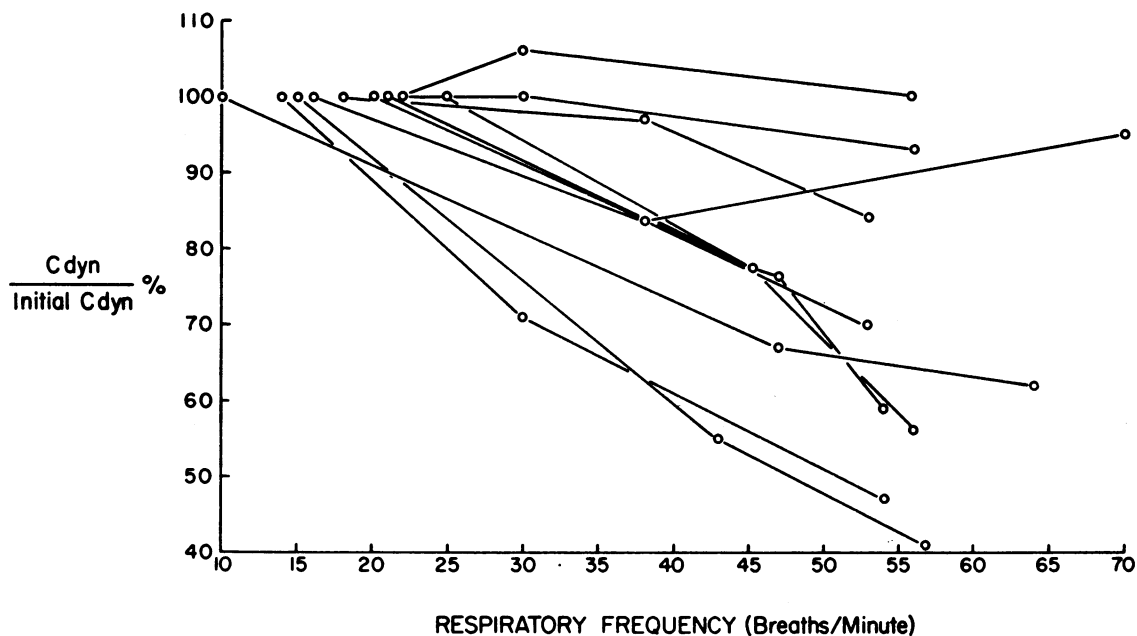


FIGURE 8 Dynamic compliance at different respiratory rates expressed as a percentage of the initial dynamic compliance (working miners with bronchitis).

TABLE IV
Mean Data on Subjects in Group 2

Radiographic category	Number of subjects		Age	Time underground	Cigarettes	$\frac{FEV_1}{FVC}$	Total lung capacity	Residual volume	$\frac{RV}{TLC}$	Functional residual capacity
			yr	yr	pack yr	%	% predicted	% predicted		liters
B	16	Mean	65	32	26	56	113	138	53	4.3
		SD	9	9	33	16	18	44	14	1.5
C	9	Mean	57	26	29	62	102	128	48	4.4
		SD	8	11	30	11	18	59	16	1.3

TABLE V
Mechanics—Mean Results in Group 2 Subjects

Radiographic category		Maximal voluntary ventilation	Airway resistance at FRC	Pulmonary recoil pressure at TLC	Static compliance	Dynamic compliance	Coefficient of retraction
		liter/min	cm H ₂ O/liter per sec	cm H ₂ O	liter/cm H ₂ O	liter/cm H ₂ O	cm H ₂ O/liter of TLC
B	Mean	73	4.1	32	0.21	0.14	4.9
	SD	37	1.6	16	0.10	0.06	2.3
C	Mean	77	3.6	33	0.16	0.10	5.8
	SD	33	0.9	13	0.09	0.05	2.7

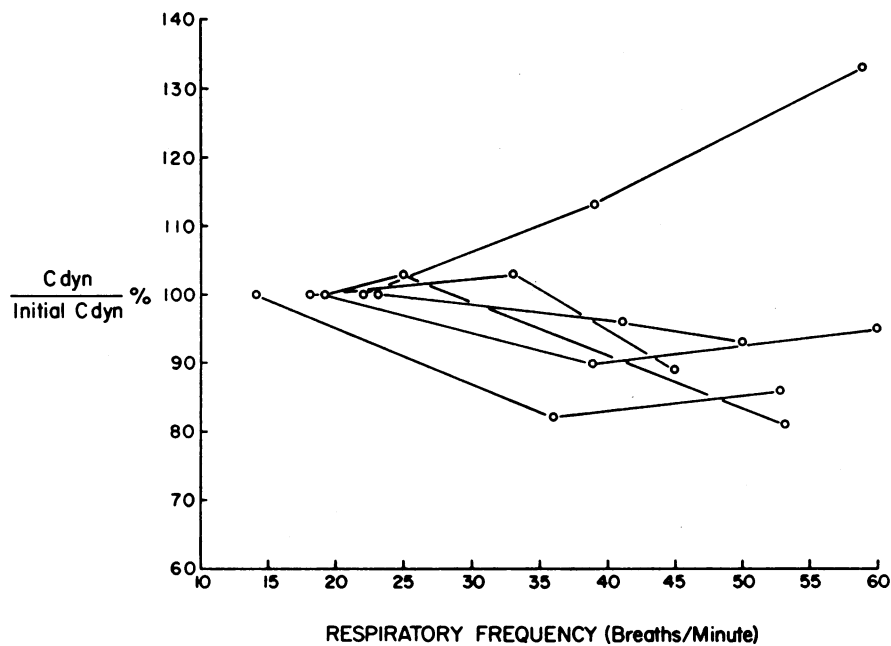


FIGURE 9 Dynamic compliance at different respiratory rates expressed as a percentage of the initial dynamic compliance (normal controls).

might include an increase in residual volume, as has already been shown by Morgan, Burgess, Lapp, Seaton, and Reger (5), and alterations in pulmonary mechanics, such as a high compliance and a low pulmonary recoil pressure. However, these latter changes could be masked if significant interstitial fibrosis were present in the coal macula.

In a detailed study of lung mechanics in CWP, Leathart (18) found an increase in the nonelastic work of respiration in many instances. He postulated that this was related to increased expiratory airway resistance, but he did not confirm this hypothesis. He found inspiratory resistance to be normal. Pulmonary compliance was slightly decreased in his elderly subjects, but was normal in the younger ones, and showed no relationship to CWP category. This fall in compliance in the elderly may have been related to an increase in airway resistance in these subjects, as the author measured dynamic rather than static compliance.

Ferris and Frank (19) studied a group of 25 coal miners with respiratory symptoms and found compliance to be somewhat reduced in subjects with complicated CWP. In the subjects with no or simple CWP, there was a wide scatter of values of compliance, with a tendency for a decrease with increasing disability. Many of these subjects also had an increased airway resistance.

Miners with respiratory symptoms (group 1A). The results in our subjects indicate that the majority of miners with symptoms who have no evidence of airway obstruction have normal pulmonary mechanics. A large number, however, have a lower dynamic than static compliance. A negative correlation was found between coefficient of retraction and residual volume, functional residual capacity, and residual volume divided by total lung capacity, even in those subjects with no airway obstruction. As these measurements have themselves been shown to correlate with the pathological demonstration of emphysema (20), a low coefficient of retraction may well also be a guide to the presence of emphysema, which was therefore probably present in a number of our subjects. The absence of any correlation of coefficient of retraction with CWP category either may mean that the emphysema is a coincidental process or may simply reflect the relatively small numbers of subjects studied.

Among the subjects with complicated CWP (group 2), a higher proportion had a reduced compliance, a high recoil pressure, and a raised coefficient of retraction. These men evidently had a predominance of fibrosis over emphysema. Nevertheless, several subjects with complicated CWP still had lung mechanics that were either normal or suggestive of emphysema. In these latter subjects the presence of traction bullae and compensatory overdistension in the parts of the lung not involved

by fibrosis provides an adequate explanation for this anomalous finding.

Small-airway disease. Minor abnormalities in gas exchange have been demonstrated in coal workers with respiratory symptoms (21), though these usually improve with exercise in the subjects without airway obstruction (4). These findings are best attributed to ventilation-perfusion abnormalities. Such disorders might conceivably be due to abnormalities of perfusion caused by small-vessel disease, though this appears unlikely in view of recent studies of hemodynamics in such subjects (22, 23). A more likely cause is maldistribution of ventilation, which might be related either to focal emphysema or to obstructive disease of the small (less than 1 mm in diameter) airways. This latter type of lesion is often not detected by spirometry or by measurements of airway resistance, as the contribution of the airways of this size to total airway resistance is usually less than 15% (24, 25). The only technique currently available to assess the presence of abnormal resistance to airflow through the small airways is the measurement of compliance at increasing rates of respiration (26). A fall in dynamic compliance at faster rates has been assumed to indicate that the peripheral airways are narrowed sufficiently to obstruct inflation of the parts of the lung distal to them in the time course of each breath. Thus, the distensibility of the lung appears to decrease under dynamic conditions, and therefore the measured compliance is reduced. This technique has been used when the total airway resistance is normal to adduce evidence of small airway disease in subjects with early chronic bronchitis and in asthmatics in remission since an increased resistance in the larger airways might have a similar effect on dynamic compliance (25). Although frequency dependence of compliance is generally accepted as evidence of small-airway disease, it is possible that nonuniform emphysematous involvement of the lungs might be associated with different time constants for the different regions. This possibility must be borne in mind in view of the reduced lung recoil that was demonstrated in many of our subjects. Nonetheless, no relationship between frequency dependence and diminished retractive forces was present in them.

Our finding of a fall in dynamic compliance at faster rates of respiration in the working miners (group 1B) may mean that simple CWP causes an increase in resistance to flow through the small airways. In the non-bronchitic group, no other cause for the finding was obvious: all had normal airway resistance and essentially normal static compliance and pressure-volume curves. The change is not likely to be an effect of age, as it did not occur in the six control subjects. Woolcock, Vincent, and Macklem (26) found a fall in dynamic compliance in one normal subject, but were able to reverse

this with bronchodilators, whereas in our subjects, bronchodilators had no effect. It is not possible to say, from the present study, whether the changes are related to pneumoconiosis or to the effect of working in coal mines, inasmuch as we have not studied a comparable group of subjects exposed to dust but without pneumoconiosis. It is possible that the lesion causing frequency dependence of compliance is in the small non-respiratory bronchioles rather than in the acinus and that it represents a bronchiolitis related to irritation by dust rather than simple pneumoconiosis itself. Whatever its pathological basis, the finding of frequency dependence of compliance in these subjects suggests small-airway disease, and may help to explain the presence of abnormalities in gas exchange found in coal miners.

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