Hyperinflation of the lungs in coal miners

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The residual volume and total lung capacity of 1,455 working Pennsylvania coal miners were determined as part of a larger epidemiological study. The age of the subjects varied between 18 and 65 with a mean of 48·7 years. The total lung capacity of the subjects was determined from standard posteroanterior and lateral chest films while the forced vital capacity was determined by spirometry (O'Shea *et al.*, 1970). The effect of increasing radiographic category of simple coal workers' pneumoconiosis on lung volumes was investigated. It was shown that the residual volume increased with radiographic category and that this occurred whether or not the miners had obstructive airways disease. The presence of obstruction had an additional effect over and above that due to coal dust alone, so that the largest increase in residual volume was found in miners who had both obstruction and radiographic evidence of simple coal workers' pneumoconiosis.

The basic pathological lesion of coal workers' pneumoconiosis (C.W.P.), the coal macule, is characterized by a large amount of dust aggregated around the first and second divisions of the respiratory bronchiole, a little fibrosis—usually of the reticulin type—and the frequent presence of enlarged air spaces in the centre of the coal dust aggregates (Gough, 1940 ; Heppleston, 1953). The bronchiolar dilatation that is found in C.W.P. is commonly referred to as focal emphysema, and although it affects the same region as does the centrilobular variety of emphysema, it may be distinguished from the latter by the absence of an associated bronchiolitis and the presence of aggregates of coal dust. While simple C.W.P. seems to have little effect on the standard tests of ventilatory capacity until progressive massive fibrosis (P.M.F.) is reached (Gilson and Hugh-Jones, 1955), it is difficult to believe that the atrophy of the bronchiolar smooth muscle and the presence of widespread focal emphysema do not lead to changes in some of the lung volumes, in particular in the residual volume (RV) and functional residual capacity (FRC). The aim of this study was to see whether the presence of C.W.P. in the absence of obstructive disease is associated with an increase in the amount of air distal to the terminal bronchiole.

MATERIALS AND METHODS[1]

One thousand four hundred and fifty-five working miners from six mines in central and western Pennsylvania were included in the study. The average age was 48·7 with a range of 18 to 65 years. Of these miners, 81 were below 30 years, 110 were between 30 and 39, 492 between 40 and 49, 661 were between 50 and 59, and 111 were 60 years or over. The mean height was 68·9 in (1·75 m). Participation was entirely voluntary, and in no mine was there less than a 96% response. Thirty-seven men employed at a government research facility were studied as controls. Although some had relatively sedentary jobs, other were employed in a janitorial capacity and hence were used to physical work. Their ages ranged between 41 and 59 with a mean of 47·4 years, while their height ranged between 65 and 76 in (1·6 and 1·9 m) with a mean of 70·2 in (1·7 m).

Each participating subject answered a short questionnaire concerning respiratory symptoms and occupation. A standard 6-foot postero-anterior and left lateral chest film were taken. The forced expiratory vital capacity (FVC), forced expiratory volume in one second ($FEV_{1·0}$), and a flow-volume loop (FV loop) were measured with a waterless spirometer (Electro/Med Model 780) equipped with an air

[1] Mention of brand names does not constitute endorsement by the U.S. Public Health Service.

temperature probe (Yellow Spring Model 405). The spirometer has an internal calibrator that produces electrical voltages proportional to flow and volume. These are checked periodically by the use of a calibrated 1,000 ml plastic syringe and by constant flows over the range from 0 to 10 litres per second using a calibrated manometer (Vol-O-Flow, National Instrument Laboratories, Inc., Rockville, Md). The electrical calibrations of the spirometer have not been found to vary appreciably over several months of continuous operation. An electronic pulse generator was used to superimpose timing marks on to the FV loop to permit measurement of the timed lung volumes (Hankinson and Lapp, 1970). Flow-volume loops of FVC manœuvres were recorded on a storage oscilloscope (Tektronics Model 564). After two practice manœuvres, three forced expirations were recorded and the loops were photographed with an attached camera (Polaroid C-12). Measurements were made from the photographs, and the highest of the three was accepted as the observed value.

We used the simplified regression equations of Needham, Rogan, and McDonald (1954) for determining predicted residual volume (RV), total lung capacity (TLC), and the ratio of RV/TLC. Their figures were converted from A.T.P.S. to B.T.P.S. (assuming a constant ambient temperature of 20° C and a barometric pressure of 760 mm) to allow comparison with the measurements made in this study. The TLC was determined by the radiographic method of Barnhard, Pierce, Joyce, and Bates (1960). Previous studies carried out in the Appalachian Laboratory for Occupational Respiratory Diseases have shown that this is an acceptable method which gives similar results to those obtained by the body plethysmograph (O'Shea et al., 1970; Reger and Jacobs, 1970). The subjects were divided into those with and without obstructive airways disease, according to whether their $\frac{\text{FEV}_1}{\text{FVC}}$ % was or was not less than 70 %. The chest radiographs were independently classified by three observers according to the UICC classification

of pneumoconiosis (Bohlig et al., 1970) and the consensus was accepted. Where this was not achieved, a fourth reader was included and a consensus was thus obtained. For the purposes of this study, simple pneumoconiosis was divided into categories 1, 2, and 3. However, owing to the relatively small number of subjects with P.M.F., subjects with the latter form of the disease were not subdivided into categories A, B, and C.

All the subjects except those with P.M.F. were separated into two main groups depending on the presence or absence of airways obstruction. Each group was then subdivided according to radiographic category into three subgroups, thus making a total of six groups, namely:

Group 1—non-obstructed subjects without evidence of C.W.P.

Group 2—subjects with obstructive airways disease but without evidence of C.W.P.

Group 3—non-obstructed subjects with category 1

Group 4—obstructed subjects with category 1

Group 5—non-obstructed subjects with categories 2 and 3

Group 6—obstructed subjects with categories 2 and 3.

Since there were relatively few subjects with P.M.F. and since most had evidence of airways obstruction, no attempt was made to subdivide them on the basis of the obstructive airways disease. Group 7, therefore, included all the subjects with P.M.F. All tests for statistical reliability were made at the 95% confidence level.

<div style="text-align:center">

RESULTS

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RELATION OF RADIOGRAPHIC CATEGORY TO RESIDUAL VOLUME　The mean ratio of the observed residual volume (RV_o) to predicted (RV_p) expressed as a percentage (RV_o/RV_p)% for the first six groups is shown in Table I. It is apparent from

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T A B L E　I

MINERS WITH SIMPLE PNEUMOCONIOSIS

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Category	Non-obstructed				Obstructed			
	No. of Subjects	Mean (RV_o/RV_p) %	Mean (TLC_o/TLC_p) %	Mean $\frac{RV_o/TLC_o}{(RV/TLC_p)}$ %	No. of Subjects	Mean (RV_o/RV_p) %	Mean (TLC_o/TLC_p) %	Mean $\frac{RV_o/TLC_o}{(RV/TLC_p)}$ %
0	561	107·6 (1·69)	102·6 (0·65)	88·5 (0·98)	214	132·4 (2·61)	111·7 (0·97)	99·6 (1·47)
1	308	118·8 (2·12)	105·9 (0·89)	94·7 (1·12)	154	136·6 (3·56)	111·4 (1·28)	101·2 (1·66)
2 & 3	128	123·2 (2·99)	107·0 (1·23)	97·6 (1·64)	55	146·3 (5·52)	114·8 (2·08)	106·9 (2·64)
Controls	33	95·8 (4·46)	98·0 (2·23)	80·3 (2·78)				

Figures in parentheses are standard errors of the mean.

the table that the subjects without obstruction have a lower mean $(RV_o/RV_p)\%$ than do those with obstruction. Also of interest is the fact that the non-obstructed subjects with category 1 (group 3) and categories 2 and 3 (group 5) simple pneumoconiosis have a significantly increased $(RV_o/RV_p)\%$ when compared to the non-obstructed, non-pneumoconiotic miners. This would seem to indicate that radiographic evidence of C.W.P. is associated with an increased residual volume in the absence of obstruction of the large airways (Fig. 1). Although the mean $(RV_o/RV_p)\%$
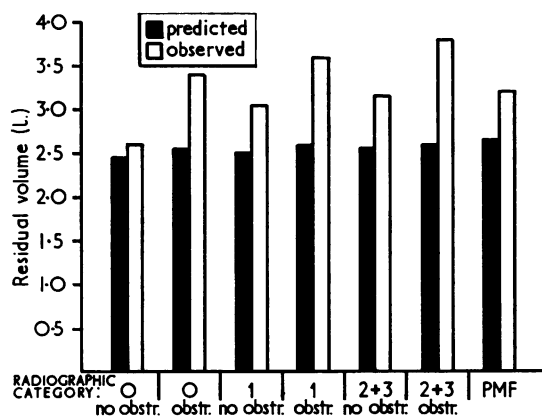

FIG. 1. *Mean residual volume (B.T.P.S.) of seven groups of miners.*

FIG. 2. *Relation of* $\dfrac{Residual\ volume\ (obs.)}{Residual\ volume\ (pred.)}$ *to radiographic category.*

is somewhat higher in the non-obstructed miners with categories 2 and 3 (group 5) than it is in the non-obstructed miners with category 1 (group 3), the difference is not significant.

The same trend is apparent in the miners who have evidence of obstruction. Here the difference in mean $(RV_o/RV_p)\%$ between the obstructed subjects without pneumoconiosis (group 2) and those who have obstruction with category 1 (group 4) is not significant. However, there was a significant difference in the obstructed subjects without pneumoconiosis (group 2) and the obstructed subjects with categories 2 and 3 (group 6). The differences in the (RV_o/RV_p) ratio for the three obstructed groups could not be accounted for by different degrees of obstruction between the groups; thus, the mean $\dfrac{FEV_1}{FVC}\%$ for groups 2, 4, and 6 was 62·2, 62·7, 63·6%, respectively. In all instances, the observed mean value for the RV is greater than the predicted value (Figs 1 and 2).

The control group (Table I) had a relatively normal mean (RV_o/RV_p) and did not differ sig-
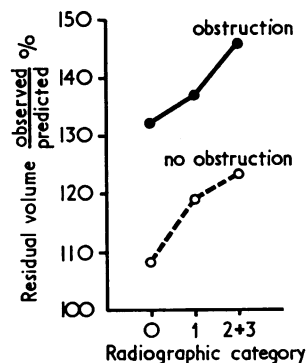
nificantly from the miners who had neither obstruction nor pneumoconiosis. Nonetheless, there was a significant difference between the mean ratio for the non-obstructed miners as a whole and the controls.

In regard to the subjects with P.M.F. (group 7), most showed some degree of airways obstruction and hence their mean $(RV_o/RV_p)\%$ was greater than that of the subjects without pneumoconiosis or obstruction (Table II).

TABLE II
MINERS WITH P.M.F.

No. of Subjects	Mean $(RV_o/RV_p)\%$	Mean $(TLC_o/TLC_p)\%$	Mean $\dfrac{RV_o/TLC_o}{(RV/TLC)_p}\%$
35	121·9 (5·39)	108·7 (2·45)	95·5 (3·05)

RELATION OF RADIOGRAPHIC CATEGORY TO TOTAL LUNG CAPACITY When the mean ratio of observed total lung capacity (TLC_o) to predicted (TLC_p) expressed as a percentage $(TLC_o/TLC_p)\%$ for each group is compared, a slight upward trend of the ratio with increasing radiographic category is evident (Table I). There is a significant difference, however, only between group 1 (non-obstructed, non-pneumoconiotic) and groups 3 and 5 (non-obstructed with category 1 and non-obstructed with categories 2 and 3). The mean values for TLC_o and TLC_p are shown in Figure 3.

RELATION OF RADIOGRAPHIC CATEGORY TO RESIDUAL VOLUME/TOTAL LUNG CAPACITY RATIO $(RV/TLC)\%$ If the mean ratio of $RV_o/TLC_o/(RV/TLC)_p$ expressed as a percentage for each
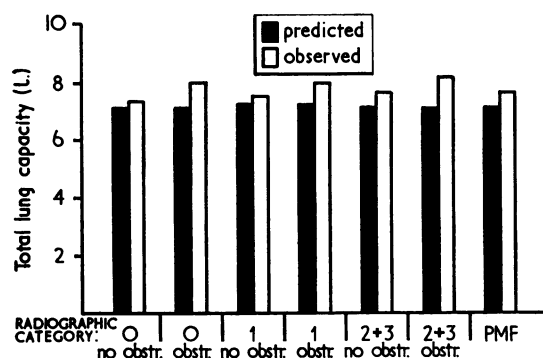
FIG. 3. *Mean total lung capacity (B.T.P.S.) of seven groups of miners.*

FIG. 4. *Relation of* $\dfrac{\text{Residual volume (obs.)}}{\text{Residual volume (pred.)}}$ *in non-obstructed miners to radiographic category.*

FIG. 5. *Relation of* $\dfrac{\text{Residual volume (obs.)}}{\text{Residual volume (pred.)}}$ *in obstructed miners to radiographic category.*

group is compared, again there is an upward trend with increasing radiographic category. The difference is significant for group 1 (non-obstructed, non-pneumoconiotic) as compared to groups 3 and 5 (non-obstructed with category 1 and non-obstructed with categories 2 and 3). There is also a significant difference between the obstructed non-pneumoconiotic miners (group 2) and the obstructed miners with categories 2 and 3 (group 6). Although the ratio of $RV_o/TLC_o/(RV/TLC)_p$ is less than 100% in all save the groups with obstruction, in all cases it is greater than in the normal controls. This discrepancy between a higher than predicted RV_o and a lower than predicted RV_o/TLC_o is explained by the fact that Needham's formula for RV/TLC gives a higher value than the ratio of his formulae for RV and TLC separately.

INFLUENCE OF SMOKING ON RESIDUAL VOLUME IN MINERS WITH AND WITHOUT OBSTRUCTION ACCORDING TO RADIOGRAPHIC CATEGORY When the miners without obstruction are divided into smokers, ex-smokers, and non-smokers, and the mean $(RV_o/RV_p)\%$ for each subgroup is plotted against radiographic category, there is a constant upward trend regardless of smoking habits (Fig. 4). Turning now to the miners with airways obstruction, some apparently anomalous findings are evident (Fig. 5). First, the non-smoking miners without pneumoconiosis have a higher mean $(RV_o/RV_p)\%$ than do the non-smoking miners with category 1. The same situation exists in the ex-smokers. Nonetheless, the mean $(RV_o/RV_p)\%$ for both the non-smokers and the ex-smokers with categories 2 and 3 is markedly higher than the corresponding ratios for category 0 and category 1. This unexpected finding, viz., the $(RV_o/$
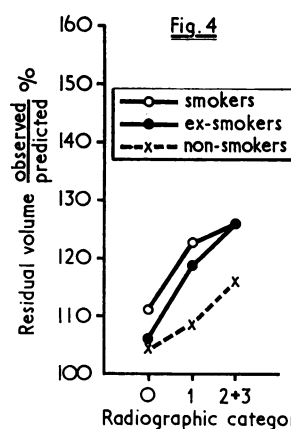
$RV_p)\%$ being higher in the obstructed miners without radiographic evidence of pneumoconiosis prompted us to go back to these men's histories. It became evident that over 50% of the non-smokers with obstruction had evidence of bronchial asthma and this accounted for the abnormally elevated ratio. The same explanation accounts for the findings in the non-pneumoconiotic ex-smokers.

DISCUSSION

It has been suggested that overinflation of the lungs plays a role in producing respiratory disability in coal miners (Ogilvie, Brown, and Kearns, 1967). There are, however, no studies of the lung volumes in large groups of working miners available that give substance to this impression. Gilson and Hugh-Jones (1955) in their studies failed to show a relation between radiographic category and either RV or $RV/TLC\%$ but their studies included only a limited number of subjects.

There are three explanations which could account for the observed mean RV of the non-obstructed miners being significantly greater than both the predicted RV and the RV of the controls. First, the characteristics of the population included in the study may differ from the Scottish subjects that Needham, Rogan, and McDonald (1954) used when they established their

predicted values. Against this is the fact that the mean RV of the control group of subjects is very close to the predicted mean and indeed tends to be slightly smaller.

Second, the presence of focal emphysema itself could be responsible for the increased residual volume. This seems unlikely since in the pathogenesis of focal emphysema of C.W.P., disruption of the bronchioles is seldom an early feature of the disease (Heppleston and Leopold, 1961), while we found an increased RV in miners without radiographic abnormalities. A third possible cause for the divergence of the predicted and observed RV may lie in the fact that the coal macule leads to an increase in the resistance to flow in the peripheral airways and that the latter may not be detected by standard ventilatory tests. It is further suggested that, while this increase in the distal airways resistance may be sufficient to increase the FRC and the RV, it may be insufficient to produce changes in the forced expirogram (Hogg, Macklem, and Thurlbeck, 1968). The demonstration by Macklem and Mead (1967) that more than 80% of the total airways resistance resides in the proximal airways provides an explanation for this anomaly. Nevertheless, despite the small contribution of the smaller airways to overall flow resistance, their patency has a major influence on lung distensibility. Thus, if 50% of the peripheral bronchioles were obstructed, there would be minimal changes in the total airways resistance, but the distensibility of the lungs would be reduced by half. Since the radiographic category of C.W.P. is closely related to the amount of dust present in the lungs, and since the radiographic abnormalities are produced by the superimposition of coal macules upon one another, then it would be possible for small increases in residual volume to occur before C.W.P. becomes evident on the chest film. This latter explanation seems more probable to us, viz., that C.W.P. is associated with an increase in resistance to flow in the distal airways. Clearly, this possibility needs further study.

Meanwhile, the results of our study suggest that the average RV of coal miners is greater than that of a non coal mining population. As expected, the increase is most marked in miners who have obstructive airways disease but is apparent in those without. Although it is conceded that in severe airways obstruction occasionally there is a difference between the FVC and VC, and hence the subtraction of the FVC from TLC might occasionally give a spuriously high RV, we do not feel that this factor played a significant role

in our study. In this context it is important to bear in mind that the subjects included in this study were all working miners, a circumstance which would tend to exclude subjects with severe obstruction and associated gross changes in RV and in whom there might well be a disparity between FVC and VC. Aside from the increased RV in subjects with obstruction, we demonstrated that the RV increased significantly with increasing radiographic category.

This occurred in the non-obstructed subjects, whether they were smokers or not. Smoking undoubtedly has an additive effect, and the highest RV_o/RV_p ratios were in general present in the pneumoconiotic smokers. The apparently anomalous situation in which the obstructed non-pneumoconiotic groups of ex- and non-smokers were shown to have an unexpectedly high residual volume was explained by finding a high proportion of asthmatic subjects in these groups. In normal circumstances natural selection usually compels the asthmatic subject to leave the coal mine before he has a chance to develop C.W.P. Thus, it is extremely rare to find an asthmatic miner with radiographic evidence of C.W.P. unless the asthma is of recent onset.

The other effects of differential migration are difficult to assess. Nonetheless, we think that in subjects who already have chronic bronchitis, the additional effect of coal dust, with its associated increase in RV, might be sufficient to worsen any respiratory symptoms they already have. Hence, they might tend to leave the occupation prematurely—perhaps before they had time to develop radiographic evidence of the disease. The extent of the effects of the increment in RV that results from the inhalation of coal dust remains a matter for conjecture. Nevertheless, our findings suggest that pre-existing airways disease with chronic obstruction may well be worsened by the inhalation and retention of coal dust.

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