Pulmonary Air Space Size in Coal Miners[1-3]

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SUMMARY

Persistence of a monodisperse aerosol (mean diameter, 0.55 μm) in the human respiratory tract decreases exponentially with time of breath holding. The disappearance of aerosol from inspired gas with and without breath holding was expressed as half-life ($t\frac{1}{2}$) of aerosol persistence. The $t\frac{1}{2}$ of aerosol persistence can be used to estimate the average or effective diameter of the parenchymal air spaces.

Aerosol half-life, lung volumes, maximal expiratory flow at 50 per cent of vital capacity, airway resistance, and single-breath CO diffusing capacity were measured in 35 underground coal miners with radiographic category 0 (no) pneumoconiosis, 34 with radiographic type q (micronodular) pneumoconiosis, and 58 with type p (pinhead) pneumoconiosis.

There were no significant differences between the miners with type p and those with type q simple pneumoconiosis with regard to mean height, age, total lung capacity, forced vital capacity, ratio of forced expiratory volume in one sec to forced vital capacity, maximal expiratory flow at 50 per cent of vital capacity, or CO diffusing capacity. In contrast, miners with type p opacities had a significantly longer mean aerosol persistence ($t\frac{1}{2}$) than did miners with either type q or those with no (category 0) pneumoconiosis. The mean $t\frac{1}{2}$ values for the latter 2 groups did not differ significantly from previously reported values for 36 male nonminers. The mean percentage of aerosol recovered at zero breath holding time was significantly less for miners with type p pneumoconiosis than for miners with type q or no (category 0) pneumoconiosis. The smaller percentage recovered at zero breath holding time was also associated with cigarette smoking and symptoms of bronchitis.

These data are consistent with a hypothesis that underground coal miners with type p pneumoconiosis have narrower small conducting airways and abnormally large peripheral air spaces. It is likely that these differences are related in some way to the reaction in coal miners to dust deposition and cigarette smoking.

Introduction

Previous studies have demonstrated the feasibility of using the rate of aerosol deposition during breath holding as an estimate of "effective" or average pulmonary air space size (1). Air space sizes measured by this method have been shown to correlate poorly with age, height,

weight, and lung volumes. These previous results suggest that marked differences in air space sizes exist in subjects with similar heights and lung volumes. Palmes and Lippmann (2) have also reported that steady-state aerosol deposition and air space sizes are extremely variable

in normal subjects. Because simple coal work-
er's pneumoconiosis is caused by prolonged
inhalation of coal mine dust, and because the
deposition of aerosols in the respiratory tract of
normal subjects is extremely variable, a study
was initiated to determine whether the variabil-
ity in the response to coal mine dust could be
explained by differences in aerosol deposition.

Materials and Methods

A male, nonminer population of 36 members of the
professional and technical staff of the Appalachian
Laboratory for Occupational Safety and Health
(ALOSH), the West Virginia University Medical
Center, and New York University Medical Center was
also studied, and previously reported results (1) are
included here for comparison.

One hundred twenty-seven working underground
coal miners from mines in northern West Virginia
and southwestern Pennsylvania were selected for the
present study. Posteroanterior and lateral chest ra-
diographs, pulmonary function tests, single-breath
aerosol tests, and the British Medical Research Coun-
cil (MRC) questionnaire (3) (which provided an
occupational, smoking, and respiratory history)
were administered to each subject. The chest radio-
graphs were interpreted according to the ILO U/C
Classification of Pneumoconiosis (4) by radiologists
who had previously passed the U. S. Public Health
Service proficiency examination (B readers). Sub-
jects who produced phlegm persistently were con-
sidered chronic bronchitics, regardless of complaints
of cough.

Spirometric examination was performed using a
waterless, electronic spirometer (Model 800, Ohio
Medical Products, Madison, Wis.). For each sub-
ject, at least 5 forced vital capacity maneuvers were
recorded on FM analog tape and were later pro-
cessed on a PDP-12 laboratory computer (Digital
Equipment Corporation, Maynard, Mass.). Total lung
capacity and airway resistance were measured on a
constant volume body plethysmograph (Model 3000,
Ohio Medical Products). Diffusion capacity for CO
(DL_{CO}) was measured by the single-breath technique
using a modular lung function analyzer (Warren E.
Collins, Inc., Braintree, Mass.).

The predicted values for forced vital capacity were
obtained from Kory and associates (5), and the pre-
dicted values for DL_{CO} were obtained from Cotes
(6).

The procedure of estimating air space sizes by the
rate of loss of monodisperse 0.55-μm aerosol parti-
cles ($\sigma g < 1.2$) of triphenylphosphate was identical
to that used in the previous study of healthy sub-
jects (1). The total maneuver involved several quiet
breaths followed by an inhalation to total lung
capacity at which point the programmed sequence
began. The subjects exhaled 1.2 liters, inhaled
1.0 liter of aerosol at normal tidal flow rates, held

their breath at various times ranging from 0 to
30 sec, and exhaled 2.0 liters into a bag, again at nor-
mal tidal flow rates. These volumes were precisely
controlled by a programmed sequencer. There was
a tendency for a subject to exhale more rapidly after
long breath-holding times; when this occurred, the
test was repeated. Inhaled and exhaled aerosol con-
centrations were measured by a light-scattering
technique, and the quantity of aerosol exhaled was
divided by the quantity inhaled to give the persis-
tence for the time the breath was held. Because per-
sistence decreases exponentially with the time of
breath holding (7), it can be expressed in terms of
half-life ($t\frac{1}{2}$). This can be used to calculate, for a
tubular model, the average or "effective" diameter
of the space in which the aerosol is confined.

Aerosol is also lost during inspiration and expira-
tion both to the respiratory tract walls and, to a
lesser degree, to the tubing, valves, and bags of the
apparatus. The fraction lost during the non–breath-
holding portion of the maneuver (Y_0) was estimated
by extrapolating to zero time from the curve relat-
ing aerosol persistence and time of breath holding.

The study population of 127 miners was divided
into 3 groups according to chest radiographic cate-
gory and type of opacity. The first group consisted
of 35 miners with a radiographic category of 0/-
or 0/0 (no pneumoconiosis). The second group
consisted of 58 miners whose radiographs had pre-
dominantly the type p rounded opacities, which
range to approximately 1.5 mm in diameter. The
third group consisted of 34 miners whose radio-
graphs had predominantly type q rounded opaci-
ties, which range from approximately 1.5 mm to
approximately 3 mm in diameter. Those miners with
a type p or q opacity must, by definition, have a
radiographic category of 0/1 or greater, and the
distributions of radiographic categories for the type
p and q groups are given in table 1.

Results

The mean values and standard deviations for
age, height, weight, pulmonary function in-
dices, percentage of aerosol recovered at Y_0, and
aerosol $t\frac{1}{2}$ for the various groups are shown
in table 2. Values for the control population of
nonminers, who were part of the study conduct-
ed in 1975 (1), are also shown in table 2 for

TABLE 1

DISTRIBUTION OF
RADIOGRAPHIC CATEGORIES

Opacity Type	Radiographic Category		
	0/1	1	2
p, no. (%)	30 (51)	23 (40)	5 (9)
q, no. (%)	4 (12)	18 (53)	12 (35)

flow at 50 per cent of vital capacity ($\dot{V}max_{50}$) between the miners with category 0 pneumoconiosis and those with either q- or p-opacity pneumoconiosis. The smaller values for $\dot{V}max_{50}$ observed in miners with either q or p opacities, when compared to the corresponding values for category 0 miners, was, for the most part, due to differences in age and length of exposure to coal dust (analysis of covariance). The results were not surprising, because the lack of correlation between radiographic category and indices of ventilatory capacity has also been reported by Morgan and co-workers (8), Hankinson and associates (9), and Rogan and co-workers (10).

The only significant differences, which were not explained by differences in age, were found in the mean $t\frac{1}{2}$ of aerosol persistence and the percentage recovered at Y_0. Miners with no pneumoconiosis had a mean $t\frac{1}{2}$ that was not significantly different from the mean $t\frac{1}{2}$ value for 36 healthy men studied by us in 1975. Miners with type q small opacities (1.5 to 3.0 mm in diameter) had a mean $t\frac{1}{2}$ that was not significantly different from the $t\frac{1}{2}$ obtained for miners with no pneumoconiosis or from the control population. In contrast, miners whose chest radiographs had type p small opacities (less than 1.5 mm in diameter) had a mean $t\frac{1}{2}$ that was significantly different from either the type q or category 0 miners or the healthy male control subjects.

The cumulative frequency diagram (figure 1) comparing the calculated air space size for miners in the current study shows clearly the
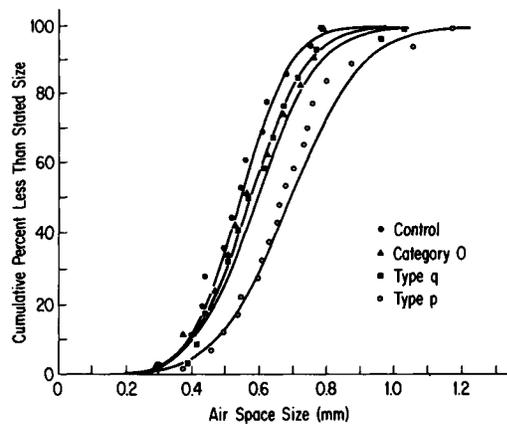
comparison with values for the groups of coal miners. Smokers, ex-smokers, and nonsmokers were combined in each of the radiographic groups.

As expected, groups of miners with q and p opacities were, on the average, 16 years older and had spent more years working underground than had miners with no pneumoconiosis (Category 0), but there was no significant difference between the ages of the q and p miners. There were no significant differences between the mean values for any of the pulmonary function tests other than maximal expiratory

TABLE 2
SUMMARY STATISTICS

Subject Group		Height (inches)	Weight (lbs.)	Age (years)	Years Under-ground	DLCO (% of pre-dicted)	FVC (% of pre-dicted)	FEV₁/FVC (%)	$\dot{V}max_{50}$ (liter/sec)	TLC (liters)	Raw (cm H₂O/liter/sec)	Y₀ (% aerosol recovered)	t½ (sec)
Nonminers*	No.	36	36	36	—	31	36	36	—	36	36	—	36
	Mean	69.9	165.9	32.9	—	101.3	105.5	80.3	—	6.50	1.58	—	20.0
	SD	1.9	19.8	10.7	—	10.4	12.6	6.43	—	0.95	0.44	—	4.4
Miners, category 0	No.	35	35	35	35	30	35	35	32	35	34	35	35
	Mean	68.4	176.1	40.7	13.3	105.9	106.2	73.9†	3.99	6.51	1.93	89.4	21.8
	SD	2.42	23.2	11.1	11.9	16.6	13.8	7.80	1.79	0.75	0.74	5.09	5.46
Miners, type q	No.	34	34	34	34	26	34	32	29	34	34	34	34
	Mean	67.9	176.3	56.4†**	32.6**	105.1	102.9	69.9†	2.97**	6.62	1.54**	88.4	21.8
	SD	3.67	23.9	6.8	10.5	26.5	17.6	8.67	1.39	1.10	0.49	5.64	5.46
Miners, type p	No.	58	58	58	58	56	58	58	58	57	56	58	58
	Mean	68.6	181.7†	56.2†**	29.2†**	105.9	107.0	70.0†**	3.19**	6.64	1.89†††	84.7†**	25.5†**††
	SD	2.51	28.3	4.62	9.59	27.3	16.1	8.80	1.34	0.98	0.63	6.89	6.41

Definitions of abbreviations: DLCO = carbon monoxide diffusing capacity; FVC = forced vital capacity; FEV₁/FVC = ratio of 1-sec forced expiratory volume to FVC; $\dot{V}max_{50}$ = maximal expiratory flow at 50 per cent of vital capacity; TLC = total lung capacity; Raw = airway resistance; Y_0 = zero time of breath holding; $t\frac{1}{2}$ = half-life of aerosol.
* Values obtained from Lapp and associates (1).
† Significantly different from nonminers; $P < 0.05$.
** Significantly different from miners in category 0; $P < 0.05$.
†† Significantly different from miners with type q pneumoconiosis; $P < 0.05$.

Fig. 1. Cumulative frequency diagram comparing air space size calculated from aerosol half-life ($t\frac{1}{2}$) for each of the 4 groups (air space diameter = $t\frac{1}{2} \times 0.027$ mm per sec).

differences in the distribution of $t\frac{1}{2}$ or air space sizes for the groups. Air space size was calculated from $t\frac{1}{2}$ using the equation described in the previous study (1); air space diameter = $t\frac{1}{2} \times 0.027$ mm per sec. Miners in category 0 and those with type q pneumoconiosis had similar distributions of $t\frac{1}{2}$ values or "effective" air space diameters. By contrast, miners with type p opacities had significantly larger $t\frac{1}{2}$ values or larger air spaces in that portion of the lungs where the aerosol remained during breath holding.

As shown in table 2, miners with type p pneumoconiosis also had a smaller average percentage of aerosol recovered at Y_0 than did miners with type q pneumoconiosis and those with no pneumoconiosis. As mentioned previously, the percentage recovered at Y_0 estimates what fraction of the aerosol was lost during the non-breath-holding portions of the study. Because the apparatus and procedure were the same for all subjects, and the inspiratory and expiratory volumes were controlled by a programmed sequence, it is logical to conclude that more aerosol was deposited in the central respiratory passages in miners with p pneumoconiosis than in miners in the other 2 groups during inhalation and exhalation.

Although both mean $t\frac{1}{2}$ and Y_0 for miners with type p pneumoconiosis differed from those values found for the other groups, $t\frac{1}{2}$ and Y_0 were not correlated ($r = -0.18$ for all miners, and $r = 0.01$ for the type p opacity group). This lack of correlation between $t\frac{1}{2}$ and Y_0 suggests that either the mechanisms causing changes in $t\frac{1}{2}$ and Y_0 are different or the changes occur at different sites.

The mean values for $t\frac{1}{2}$, the percentage of aerosol recovered at Y_0, and $\dot{V}max_{50}$ for different radiographic groups and smoking status are shown in table 3. In comparison to control subjects or category 0 group, miners with type p pneumoconiosis had significantly larger $t\frac{1}{2}$ values, regardless of their smoking status; therefore, smokers, ex-smokers, and nonsmokers were combined for each of the radiographic groups shown in table 2. The mean percentage of aerosol recovered at Y_0 was significantly less in the smoking miners with type p pneumoconiosis than in nonsmoking miners with type p pneumoconiosis. Mean $\dot{V}max_{50}$ values were significantly smaller in the smoking miners than in the nonsmoking miners. Lower flow rates were observed in miners with type p and type q pneumoconiosis than in those in category 0, and

this was, for the most part, due to the differences in age between these groups. There was no significant difference in $\dot{V}max_{50}$ between the miners with type p and type q pneumoconiosis. This result was not surprising, because the lack of a relationship between flow rates and radiographic category has also been reported by Hankinson and associates (9) in a much larger cross-sectional study.

In general, the mean percentage of aerosol recovered at Y_0 was less in smokers than in nonsmokers, whereas mean $t\frac{1}{2}$ was approximately equal for the 2 groups. However, mean $t\frac{1}{2}$ was

TABLE 3

MEANS AND STANDARD DEVIATIONS BY SMOKING STATUS AND RADIOGRAPHIC TYPE

Status	No.	Age (years)	$\dot{V}max_{50}$ (liter/sec)	t½ (sec)	Y_0	Pack-Years
Nonsmokers						
Controls	22	29.8 (8.2)	—	18.8 (3.90)	—	—
Category 0	13	39.5 (10.5)*,***	4.09 (1.69)	21.5 (6.31)	89.1 (4.33)	—
Type q	15	56.3 (6.3)*,***	3.29 (1.31)	21.4 (5.76)	90.0 (6.13)	—
Type p	19	55.7 (3.8)*,***	4.07 (0.98)	24.2 (4.97)*	87.1 (7.34)	—
All miners	47	51.4 (10.1)*	3.88 (1.29)	22.5 (5.26)†	88.5 (6.47)	—
Smokers						
Controls	2	25.0 (—)	—	20.6 (—)	—	—
Category 0	13	38.5 (10.3)	4.04 (1.51)	19.4 (5.08)	90.9 (3.96)††,***	14.4 (14.3)
Type q	5	55.0 (9.62)**	2.32 (1.54)††	22.4 (4.20)	85.5 (4.97)††	28.6 (17.2)
Type p	24	55.8 (5.63)**	2.59 (1.27)††,***	24.9 (6.39)	82.6 (6.69)**,***	26.2 (18.2)††
All miners	42	50.4 (11.1)	3.01 (1.52)*,***	22.9 (6.19)	85.5 (6.83)	22.8 (17.5)
Ex-smokers						
Controls	12	40.0 (12.4)	—	22.2 (4.80)***	—	—
Category 0	9	45.6 (12.7)	3.80 (2.40)	22.9 (4.26)	87.5 (7.07)	24.6 (30.1)
Type q	14	56.9 (6.66)*,††	2.98 (1.42)	22.1 (5.84)	87.6 (5.05)	18.9 (23.8)
Type p	15	57.5 (3.72)*,†††	3.02 (1.31)*	28.2 (7.62)†,†††	85.1 (5.89)	28.5 (25.8)
All miners	38	54.4 (8.98)*	3.19 (1.65)*	24.4 (6.42)*,***	86.6 (5.78)	24.0 (25.8)

For definitions of abbreviations, see table 2.
* Significantly different from control values; $P < 0.01$.
† Significantly different from control values; $P < 0.05$.
** Significantly different from control values; $P < 0.01$.
†† Significantly different from category 0; $P < 0.01$.
*** Significantly different from category 0; $P < 0.05$.
‡ Significantly different from category 0; $P < 0.05$.
‡‡ Significantly different from nonsmokers; $P < 0.05$.
††† Significantly different from type q; $P < 0.05$.

larger for ex-smokers than for nonsmokers, whereas mean Y_0 for ex-smokers was only slightly decreased.

Discussion

Significantly larger $t\frac{1}{2}$ values with type p pneumoconiosis in the absence of any difference in D_{LCO} is explicable by the fact that the rate of diffusion through air is approximately 10^5 times greater for gas molecules than for aerosol particles of this size. Therefore, air space size is not a limiting factor in gas exchange.

We have shown that air spaces in those regions of the lungs where aerosol remains during breath holding are larger in miners with p opacities than in those with no opacities or type q opacities, regardless of smoking status. Because the aerosol particles are approximately 0.55 μm in diameter, and the inhalation of 1.0 liter should be sufficient to fill air spaces well beyond the major bronchi (anatomic dead space), most of the aerosol particles remain, during breath holding, in small airways (less than 2 mm in diameter) and air spaces distal to the terminal bronchioles. In addition, the rate of aerosol disappearance during breath holding tends to be dominated by the smallest compartment in which the aerosol remains, or smaller airways and air spaces distal to the terminal bronchioles. Heppleston (11) has shown that it is in this region that the changes occur that bring about focal emphysema associated with coal macule formation, which he recognized as the characteristic lesion of coal mine dust deposition. In a pathologic study of emphysema in coal worker's pneumoconiosis, Ryder and co-workers (12) described their measurement of emphysema as "a simple measurement of the magnitude and extent of abnormal airspaces distal to the terminal bronchiole." They found predominantly focal emphysema and a mean emphysema count at necropsy for type p pneumonconiosis more than twice that observed for type m and n (q) pneumoconiosis. A greater mean emphysema count

for type p pneumoconiosis is consistent with our finding of larger $t\frac{1}{2}$ values or effective air space diameter with type p pneumoconiosis. These data are also consistent with the findings of Cotes and associates (13), who observed a smaller transfer factor per unit lung volume (Kco) and more compliant lungs in miners with type p opacities than in men with type m (q) opacities.

Larger effective air space diameters ($t\frac{1}{2}$ values) were observed in ex-smokers than in nonsmokers or smokers. The fact that smokers do not also have increased effective air space diameters is possibly the result of a simultaneous occurrence of mild changes consistent with both airway narrowing and focal emphysema. The narrowing of the airways associated with bronchitis could mask the occurrence of focal emphysema, resulting in normal $t\frac{1}{2}$ values in smokers. When a miner becomes an ex-smoker, some reversal of bronchitis occurs, the focal emphysema is unmasked, and an increase in effective air space diameter ($t\frac{1}{2}$) is observed (table 3). This hypothesis is further supported by the lack of correlation between $t\frac{1}{2}$ and Y_0, which suggests that $t\frac{1}{2}$ and Y_0 are associated with different disease mechanisms.

A smaller Y_0 suggests that increased deposition occurs because of a decrease in the effective cross-section for airflow in the air spaces through which the aerosol must pass during inhalation and exhalation. Because these maneuvers are performed near total lung capacity, and flow rates are relatively low, decreased Y_0 is best explained by airway narrowing rather than by dynamic compression of the airways.

This hypothesis of airway narrowing is consistent with the smaller values for Y_0 and $\dot{V}max_{50}$ observed in both smokers and bronchitic subjects (table 4). It is also consistent with the finding of Lippmann and associates (14), who observed a much larger tracheobronchial deposition of particles one to 5 μm in diameter in asthmatic and bronchitic subjects than in nonsmoking normal subjects during steady-state

TABLE 4

MEAN $t\frac{1}{2}$ AND Y_0 FOR BRONCHITIC GROUPS

Group	No.	$t\frac{1}{2}$ (sec)		Y_0 (%)		FEV_1/FVC (%)	
		Mean	SD	Mean	SD	Mean	SD
Nonbronchitics	59	22.0	6.79	88.4	5.17	72.7	7.14
Bronchitics	68	24.4*	6.79	85.7*	7.13	69.7*	9.55

For definitions of abbreviations, see table 2.
*Bronchitics significantly different from nonbronchitics, $P < 0.05$.

breathing of aserosols. In addition, Love and Muir (15) found a significantly greater steady-state deposition of particles one μm in diameter in smoking miners. The smoking miners in their study had mean values for forced expiratory flow during the middle half of the forced vital capacity that were significantly less than those observed in the nonsmoking miners. Love and Muir postulated that if the airways are narrowed, there could be an increased turbulent deposition of particles one μm in diameter in these regions. If this were the case, then the smaller Y_0 values observed in our study would correlate with an increase in steady-state aerosol deposition and narrowing of the airways.

In a study using a particle 0.5 μm in diameter and a single-breath aerosol deposition technique similar to that used in this study, Muir (16) found a much lower rate of recovery of 0.5-μm particles in subjects with airway obstruction. This finding is also consistent with the smaller Y_0 and $\dot{V}max_{50}$ values observed in our smoking and bronchitic miners.

The smaller Y_0 in miners with p pneumoconiosis were probably caused by chronic bronchitis that resulted from smoking habits and exposure to coal mine dust. The absence of smaller Y_0 values in miners with type q pneumoconiosis was probably a result of the fact that there were fewer smokers in this group. Miners in radiographic category 0 had worked fewer years underground and therefore had a lower prevalence of chronic bronchitis (17) and less change in Y_0.

These differences in $t\frac{1}{2}$ and percentage of aerosol recovered at Y_0 between type of radiographic opacities cannot be explained by differences in the severity of radiographic category. In this study, miners with type q opacities actually had a greater occurrence of the more severe radiographic categories than did the miners with type p opacities (table 1). The percentage of aerosol recovered at Y_0 and $t\frac{1}{2}$ appears to be more related to the type of opacity than to the severity of the radiographic category.

The significantly larger $t\frac{1}{2}$ values associated with type p pneumoconiosis in the absence of decreased $\dot{V}max_{50}$ may seem inconsistent. However, other studies (8–10) have been unable to establish a relationship between radiographic category and indices of ventilatory capacity. Moreover, the miners in this study had relatively low radiographic categories of pneumoconio-

sis. It is therefore possible that the aerosol measurement of $t\frac{1}{2}$ is more sensitive than $\dot{V}max_{50}$ in detecting changes that occur with radiographic type. This may be due partially to the fact that the measurement is made at or near total lung capacity.

The lack of correlation between $t\frac{1}{2}$ and Y_0 suggests that the mechanisms that cause changes in $t\frac{1}{2}$ and Y_0 are different, or that changes occur at different sites. Although smaller Y_0 values are probably associated with narrowing of the airways caused by smoking and bronchitis, $t\frac{1}{2}$ is probably associated with changes in the terminal bronchioles and air spaces distal to the terminal bronchioles.

References

1. Lapp, N. L., Hankinson, J. L., Amandus, H., and Palmes, E. D.: Variability in the size of airspaces in normal human lungs as estimated by aerosols, Thorax, 1975, 30, 293.
2. Palmes, E. D., and Lippmann, M.: Influence of respiratory air space dimensions on aerosol deposition, in Inhaled Particles IV, Part 1, W. H. Walton, ed., Pergamon Press, Oxford and New York, 1975, p. 127.
3. Medical Research Council's Committee on the Aetiology of Chronic Bronchitis. Standardized questionnaire on respiratory symptoms, Br Med J, 1966, 2, 1665.
4. Cooperative Study by UICC Committee: UICC/Cincinnati classification of the radiographic appearances of pneumoconiosis, Chest, 1970, 58, 57.
5. Kory, R. C., Callahan, R., Boren, H. G., and Syner, J. C.: The Veterans Administration–Army Cooperative Study of Pulmonary Function: I. Clinical spirometry in normal men, Am J Med, 1961, 30, 243.
6. Cotes, J. E.: Lung Function, Blackwell Scientific Publications, Osney Mead, Oxford, 1975, p. 381.
7. Palmes, E. D., Altshuler, B., and Nelson, N.: Deposition of aerosols in the human respiratory tract during breath holding, in Inhaled Particles and Vapours II, C. N. Davies, ed., Pergamon Press, London, 1967, p. 339.
8. Morgan, W. K. C., Handelsman, L., Kibelstis, J., Lapp, N. L., and Reger, R.: Ventilatory capacity and lung volumes of U.S. coal miners, Arch Environ Health, 1974, 28, 182.
9. Hankinson, J. L., Reger, R. B., Fairman, R. P., Lapp, N. L., and Morgan, W. K. C.: Factors in-

fluencing expiratory flow rates in coal miners, in *Inhaled Particles IV*, W. H. Walton, ed., Pergamon Press, Oxford and New York. 1977, p. 737.

10. Rogan, J. M., Attfield, M. D., Jacobsen, M., Rae, S., Walker, D. D., and Walton, W. H.: Role of dust in the working environment in development of chronic bronchitis in British coal miners, Br J Ind Med, 1973, *30*, 217.

11. Heppleston, A. G.: The pathological anatomy of simple pneumoconiosis in coal workers, J Pathol Bacteriol, 1953, *66*, 235.

12. Ryder, R., Lyons, J. P., Campbell, H., and Gough, J.: Emphysema in coal workers' pneumoconiosis, Br Med J, 1970, *3*, 481.

13. Cotes, J. E., Deivanayagam, C. N., Field, G. B., and Billiet, L.: Relation between type of simple pneumoconiosis (p or m) and lung function, in *Inhaled Particles III*, vol. 2, W. H. Walton, ed.,

Unwin Bros., Old Woking, England, 1971, p. 633.

14. Lippmann, M., Albert, R. E., and Peterson, H. T.: The regional deposition of inhaled aerosols in man, in *Inhaled Particles III*, vol. 1, W. H. Walton, ed., Unwin Bros., Old Woking, 1971, p. 105.

15. Love, R. G., and Muir, D. C. F.: Aerosol deposition and airway obstruction, Am Rev Respir Dis, 1976, *114*, 891.

16. Muir, D. C. F.: The effect of airways obstruction on the single breath aerosol curve, in *Airway Dynamics, Physiology and Pharmacology*, Arend Bouhuys, ed., Charles C Thomas, Springfield, Ill., 1970, p. 319.

17. Kibelstis, J. A., Morgan, E. J., Reger, R., Lapp, N. L., Seaton, A., and Morgan, W. K. C.: Prevalence of bronchitis and airway obstruction in American bituminous coal miners, Am Rev Respir Dis, 1973, *108*, 886.