FACTORS INFLUENCING DUST RETENTION IN THE PULMONARY PARENCHYMA *

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INTRODUCTION

Prolonged underground work during the last three decades in British coal mines produced a 10% incidence of radiographically evident lung lesions and a 1–3% incidence of disabling pulmonary fibrosis.[1] Although the probability of developing coal workers' pneumoconiosis is clearly related to the dust levels in the mines;[2] the question arises as to whether there are identifiable and/or rectifiable susceptibility factors that favor the development of disease in some individuals under conditions that do not produce coal workers' pneumoconiosis in most miners. The problem is of more than academic interest, since the identification and control of factors that cause high susceptibility might be a useful supplement to dust suppression measures and might ease constraints on exposure for the general mining population.

Two possible reasons for high susceptibility to coal workers' pneumoconiosis can be identified. One has to do with greater reactive injury to coal dust in the lung; the other involves factors that result in a greater effective dose to the pulmonary parenchyma. The purpose of this paper is to present some observations suggesting that substantial individual differences exist in the effectiveness of particle deposition in the airways and consequently proportionate differences in the effective dose of inhaled coal dust that reaches the pulmonary parenchyma.

METHODS

The techniques used for measuring regional deposition have been described elsewhere [3] and will be discussed only briefly here. Insoluble monodispersed radioactive particles are inhaled by the subject. The retention of the tagged particles is measured by gamma ray detectors viewing the head and chest in a whole body counter.

The technique used to generate the aerosol involves the atomization of an aqueous colloid of ferric oxide with a spinning disk generator [4] capable of producing monodispersed aerosols with diameters between 0.8 microns to 7.0 microns and with a geometric standard deviation less than 1.1. The ferric oxide colloid is spiked with colloids containing technetium 99m or gold 198.

The radioactive tag constitutes less than 1% by weight in the resultant particles. The dried particles leaving the aerosol generator consist of spherical aggregates of the primary colloidal particles that have good structural stability in a tissue environment. The density of the aggregate iron oxide particles is 2.56 g/cm^3.

The subject breathes the aerosol directly from the generator. Most studies involve two consecutive one-minute inhalation periods. Each of the two aerosols is tagged with a different isotope so that the deposition and clearance of each can be measured simultaneously. The subject inhales either through a nose mask or a mouthpiece at a frequency of 14 per minute, with a uniform tidal volume between 700 and 1200 cm^3. The exhaled air is separated from the inhaled by an electrically driven three-way ball valve with passages one-inch in diameter. The exhaled particles are collected in a filter. The respiratory flow rates are measured with a hot wire anemometer to obtain peak and average inhalation rates.

After the inhalation, the subject immediately enters a nearby whole body counter chamber with 6-inch thick steel walls. The low background facility permits studies to be done with very small amounts of radioactivity: the total activity inhaled by the subject does not normally exceed two microcuries for the technetium isotope or 0.1 microcurie for the gold tag. The subject sits in a reclining chair and is counted with a scintillation detector array consisting of four radially-arranged 5-inch diameter by 2-inch thick collimated detectors that measure the total activity in the chest or head with minimal dependence on the geometric distribution of activity within the field of view. Alternate counts of the head or chest can be made by adjusting the height of the seat support. After the head activity is removed or cleared, the serial measurements made of the chest activity are continued in order to follow the kinetics of bronchial mucociliary clearance. Most subjects complete their mucociliary clearance within ten hours, although a few require between ten and 24 hours to complete clearance. Previously reported studies have demonstrated that the radioactivity remaining in the lung at 24 hours is lost at a very slow rate and represents alveolar deposition;[3] the ratio of chest activity remaining at 24 hours to that initially present after inhalation is used as an assessment of the fraction of the aerosol that is deposited in the alveoli.

RESULTS

About 70 subjects have been studied in about 160 studies, most of which involved simultaneous measurements of two aerosols differing in particle size. The subjects were mostly healthy individuals, with about twice as many cigarette smokers as nonsmokers.

FIGURE 1 illustrates a typical set of clearance curves obtained from a single subject, in this case a 55-year-old male cigarette smoker. It shows the serial measurements obtained for the clearance of two aerosols of different particle size on each of five different days over a period of several years. The initial chest activity of each test is normalized to 100%. It is evident from the curves that the alveolar deposition is a function of the size of the inhaled particles and ranges from about 80% at 1.3 and 2.0 microns to virtually zero at 5.8 microns and 7.3 microns. It is also evident that the consistency of the data is reasonably good, in the sense that the inhalation of comparable particle sizes on different occasions produces similar clearance patterns and levels of alveolar deposition.
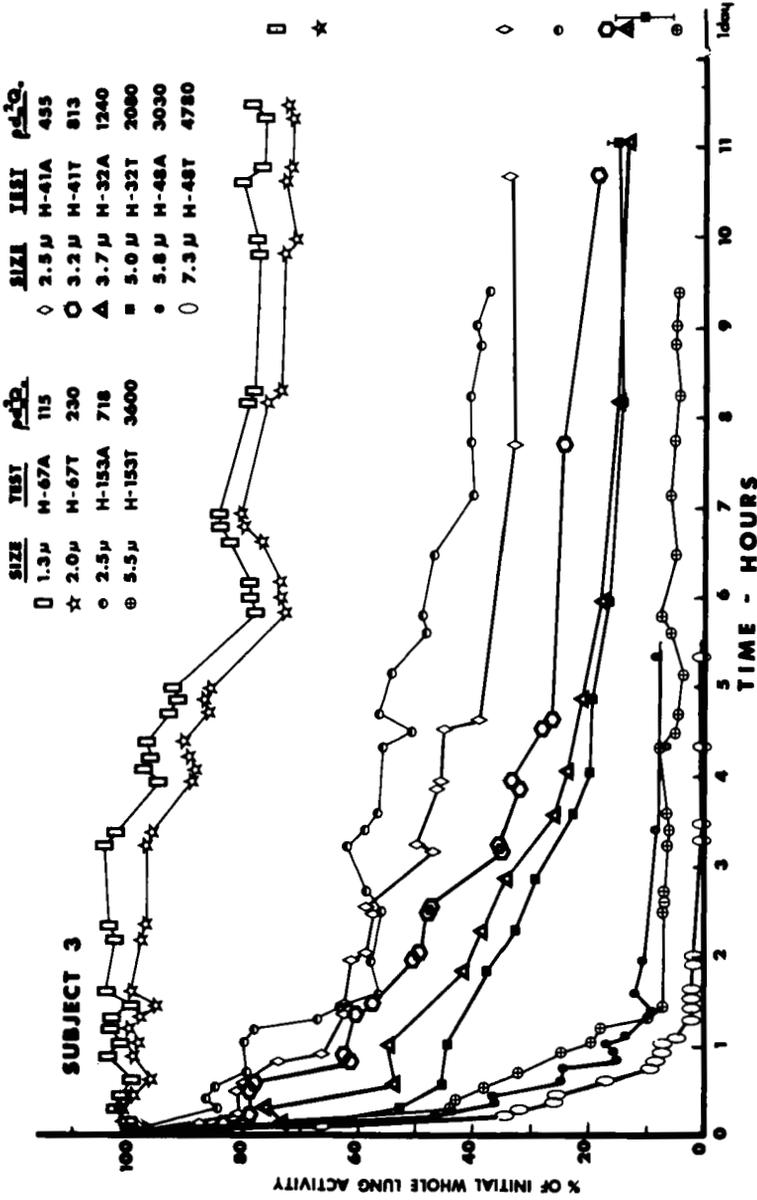
FIGURE 1. Whole lung retention following the inhalation of monodispersed tagged aerosols of the particle sizes indicated for a 55-year-old human male cigarette smoker. Tests 32, 41, and 48 were performed in 1967; test 67 in 1968, and test 153 in 1971.

A summary of some of the head deposition data is presented in FIGURES 2 and 3 as a function of the impaction parameter $\rho d^2 Q_n$, where ρ is the particle density in g/cm^3 (2.56), d is the particle diameter in microns, and Q_n is the average inspiratory flow rate in liters/min. FIGURE 2 shows the overall head deposition with mouth breathing for nonsmokers; cigar, pipe, and exsmokers; and cigarette smokers. The data points exhibit a fair amount of scatter but nevertheless appear to form an S-shaped curve characteristic of an impaction-type particle collector. Relatively little difference is apparent between smokers
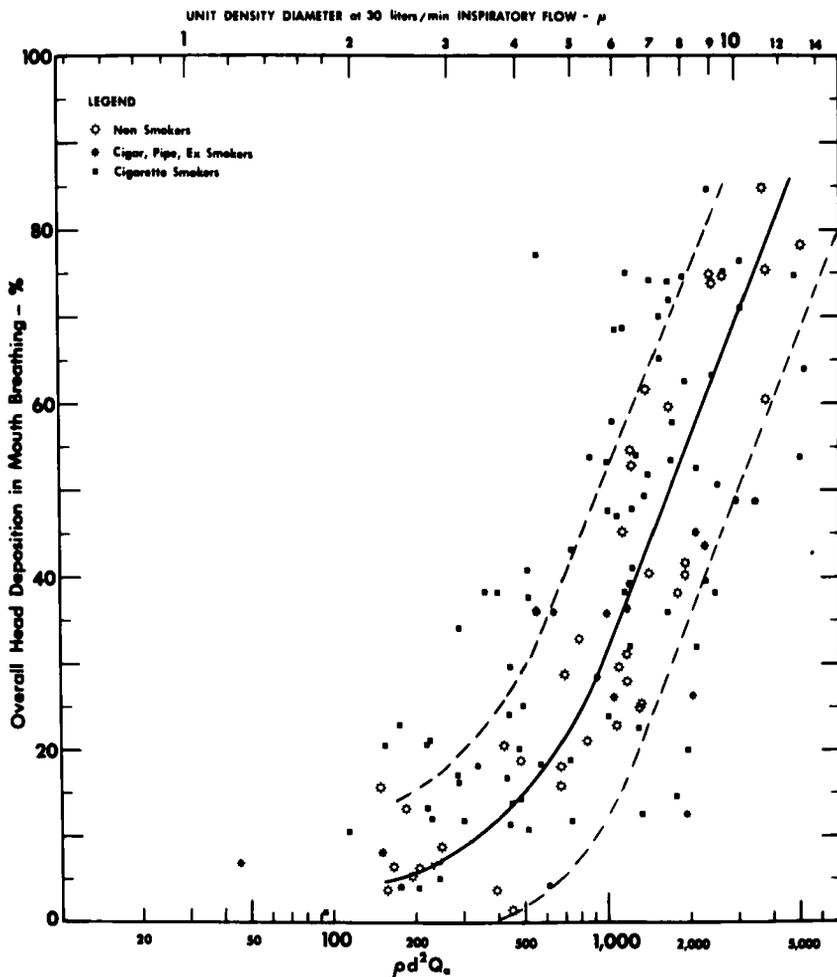

FIGURE 2. Head deposition during mouth inhalations of monodispersed tagged aerosols of various sizes for all nonsmokers; cigar, pipe, and exsmokers; and cigarette smoker tests with comparable measurements. Eye-fit median and upper and lower limit lines are drawn through the nonsmoker data, for whom the intersubject and intrasubject variability were similar.
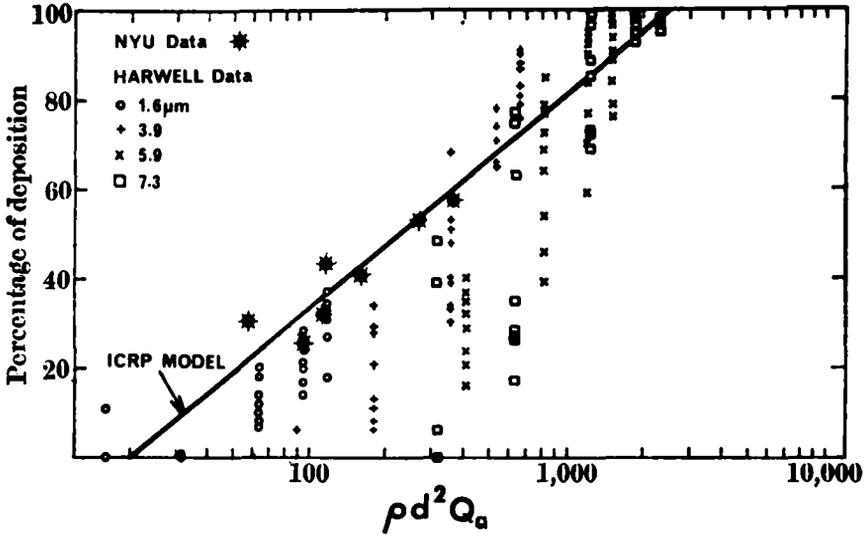
FIGURE 3. Head deposition during nasal inhalations for monodispersed tagged aerosols. The ICRP model,[5] (Pattle's data [6]), and the Harwell data [7] were based on constant flows drawn in through the nose and out of the mouth. The NYU data [8] were obtained during normal nasal inhalations, with exhalations via the mouth.

and nonsmokers in average behavior, but the former show more variability, for unexplained reasons.

FIGURE 3 shows the percentage of head deposition for nose breathing based on data available from this laboratory and others. The solid line represents the deposition model recommended by the Task Group on Lung Dynamics of ICRP Subcommittee II,[5] based on data presented by Pattle.[6] More recently, a larger body of data has been reported by Hounam and colleagues; [7] of Harwell; and, as shown in FIGURE 3, these data are not in very good agreement with ICRP's Model. The NYU data,[8] also shown on FIGURE 3, appear to agree more closely with the ICRP model than with Hounam et al.[7]

FIGURE 4 shows the percentage of alveolar deposition for particles entering the trachea with respect to the size of the inhaled particles. The alveolar deposition falls off rapidly with increasing size for particles larger than 5 microns unit density. As discussed elsewhere,[9] there is considerable intersubject variation in the extent of alveolar deposition, but there is good intrasubject reproducibility in deposition efficiency at a given particle size and little difference on the average between smokers and nonsmokers. Eye-fit limit lines have been drawn around the nonsmoker data to indicate the expected range of deposition in a normal working population.

The data from FIGURES 2, 3, and 4 were used to assess the extent of intersubject variation in the amount of alveolar deposition that might be expected to occur in a coal mining atmosphere. This assessment is based on data reported by Leiteritz and colleagues [10] for airborne dust in the coal mines of West Germany. The reported mass median size for the coal dust was ~17 microns ($\sigma_g \cong 2.3$). The reported mass median size for quartz dust was 5 microns ($\sigma_g \cong 1.9$). The average concentration of coal dust was about 50

mg/M³, with a 1% quartz content. It is assumed that the daily inhaled volume of individuals in this atmosphere was 10 M³. The calculated alveolar deposition for coal and quartz is shown in FIGURE 5 separately for mouth and nose breathing. The solid lines indicating average values for head deposition in mouth and nose breathing, shown in FIGURES 2 and 3, were used for the
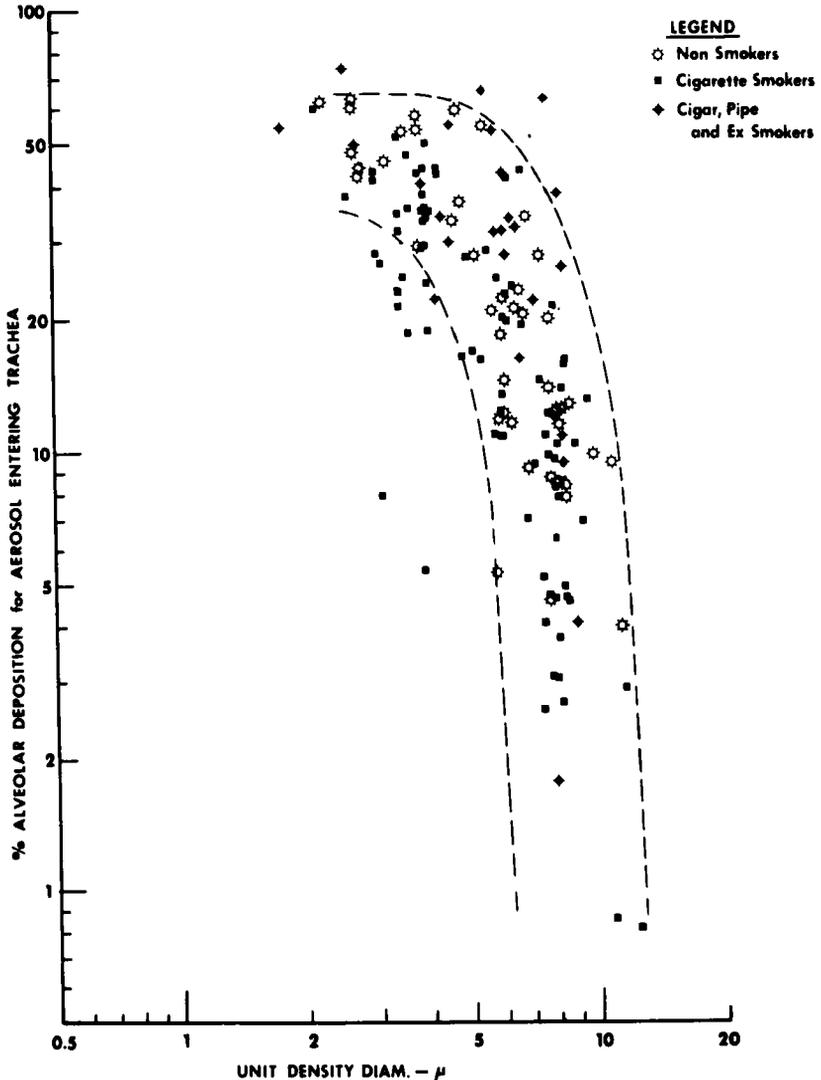

FIGURE 4.   Alveolar deposition based on the aerosol entering the trachea for all nonsmoker; cigar, pipe, and exsmoker; and cigarette smoker tests. Eye-fit upper and lower limit lines are drawn through the nonsmoker data. In this region of the respiratory tract, the intersubject variability is much greater than the intrasubject.
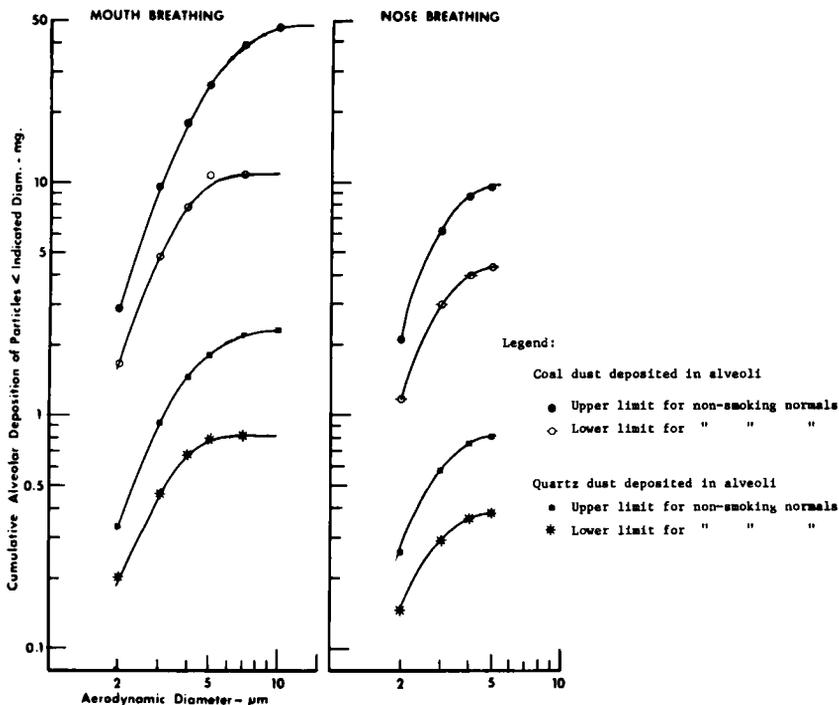
FIGURE 5. Calculated cumulative alveolar deposition vs. particle size for coal mine aerosol described by Leiteritz and colleagues.[10] (Based on an inhaled volume of 10 M³, average head depositions for mouth and nose breathing from FIGURES 2 and 3, and normal upper and lower limits for alveolar deposition from FIGURE 4.)

calculation of aerosol concentration entering the trachea. The expected alveolar deposition of this aerosol was calculated for the extremes of the normal population on the basis of the upper and lower limits for alveolar deposition for inhaled coal and quartz shown in FIGURE 4.

It can be seen from the mouth breathing curves in FIGURE 5 that subject variability produces a five-fold difference in the amount of daily alveolar deposition of coal, i.e., from 10 mg to 50 mg. Most of this difference is accounted for by particles between 5 and 10 microns in diameter.

There is a two-fold range of alveolar deposition for quartz by mouth breathing. A two-fold range also holds for nose breathing of coal or quartz.

DISCUSSION

The intersubject variation in alveolar deposition, shown in FIGURE 4, is due to the combined variability in tracheobronchial penetration and alveolar deposition. The variability is considerably less for nose breathing, because under these conditions tracheobronchial deposition is less important. These variability estimates do not conflict with the results of Love and associates,[11] who found no significant differences in deposition efficiency between simple

pneumoconiotics and normal subjects; their measurements were made with one-micron particles, whereas the major spread in the estimated alveolar deposition, shown in FIGURE 5, is accounted for by the larger particles.

Particles extracted from miners' lungs and examined in a dispersed state show peak frequencies at 1–2 microns (Leiteritz, and colleagues [12] and Cartwright.[13] It is possible that a significant portion of the difference between the size distribution of particles in coal mine atmospheres and miners' lungs is not due to the absence of large particles in the respiratory tract but to the breakup of large deposited agglomerates from the lung during sample processing. In any case, the variability estimates presented here are intended only to point up the need for studies to determine whether such large differences in effective aerosol deposition do in fact exist among miners exposed under comparable conditions. No information is available on the effective penetration of particles into the alveoli under the condition, for example, of mouth breathing induced by heavy exertion or during talking.

SUMMARY

In the present paper, estimates are presented of the range of alveolar deposition of coal and quartz dust by nose and mouth breathing in a representative coal mine atmosphere. These estimates suggest that the marked individual differences that exist in the effective penetration of particles into the alveoli may have a bearing on susceptibility to pneumoconiosis among miners.

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