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YALLAMBIE VICTORIA 3085
TELEPHONE: 433 2211

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ABSTRACT

The work of Harley and Pasternak on calculating dose conversion factors for radon daughters is re-examined. It is found that their estimates of the deposit of radon daughters on the lung airways are too low and the factor for converting from equilibrium activity of radon daughters on the airways to dose to basal cells are too high; these are re-calculated. However, it is shown that inter-subject variability of the depth of the basal cells leads to considerable uncertainty in the individual dose. Finally average dose conversion factors are re-calculated for atmospheres which may be charactersitic of underground mines; the dose conversion factors range from 8 mGy/WLM to 40 mGy/WLM as calculated from the Weibel lung model and from 3 mGy/WLM to 17 mGy/WLM as calculated from the Landahl lung model. For open cut mines there is a need for more data on such variables as the size distribution of the ambient aerosol, its concentration in air and the fractions of each daughter unattached; the last named is particularly important in determining the average dose to lung.

INTRODUCTION

The risk to the health of uranium mine workers from exposure to the decay products of radon-222 has long been recognized. Over the past 20 years detailed calculations of the dose to tissue deriving from deposits of these decay products in the lung have been carried out using simplified models of lung geometry and of the clearance mechanism (Ha72, Haq67, Al64, Ja64). Differences between these calculations have been shown in several reviews (UNSCEAR 77, Ham74, Wa70a) to arise from differences in the assumptions about such factors as the lung model chosen, the characteristics of the mine atmosphere, and the depth in lung tissue of the basal cells which are commonly regarded as the point of origin of cancerous cells. Estimates of the dose per working level month ranges from 2 mGy to 0.12 Gy. A figure of 10 mGy/WLM has been accepted by UNSCEAR in its 1977 report for the purposes of its dose calculations.

One calculation that is widely quoted is that of Harley and Pasternak who show that for a mine atmosphere with 4 percent of unattached ^{218}Po and for an assumed depth of 22 μm for the basal cells, the dose to these cells ranges from 0.23 mGy/WLM when there is equilibrium between the daughters to 11 mGy/WLM for air which is filtered to remove ^{214}Pb and ^{214}Bi. These estimates are sensitive to the choice of the depth of the basal cells for, as noted by Harley and Pasternak, a change of 5 μm in the depth of the basal cells changes the dose estimate by some 25%.

The estimated dose is also sensitive to the fraction of ^{218}Po which remains unattached to aerosols. Measurements carried out in four underground mines in the United States have shown that the fraction remaining unattached can range up to 0.20 (Ge 75) while other workers (Cr66, Ra74, Me75a) have obtained values ranging from almost zero to 0.73. Simple models have been presented which show the dependence of the unattached fraction on particle concentration, ventilation rate and the 'age' of the air. The inverse relationship between the unattached fraction and the particle concentration expected from these models has been demonstrated experimentally (Du69, Ge75). The models also show an intimate connection between the radon daughter activity ratios and the fraction of each which is unattached but this appears not to have been exploited to date; calculations of the dose from radon daughters commonly assume that a nominated fraction of only ^{218}Po is unattached while the radon daughter ratios are varied to arrive at a dose conversion factor.

The calculation of the dose to lung tissue is beset with many uncertainties such as the range of sizes of the airways, variations in the rates of clearance of mucus from the lung and the depth of the sensitive cells and so on. To obtain guidance to the safe levels of exposure to radon daughters, Walsh has turned on the epidemiological literature to derive a dose conversion factor of about 1.4 rad/WLM (14 mGy/WLM) and to suggest a rem per rad conversion factor of about 4. However, the epidemiological data is drawn from observations on underground miners and therefore should be applied cautiously to a population exposed to radon daughters in more open situations such as open-cut uranium mines, around ore stock-piles, and in houses built in regions of anomalously high radon emanation etc.

Three factors point to the need for a re-examination of the estimates of the dose to lung tissue from radon daughters. Firstly, Harley and Pasternak's estimates of the deposition of radon daughters in the lung are known to be underestimates (De78). Secondly, measurements of the depth of basal cells in tissue from different parts of the upper respiratory tract have become available which indicate that the median depth of these cells in the segmental region is ~50 μm which is somewhat greater than the value assumed by Harley and Pasternak. Indeed, better estimates of the mean dose received by the basal cells and its variability can be obtained by taking into account their observed variation in depth. Finally, there are many situations emerging - for example the development of open-cut uranium mines - where experience gained in underground mines may not be applicable. In these circumstances it is important to have a clear understanding of the dependence of dose on the size and concentration of the natural aerosol and on the disequilibrium between the radon daughters. These factors are discussed separately below and then combined to arrive at improved estimates of the dose conversion factors. It is shown that these estimates are compatible with hose obtained from the epidemiological literature by Walsh.

Deposition of Radon Daughters in the Lung

The physical phenomena important in determining the amount of inhaled particles deposited in the lung airways are (i) Brownian diffusion, (ii) impaction, (iii) sedimentation, (iv) the nature of the airflow. The relative importance of these mechanisms depend on particle size, density and the part of the bronchial tree involved. Thus for example, impaction is the dominant deposition mechanism in the upper respiratory tract for unit density particles larger than 0.5 μm diameter, while sedimentation dominates in the pulmonary region where the airflow is relatively slow (St73).

The flow of air in the lung can be divided into three regions

- a region of turbulent flow extending to about the fourth generation in the Weibel lung model (We63)
- a region of laminar flow extending from about the fourth generation to about the fifteenth generation, and
- a region beyond the fifteenth generation where bulk flow occurs as a result of alveolar expansion (Sch69).

Calculation of the deposition of ions and smaller particles on the surfaces of the lung airways commonly assume that the flow is laminar and that the Gormley-Kennedy equations (Go49) may be applied while the deposition of the larger particles by impaction or sedimentation is calculated from empirically or theoretically derived expressions. Martin and Jacobi (Ma72) have carried out experiments on the deposition of particles in a model which duplicates the first four generations of Weibel's lung geometry; their experimental data indicate that in these four generations the Gormley-Kennedy equations underestimate the quantity deposited by a factor of 10 at the trachea down to a factor of 5 at the lobar brochi. Further the deposition in the first few generations of the lung is better represented by an expression given by Landahl (La63).

In their calculation of the deposition of radon daughters in the lung, Harley and Pasternak have assumed that the Gormley-Kennedy equations are valid throughout the bronchial tree and this simplifies the calculation considerably. To estimate the deposit of the unattached and attached daughters they also assumed that:

- the unattached daughters have a diffusion coefficient of 0.054 cm^2/sec
- a single particle size, 0.3 μm, is representative of the inhaled particle spectrum
- the volume inhaled per breath is 1000 cm^3

However, it appears that their calculation is an underestimate as

- the particle size of 0.3 μm is roughly that for which the deposit in the lung is a minimum. Harley and Pasternak quote measurements by George (Ge70) which showed that the geometric standard deviation is about 2; Desrosiers (De78) points out that 33 percent of the activity is, for this size distribution, on particles smaller than 0.15 μm or larger than 0.6 μm - in both cases the lung airways have larger collection efficiencies than at 0.3 μm. More recent measurements at 27 sites in 4 underground uranium mines have shown the average diameter to be 0.17 $\pm$ 0.6 μm with an average geometric standard deviation of 2.7 $\pm$ 0.6; these particles are deposited more effectively than particles of 0.3 μm diameter (Ge75)

- Martin and Jacobi (Ma72) have shown experimentally that the use of the Gormley-Kennedy equations leads to underestimates in the deposit of 0.28 μm particles in the early generations of the lung
- the deposition of the attached and unattached daughters appears to have been calculated using a flow rate of 1000 cm^3/sec rather than 1000 cm^3 per breath. Calculations based on the Gormley-Kennedy equations show that the fraction deposited in the first few generations is underestimated by about 30%.

The deposition of unattached and attached radon daughters in the lung airways has accordingly been re-examined, using more realistic assumptions than those made by Harley and Pasternak. The present calculations are based on the lung geometries proposed by Landahl (La50) and Weibel (We63) and results for two different deposition mechanisms obtained. The first of these assumes that diffusion is the only physical process involved in the deposition (Model A), while the second includes the effects of sedimentation and impaction (Model B). The latter model also applies Landahl's expression for the deposition in the lung airways down to the segmental bronchi, and beyond this level employs the Gormley-Kennedy equations. For both models corrections are made to

- the airway dimensions in the Weibel geometry which depend on the tidal volume, as suggested by Davies (Da72)
- allow for the effect of the shape of the front of the airflow on the fraction of outside air reaching each airway
- allow for the shape of the particle size spectrum; calculations of the amount deposited are carried out for the particle size which characterises each of N subdivisions of the particle size distribution and then summed to obtain the total deposit

The fraction of unattached and attached daughters entering the trachea which are captured in each generation of the upper respiratory tract are presented in Tables 1 and 2 respectively. Details of the expressions used in these estimates are presented in Appendix I. It is clear from these tables that the adoption of Landahl's equation increased the estimate of the deposit of unattached daughters by a factor of 3 over that obtained by using the Gormley-Kennedy equations while the estimate for the attached daughters increased by a factor of 20. Comparison can be made also with Martin and Jacobi's experimental data for the fraction of 0.28 μm particles deposited at flow rates ranging from 0.1 to 50 litres per minute because the fraction deposited in a given airway is related to the diffusion constant divided by the flow rate in the airway. Inspection of the experimental data shows that the estimates obtained for the fraction of unattached daughters deposited are likely to be low while the estimates for the attached daughters are too high by a factor of 2.

Dose to Basal Cells

The basal cells of the bronchial epithelium have been implicated as the site for the development of cancer (Ko66). Measurements have been carried out by Gastineau et al (Ga72) on microscopic slides of surgical specimens of the bronchial epithelium to provide the lengths of the overlying cilia, the thickness of the epithelial tissue and the thickness of the basal cell layer. Table 3 contains estimates obtained from the experimental data of Gastineau et al of statistics on the thickness of the epithelium if normal and log-normal distributions are assumed for the thickness. As the median thickness of the epithelial tissue ranges from 20 μm to 80 μm compared with a median of 7 μm for the cilia length and the basal layer thickness it is clear that the variability in the dose to the basal cells is primarily due to the variability in their distance from alpha emitting contaminants in the mucus.

The distance of the basal cells from the mucus layer is given by

distance to basal cells = (mucus layer thickness) + (cilia length) + (epithelial thickness) - (basal layer thickness) (1)

A proper calculation of the dose to the basal cells should utilize the frequency distribution of each component of (1) above. However a tolerable approximation is obtained by noting from the data presented by Gastineau et al that

- the mucus layer is 7 μm thick
- the cilia length is approximately equal to the basal layer thickness of 7 μm and so the distance from the bottom of the mucus layer to the basal cells is approximately the thickness of the epithelial tissue.

A calculation of the fraction of basal cells within range of alpha particles emitted by ^{218}Po and ^{214}Po gives a reasonably close fit to the fraction calculated from the experimental data when it is assumed that the thickness of the epithelial tissue is distributed log-normally; therefore, the present calculations assume the log-normal distribution is applicable.

The dose to the basal cells of a nominated fraction of the population who may be at most risk can be calculated as follows. The average dose, $\bar{D}$, to the fraction, f, of the population who have epithelial tissue of thickness x_f or less is

$$\bar{D} = \int_{x_o}^{x_f} D(x)\, p(x)\, dx \Big/ \int_{x_o}^{x_f} p(x)\, dx$$

where $D(x)$ is the dose to the basal cells at a distance x from the base of the mucus layer

$p(x)$ the probability density function for the thickness of epithelial tissue

x_o the depth of the serous layer in which the cilia reside

and x_f is obtainable from $\int_{x_o}^{x_f} p(x)\,dx = f$

The function $D(x)$ has been calculated numerically using the relationship between the dose and stopping power given by Desrosiers et al (De78) for alpha-emitting material deposited on cylindrical airways; the stopping power has been obtained from data presented by Walsh (Wa70b) using quadratic interpolation to obtain intermediate values. The calculation also incorporates the separate contributions to $D(x)$ from deposit on the near and far walls of the airway; in the latter case a correction for the attenuation of the alpha particle energy by air is made. Harley and Pasternak (Ha72) have calculated $D(x)$ for tissue overlaid with mucus of 15 μm thickness and there is good agreement between the present method for calculation of $D(x)$ and theirs.

Figure 1 and Figure 2 present for alpha particles emitted by ^{218}Po and ^{214}Po estimates of $\bar{D}$ for f ranging from 0.010 to 0.999. It has been assumed that:

- the diameters of the airways are approximately those given in the Weibel model for each region of the lung considered
- the radon daughters are uniformly dispersed through a mucus layer 7 μm thick
- the mucus is spread over a serous layer 7.5 μm thick which does not contain radon daughters
- $p(x)$ is log-normal

The figures clearly show the effect of the variability of the depth of the basal cells on the dose - the range of the depths is sufficient for 5 percent of the population to receive a dose from alpha particles from ^{218}Po of 2 to 15 times higher than the average while for alpha particles from ^{214}Po the dose received is 3 times higher. Not surprisingly, the dose-rate as calculated here is smaller than obtained by Harley and Pasternak who assumed that the basal cells are 22 μm from the surface of the epithelial tissue. Thus, the present calculations show that, in the segmental region the dose rate for ^{218}Po is 1.8 picograys/sec per Bq/m^2 whereas Harley and Pasternak obtained 7.5 picograys/sec per Bq/m^2.

[illegible] Mine Atmospheres

As pointed out in the review by Hamrick and Walsh (Ham74), variations in the estimates of dose to lung tissue have come about from various causes such as assumptions about the characteristics of the inhaled mine atmosphere, the respiratory tract model adopted, the choice of critical tissue and the depth of the basal cells in the tissue. Large variations arise as a result of assumptions on the fraction of unattached daughters. Figure 3 gives a plot of the estimates of the dose per WLM reported in the literature against the fraction of daughters unattached.

Raabe (Raa69) and Jacobi (Ja72) have presented simple models which relate the fraction of unattached daughters to such factors as the size of the particulates in the atmosphere and their concentration. Raabe's model is adopted in the present calculations. From his expressions*, the ratio of the daughter activities and the attached fraction can be calculated for air of a given age relative to the time when the air was pure ^{222}Rn and contained particulates with a specified average diameter. The data obtained in underground mines (Ge75) indicates that, if it is assumed the activity of each particle is proportional to its surface area, the diameter of the average surface for aerosols from these mines is 0.06 μm while the particle concentrations range from 10^4 per cubic centimetre to 10^5 per cubic centimetre. From data given by Junge (Ju63) it can be deduced that the diameter of the average surface for the continental tropospheric aerosol is 0.12 μm; he quotes concentrations of 1.5×10^4 per cubic centimetre for his model aerosol although the concentration can range from 700 per cubic centimetre in clean air to 10^5 per cubic centimetre in polluted areas (Br77). Figure 4 to Figure 6 show the variation of the unattached fraction for particle concentration ranges from 10^3 per cubic centimetre to 10^5 per cubic centimetre and the 'age' of the air ranges from 0.1 minute to 1000 minutes. These figures clearly show that it is possible for the unattached fraction to vary over a range comparable to that found by Craft et al (Cr66) who produced measurement results for the unattached fraction ranging from 0 percent to 73 percent.

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* Equation (14) in Raabe's paper (Raa69) is incorrect - in line 3, $(1-\alpha_a)$ should be replaced by $(1-\alpha_b)$ and in line 4 $\lambda_a / (\lambda_a + \lambda_b)$ should be replaced by $\alpha_a / (\lambda_b + \lambda_s)$.

Such large variations in the unattached fraction imply that the dose to the lung from inhaled radon daughters must vary over a considerable range. To examine this, two additional features have been incorporated into the analysis discussed earlier which

- use the 'age' of the air, the diameter of the average surface and the particle concentration to derive
  - the activity of each daughter in an atmosphere containing one working level
  - the unattached fraction for each daughter
- allow for the clearance of the daughters deposited from each region of the lung; the clearance rates adopted for use with the Weibel and Landahl geometrics are those given by Haque and Collinson (Haq67) and by Altshuler et al (Al64), respectively.

The analysis produces not only the fraction of the attached or unattached daughters deposited in each region of the lung but also the equilibrium activity in each region for each daughter with and without the clearance mechanism operating.

Calculations of the average dose to several regions of the upper respiratory tract have been made for

- an aerosol of activity median diameter of 0.17 μm, a geometric standard deviation of 2.7 and a concentration of 2.11×10^5 per cubic centimetre; at this concentration 4% of ^{218}Po is unattached at equilibrium
- an aerosol of activity median diameter of 0.3 μm, a geometric standard deviation of 2 and a concentration of 2.45×10^4 per cubic centimetre; at this concentration 4% of ^{218}Po is unattached at equilibrium
- the model tropospheric aerosol with a size distribution as given by Junge; it has an estimated activity median diameter of 0.23, a geometric standard deviation of 2.3 and a concentration of 1.52×10^4 per cubic centimetre.

The calculations showed the highest doses to be received in the segmental region when the clearance mechanism is active and in the lobar region when there is no clearance. Table 4 summarises the results of the calculations for the first aerosol. The dose conversion factors obtained for the second aerosol are identical at ages of 0.1 min to 5 min and 30% lower near equilibrium while the third aerosol gave conversion factors which are 10% higher at a given age than shown in the Table. The calculations have been repeated with the Landahl model; the results are 50% to 60% lower than those tabled for the Weibel model.

DISCUSSION

In the previous section it has been demonstrated that the average dose to the basal cells depends, as is well known, on they physical characteristics of the atmosphere inhaled including the fraction of radon daughters unattached, and can vary by an order of magnitude. The dose to an individual, however, is subject to large uncertainties through variability of

- the deposition of material on the lung airways
- the rates at which mucus is cleared from the surface of the lung airways
- the depth of the basal cells

The contribution of each of these factors to the uncertainty of the individual dose are examined below.

It is well known that there are large differences between individuals in the efficiency for the removal of particulates from the air by the respiratory tract. These differences arise through variation in the size and shape of the airways and through variations in their branching angle (Li72). Further, the deposit is not uniform - enhanced deposition occurs at the branchings in the lung airways which cannot be explained solely by the impaction mechanism (Ma72). The available experimental data (Pa77) shows that the coefficient of variation for the fraction of particulates depositing in the upper respiratory tract is much greater between subjects than within subjects with values of about 0.6 and 0.3 respectively. The range in the fraction deposited is such that it is a factor of 2 above or below the average for the upper and lower 2% of the population respectively. Even deposition in the nasal passages shows considerable variability as the fraction deposited there can vary by as much as a factor of 8 (Gi72).

The rates of clearance of material from the lung airways are, of course, not static. Lippmann (Li77) quotes observations which show that the rate of clearance is significantly slower for smokers abstaining from smoking than when they are allowed to smoke freely. Long-term heavy smokers can show abnormalities in the clearance of material from the lung including, for example, intermittent clearance or long delays in the onset of clearance followed by rapid clearance. If the calculations with non-clearance are applicable to smokers then the critical tissue is not in the segmental region but in the lobar region and the dose received is 60 percent to 70 percent higher than the maximum dose received when the clearance mechanism is active.

The variability of the depth of the basal cells contributes to the greatest uncertainty in estimates of the dose. If the range of measurements on the depth of the basal cells in bronchial epithelium (Ga72) represent that seen in the population as a whole then it is estimated that 5 percent of the population most at risk through having relatively thin epithelial tissue could receive as much as 7 times the average population dose while the 5 percent of the population at least risk receive no dose. More data is needed on the inter- and intra-subject variability of the depth of the basal cells.

That the above factors create difficulties in establishing suitable dose conversion factors for use in radon daughter dosimetry has been realised by Walsh who applied epidemiological data to estimate the dose conversion factor (Wa79). He deduced that exposure to radon daughters in underground mines leads to an average dose of 14 mGy per WLM. Calculations based on the Weibel model show that the maximum dose from exposure to radon daughters occurs in the segmental region and the dose ranges from 8 mGy per WLM to 40 mGy per WLM when the fraction of unattached ^{218}Po ranges from 2 percent to 20 percent. The corresponding dose conversion factors calculated from the Landahl model range from 3 mGy per WLM to 17 mGy per WLM. Both sets of values are compatible with the estimate made by Walsh.

The dose conversion factor to use in open-air situations near areas of high radon emanation cannot be given as there is a paucity of field data. More work is needed to establish the physical characteristics of such atmospheres including the number and size distributions of particles suspended in air, the concentration of the radon daughters and the fraction of each unattached. It is likely that in the neighbourhood of an ore-body, as in an open-cut mine, a high proportion of the daughters are unattached in which case the dose conversion factor could be higher than 14 mGy per WLM indicated by underground mine experience. The calculations given here do show that the assessment of average dose requires more than a measurement of the exposure as working levels - it is desirable for the unattached fraction of each daughter be established prior to a calculation of the dose.

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TABLE 1 : Fraction of unattached daughters entering trachea depositing in upper respiratory tract

Generation	Fraction depositing $X10^2$			
	Harley and Pasternak	Model A		Model B
	V_T = 1740 cm^3	V_T = 1740 cm^3	V_T = 1000 cm^3	V_T = 1000 cm^3
0	3.86	3.97	5.75	12.2
1	3.21	3.19	4.44	9.1
2	2.68	2.64	3.59	7.15
3	2.25	2.21	2.97	5.77
4	4.78	4.68	6.18	9.58
5	6.30	6.16	7.90	10.5
6	8.07	7.88	9.71	10.8
7	10.0	9.74	11.3	6.48
8	11.8	11.4	12.3	7.00
9	12.9	12.4	11.9	6.79
10	12.7	12.2	9.86	5.63
11	10.7	10.2	6.33	3.62
12	6.98	6.66	2.70	1.54
13	3.04	2.88	0.58	0.33
14	0.73	0.69	0.05	0.03
15	0.06	0.06	6.5×10^{-4}	3.7×10^{-4}
16	8.7×10^{-4}	8.1×10^{-4}	0	0

Notes: 1. Model A employs diffusion as the only deposition mechanism. Model B employs Landahl's expressions down to generation 6 and the Gormley-Kennedy equations thereafter; impaction and sedimentation are assumed to act concurrently.

2. V_T is the tidal volume.

TABLE 2 : Fraction of attached daughters entering trachea depositing in upper respiratory tract

Generation	Fraction depositing X10^4				
	Harley and Pasternak	Model A			Model B
	V_T = 1740 cm^3	V_T = 1740 cm^3 N = 1	V_T = 1740 cm^3 N = 9	V_T = 1000 cm^3 N = 9	V_T = 1000 cm^3 N = 9
0	0.55	0.50	0.63	0.91	9.54
1	0.47	0.42	0.53	0.75	9.87
2	0.40	0.36	0.45	0.64	10.0
3	0.35	0.31	0.39	0.55	11.3
4	0.78	0.68	0.86	1.22	18.1
5	1.10	0.97	1.22	1.73	21.5
6	1.55	1.36	1.72	2.43	26.1
7	2.20	1.93	2.43	3.44	9.51
8	3.10	2.72	3.43	4.84	10.4
9	4.40	3.85	4.85	6.83	12.0
10	6.27	5.48	6.89	9.69	14.4
11	8.91	7.76	9.74	13.7	17.9
12	12.6	11.0	13.8	19.3	23.2
13	17.5	15.1	19.0	26.5	30.2
14	25.0	21.4	26.8	37.3	41.4
15	36.0	30.7	38.3	53.1	58.1
16	50.0	42.3	52.6	72.3	79.1

Notes:
1. Model A employs diffusion as the only deposition mechanism. Model B employs Landahl's expressions down to generation 6 and the Gormley-Kennedy equations thereafter; impaction and sedimentation are assumed to act concurrently.
2. V_T is the tidal volume.
3. N is the number of divisions into which the particle size distriburion is split.

TABLE 3 : Distribution of thickness of bronchial epithelium

	Bronchi				
	Main	Lobar	Segmental	Subsegmental	Transitional
EXPERIMENTAL DATA[a]					
Minimum thickness, μm	70	25	15	50	12.5
Median thickness, μm	80	50	50	50	20
Maximum thickness, μm	85	70	100	70	30
No. of measurements	6	20	63	3	12
EMPIRICAL PARAMETERS					
1. Normal distribution					
Mean thickness, μm	80	50	50	57[b]	20
Standard deviation	6	12	18	12	5.4
2. Lognormal distribution					
Median thickness, μm	80	50	50	56[b]	20
Geometric standard deviation	1.08	1.32	1.50	1.21	1.31

Notes: a. From Gastineau et al (Ga 72).
b. Based on a sample of 3 measurements 50 μm, 50 μm and 70 μm.

TABLE 4 : Dose to bronchial epithelium from radon daughters

Age of air min	Ratio of daughter activity to ^{222}Rn activity X 100			Percent of daughters unattached			Maximum dose to basal cells mGy/WLM					
							Without clearance			With clearance		
	Po-218	Pb-214	Bi-214	Po-218	Pb-214	Bi-214	LB	SB	SSB	LB	SB	SSB
0.1	2.2	0.003	0.0	77.2	70.2	66.9	210	180	24	58	120	24
0.2	4.4	0.012	0.0	61.2	50.2	45.3	170	140	19	47	100	19
0.5	10.7	0.070	0.0	35.1	20.6	15.3	100	86	12	28	61	12
1.0	20.3	0.270	0.003	19.7	6.8	3.5	63	52	6.8	17	38	6.8
2.0	36.5	1.0	0.023	11.0	1.9	0.5	40	34	4.3	11	25	4.3
5.0	67.9	5.0	0.306	5.9	0.4	0.0	27	22	2.7	7.5	17	2.7
10.0	89.7	14.2	1.8	4.5	0.1	0.0	24	19	2.3	6.6	15	2.3
100.0	100.0	91.5	77.7	4.0	0.0	0.0	22	17	2.0	6.8	15	2.0
1000.0	100.0	100.0	100.0	4.0	0.0	0.0	22	17	2.0	6.8	15	2.0

Note:

1. The calculations are based on the Weibel model and assume:

   activity median diameter = 0.17 μm, geometric standard deviation = 2.7,
   diameter of average surface = 0.063 μm, particle concentration = 2.1×10^5 per cm^3,
   diffusion coefficient for unattached daughters = 0.054 cm^2/sec

2. LB = Lobar bronchi
   SB = Segmental bronchi
   SSB = Sub-segmental bronchi

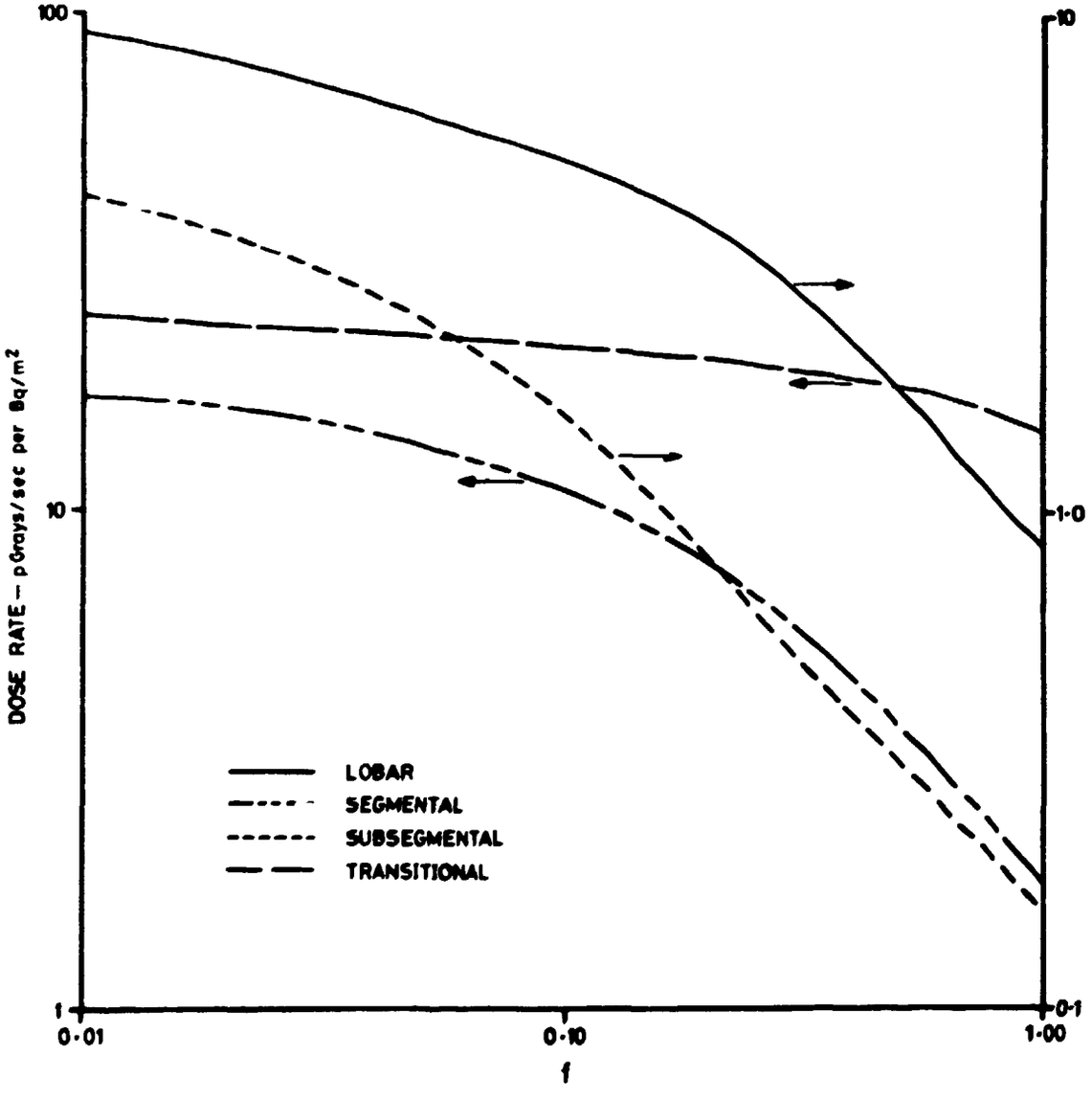

FIGURE 1. Average dose-rate from ^{218}Po alpha particles to basal cells in different regions of the lung for a fraction, f, of the population most at risk estimated on the basis that the epithelial thickness is distributed log-normally; the average dose-rate corresponds to f = 1.

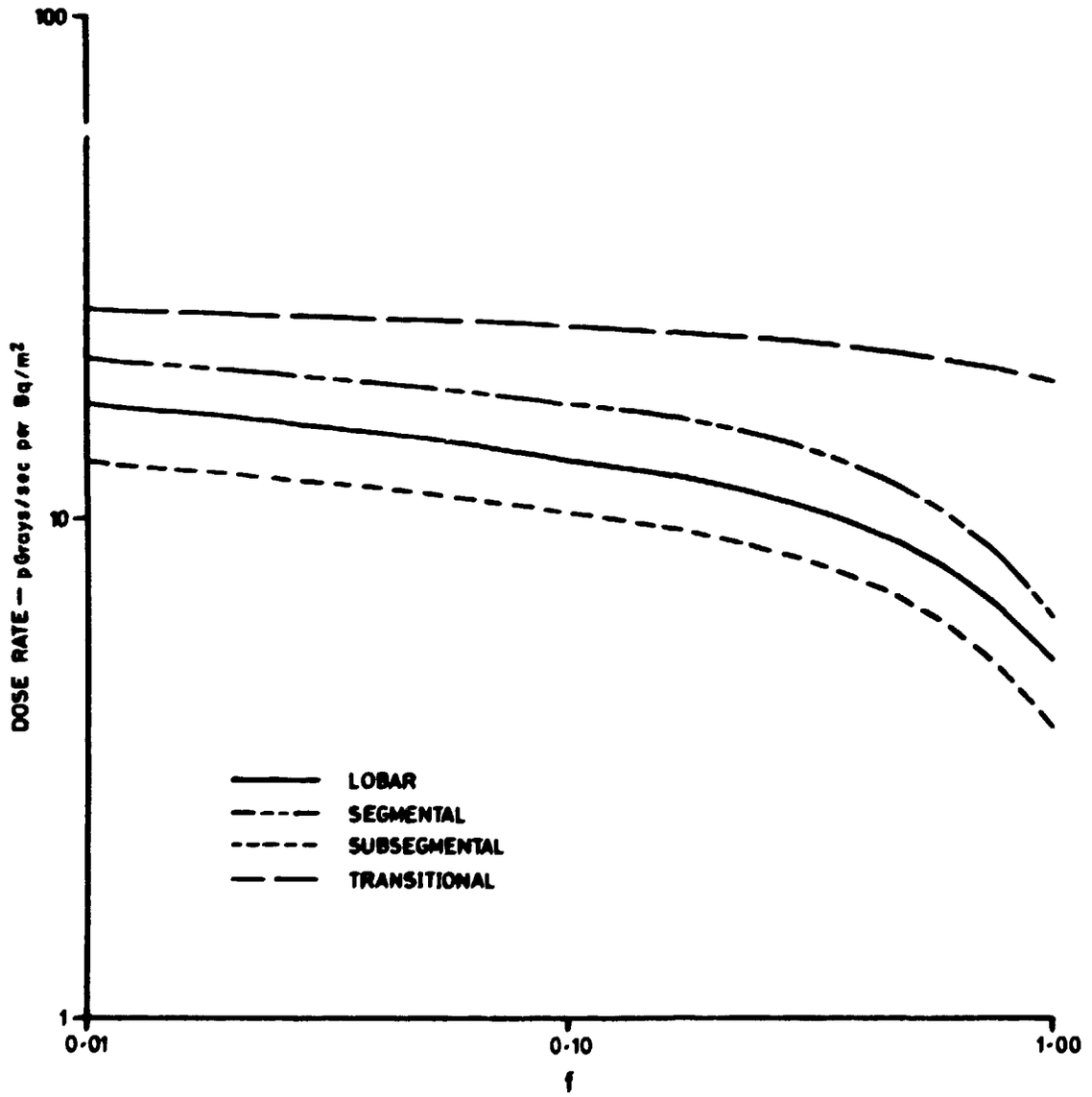

FIGURE 2. Average dose-rate from ^{214}Po alpha particles to basal cells in different regions of the lung for a fraction, f, of the population most at risk estimated on the basis that the epithelial thickness is distributed log-normally; the average dose-rate corresponds to f = 1.

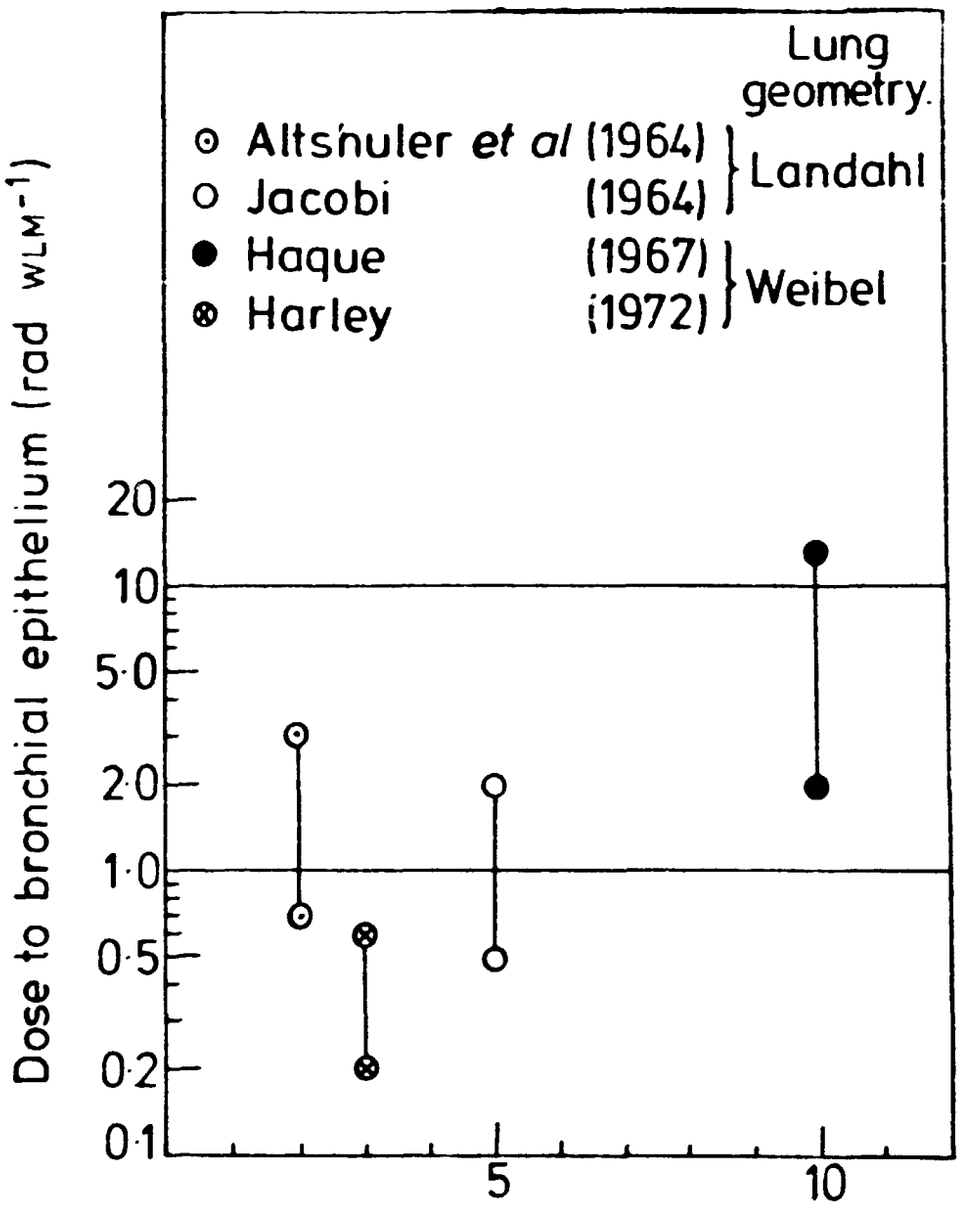

FIGURE 3. Comparison of different estimates of the mean α-doses per WLM to the basal cells of the segmental and sub-segmental bronchi, based on the Landahl and Weibel lung geometries.

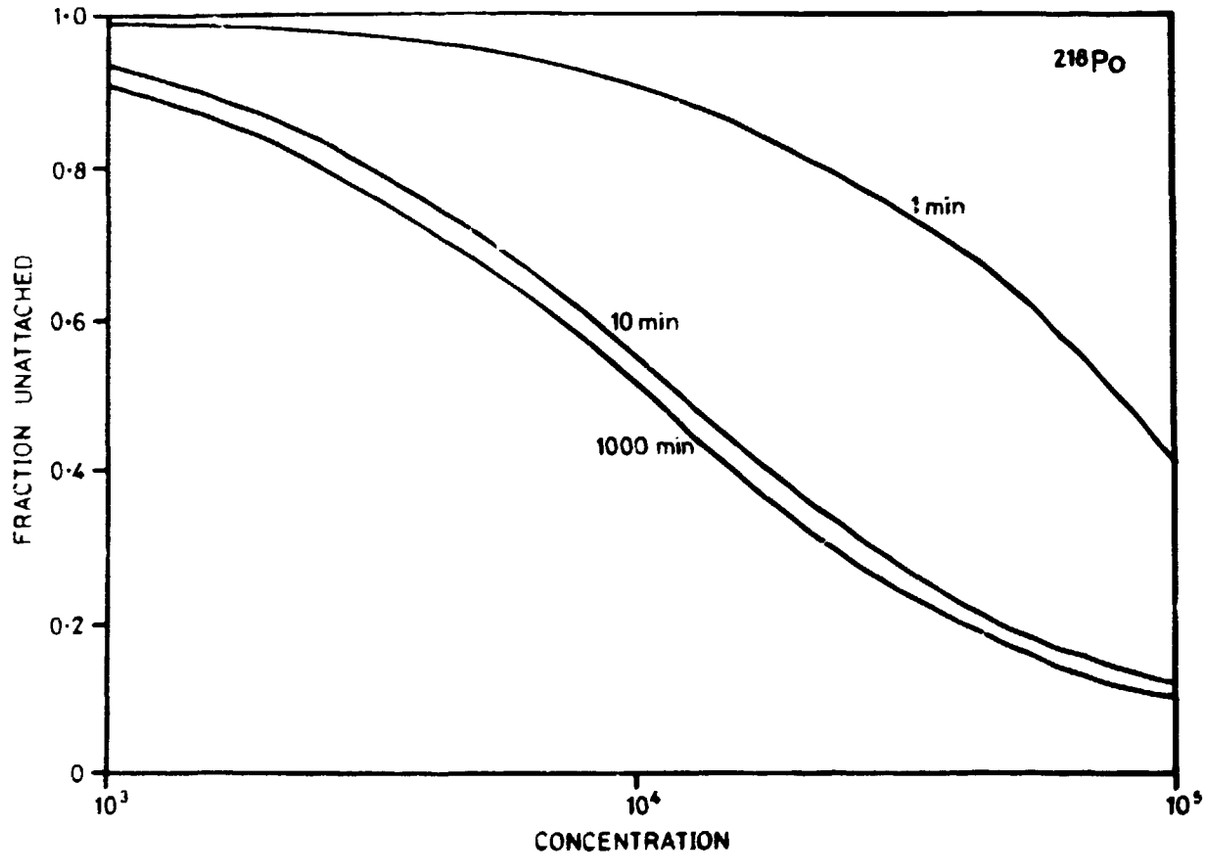

FIGURE 4. Fraction of ^{218}Po unattached to aerosols for air of ages 1 min., 10 min. and 1000 min. The average surface diameter assumed for the aerosol is 0.0 μm.

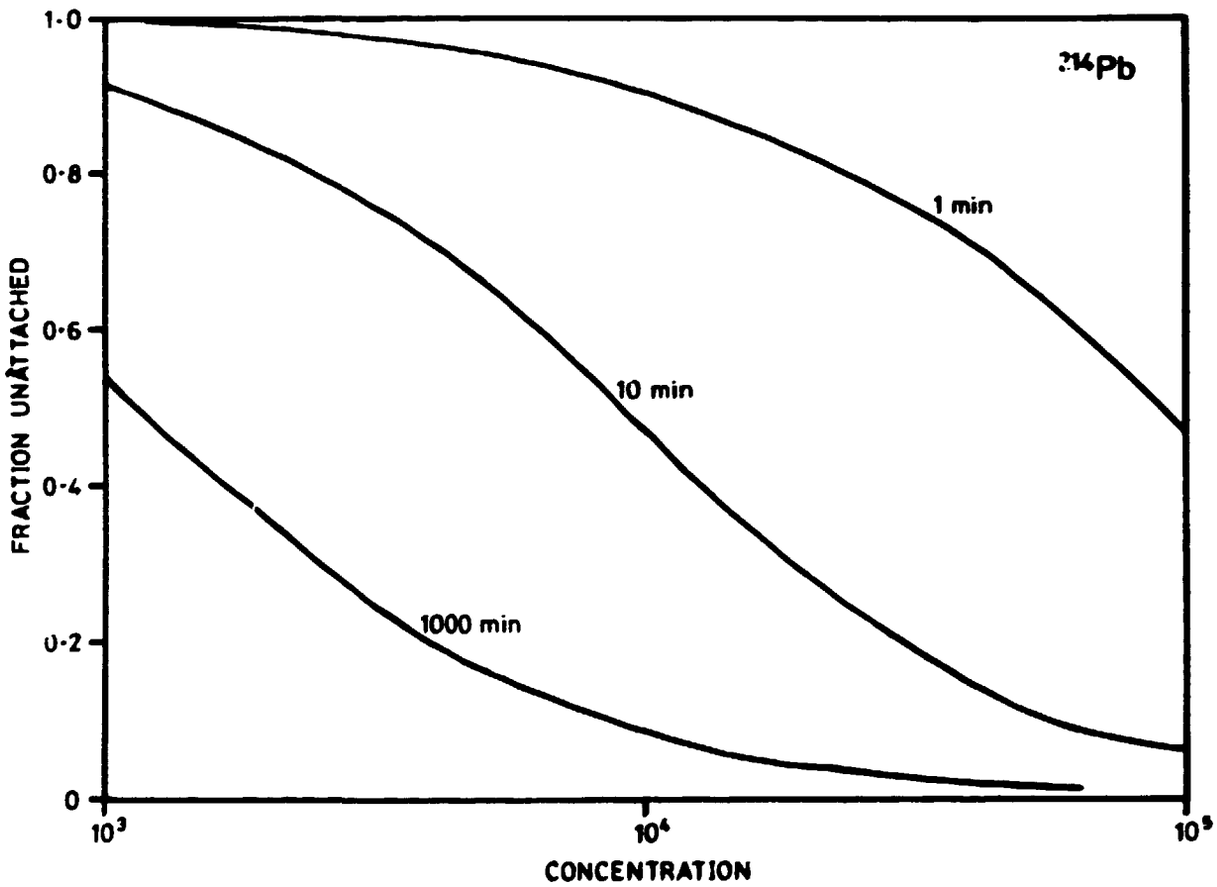

FIGURE 5. Fraction of ^{214}Pb unattached to aerosols for air of ages 1 min., 10 min. and 1000 min. The average surface diameter assumed for the aerosol is 0.06 μm.

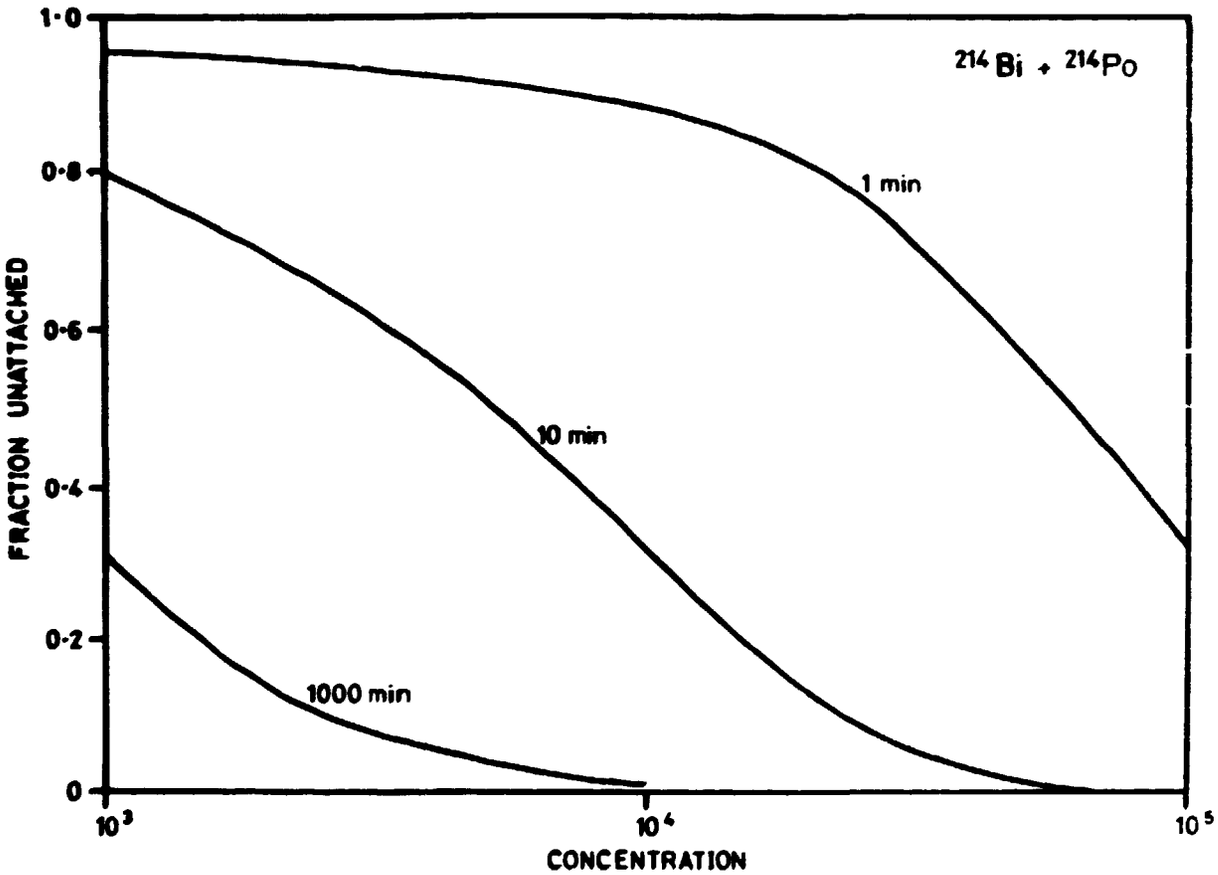

FIGURE 6. Fraction of $^{214}Bi + ^{214}Po$ unattached to aerosols for air of ages 1 min., 10 min. and 1000 min. The average surface diameter assumed for the aerosol is 0.06 μm.

APPENDIX I

FORMULAE USED TO ESTIMATE THE DEPOSIT TO LUNG AIRWAYS

I.1 Deposition in Nasopharynx

Fraction of particles with aerodynamic diameter d_p, expressed as μm, deposited in nasopharynx is given by (Me75b):

$$f_N = -0.63 + 0.51 \log (d_p^2 F)$$

I.2 Deposition in Lung Airways

I.2.1 Deposition by diffusion

(a) Laminar flow regime

The fraction deposited, f_D, is given by the Gormley-Kennedy equations (Go49):

$$f_D = \begin{cases} 4.07h^{2/3} - 2.4h - 0.446h^{4/3} & h < 0.0156 \\ 1 - 0.819 \exp(-7.314h) - 0.097 \exp(-44.6h) - 0.0325 \exp(-1.4h) & h > 0.0156 \end{cases}$$

where $h = \pi N_1 D/2V$

(b) Plug flow regime

The fraction deposited, F_D, is calculated from an expression given by Landahl (La63),

$$f_D = 2\sqrt{2h}\,(1 - 2\sqrt{2}h/9)$$

where h is $= \pi N_1 D/2V$

I.2.2 Deposition by impaction

The expressions for the fraction deposited by impaction, f_I, given by Takashi and I to (Ta76) have been modified slightly to give better agreement with the experimental data of Schlesinger and Lippmann (Sc72), thus

$$f_I = y/(1+y)$$

where $y = 0.4w + 4w^2$

$$w = 4d_p^2 \rho_p Q_{j-1}/9\pi d_{j-1}^2 d_j$$

I.2.3 Deposition by sedimentation

The expression for the fraction deposited, f_S, is due to Thomas (Th58)

$$f_S = 2\left[\sin^{-1}\alpha - \alpha\beta(1-2\alpha^2)\right]/\pi$$

where $\alpha^3 = 3\pi v_s l d \cos\phi/16Q$

$$\beta = \sqrt{(1-\alpha^2)}$$

1.2.4 Total fraction deposited

The fraction of activity entering the airway deposited, f_T, is

$$f_T = 1-(1-f_D)\ (1-f_I)\ (1-f_S)$$

1.3 Activity Suspended in or Leaving Airway

1.3.1 Laminar flow regime

Fraction of activity entering airway suspended is

$$(1-f_T)\ v(1-v/4Vt)/Vt$$

Fraction of activity entering airway leaving is

$$(1-f_T)\ (1-v/2Vt)$$

where t is the effective inhalation time for airway

Effective inhalation time for next generation is

$$t(1-v/2Vt)^2$$

1.3.2 Plug flow regime

Fraction of activity entering airway suspended is

$$(1-f_T)\ v/Vt$$

Fraction of activity entering airway leaving is

$$(1-f_T)\ (1-v/Vt)$$

Effective inhalation time in next generation is

$$t-v/V$$

1.4 Diffusion Coefficient and Settling Velocity for Particles in Air

These are calculated from expressions given by Junge (Ju63, p125), viz.

$$D = akT/3\pi\mu d_p$$

$$v_s = \pi\rho_p d_p^3\ gD/kT$$

where $a = 1 + 2bl_f/d_p$

$$b = 1.26 + 0.40 \exp(-0.55\ d_p/l_f)$$

1.5 Equilibrium Activity

The equilibrium activity, A_{ij}, of nuclide i in generation j is

$$A_{ij} = (\lambda_i A_{i-1,j} + r_{j+1} A_{i,j+1} + R_{i,j})/(\lambda_i + r_j)$$

List of Symbols

d	diameter of airway
d_{j-1}, d_j	diameters of airways in generations j-1 and j when the direction of flow for inhaled or exhaled air is from generation j-1 to j
d_p	aerodynamic diameter of particle
D	diffusion coefficient
F	flow rate for inhaled or exhaled air expressed as litres per minute
g	acceleration due to gravity
k	Boltzmann's constant
l	length of airway in a generation
l_f	mean free path in air
N	number of airways in a generation
Q_{j-1}	flow rate for air in airways of generation j-1 when the direction of flow for inhaled or exhaled air is from generation j-1 to j
Q	flow rate for air in an airway
r_j	clearance rate of mucus
R_j	rate activity is deposited on airway j
T	absolute temperature
v	total volume of airways for each generation
V	flow rate of inhaled or exhaled air
λ	decay constant
μ	viscosity of air
ρ_p	density of particle
ϕ	angle of inclination of airway; a value of 50^o has been adopted for the calculations