Overview Of The Unattached Fraction Of Radon Progeny and It's Significance To Lung Dosimetry.

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ABSTRACT:
The health risk arising from exposure to radon progeny is strongly related to the deposition of radon progeny in the lungs. It is believed that greater risk is related to the unattached fraction. Achievement of accurate estimations of the radiation dose to the lungs, requires knowledge of both the size and concentration of the unattached fraction.

In spite of the capabilities available today to obtain this data, several fundamental issues still need to be resolved. Most notably: 1)A clear and universally accepted clarification of precisely how the unattached fraction is to be defined, 2)Development of standardized measurement instrumentation for the detection of unattached fractions. Only then can meaningful scientific comparisons be made.

The complex issues surrounding the unattached fraction and lung dosimetry models are difficult to understand. A clear overview is presented here of the relevant characteristics, parameters and measurement methods needed to achieve an introduction to this subject. This paper is pertinent also to electrostatic air cleaners - a technology gaining momentum as an alternative to sub-slab mitigation techniques in reducing the risk of lung cancer. Recent field trial results have indicated that at low radon concentrations, electronic air cleaners are capable of reducing indoor levels.

1.0 INTRODUCTION:

Extensive epidemiologic evidence gained from studies of underground miners exposure to radon progeny, has irrefutably shown that radon causes lung cancer(1,2,3). Scientific organizations such as; the U.S. National Council on Radiological Protection and Measurements(NCRP), the International Commission on Radiological Protection(ICRP), the Committee on the Biological Effects of Ionizing Radiation of the National Research Council(BEIR) and the United Nations Scientific Committee on the Effects of Atomic Radiation(UNSCEAR) continue to actively research and promote ongoing studies into the association of radon with lung cancer(4,5,6).

Lung cancer, the most common type of lethal cancer, arising mainly in the bronchial airways, is clearly seen in Figure 1 to be the dominant form. Most of the data has been associated with cigarette smoking studies.

Site	Males & Females
Lip	1,800
Tongue	2,800
Other Oral	6,000
Pharynx	4,500
Larynx	6,800
Lung	76,000
Other respiratory	2,500

Figure 1: Estimated Number of Cancer Cases by type in the United States(1972). Ref 31.

The risk of contracting lung cancer as a result of exposure to radon progeny, is related directly to the radiation dose directed to lung tissue. Dosimetric limits have been set by the NCRP based upon historical development of dose calculations(7,8,9,10,11). However, dose estimates to the lung tissue cannot be measured and have instead to be calculated by the use of various lung models(12,13). The relationship between exposure(as measured traditionally in WLM) and dose to the target cells/tissues in the respiratory tract is extremely complex, being dependent upon biological, physical and chemical factors(7).

Most of the tissues at risk are located in the lower respiratory tract(termed the tracheobronchial compartment) with the tissues specifically in the bronchial epithelium region having the greatest risk(3,4). Different breathing patterns, anatomical lung characteristics, age and sex differences, tissue thickness, rate of mucociliary clearance are some of the key factors affecting the computed dose calculations. It is evident therefore as a result of these and many other contributory factors, that the current international work on respiratory tract dosimetry models will continue to be updated and improved.

The inter-relation and influence of the unattached fraction on the accuracy of lung dose models is commonly not realized. The unattached fraction is generally dealt with as an aerosol science with no more than a cursory reference to health risk. Similarly, lung dosimetry investigations focuses heavily on the mechanisms of respiratory tract dynamics at the expense of the unattached fraction. The inter-dependency of these two disciplines is however much closer.

Realization can only be achieved by having a fundamental appreciation of these two sciences. The purpose of this review paper therefore, is to present a clear overview of both lung dosimetry and radon unattached fraction studies, with particular emphasis on establishing the link between these two sciences.

2.0 RADIATION LUNG DOSIMETRY:

2.1 Respiratory Tract.

One of the most important issues affecting the calculation of lung dosimetery is the epithelium thickness within the tracheobronchial region.

The thickness of the airway epithelium significantly affects the dose calculation since the distance travelled by the alpha particles of radon progeny, is of the same order of magnitude of epithelial thickness in the human bronchi. These ranges in tissue are shown in Figure 2.

Nuclide	Energy(Mev)	Range(um)
Rn 222(Radon)	5.49	41
Po 218(RaA)	6.00	48
Po 214(RaC')	7.69	71

Figure 2: Penetration Ranges in Tissue of Alpha Particles emitted by Radon. Ref 32.

It is seen that these ranges are comparable with the normal distribution of epithelial thickness, as shown in Figure 3. Variations therefore in assumed epithelial thickness, will lead to differing dose estimates.

Airway Classification	Thickness(um)
Main Bronchi	80
Lobar Bronchi	50
Segmental Bronchi	50
Transitional Bronchi	20
Bronchioles	15

Figure 3: Mean Thickness of Normal Human Epithelium. Ref 32.

Bronchial dose has been reported to be effectively independent of the size distribution of the unattached fraction but decreasing significantly as the size of the attached fraction increases(1,2,3). Nasal deposition efficiency for the unattached fraction is significant whereas a much smaller fraction is deposited in the mouth through oral breathing(4,7,10). The nasopharyngeal(N-P) and tracheobronchial(T-B) regions therefore as defined by the ICRP(12), are most commonly modelled for deposition efficiency characteristics(14,15,16,17). Sophisticated dose models have also been developed in which there is an averaging of all the sensitive cells in the T-B region(18,19,20,21).

Broadly, there are three prime factors which can influence dosimetry calculations; the physical characteristics of the inhaled air, breathing patterns and the physiological-anatomical characteristics of the lung. Consequently, lung models can be examined from a number of different viewpoints e.g. anatomically, morphologically, biologically, etc. For the purpose of lung dosimetry studies as related to inhalation of radon progeny, it is of prime importance however to converge and unify all these models into one single respiratory tract model.

Most commonly therefore, the respiratory tract is conveniently divided for this purpose into three compartments;Nasopharyngeal(NP),Tracheobronchial(T-B) and Pulmonary(P), see Figure(4).

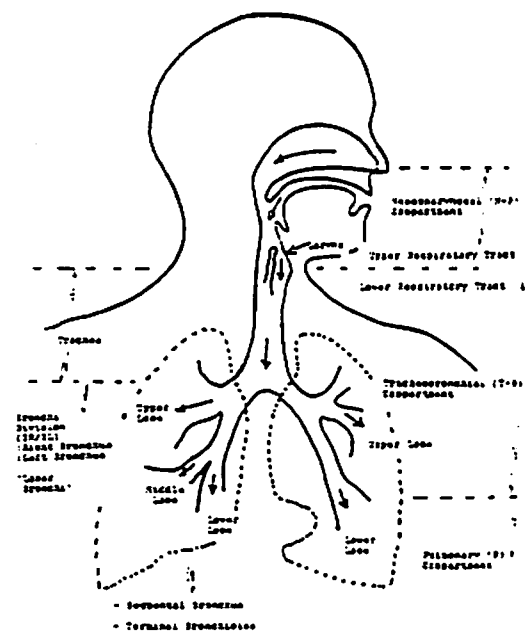

Figure 4: Regions of the Respiratory Tract.

Within the confines of the T-B region; sizes and branching patterns of the airways, thickness of the bronchial epithelium, thickness of the mucous layer, rate of mucociliary clearance etc, are the important parameters affecting the deposition and absorption of unattached particles in the airways. Most of the investigative research is directed towards the sensitive bronchial epithelium region, in which the underlying structure is essentially composed of a ciliated mucosa layer permanently in a state of flux(as a result of cilia beating on adjacent cells). To within a depth of 50-80 microns for humans(and approximately half that for animals), lie a composite of cell types; Basal, Brush, Goblet, Ciliated and Nonciliated as shown in Figure 5. Of these types the basal cell is most commonly although not exclusively studied with respect to lung cancer damage mechanisms.

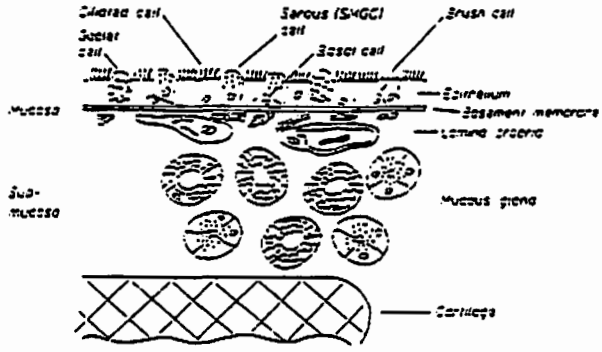

Figure 5: Cross Section of Bronchial Wall Showing Cells Found in the Epithelium.

2.2 Dose Conversion Factors.

Characterization of health risk arising from exposure to radon progeny is defined in terms of dose i.e. the level of absorbed radiation by a particular body. The units of DOSE are formally expressed as Rad or Gy, where 1Gy = 100Rad. A 'biologically relevant' definition, the DOSE EQUIVALENT, is defined as:

Dose Equivalent = Absorbed Dose x A Quality Factor

where the quality factor is a measure of the 'relative biological effectiveness'.

The Dose Equivalent is expressed in units of Rem or Sv, where 1Sv = 100Rem, since the quality factor for alpha particles is 20. Conversion equivalency between the two terms is generally represented by:

1 Gy of alpha particle dose = 20 Sv tissue dose equivalent.

These conversion factors(3) thus allow risk estimates to be made between absorbed dose and exposure levels. Most estimates of the dose conversion factors for unattached fractions vary(for the unattached fraction) from 100 - 200 mGy per WLM(3), where WLM is the number of Working Level Months of Exposure. The spread in values arise from the results of different studies in which differing lung models, epithelium thicknesses etc are assumed. This in turn results in a spread of values for the depth of target cells.
An additional uncertainty factor, stems from the assumed particle size distribution of the unattached fraction, which is generally reported to be ill defined(22).

The dose per unit exposure i.e. mGy per WLM as calculated for differing aerosol sizes, shows an inverse relationship i.e. estimated values range from 2-13 mGy per WLM for attached fractions and 100-200 mGy per WLM for unattached fractions(3). Some study findings are shown in Figure 6. It is clear therefore, that concentration and size distribution of the unattached fraction is key to an accurate 'dose per unit exposure' calculation.

Author	Dose Conversion Factor (mGy/WLM)	
	Unattached	Total
Jacobi(1964)	70	31
Harley & Pasternak(1972)	240	3.6
Jacobi & Eisfeld(1980)	36	5

Figure 6: Dose Calculations
for the Unattached and Total Radon Progeny.
Ref 3.

3.0 UNATTACHED FRACTION:

Radon progeny upon initial formation, quickly attach themselves to aerosol particles, see Figure 7. A variable fraction however remain unattached. These unattached fractions, are considered to be the dominant factor influencing the dose received by target cells in the bronchial epithelium. The dose locally in this region, is reported to increase as the proportion and concentration of the unattached fraction increases.

Within the lower respiratory tract, the unattached fraction is considered to have a greater deposition efficiency then the larger sized attached fraction. Generally, particles in the size range 0.5nm to 3nm can be considered to be characteristic of the unattached fraction(15,22).

For purposes of comparison, the relative particle sizes can be taken to be(15);

Unattached Fraction	=1nm
Attached Fraction	=25nm
Larger Indoor Aerosols	=125nm
Dusty Atmospheric Particles	=500nm

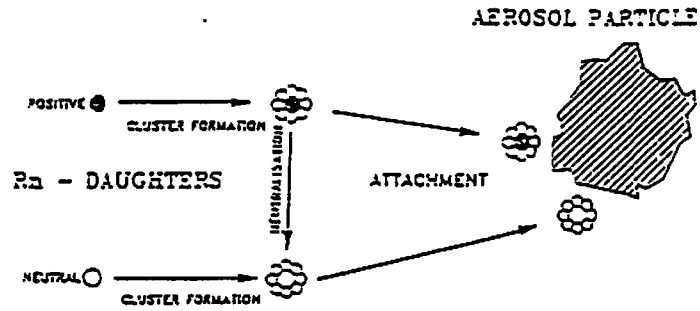

Figure 7: Unattached and Attached Fractions of Radon Decay Products. Ref. 33.

3.1 Measurement Methods.

Lung dosimetry models, dealing with the estimation of health risk, require specific information on two important parameters: (1)The fraction of the unattached progeny and (2)The size of this fraction, defined as the 'Activity Median Diameter'(22).

The most common method for the collection of these particles, is termed the 'Diffusion Method'. Other methods do exist but are considered not to be as effective. In the electrostatic collection method for example, Po-218 ions are rapidly neutralized in the atmosphere and therefore results in an underestimation of the true proportion of the unattached fraction. Additionally, only a small fraction of the unattached fraction is charged(typically 10%), and therefore the statistical precision will be limited. Early 'diffusion methods' instruments for detection of the unattached fraction consisted of either diffusion tubes or diffusion batteries.

Later, 'wire screens' were developed in order to simplify ease of usage. Today wire screens are commonly used for grab sampling methods. An additional component needed for dose models is the associated 'activity' of the alpha particle energy of the unattached fraction.

There are difficulties associated with measuring the activity on both the front and back of the wire screen, given that only one face of the wire screen is available for

analysis. Alpha particle energy is also lost within the screen weave itself. Consequently, an improved continuous sampling method(22), developed by Professor P. K. Hopke, has been applied to circumvent this problem, as shown in Figure 8.

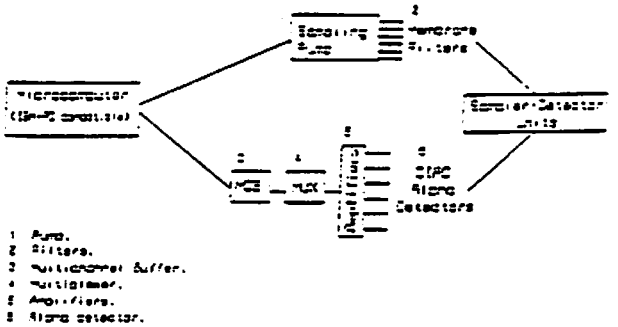

Figure 8: Block Diagram of Graded Screen Array Continuous Measurement System. Ref. 23.

In this method, a simultaneous measurement is made using both a 'reference filter' and a 'wire screen backup filter', to give a more reliable estimate of the unattached fraction. A typical plot(see Figure 9) of the radioactive particle size distribution shows the occurrence of the unattached peak at around 1nm for the Po-218 component. There are limitations however in the accuracy of measurements when the activities are low and the statistical precision is compromised.

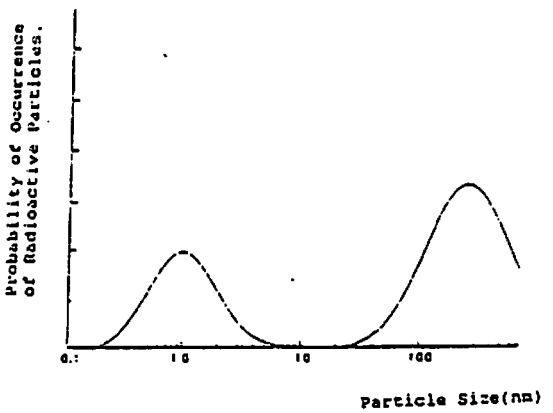

Figure 9: Typical Plot of Po-218 Activity Size Distribution, showing Unattached Fraction Peak around 1nm. Ref. 23.

3.2 Diffusion Coefficient.

Analysis of the unattached fraction is linked with the definition of a unique parameter called the 'Diffusion Coefficient'. Traditionally, this parameter has been assigned a single value of 0.054 cm2 s-1, as determined for the unattached RaA component. More recent measurements however(15) have shown that the unattached fraction can be

more accurately characterized as an ultrafine particle in the size range: 0.5nm to 3nm. Correspondingly therefore the diffusion coefficients would now be range from: 0.005 to 0.1 cm2 s-1.

The unattached fraction particle size is hence associated with a range of values rather than a single discrete number. In turn the dose conversion factors, will correspondingly have a spectrum of values as opposed to a single number.

For improved accuracy of health risk estimates therefore, a range of diffusion coefficients should be used instead. Unfortunately further complications can arise in the assessment of the magnitude of this parameter, since the presence of anomalies such as e.g. trace gases can be a significant influencing factor(22) on the value for the diffusion coefficient.

4.0 AIR CLEANING SYSTEMS:

The human health risk arising from the exposure and inhalation to radon progeny has prompted the development of mitigation equipment and techniques. Traditionally and currently in North America, sub-slab ventilation methods remain the most commonly deployed technique for reducing radon(gas) levels within residential dwellings. However, a new generation of alternative systems based on the techniques of air filtration and ion generation has emerged. A typical system is shown in Figure 10.

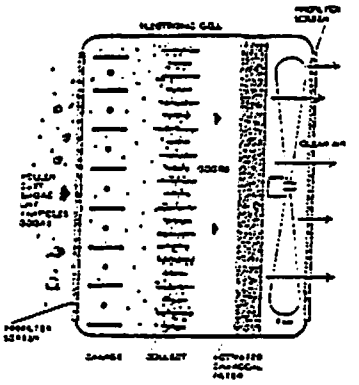

Figure 10: Typical Electronic Air Cleaner System. Ref. 30.

Such air cleaning systems have been evaluated by different researchers, in an attempt to characterize filtration rates and other variables needed to calculate dose to the bronchial region(24,25,26).

Initial investigations(18,19,20) focused on the influence of air cleaning systems on the concentrations of radon progeny(total and unattached fractions). Large differences in the estimated doses have been attributed mainly to the

different dosimetric models used - each making different assumptions about the influence of the unattached fraction to the bronchial dose. Nevertheless it is generally accepted that 'dose reductions' are always smaller than the 'total PAEC reductions'.

The major 'problems' associated with these discrepancies are:
1)Not all measurement systems were able to determine particle size distribution to less than 10nm in diameter.

2)Dose estimates were based on very simple lung dose models.

3)Only estimates of the unattached fraction were made.

4)A consistent definition of the critical particle size associated with the unattached fraction, does not exist today, hence estimates of the unattached fraction to date are further confounded.

5)Inconsistencies between various methods used for measuring the unattached fraction, prevent any scientific comparison of results.

Most recent investigations have indicated that the dose conversion factor is strongly dependent upon the actual activity size(see Figure 11) - it is therefore imperative that greater accuracy of characterization of the unattached fraction is need when evaluation the effectiveness of air cleaners for the removal of radon decay products.

Aerosol Size(nm)	Dose(mGy/WLM)
<50(unattached)	150
50	20
100	10
150	7
200	5
300	4
400 to 500	3

Figure 11: Representative values of Mean Bronchial Dose as a Function of Aerosol Size. Ref. 3.

5.0 DISCUSSION:

5.1 Findings to date.

The 1988 lung dosimetric model developed by James and Birchall(18), is most commonly used for evaluation of the absorbed dose. This model enables an average dose to be calculated for all sensitive cells in the bronchial region of the lung, normalized to a unit exposure of PAEC. Albeit a 'simple' model, nevertheless the parametric factors influencing the dose estimates are many.

Some key factors contributing to the average dose figure are:

1)Male/female/children

2)Low/high breathing rates

3)Activity status e.g. sleeping/resting/light/heavy work

4)Occupancy factors

5)Cooking/cleaning activities

For example, the dose conversion factor increases by a factor of 2.5 times when the breathing rate increases from slow(125 cm3 s-1) to fast(833 cm3 s-1). This factor applies to the unattached fraction centered around 1nm in size. For activity extremes ranging from sleeping to heavy work, the dose conversion factor can increase by a factor of x5(see Figure 12).

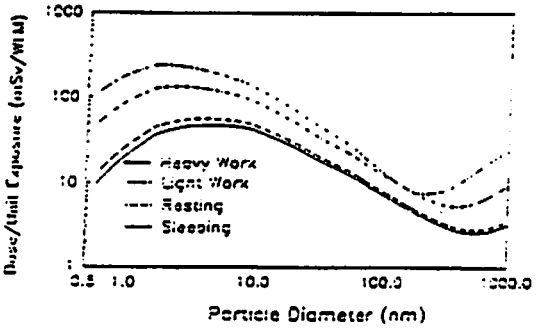

Figure 12: Mean Annual Dose to Bronchial Epithelial Cells as Function of Particle Size. Ref. 3.

It can be seen from these results(18) that numerous factors influence the accuracy of these dose estimates and hence critical parameters such as the unattached fraction size distribution, have to be characterized.

The unattached fraction in residential environments is typically taken to be 5 to 15%(of the total PAEC) when there are no aerosol sources and decreasing to below 5% in the presence of cigarette smoke, cooking, heating(28,29). Studies of the unattached fraction have generally been as an aerosol technology, while studies in lung dosimetry have more of a focus towards the medical physics aspect.

Apart from a few investigators, notably Prof. Philip Hopke, the association between the two disciplines has not been too widely investigated. Fundamental issues concerning, basic definitions, methods of measurement and unified methods for comparison still need to be established. The workshop held at the University of Illinois(April 24-25,1989) included many experts in the field, such as Dr. A.C. James, Dr. E.O. Knudsen, Dr. A. Reineking et al, who convened for the purpose of providing specific recommendations for future measurement efforts of the unattached fraction.

An extensive investigation of three single family houses located in Springfield, PA, Princeton, NJ, and Northford, CT, included assessment of the effectiveness of electronic and air filtration cleaners for removing radon progeny(30). The conclusions from this major study are shown in Figure 13.

Radon Concentration	Recommendation
<12 pCi/L	Electronic Air Cleaner
12 - 18 pCi/L	Air Filtration System
>18 pCi/L	Sub-slab Ventilation

Figure 13: Recommendations from Air Cleaner Study Findings. Ref. 30.

5.2 Future Goals.

Improvements to lung dose estimates is seen to arise from three major sources:

1) Generation of a new, improved dosimetry model, which takes into account the differing radiation sensitivities of tissues in the respiratory tract.

2)Determination of the exact size distribution of the most diffusive particle activity in the nasal and bronchial regions.

3)Acceptance of a unified system of definition and measurement for the unattached fraction, in order that different dose models and 'dose conversion factors' can be sensibly compared.

Until such improvements can be implemented, uncertainties will continue to abound in the estimation of nasal, oral, and bronchial deposition/penetration rates.

The ICRP task group is proposing to revise the lung dosimetry model. Improvements to the new model will now consider the relative sensitivities of tissues in the respiratory tract. Specific tissues are examined both in terms of the differing doses they are estimated to receive and the relative response to these doses.

Tissues, for example in the nasal region are less sensitive than those in the bronchial region. However if a higher equivalent dose were to be received by the nasal region then their contribution to the overall average dose would be more significant.

Complete characterization of the activity size distribution for the unattached fraction can now be accomplished with automated systems(23). However there are only a limited number of such systems available, which are additionally expensive to build and complex to use.

6.0 CONCLUSION:

The DOE's Radon Research Program(DOE/ER-0488P), under the auspices of Dr. Susan Rose, places considerable emphasis on the need to reduce the uncertainties in risk estimates, associated with dose-response relationships of radon progeny and lung cancer. There are, as the DOE clearly states, potential errors in measurement, exposure, diagnosis, model selection and low dose extrapolation. Contributory R&D efforts in any of these areas, will aid the development of improved risk estimate models.

In recognition of the need therefore to accurately characterize the unattached fraction of radon progeny, TN Electronics in conjunction with the considerable expertise of Professor Philip K. Hopke, is developing a field portable continuous measurement system. The system will be capable of measuring unattached fractions in the 0.5 to 3nm range, but extending in analysis up to 10nm for the most dose-effective activity. The prime application are believed to be in the following areas although some researchers might have their own individual needs:

1)Field measurements of the unattached fraction for inhalation studies of the ultra-fine particles in the respiratory tract.

2)Characterization of the radioactive aerosols in both the ambient and mine atmosphere for the study physical/chemical interactions of the radon progeny in the air.
3)Lung dosimetry studies requiring measurement of both the nasal and bronchial deposition efficiencies for dose estimates.

4)Investigation of effectiveness of indoor air cleaner systems(ion generation & filtration) in reducing the unattached fraction.

5)Radon chamber measurements of the unattached fraction for improved parametric characterization of measuring instruments.

A better understanding of the significance of the unattached fraction is needed if major advances are to be made in the study of the health effects of radon progeny.

<u>References:</u>

(1)Samet J.M.: Radon and lung cancer. Journal of the National Cancer Institute. Vol. 81, No. 10, pp. 745-757, May22, 1989.
(2)Fabrikant J.I.: Radon and lung cancer-The BEIR IV Report. Health Physics. Vol. 59, No. 1, pp. 89-97, July, 1990.
(3)James A.C.: Lung Dosimetry. In: Nazaroff W.W.; Nero A.V., Jr., eds. 'Radon and its Decay Products in Indoor Air'. New York.: John Wiley and Sons; pp. 259-309, 1988.
(4)National Research Council, Committee on the Biological Effects of Ionizing Radiation. The health effects of Radon and other internally deposited alpha-emitters(BEIR IV). Washington DC. National Academy Press; 1988.
(5)International Commission of Radiological Protection. Lung Cancer from Indoor Exposures to Radon Daughters. Oxford: Pergamon Press; ICRP Publications 50; 1987.
(6)United Nations Scientific Committee on the Effects of Atomic Radiation. Sources, Effects and Risks of Ionizing Radiation. New York: United Nations: 1988.
(7)National Council on Radiological Protection and Measurements. Evaluation of Occupational and Environmental Exposures to Radon and Radon Daughters in the United States. NCRP Report No. 78, Bethesda, 1984.
(8)United Nations Scientific Committee on the Effects of Atomic Radiations. Ionizing Radiations:Sources and Biological Effects, Annex D, Report to the General Assembly, UN, 141, New York, 1982.

(9)International Commission on Radiological Protection. Limits for Inhalation of Radon Daughters by Workers. ICRP Publication 32, Ann. of ICRP, 6(1), 1981.
(10)International Commission on Radiological Protection. Limits on Intake of Radionuclides by Workers. ICRP Publication 30, Part 1, Ann. of ICRP, 2(3/4), 1979.
(11)International Commission on Radiological Protection. Recommendations of the International Commission on Radiological Protection. ICRP Publication 26, Ann. of ICRP, 1(3), 1977.
(12)Bair W.J.: Human respiratory tract model for radiological protection - A revision of the ICRP dosimetric model for the repiratory system. Health Physics. Vol. 57, Sup. 1, pp. 249-252, 1989.
(13)Cohen B.S.; Briant J.K.: Flow distribution in human and canine tracheobronchial airway casts. Health Physics. Vol. 57, Sup. 1, pp. 21-27, 1989.
(14)Cheng Y.S.; Yamada Y.;Yeh H.C: Diffusional deposition of ultrafine aerosols in a human nasal cast. J. Aerosol Sci. Vol. 19, pp. 741-751, 1988.
(15)Ramamurthi M.; Hopke P.K.: On improving the validity of wire screen unattached fraction Rn daughter measurements. Health Physics, Vol. 56, pp.189-194, 1989.
(16)James A.C.; Roth R.C.; Kuennen R.W.; Cross F.T.: The efficacy of a high efficiency room air treatment system in mitigating dose from radon decay products, presented at the American Association of Aerosol Research meeting, Reno Nevada, 1989.
(17)Yeh H.C.; Schum G.M.: Models of human airways and their application to inhaled particle deposition. Bull. Math. Biol. Vol.42, pp.461-480, 1980.
(18)James A.C.; Greenhalgh J.R.; Birchall A.: A dosimetric model for tissues of the human respiratory tract at risk from inhaled radon and thoron daughters. In: Radiological Protection - Advances in Theory and Practice, Proc. 5th Congress IRPA, Jerusalem. Pergamon Press, Oxford pp. 1045-1048, March 1980.
(19)Jacobi W.; Eisfield K.: Internal dosimetry of radon 222, radon 220, and their short lived daughters, GSF report S-626, Gesellscaft fur Strahlen und Umweltforschung, Munich Neuherberg, West Germany, 1980.
(20)Harley N.H.; Pasternak B.S.: Experimental absorption measurements applied to lung dose from radon daughters. Health Physics, Vol.23, pp.771-782, 1972.
(21)Harley N.H.; Pasternak B.S.: Experimental radon daughter alpha dose factors in a five lobed human lung. Health Physics, Vol.42, pp.789-799, 1982.
(22)Hopke P K.: A critical review of measurements of the unattached fraction of radon decay products. DOE Technical report series. DOE/ER-0451P, 1990.
(23)Ramamurthi M.; Hopke P.K.: An automated, semicontinuous system for measuring indoor radon progeny activity weighted size distribution, dp= 0.5-500nm. Aerosol Science and Technology, Vol.14, pp.82-92, 1991.

(24)Lehtimaki M.; Graeffe K.;Janka K.; Kulmala V.; Rajala M.: On the behavior of radon daughters in indoor air. Rad. Prot. Dosim., Vol.7, pp.165-168, 1984.
(25)Rajala M.; Lanka K.; Lehtimaki M.;Kulmala V.; Graeffe G.; Keskinen J.: The control of radon progeny by air treatment devices. Sci. Total Environ., Vol.45, pp.493-498, 1985.
(26)Rajala M.; Janla K.; Lehtimaki M.; Kulmala V.; Graeffe G.: the influence of an electrostatic precipitator and mechanical filter on Rn decay products. Health Phys., Vol. 50, pp.447-455, 1986.
(27)Jonassen N.: Air filtration and radon daughter levels. Environ. Int.,Vol.8, pp.71-75, 1982.
(28)Reineking A,; Becker K.H.; Porstendorfer J.: Measurement of the unattached fractions of radon daughters in houses. Sci. Total Environ. Vol.45, pp.261-270,1985.
(29)Vanmarke H,; Janssens A,; Raes F.: The behavior of radon daughters in the domestic environment, In Radon and its Decay Products: Occurrence, Properties and Health Effects. Ed. P. K. Hopke. American Chemical Society, Washington D.C. pp.301-323, 1987.
(30)Li C.S. PhD thesis under Professor P.K. Hopke(Advisor). Field evaluation and health assessment of air cleaners in removing radon decay products in domestic environments. Dept. of Civil Engineering. University of Illinois at Urbana-Champaign, 1990.
(31)Schneiderman M.A.; Decoufle P.; Browm C.C.: Thresholds for environmental cancer, biologic and statistical considerations. Ann. NY Acad. Sci. Vol.329, pp.92, 1979.
(32)Gastineau R.M.; Walsh P.J.; Underwood N.: Thickness of bronchial epithelium with relation to exposure to radon. Health Phys. Vol.23, pp.857, 1972.
(33)Reineking A; Porstendorfer J.: Unattached fraction of short lived Rn decay products in indoor and outdoor environments: An improved single screen method and results. Health Physics. Vol. 56, no.6, pp.715-727, 1990.