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Bronchial Rn dose survey for residences

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Abstract

The bronchial dosimeter for Rn progeny proposed by Yu and Guan in 1998 was employed to survey the bronchial dose from Rn progeny in 30 residences in Hong Kong. An average bronchial deposition fraction of Rn progeny was obtained as 0.0334, which gave an average dose conversion factor (DCF) of 8.5 mSv WLM^{-1}. The mean values of potential α energy concentration (PAEC) deposited in the tracheobronchial region ($PAEC_{T-B}$), total PAEC in air ($PAEC_T$), annual effective dose (E), concentration of Rn gas (RC) and annual dose conversion factor (ADCF) for all the residential sites combined were 0.11 ± 0.05, 3.1 ± 1.4 mWL, 1.2 ± 0.5 mSv yr^{-1}, 23 ± 10 Bq m^{-3} and 0.055 ± 0.020 (mSv yr^{-1} per Bqm^{-3}), respectively, with air-conditioned sites (AC sites) and non-AC sites having significantly different mean ADCF values. The indoor relative humidity affected $PAEC_T$ and RC with high confidence levels ($>95\%$).

Keywords: Dose conversion factor; Rn; Dose; Dosimeter; Lung model; Deposition

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1. Introduction

Bronchial deposition of Rn progeny (^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po) is believed to cause lung cancers. Some effort has thus been devoted to assess the bronchial dose from Rn progeny. Traditionally, the assessments were carried out using dosimetric lung models, in which the unattached fraction f_p of potential α energy concentration (PAEC) of Rn progeny was an important parameter. The measurement of f_p was commonly carried out using wire screens, but the inability to separate the unattached fraction from the attached fraction of Rn progeny due to the intrinsic collection efficiency characteristics of wire screens (Ramamurthi & Hopke, 1989) presented problems. Therefore, realistic assessments of bronchial dose from Rn progeny still seems implausible.

A breakthrough was proposed by Hopke, Ramamurthi and Knutson (1990) to use multiple metal wire screens to mimic the deposition properties of Rn progeny in the nasal (N) and tracheobronchial (T-B) regions directly. Based on the modified version (Ramamurthi & Hopke, 1989) of the formula derived from the experimental data of the penetration of ultrafine particles through a nasal cast (Cheng, Yamada, Yeh & Swift, 1988), and using the wire screen penetration theory (Cheng & Yeh, 1980; Cheng, Keating & Kanapilly, 1980), they were successful in using a 400-mesh screen with a face velocity of $12\,\mathrm{cm\,s^{-1}}$ for the simulation of Rn progeny deposition in the N region. Furthermore, Hopke et al. (1990) calculated the deposition characteristics of the progeny in the T-B region using (i) the lung model parameters given by James (1988) and Yeh and Schum (1980); (ii) the deposition relations given by Yu and Diu (1982) for laminar flow diffusional deposition (Ingham, 1975) and deposition by impaction and sedimentation; and (iii) the correction factors given by Cohen, Sussman and Lippman (1990) for incomplete development of uniform laminar flow. Again, they were successful in using four layers of 400-mesh wire screens with a face velocity of $12\,\mathrm{cm\,s^{-1}}$ for the simulation of Rn progeny deposition in the T-B region.

Based on these findings, many workers (Jonassen & Jensen, 1991; George & Knutson, 1992) measured the deposition fractions of Rn progeny in these regions under certain conditions. Oberstedt and Vanmarcke (1995) carried out precise calibrations for the system, and named the system as the "bronchial dosimeter". This first-generation bronchial dosimeter consisted of multiple metal wire screens and required three samplers and three α spectroscopic systems. Although this first-generation bronchial dosimeter removed the difficulties and problems in measuring f_p and provided information for direct calculations of the bronchial dose from Rn progeny, the requirement of three samplers and three α spectroscopic systems precluded this configuration from practical real-life measurements. Yu and Guan (1998) proposed a second-generation bronchial dosimeter similar to a normal measurement system for Rn progeny or PAEC and consisted of only a single sampler and employed only one 400-mesh wire screen and one filter. With this bronchial dosimeter, Yu and Guan (1998) hoped that the "dose estimation" from large-scale Rn surveys could be ultimately replaced by large-scale "dose surveys" in the future.

The first dose survey for offices was carried out using the present method by Yu, Lau, Guan, Lo and Young (2000). However, Yu, Young and Li (1996) and Yu et al.

(1999) showed that the Rn properties in offices were very different from those in residences. Therefore, it is pertinent to investigate the Rn bronchial doses for residences and offices separately. The present work was devoted to the survey of bronchial dose from Rn progeny in residences. Possible dependence of the bronchial dose on different environmental parameters were also investigated.

2. Experiment

The second-generation bronchial dosimeter proposed by Yu and Guan (1998) was employed for the present survey of bronchial dose from Rn progeny in residences, and all bronchial dosimeters refer to this configuration in the rest of this paper. Fig. 1 is the schematic diagram for the sampling set-up. The sampler housed a 400-mesh wire screen and a filter, through which the sampled air was drawn into a ZnS scintillation cell. The ZnS scintillation cell was not a requirement for the bronchial dosimeter, but was included for simultaneous measurements of Rn concentrations, which could then be combined with bronchial doses to give the annual dose conversion factor (ADCF) (in $\mathrm{mSv\,yr^{-1}}$ per $\mathrm{Bqm^{-3}}$).

The filter employed was the Thompson–Nielson TN-WL-MS filter with 0.8 μm pore size. The factor controlling the sampling characteristics of the wire screen was the wire velocity factor KVF ($\mathrm{cm^2\,s^{-1}}$) which was directly related to the inspirational/expirational volumetric flow rate Q ($\mathrm{l\,min^{-1}}$). According to Hopke et

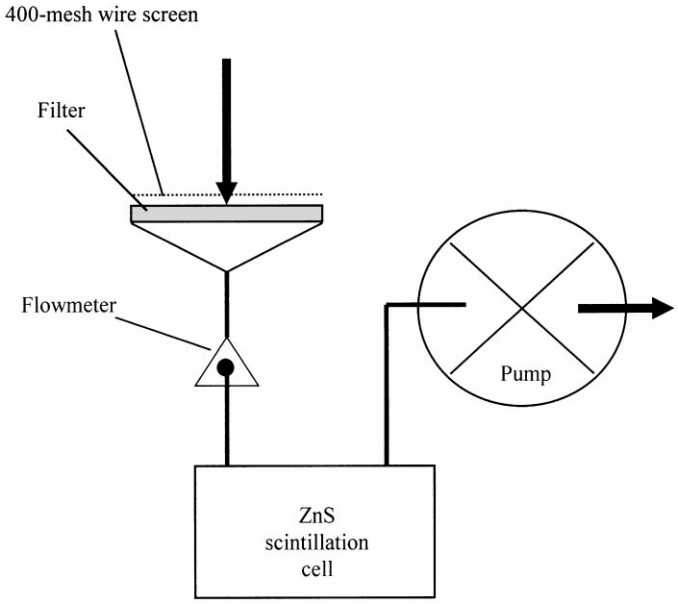

Fig. 1. Schematic diagram of the sampling set-up of the bronchial dosimeter.

al. (1990), Q was taken to be 30 l min^{-1} so KVF = 0.0473 cm^2 s^{-1}. The sampling face velocity U (cm s^{-1}) was then calculated from KVF and the wire factor WF of the employed wire screen. For the 400-mesh wire screens employed in the present study U was determined as 12 cm s^{-1}. Both the filter and the wire screen had an effective diameter of 2.128 cm.

The wire screen and the filter were counted using the Canada RDA-200 Rn/Rn progeny detector. The three-count filter method or the modified Tsivoglou method (Thomas 1972) was employed to measure the PAEC values recorded by the wire screen and the filter, namely, $\mathrm{PAEC_S}$ and $\mathrm{PAEC_F}$, respectively. Counting periods of 2–5, 6–20 and 21–30 min were employed after sampling of 30 min, giving counts N_1^{F}, N_2^{F} and N_3^{F}, respectively, for the filter and counts N_1^{S}, N_2^{S} and N_3^{S}, respectively, for the wire screen (with Poisson counting errors as their associated uncertainties), and the $\mathrm{PAEC_F}$ and $\mathrm{PAEC_S}$ were calculated by

$$\mathrm{PAEC_F} = \frac{1}{v\eta_1 es}(0.0490N_1^{\mathrm{F}} - 0.0196N_2^{\mathrm{F}} + 0.0374N_3^{\mathrm{F}})\ \mathrm{mWL}, \tag{1}$$

$$\mathrm{PAEC_S} = \frac{(\mathrm{SL})}{v\eta_2(\mathrm{FT})}(0.0490N_1^{\mathrm{S}} - 0.0196N_2^{\mathrm{S}} + 0.0374N_3^{\mathrm{S}})\ \mathrm{mWL}, \tag{2}$$

where v is the air flow rate (l min^{-1}) corresponding to a face velocity of 12 cm s^{-1}, e and s, respectively, the self-absorption coefficient for α particles and the collection efficiency for Rn progeny of the filter paper, η_1 and η_2, respetively, the efficiency of the system for detecting α particles from the filter and the wire screen, FT the front-to-total activity ratio which takes into account that some progeny are attached to the back of the wire screen rather than on the surface, and SL the screen loss factor (see Ren & Solomon, 1993; Yu & Guan, 1998). For our experiments, $e \times s = 0.8$, $\eta_1 = 0.397$, $\eta_2 = 0.484$, FT = 0.67 and SL = 1.19.

The ZnS scintillation cell had a volume of 160 ml. After sampling, the scintillation cell was sealed for 3 h until equilibrium was reached between the Rn gas and its progeny inside the scintillation cell, and the concentration of the Rn gas (RC, in Bq m^{-3}) was then measured also by the Canada RDA-200 Rn/Rn progeny detector.

According to Yu and Guan (1998), the PAEC deposited in the tracheobronchial region ($\mathrm{PAEC_{T-B}}$), annual effective dose (E), and the ADCF were calculated by

$$\mathrm{PAEC_T} = \mathrm{PAEC_S} + \mathrm{PAEC_F}, \tag{3}$$

$$\varepsilon = \mathrm{PAEC_S}/\mathrm{PAEC_T}, \tag{4}$$

$$\mathrm{PAEC_{T-B}} = \mathrm{PAEC_T} \times \Gamma(\mathrm{mWL}), \tag{5}$$

$$E = 10.5 \times \mathrm{PAEC_{T-B}}(\mathrm{mSv\ yr^{-1}}), \tag{6}$$

$$\mathrm{ADCF} = E/\mathrm{RC}(\mathrm{mSv\ yr^{-1}\ per\ Bqm^{-3}}), \tag{7}$$

where

$$\Gamma = (0.0673 \pm 0.0002)\varepsilon + (0.0316 \pm 0.0000). \tag{8}$$

Eq. (8) was derived by Yu and Guan (1998) for a wire screen with $KVF = 0.0473\,cm^2\,s^{-1}$ and for a typical indoor environment.

The dose surveys were carried out from August 1998 to January 1999. A total of 30 residences (all were reinforced concrete buildings) were surveyed on a random basis. All the surveyed residential sites were occupied during the measurements. The time of each measurement was confined to between 9 a.m. and 5 p.m. during the daytime to ensure more uniform experimental conditions. The air sampling points were chosen to be as calm as possible; i.e., they were away from windows, doors and air-conditioning units, since the concentration of Rn and its progeny would be greatly influenced by the air flow.

3. Results and discussion

The calculated $PAEC_{T-B}$ and the total PAEC in air ($PAEC_T$) values are shown in Fig. 2 for the 30 dwelling sites, and a linear relationship seemed to fit the $PAEC_{T-B}$ and $PAEC_T$ values reasonably well (slope $= 0.0334 \pm 0.0011$, intercept $= 0.00938 \pm 0.00319$, $\pm$ means 95% confidence intervals). The slope was in fact the average deposition fraction Γ, which depended on ε (see Eq. (8)). For our range of ε (<0.2, see Fig. 3), the dependence of Γ on ε was small, so Γ was essentially a constant and so $PAEC_{T-B}$ and $PAEC_T$ were highly correlated. From $\Gamma = 0.0334$, an average dose conversion factor DCF of $8.5\,mSv\,WLM^{-1}$ (i.e., $\Gamma \times 212 \times 1.2$) was obtained (see discussions of Yu & Guan, 1998; Yu et al., 2000), which were close to

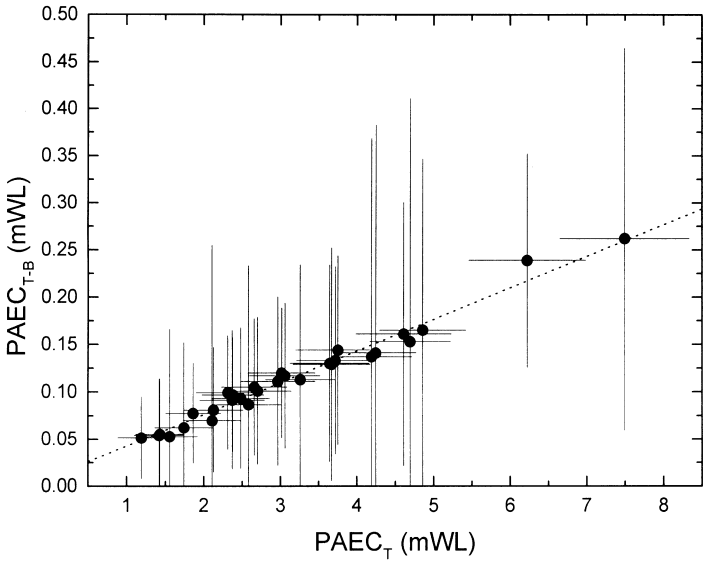

Fig. 2. Measured $PAEC_{T-B}$ and $PAEC_T$ values for the 30 dwelling sites. Dashed line: linear fit to all data (slope $= 0.0334 \pm 0.0011$, intercept $= 0.00938 \pm 0.00319$, $\pm$ terms indicate 95% confidence intervals).

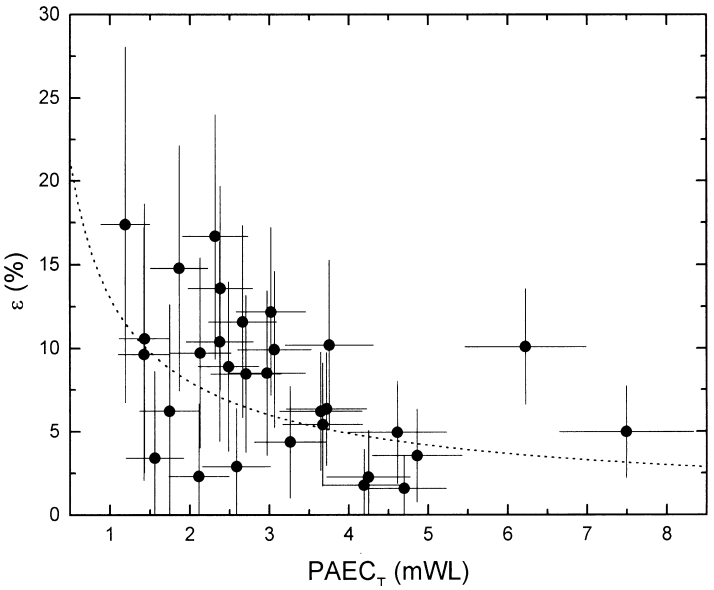

Fig. 3. Measured ε and $PAEC_T$ values for the 30 dwelling sites. Dashed line: non-linear fit to all data $\{\varepsilon\ (\%) = (13.0 \pm 4.1) \times [PAEC_T\ (mWL)]^{-\ (0.705 \pm 0.268)}$, $\pm$ terms indicate 95% confidence intervals$\}$.

the DCF of $10\,mSv\,WLM^{-1}$ proposed by James (1987) and $7.3\,mSv\,WLM^{-1}$ obtained by Porstendörfer and Reineking (1999) for dwellings with normal aerosol conditions. Note the different definitions and units for DCF and ADCF, and note that the corresponding value obtained by Yu et al. (2000) using the same bronchial dosimeter for offices was $9.5\,mSv\,WLM^{-1}$.

It is worth remarking here that, although Γ had small dependence on $PAEC_T$, ε could have an entirely different behavior. Fig. 3 shows the dependence of ε on $PAEC_T$. A non-linear fit gave $\varepsilon\ (\%) = (13.0 \pm 4.1) \times [PAEC_T\ (mWL)]^{-\ (0.705 \pm 0.268)}$, with $\pm$ values as the 95% confidence intervals. Since ε surrogates the unattached fraction f_p and $PAEC_T$ surrogates the number of aerosol particles Z in air (Yu et al., 2000), the above result suggested that f_p decreased with Z, which agreed with previous findings (e.g., George & Hinchliffe, 1972; Robkin, 1987; Porstendörfer, 1996; Porstendörfer & Reineking, 1999; Yu et al., 2000).

The mean values (accompanied by their standard deviations) of $PAEC_{T-B}$, $PAEC_T$, E, RC and ADCF for all the 30 sites were 0.11 ± 0.05, $3.1 \pm 1.4\,mWL$, $1.2 \pm 0.5\,mSv\,yr^{-1}$, $23 \pm 10\,Bqm^{-3}$ and 0.055 ± 0.020 ($mSv\,yr^{-1}\,Bq^{-1}\,m^{-3}$), respectively. In Table 1, the mean values for sites with air-conditioning (AC sites), electric fans (EF sites), natural ventilation (N sites) are shown.

The data were compared by Mann–Whitney rank sum tests so that the p values for any two sets of data could also be calculated. In the present study, a significant difference referred to a p value of less than 5%. Since the values for N sites and EF sites were not significantly different while some of their values were significantly different from those for AC sites, and since there were only a small number (6) of EF

Table 1
Effects of air-cooling methods

Sites	No. of sites	$PAEC_T$ (mWL)	$PAEC_{T-B}$ (mWL)	E (mSv yr^{-1})	RC (Bq m^{-3})	ADCF (mSv yr^{-1} Bq^{-1} m^{-3})
AC	8	2.7 ± 2.1	0.10 ± 0.07	1.0 ± 0.7	28 ± 15	0.036 ± 0.010
EF	6	3.7 ± 1.6	0.13 ± 0.06	1.4 ± 0.6	25 ± 12	0.059 ± 0.023
N	16	3.0 ± 1.1	0.11 ± 0.04	1.1 ± 0.4	20 ± 6	0.060 ± 0.020
p (%)						
AC/N		16	21	21	5	0.3
AC/EF		14	14	14	95	3
N/EF		44	57	57	26	71
Non-AC	22	3.2 ± 1.2	0.11 ± 0.04	1.2 ± 0.4	21 ± 8	0.060 ± 0.020
p (%)						
AC/non-AC		10	13	13	12	0.2

Table 2
The effects of indoor relative humidity

Indoor relative humidity	No. of sites	$PAEC_T$ (mWL)	$PAEC_{T-B}$ (mWL)	E (mSv yr^{-1})	RC (Bq m^{-3})	ADCF (mSv yr^{-1} Bq^{-1} m^{-3})
$\geqslant 68\%$	10	2.7 ± 1.1	0.099 ± 0.037	1.0 ± 0.4	17 ± 3	0.062 ± 0.023
$<68\%$	12	3.6 ± 1.2	0.13 ± 0.04	1.3 ± 0.5	24 ± 9	0.058 ± 0.018
P (%)		5	13	13	3	56

sites, the N sites and EF sites were grouped together to form the category of non-AC sites in further discussions.

It can be seen that air-conditioning had a significant effect on ADCF. The smaller ADCF value was explained by the filtration of Rn progeny in the air-conditioning systems. The average ADCF values for AC sites and non-AC sites also agreed well with previously measured values for a closed room and a room with air conditioning (Yu & Guan, 1998). The RC values for AC sites were expected to be higher than those for non-AC sites due to poorer fresh air exchange for AC sites. The experimental data showed that AC sites had higher RC values but the differences were not statistically significant.

The effects of relative humidity for non-AC sites are shown in Table 2. The data were divided into the categories for relative humidity $\geqslant 68$ and $<68\%$ to give similar sub-sample sizes. The results showed that relative humidity affected $PAEC_T$ and RC with high confidence levels.

4. Conclusions

(1) The single-sampler bronchial dosimeter for Rn progeny proposed by Yu and Guan (1998) was employed for a direct survey of bronchial dose from Rn progeny in 30 residences in Hong Kong.

(2) The bronchial deposition fraction of Rn progeny was insensitive to the total potential α energy concentration of Rn progeny ($PAEC_T$) and the average value was obtained as 0.0334, which gave an average dose conversion factor (DCF) of $8.5\,mSv\,WLM^{-1}$, which is close to the dose conversion factor of $10\,mSv\,WLM^{-1}$ proposed by James (1987) and $7.3\,mSv\,WLM^{-1}$ obtained by Porstendörfer and Reineking (1999) for dwellings with normal aerosol conditions.

(3) The nasal deposition fraction ε was sensitive to $PAEC_T$. A non-linear fit gave $\varepsilon\ (\%) = (13.0 \pm 4.1) \times [PAEC_T\ (mWL)]^{-(0.705 \pm 0.268)}$, with $\pm$ values as the 95% confidence intervals. This phenomenon suggested that the unattached fraction of Rn progeny decreased with the number of aerosol particles Z in air, which is consistent with the conclusions made by Porstendörfer and Reineking (1999).

(4) The mean values of $PAEC_{T-B}$, $PAEC_T$, E, RC and ADCF were found to be 0.11 ± 0.05, $3.1 \pm 1.4\,mWL$, $1.2 \pm 0.5\,mSv\,yr^{-1}$, $23 \pm 10\,Bq\,m^{-3}$ and 0.055 ± 0.020 ($mSv\,yr^{-1}$ per Bqm^{-3}), respectively ($\pm$ values representing 1 standard deviation).

(5) Different air-cooling methods, namely, air-conditioned (AC sites), natural ventilation (N sites) and electric fans (EF sites) significantly affected the mean values of RC and ADCF. The mean values for N sites and EF sites were not significantly different while some of their values were significantly different from those for AC sites, so the N sites and EF sites were grouped together to form the category of non-AC sites in the present paper.

(6) The effects of the indoor relative humidity on the bronchial dose at non-AC sites were also investigated. It was found that the indoor relative humidity affected $PAEC_T$ and ADCF.

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References

Cheng, A. Y. S., Keating, J. A., & Kanapilly, G. M. (1980). Theory and calibration of a screen-type diffusion battery. *Journal of Aerosol Science*, *11*, 549–556.

Cheng, A. Y. S., Yamada, Y., Yeh, H. C., & Swift, D. L. (1988). Diffusional deposition of ultrafine aerosols in a human nasal cast. *Journal of Aerosol Science*, *19*, 741–751.

Cheng, A. Y. S., & Yeh, H. C. (1980). Theory of screen type diffusion battery. *Journal of Aerosol Science*, *11*, 313–319.

Cohen, B. S., Sussman, R. G., & Lippman, M. (1990). Ultrafine particle deposition in a human rracheobronchial cast. *Aerosol Science and Technology*, *12*, 1082–1091.

George, A. C., & Hinchliffe, L. (1972). Measurements of uncombined radon daughters in uranium mines. *Health Physics*, *23*, 791–803.

George, A. C., & Knutson, E. O. (1992). Radon progeny deposition in the nasal and tracheobronchial regions of the respiratory tract. *Radiation Protection Dosimetry*, *45*, 689–693.

Hopke, P. K., Ramamurthi, M., & Knutson, E. O. (1990). A measurement system for radon decay product lung deposition based on respiratory models. *Health Physics*, *58*, 291–295.

Ingham, D. B. (1975). Diffusion of aerosols from a stream flowing through a cylindrical tube. *Journal of Aerosol Science*, *6*, 125–132.

James, A. C. (1987). A reconsideration of cells at risk and other key factors in radon daughter dosimetry. In P. K. Hopke, *Radon and its decay products: Occurrence, properties and health effects* (pp. 400–418). Washington, DC: American Chemical Society.

James, A. C. (1988). Lung dosimetry. In W. W. Nazaroff, & A. V. Nero, *Radon and its decay products in indoor air* (pp. 259–309). New York: Wiley.

Jonassen, N., & Jensen, B. (1991). Measurement of simulated lung deposition of radon daughters. *Radiation Protection Dosimetry*, *45*, 669–671.

Oberstedt, S., & Vanmarcke, H. (1995). The bronchial dosemeter. *Radiation Protection Dosimetry*, *59*, 285–290.

Porstendörfer, J. (1996). Radon: measurements related to dose. *Environmental International*, *22*(Suppl.1), S563–S583.

Porstendörfer, J., & Reineking, A. (1999). Radon: characteristics in air and dose conversion factors. *Health Physics,*, *76*, 300–305.

Ramamurthi, M., & Hopke, P. K. (1989). On improving the validity of wire screen unattached fraction Rn daughter measurements. *Health Physics*, *56*, 189–194.

Ren, T. S., & Solomon, S. B. (1993). Measurement of counting efficiencies for alpha particles of radon daughters deposited on wire screens. *Radiation Protection*, *13*, 8–15 (in Chinese).

Robkin, M. A. (1987). Terminology for describing radon concentration and exposure. In D. Bodansky, M. A. Robkin, & D. R. Stadler, *Indoor radon and its hazards* (pp. 17–29). Washington, DC: University of Washington Press.

Thomas, J. W. (1972). Measurement of radon daughters in air. *Health Physics*, *23*, 783–789.

Yeh, H. C., & Schum, G. M. (1980). Models of the human lung airways and their application to inhaled particle deposition. *Bulletin of Mathematical Biology*, *42*, 461–480.

Yu, C. P., & Diu, C. K. (1982). A comparative study of aerosol deposition in different lung models. *American Industrial Hygiene Association Journal*, *43*, 54–65.

Yu, K. N., Cheung, T., Guan, Z. J., Young, E. C. M., Mui, B. W. N., & Wong, Y. Y. (1999). ^{222}Rn, ^{220}Rn and their progeny concentrations in residences in Hong Kong. *Journal of Environmental Radioactivity*, *45*, 291–308.

Yu, K. N., & Guan, Z. J. (1998). A portable bronchial dosimeter for radon progeny. *Health Physics*, *75*, 147–152.

Yu, K. N., Lau, B. M. F., Guan, Z. J., Lo, T. Y., & Young, E. C. M. (2000). Survey of Rn dose conversion factor for offices. *Journal of Environmental Radioactivity*, *51*, 83–89.

Yu, K. N., Young, E. C. M., & Li, K. C. (1996). A survey of radon properties for dwellings for Hong Kong. *Radiation Protection Dosimetry*, *63*, 55–62.