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Lung Dose Estimation of ^{222}Rn and ^{220}Rn Progeny Based on IMBA Professional® Software

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Radiation doses associated with exposures to ^{222}Rn (radon) and ^{220}Rn (thoron) are primarily due to inhalation of their short-lived progeny instead of the gas. The dosimetric data of radon are commonly used to assess the risk of radon-induced lung cancer derived from epidemiological studies of underground miners and from residential pooled analyzes. For estimation of the lung dose due to radon and thoron progeny, the dose conversion factor, which is the ratio of the activity concentration or PAEC of the decay products and dose is needed. There are three commonly used internal dosimetric software RADEP, LUDEP, and IMBA, which can be competent to implement to most of the biokinetic and dosimetric models recommended by ICRP to deduce the dose conversion factor and moreover to estimate the lung dose. Although all of the three internal dosimetric software use the same dosimetric model recommended by ICRP, due to the different data handling techniques, there are minor differences between the estimation results of the internal dose. There were several researchers who used the RADEP and LUDEP to conduct the dose calculation of lung dose of radon and thoron, but fewer researches gave the effective dose coefficient especially on IMBA. In this research, therefore, the dose conversion factor based on IMBA was calculated based on the reference parameters provided by the ICRP 66 and 137 and was compared with the published value of RADEP and LUDEP.

Key words: dose conversion factor, ^{222}Rn and ^{220}Rn progeny, dosimetric model, lung-to-blood absorption rate

1. Introduction

Radiation doses to the lungs associated with exposure to radon and thoron are primarily due to inhalation of their short-lived progeny instead of the gas. The dosimetric data of radon is commonly used for research on the risk of radon-induced lung cancer derived from epidemiological studies of underground miners and from residential pooled analyzes[1, 2]. The effective dose due to radon and thoron progeny inhalation is defined as:

$$E = DCF \times H \times EEC \quad (1)$$

where DCF is the dose conversion factor, H is occupied hours per one year, usually use 7000 h, which is corresponded to residential exposures, EEC is the equilibrium equivalent concentration for radon and thoron

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Table 1. Major input parameters used for dose calculation by IMBA

Input category	Parameter Input	value
Deposition	Exposure	Light-worker
	Breathing rate ($m^3 h^{-1}$)	1.2
	Activity median diameter (nm)	0.6 - 10,000
Absorption	Type of absorption behavior	ICRP 137/ "Type F" for ^{214}Bi and ^{212}Bi
	f1*	0.1 for ^{218}Po 0.2 for ^{214}Pb and ^{212}Pb 0.05 for ^{214}Bi and 212Bi (ICRP 137)
Bio-kinetic model	—	ICRP 30/56
Dose calculation	Radiation weighting factor (alpha particles)	20
	Tissue weighting factor	
	Lung	0.12
	Assigned partition for tissue weighting factor among thoracic region (BB:bb:AI)	0.333:0.333:0.333

*f1 value is the fraction of an ingested element absorbed directly into body fluids.

progeny.

Therefore, for estimation of the lung dose due to radon and thoron progeny, the dose conversion factor, which is the ratio of the activity concentration or potential alpha energy concentration (PAEC) of the decay products and the dose is needed[3]. The dose conversion factor, which can also be called the effective dose coefficient is the effective dose per equilibrium equivalent concentration expressed in units of mSv per working level month (WLM), mSv per mJ h m^{-3}, or mSv per Bq h m^{-3} [4]. To deduce the dose conversion factor moreover estimate the lung dose, there are three types of dosimetry model are available: (i) the deterministic regional compartment model, which are based on the ICRP Human Respiratory Tract Model[5], (ii) the deterministic airway generation model such as the RADOS model[6], which consists of 15 symmetric airway generations, and (iii) the stochastic airway generation model, the IDEAL dosimetry model, which consists of a variable number of asymmetric airway generations. Although there are significant differences in their structure and different computational methods, all of them are based on the same physical and physiological mechanisms, and the weighted equivalent doses calculated by the three types of model agree quite well[6].

There are three commonly used commercial available deterministic regional compartment model, Radon Dose Evaluation Program (RADEP)[7], Lung Dose Evaluation Program (LUDEP, National Radiological Protection Board, United Kingdom)[8] and Integrated Modules for Bioassay Analysis (IMBA Professional®, Health Protection Agency, United Kingdom)[9]. All of them implement most of the biokinetic and dosimetric models recommended by the International Commission on Radiological Protection (ICRP) and are applicable to this work. They allow users to specify their own parameter values and especially IMBA, it applies sophisticated data handling techniques to their customized internal dose calculation. All of the three internal dosimetric software incorporates the same source code to make calculations of respiratory tract deposition with the primary tabulated values of regional deposition recommended by ICRP 66[5].

Although all of the three deterministic regional compartment models use the same dosimetric model recommended by ICRP, due to the different data handling techniques and the default set of parameters, there are minor differences between the estimation results of the internal dose. Several researchers used the RADEP and LUDEP to conduct the dose calculation for lung dose of radon and thoron[3, 10], but fewer researches[6] gave the effective dose coefficients especially on IMBA. Compared to LUDEP and RADEP, IMBA is faster and much more compatible with the existing system and provided optional optimization functionality in dose assessment. In this research, therefore, the dose conversion factor based on IMBA is calculated with the reference parameters provided by the ICRP 137 and is compared with the published value of RADEP and LUDEP.

2. Materials and Methods

The dose calculations were conducted using IMBA, which was developed in recognition of the growing need for software tools to facilitate the use of the new ICRP biokinetic models[9, 11]. These enable users not only to use the standard ICRP models, but also to change many of the parameter values from ICRP defaults, and to apply sophisticated data handling techniques to internal dose calculations such as fitting measurement data with the maximum likelihood method; using multiple chronic and acute intakes; and dealing with different data types[9]. In this research, the Human Respiratory Tract Model for Radiological Protection (ICRP Publication 66) was adopted to estimate the lung dose of radon and thoron progeny. And the gastrointestinal tract model (GI-Tract Model) was used to supplement the completed internal exposure

Table 2. Parameter values for radon and thoron progeny in typical indoor conditions[3, 4, 12]

Parameter	Unattached	Attached		
		Nucleation	Accumulation	Coarse
Aerosol size (nm)	0-10 AMTD	10-100 AMTD/AMAD	100-1000 AMAD	>1000 AMAD
Geometric standard deviation	1.3	2	2	1.5
Particle density (kg m^{-3})	1000	1400	1400	1400
Shape factor	1	1.1	1.1	1.1
Hygroscopic growth factor	1	1.5	1.5	1.5
Equilibrium factor	0.4(radon) / 0.02(thoron)			
Breathing rate (m^3 h^{-1})	1.2			

by inhalation from the beginning of the respiratory tract to the discharge of the human body and guarantee the integrity of the structure of IMBA. The major parameters used for the calculation are listed in Table 1.

2.1. The deposition model

Because the radiation doses associated with exposure to radon and thoron are primarily due to inhalation of their short-lived progeny instead of the gases. And the activity size distribution of radon and thoron progeny is a dominant parameter related to DCF. Therefore, in this research, the lung dose estimation of radon and thoron based on IMBA only considers the deposition behavior of aerosols in the respiratory tract. The wide range of particle sizes from atomic dimensions to large environmental aerosols (from 0.6 nm to 10,000 nm) characterized by an activity median aerodynamic diameter (AMAD) and activity median thermodynamic diameter (AMTD, < 300 nm) was applied to the deposition process. For the hygroscopic growth factor of the aerosol size, it is necessary to replace the single value of particle aerodynamic diameter and the diffusion coefficient in each regional filter[4]. In this research, for modeling purposes and simplicity, it is assumed that activity median diameter (AMD) increases by the hygroscopic growth factor instantaneously as the particle enters the nose or mouth[4]. In the calculation, the hygroscopic growth factor directly multiplies the AMD value before inputting the IMBA. The detail deposition process is calculated by the particle transport module. The major aerosol parameters used for the calculation are listed in Table 2.

2.2. Clearance model and bio-kinetic model

This model follows several pathways of clearance from the respiratory airway. The clearance rate from the respiratory airway is used not only for determining the exposure to the airway itself, but also for determining the amount of exposure to other tissues. The radon and thoron decay products deposited in the respiratory tract are cleared by three main routes: into the blood by absorption, to the gastrointestinal (GI) tract via the pharynx and to regional lymph nodes (LN) via lymphatic channels. In the operation interface of IMBA, the model parameters module sets particle transport, absorption, and GI-tract to describe the three clearance routes, respectively. For the lung-to-blood absorption rate for inhaled particle, compared to the single absorption model with a half-time of 10 h used in LUDEP[3, 12], in the absence of absorption values for specific radionuclide compounds, the default values are proposed for materials classified as "Type S", "Type M" and "Type F". The default "Type M" is assumed for particulate forms of most elements and recommended for use in the absence of specific information on which the exposure material can be assigned to an absorption type. In this research, the absorption parameters recommended by ICRP 137 are employed. Because the absorption parameters of bismuth recommended by ICRP 137 is out of the calculation range of IMBA, the "Type F" which is close to the recommended value of ICRP 137 is adopted for ^{214}Bi and ^{212}Bi. The bio-kinetic model uses the default value of ICRP 30 and 56 in the calculation.

2.3. Dose calculation

To calculate the effective dose coefficient, the tissue weighting factor uses most of the default values of ICRP 60 / 66 / 68. The weighting factor of the thoracic region and extrathoracic region adopts the value from the reference value of ICRP 66[5]. For the extrathoracic region, a weighting factor of 0.025 is to be applied from the remainder fraction, which can be used for the specified organ or tissue receiving an equivalent dose in excess of the highest dose in any of the 12 organs and tissues. For the bronchial and pulmonary regions, an equal weighting for bronchial (BB), bronchiolar (bb) and alveolar (AI) as recommended in ICRP 66 is employed to estimate the contribution of the effective dose.

2.4. Calculation of dose conversion factor

The dose conversion factor of radon and thoron, the dose conversion factor with regard to the different absorption type, and the equivalent dose per unit exposure with

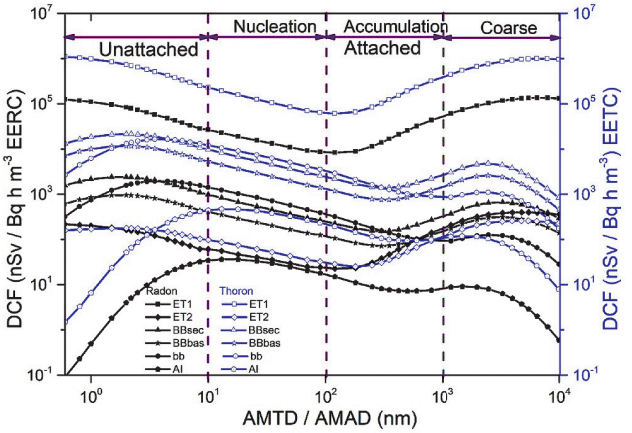

Fig. 1. The effective dose per EETC and EERC for each region of thoracic and extrathoracic region as a function of particle size of a monodispersed aerosol for a light worker with an average breathing rate of 1.2 m^3 h^{-1}.

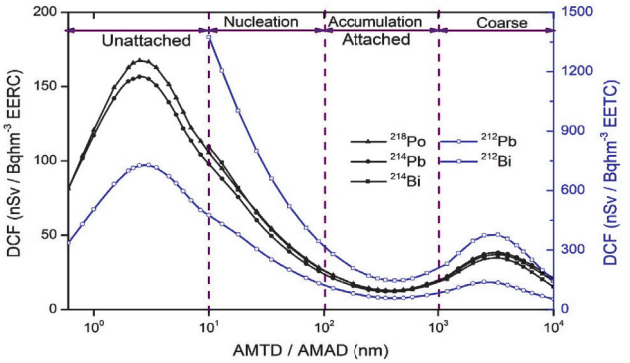

Fig. 2. The effective dose per EETC and EERC for each short-lived radon and thoron decay product as a function of particle size of a monodispersed aerosol for a light worker with an average breathing rate of 1.2 m^3h^{-1}. The unattached fraction of ^{214}Bi and ^{212}Bi is not included in the figure because of the "0" activity ratio of the composition in the calculation of the EEC.

respect to each region of the lung tissues are calculated.

The dose conversion factor is the effective dose per unit exposure to airborne short-lived radon and thoron progeny and is calculated in terms of Sv per potential alpha energy (PAE) exposure in the unit of Sv per WLM or Sv per J h m^{-3}. It can be calculated by the following equation:

$$DCF^M = B \cdot t \cdot P \cdot \frac{\sum_i c^M(i) e^M(i)}{\sum_i c^M(i) P(i)} \quad (2)$$

where B (in m^3 h^{-1}) is the average breathing rate of the reference worker, 1.2m^3 h^{-1} and t (in h) is the exposure period of 170 h. $C(i)$ (in Bq m^{-3}) is the activity concentration of the progeny radionuclide (i = A, B, C for ^{218}Po, ^{214}Pb, and ^{214}Bi, the first three progenies of radon or i = B, C for ^{212}Pb and ^{212}Bi of thoron). P is the PAEC of 1 WLM (1.286×10^8 MeV m^{-3}), $P(i)$ is the PAEC of unit activity of the progeny radionuclide. $e(i)$ (in Sv Bq^{-1}) is the effective dose coefficient of the progeny radionuclide. The superscribe of ^{M} is the size of the aerosol particle. For PAEC exposures of radon, the units mSv WLM^{-1} are converted to mSv per Bq h m^{-3} by multiplying by ($1/6.37\times10^5$) WLM per Bq h m^{-3} of equilibrium equivalent radon concentration (EERC). In terms of the radon gas exposures, the results need to multiply the equilibrium factor, F. For exposure to thoron, the units mSv WLM^{-1} were converted to mSv per Bq h m^{-3} of equilibrium equivalent thoron concentration (EETC) by multiplying by ($1/4.68\times10^4$) WLM per Bq h m^{-3}. In this research, it only considered the PAE exposure in the calculation of the effective dose.

In practice, the activity concentration of radon progeny varies with the particular environmental conditions of exposure. Based on the measurements of the activity concentration of ^{218}Po, ^{214}Pb, and ^{214}Bi, the activity ratio of radon progeny are assumed here for dosimetry[4]:

Equilibrium factor F: 0.4

Unattached: C(A) : C(B) : C(C) =1 : 0.1 : 0

Attached: C(A) : C(B) : C(C) = 1 : 0.75 : 0.6

For thoron progeny, because of the contribution of ^{216}Po to EETC can be negligible, the dose calculation of thoron progeny is not considering the contribution of ^{216}Po. The activity ratios assumed here are recommended by the Committee of the National Research Council[13]:

Unattached: C(B) : C(C) = 1.0 : 0

Attached: C(B) : C(C) = 1 : 0.25

3. Results and Discussion

3.1. Dose calculation by IMBA

The effective dose per EERC and EETC and the equivalent dose per EERC and EETC as a function of the particle size of the monodisperse aerosol for a light worker were calculated by IMBA. The particle size is expressed by using the AMAD and AMTD. In order to simplify the figure, the particle's thermodynamic diameter can be approximately given in terms of its aerodynamic diameter by equation 3[5, 14]:

$$\mathrm{AMTD} = \mathrm{AMAD}\sqrt{(1000\chi/\rho)} \quad (3)$$

where χ is the dynamic shape factor; ρ is the particle density (kg m^{-3}).

The tendency of the DCF of each region of the thoracic and extrathoracic region over the whole range of the particle size is shown in Figure 1. Particle deposition can be caused both by aerodynamic and thermodynamic processes depending on the particle size. In the case of the unattached fraction due to its size (approx. diameter range 0.5-5 nm), the only relevant deposition

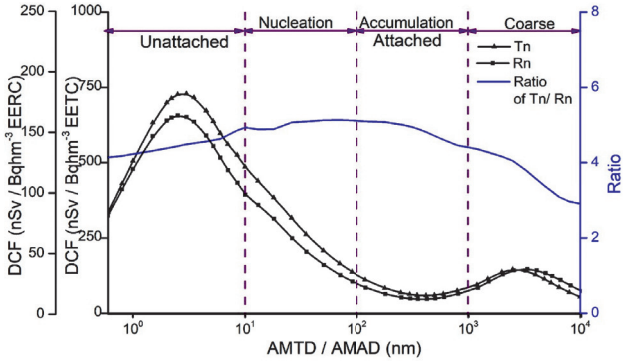

Fig. 3. The effective dose per EETC and EERC, and their ratio as a function of particle size of a monodispersed aerosol for a lightworker with an average breathing rate of 1.2 $m^3 h^{-1}$.

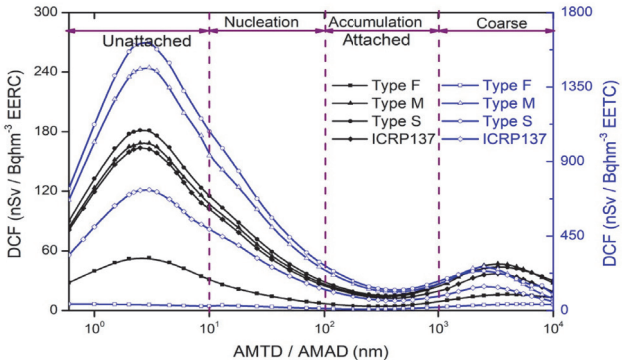

Fig. 4. Effective dose per EERC and EETC of three default absorption types as a function of the particle size of a monodispersed aerosol for a light worker with an average breathing rate of 1.2 $m^3 h^{-1}$.

mechanism is the thermodynamic process of diffusion. For large particle sizes, the aerodynamic process such as gravitational sedimentation and inertial impaction are more important. In the deposition process of the radioactive aerosol to the human respiratory tract, the radioactive aerosol enter to the respiratory tract from the nose and mouth to the extrathoracic region, and is affected by the multiple effects of inertial forces, gravitational force, and brownian motion, most of the aerosol particle is directly deposited in the extrathoracic (ET) region. Moreover, in the extrathoracic airways, the anterior nasal passages (ET1) are assumed to be subjected only to removal by extrinsic. The bulk of material deposited in the nasopharynx or larynx (ET2) is subjected to fast clearance in the layer of fluid that covers these airways. Therefore, in the extrathoracic region, ET1 has the highest DCF compared to the other regions and the DCF of ET2 is not high. And analyzed the DCF of ET region, the unattached fraction and the coarse mode of attached fraction have higher DCF than the other ranges of particle size. There is also the same tendency of the BB region as ET region in the thoracic airways. In the thoracic airways, the particle size of radioactive aerosol has affected the effective dose efficiency by both of deposition process and clearance process. Compare to the AI region, the BB and bb region have the same tendency as ET region. The DCF of both BB and bb regions have the peaks in the range of unattached fraction and the coarse mode of the attached fraction. In the AI region, since of the high deposition rate in the nuclei mode, the DCF of AI region increases from the unattached fraction and then smoothly and slowly decreases in the accumulation mode and sharply decreases in the area of large particle size.

Compared to the equivalent dose of each region, the effective dose is calculated by the sum of the equivalent dose multiplying the appropriate tissue weighting factor of each tissue and organ. Due to the absence of adequate quantitative information about the relative sensitivities of the different respiratory tract tissues in the thorax, it is recommended that the BB, bb, and AI regions should be assigned the equal weight in ICRP 66[5]. The results of the effective dose of radon and thoron as showed in Figure 2, the radon and thoron effective dose per EEC for each short-lived radon and thoron decay product has the same tendency. The unattached fraction has the highest DCF compared to the other ranges of particle size. In the attached fraction, the nucleation mode has the highest DCF followed by the coarse mode and accumulation mode. The same tendency of each radionuclide can be explained that the radioactive element is present as a minor constituent of the inhaled particles. Absorption of the radionuclide to body fluids may well then be controlled by the dissolution of the particle matrix, rather than by the elemental form of the radionuclide, and so may be different from that generally associated with simple compounds of the element[15]. In Figure 3, the radon and thoron effective dose per EEC has the same tendency as that of each radionuclide due to their calculation from the composition ratio of the effective dose of each radionuclide. According to the definition of DCF, because of the different values corresponds to 1 WLM from the radon and thoron decay products, the ratio of effective dose per EETC and EERC is around 13.5. In this research, the average ratio is around 4.7, which is lower than the ratio in the definition, however, close to the result values from the other researchers ranged from 3.6 to 4.4[3, 16]. It means even thoron gas has a very short half-life, the contribution of thoron to the effective dose cannot be ignored.

3.2. The impact of the lung-to-blood absorption rate on estimation of effective dose

In ICRP 66, the human respiratory tract model (HRTM)[5], it is assumed that clearance from the anterior nose to extrinsic, and that elsewhere it results from competition

Table 3. Effects of the different absorption parameter values on the effective dose to inhalation exposure

Source	Dissolution parameter values			Uptake parameter values		F	Dosimetric model	Effective dose per radon / thoron progeny (nSv / Bq h m^{-3})
	fr	*Sr* (d^{-1})	*Ss* (d^{-1})	*fb*	*Sb* (d^{-1})			
Marsh and Brichall 1999[17]	0	—	1.7(10h)	0	—	0.4/-	RADEP	7.6[d]/ -
Hursh *et al.* 1970[18]	0.06	67(15min)	1.4(12h)	0	—	0.4/-	RADEP	7.4[d]/ -
Greenhalgh *et al.* 1982[19], Booker *et al.* 1969[21]	0.36	67(15min)	1.7(10h)	0.8	1.7 (10 h)	0.4/-	RADEP	8.7[d]/ -
Butterweck *et al.* 2002[20]	1	1000(1min)	—	0.6	1.7 (10 h)	0.4/-	RADEP	9.5[d]/ -
Ishikawa et al. 2001,2007[3, 12]	0	—	1.7(10h)	0	—	0.4/-	LUDEP	10.96[a] / 116
Winkler-Heil *et al.* 2007[6]	0	—	1.7(10h)	0	—	0.4/-	RADEP / IMBA RADOS IDEAL	7.4 5.2 5.6 [g]
Marsh and Bailey 2013[22]	ICRP137					0.4/-	RADEP	7.8/ -
ICRP 137[4]	ICRP137					0.4/-	—	12.6 / 120[b]
This study	ICRP137 & "Type F"					0.4/-	IMBA	8.0 (8.6[e]) / 118[b, c] 10.7 (10.5[e]) / 133[b, f]
	0	—	1.7(10h)	0	—			

* The calculations apply to the general population for adults with an average breathing rate of 0.78 m^3 h^{-1}.
[a] The effective dose per radon gas was calculated by 27.4 nSv / Bq h m^{-3} multiplying the equilibrium factor (0.4). Attached: C(A) : C(B) : C(C) = 0.695 : 0.428 : 0.194. The effective dose per radon/thoron progeny is calculated using the typical AMAD.
[b] A breathing rate of 1.2 m^3 h^{-1} was adopted to calculate the effective dose per exposure.
[c] The effective dose per radon/ thoron progeny in this study used the same typical AMAD as Ishikawa et al 2007.
[d] The effective dose per radon/thoron progeny is calculated by the actual data of activity weighted size distribution.
[e] The effective dose per radon progeny is calculated using the same ratio of radionuclides as Ishikawa et al 2001.
[f] The effective dose per radon/thoron progeny is calculated using the same parameters as Ishikawa et al 2001, 2007.
[g] Arithmetic mean of the lognormal dose distribution.

between particle transport to GI tract and lymph nodes, and absorption of material into body fluids. It is assumed that particle transport rates are the same for all materials, whereas absorption into blood is material specific. The HRTM treats absorption to blood as a two-stage process: (1) the dissociation of the particles into a material that can be absorbed into blood. (2) the uptake of material dissolved from particles, or material deposited in a soluble form. The calculation results of the effective dose per EEC by using three default absorption-type recommended by ICRP 66 are shown in Figure 4. The effective dose calculated by different absorption-type changes a lot. The "Type S" for both radon and thoron has the highest DCF between the range of unattached fraction to nuclei mode. In the accumulation and coarse mode, the "Type S" and "Type M" have similar DCF. Compared to the other absorption-type, "Type F" has the lowest DCF, and the DCF of "Type M" and "Type S" are 3.4 and 3.5 times of "Type F", respectively. The calculating result using the absorption parameters of this research manifests that the latest DCF using the absorption parameters recommended by ICRP 137 is much more conservative than "Type M", whose result is between that of "Type M" and "Type F".

3.3. Comparison of the DCF with other researches

The comparison of effects of the absorption parameters, the ratio of radionuclides, and dosimetric software on inhalation dose were carried, results are shown in Table 3.

To discuss the effects of the absorption parameters, in the previous calculations for exposure to radon and thoron progeny, for the dosimetry purpose, it assumes that all the short-lived radon and thoron progeny (^{218}Po, ^{214}Pb, ^{212}Pb, ^{214}Bi, ^{212}Bi) have the same absorption characteristics based on research into Lead[17]. It has been carried out assuming that the radon and thoron progeny have a single dissolution half-time of 10 h[3, 17-18] and that the radon progeny are not bound to respiratory tract tissue. However, the other animal and volunteer studies[19-21] indicated that some of the lead ions were bound to respiratory tract components. Based on the analysis of researches on the lung-to-blood absorption rates, the ICRP 137 gave the latest reference to the absorption parameters. Compared to the calculations of effective dose of radon progeny by only changing the absorption parameters, Marsh and Bailey concluded that the effective dose of radon progeny calculated by the parameter recommended by ICRP 137 was a little bit higher than by the single absorption parameter using the RADEP[22]. However, in this research, the effective doses of radon and thoron progeny calculated by ICRP 137 are 18.1-25.2% and 11.3% lower than those of the single absorption parameter, respectively.

To consider the effects of the ratio of radionuclides of radon progeny, which is estimated by the unattached fraction in terms of the PAEC, f_p, the effective dose per radon and thoron progeny calculated by using the ratio used in ICRP 137 changes no more than 5%. For the different dosimetric software using in the estimation of

effective dose coefficient, the effective dose per radon progeny only decreases 4.2% compared the IMBA to LUDEP, however, the effective dose per thoron progeny increases 14.7%. From the different researches, there are two main dosimetric approaches to calculate the DCF. One is applying the actual measurement data of activity weighted size distribution to calculate the size-weighted effective dose per PAE exposure and integrate over all particle diameters. Another adopts the typical AMAD to estimate the DCF. Compared to the effective dose per radon progeny calculated with different methods, the result using the typical AMAD is 2.5 – 47.4% higher than the actual measurement method. Therefore, it is better to measure the actual data to estimate the DCF if conditions are permitted.

4. Conclusion

In this research, in terms of the calculation of equivalent dose per exposure using the ICRP 66 human respiratory tract model calculating by IMBA, it shows that, in the extrathoracic region, ET1 has the highest DCF compared to the other region; except for the AI region, the equivalent dose of the other tissues have the same tendency as ET1. By analyzing the calculation results of the effective dose per exposure for each radionuclide, it is indicated that the radioactive element is present as a minor constituent of the inhaled particles.

Compared to the previous researches of the DCF, it is concluded that the absorption parameters and the calculation method are the main impact factor for estimation of DCF of radon, and the dosimetric software also plays an important role in the calculation of effective dose per thoron exposure. It is better to estimate the dose conversion factor case by case in practice.

Acknowledgments

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Conflict of Interest

The authors declare that they have no conflict of interest.

References

1. WHO. WHO handbook on indoor radon: a public health perspective. Geneva: WHO; 2009.
2. ICRP, 2010. Lung cancer risk from radon and progeny and statement on radon ICRP Publication 115; Ann. ICRP 40(1).
3. Ishikawa T, Tokonami S, Nemeth C. Calculation of dose conversion factors for thoron decay products. J Radiol Prot. 2007;27(4):447–56.
4. ICRP, 2017. Occupational Intakes of Radionuclides: Part 3. ICRP Publication 137. Ann. ICRP 46(3/4).
5. ICRP, 1994. Human Respiratory Tract Model for Radiological Protection. ICRP Publication 66. Ann. ICRP 24(1-3).
6. Winkler-Heil R, Hofmann W, Marsh J, Birchall A. Comparison of radon lung dosimetry models for the estimation of dose uncertainties. Radiat Prot Dosim. 2007;127(1-4):27–30.
7. Birchall A, James AC. Uncertainty Analysis of the Effective Dose per Unit Exposure from Radon Progeny and Implications for ICRP Risk-Weighting Factors. Radiat Prot Dosim. 1994;53(1-4):133-40.
8. Birchall A, Bailey M. R, James A. C. LUDEP: a lung dose evaluation program. Radiat Prot Dosim 1991;38:167–74.
9. Birchall A, Puncher M, Marsh J. W, *et al*. IMBA Professional Plus: a flexible approach to internal dosimetry. Radiat Prot Dosim. 2007;125:194–7.
10. Guo Q, Zhang L, Guo L. Assessment of the unattached fraction of indoor radon progeny and its contribution to dose: a pilot study in China. J Radiol Prot. 2012;32(4):447–54.
11. Birchall A, Jarvis NS, Peace MS, *et al*. The IMBA suite: integrated modules for bioassay analysis. Radiat Prot Dosim. 1998;79(1-4):107–10.
12. Ishikawa T, Tokonami S, Yonehara H, *et al*. Effects of activity size distribution on dose conversion factor for radon progeny Japan. Health Phys. 2001;36:329–38.
13. National Research Council. Comparative Dosimetry of Radon in Mines and Homes. Washington, DC: The National Academies Press; 1991.
14. Willeke K. Temperature dependence of particle slip in a gaseous medium. J Aerosol Sci. 1976;7:381–87.
15. ICRP, 1993. Age-dependent Doses to Members of the Public from Intake of Radionuclides - Part 2 Ingestion Dose Coefficients. ICRP Publication 67. Ann. ICRP 23 (3-4).
16. UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) . Sources and effects of ionizing radiation. New York, United States: United Nations; 2008
17. Marsh JW, Birchall A. Determination of Lung-to-Blood Absorption Rates for Lead and Bismuth which are Appropriate for Radon Progeny, Radiat Prot Dosim. 1999;83(4):331–7.
18. Hursh J B, Mercer TT. Measurement of ^{212}Pb loss rate from human lungs. J Appl Physiol. 1970;28:268–74.
19. Greenhalgh J R, Birchall A, James AC, *et al*. Differential retention of ^{212}Pb ions and insoluble particles in nasal mucosa of the rat. Phys Med Biol. 1982;27:837–51.
20. Butterweck G, Schuler Ch, Vezzù G, *et al*. Experimental determination of the absorption rate of unattached radon progeny from respiratory tract to blood. Radiat Prot Dosim. 2002;102(4):343–8.
21. Booker DV, Chamberlain AC, Newton D, *et al*. Uptake of radioactive lead following inhalation and injection. Br J Radiol. 1969;42:457–66.
22. Marsh J.W, Bailey M.R. A review of lung-to-blood absorption rates for radon progeny. Radiat Prot Dosim. 2013;157(4):499–51.