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A new sampler for simulating aerosol deposition in the respiratory tract

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Abstract For estimation of the deposition fractions of radon progeny in different regions of the respiratory tract, a new sampler consisting of three different configurations of sampling heads was developed. The deposition fractions of aerosols on the wire screens inside the sampling heads were calculated with the fan model of filtration theory. The deposition fractions of aerosols in different regions of the respiratory tract were calculated with the lung dose evaluation program (LUDEP©) developed by National Radiological Protection Board (NRPB) as references. In general indoor and mine environments, the deviation between the deposition fractions of attached aerosol on the wire screens designed in this study and its reference values in the respiratory tract is less than 5%. It is possible to accurately estimate the deposition fractions of radon progeny in different regions of the respiratory tract through mimic measurements of radon progeny collected with the new sampler.

Key words Aerosol, Radon progeny, Human respiratory tract, Wire screens

CLC numbers X837, X125

1 Introduction

Over the past decades considerable attentions were focused on potential hazard from the exposure of radon (^{222}Rn) and its progeny to the public in work place or at home. It is commonly agreed that inhalation of airborne short-lived ^{222}Rn progeny in indoor and outdoor environment contributes the largest amount of natural radiation exposure to the public [1]. And the major health concern comes from the deposition fraction of ^{222}Rn progeny and their alpha energy exposure to the epithelium of human respiratory tract. Therefore, information about the deposition fraction of ^{222}Rn progeny in the respiratory tract is useful for accurate hazard evaluation of radon exposure.

Direct measurement of ^{222}Rn progeny deposited in the respiratory tract is tedious and unpractical for the general public [2, 3]. Traditional method for evaluating the deposition fraction of ^{222}Rn progeny in the respiratory tract was based on the particle size information, i.e. the activity median diameter (AMD) and its geometric standard deviation (GSD). However, the system for measuring the AMD and GSD is expensive, with complex analyzing procedures [4-6]. In view of these, Hopke *et al*. [7] suggested using multiple metal wire screens to simulate the deposition properties of radon progeny in the nasal and tracheobronchial (T-B) regions, and several types of sampling systems were developed [8-10]. However, most of the systems were developed on the basis of previous human respiratory tract model (ICRP 30) [11].

In this study, based on the idea proposed by Hopke *et al*. and the new human respiratory tract model (ICRP 66) [12], a new sampler consisting of three different configurations of sampling heads made of stainless steel and wire screens was developed for simulating the deposition characteristics of ^{222}Rn progeny in the human respiratory tract, and its

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characteristics are compared with the previous sampling system.

2 Methodology

2.1 Calculation of aerosol deposition on wire screens

Based on the aerosol penetration mechanism, a semi-empirical formula of aerosol penetration through wire screens was given by Cheng *et al*. [13, 14], and the latest formula modified by the experimental data in Ref. [15] was used in this study. In the condition of Reynolds number less than one, the aerosol penetration (P) through wire screens can be calculated by Eq.(1), and the deposition fraction is expressed as $100\times(1-P)$.

$$P=\exp\left[-nB\frac{4\alpha h}{\pi(1-\alpha)d_{\mathrm{f}}}\right] \quad (1)$$

where n is the number of wire screens, h is the thickness of screen, d_{f} is the diameter of wire, B is the single fiber collection efficiency including diffusion, interception, inertial impaction and a correction term for diffusion interception [16], and α is the solid volume fraction (SVF) defined as:

$$\alpha=\frac{4m}{\pi d_{\mathrm{f}}^2 h\rho_{\mathrm{f}}} \quad (2)$$

where m and ρ_{f} are the mass and specific density of screen, respectively, d_{f} and h are the same parameters as in Eq. (1).

2.2 Parameters selected for the theoretical calculation

Besides aerosol characteristics, the deposition fraction of aerosols in the respiratory tract depends on the breathing rate. In this study, typical values of breathing rates for workers (Mines) and members of the public (Homes) were chosen as 1.2 and 0.78 m^3/h, respectively [17]. The face velocities of airflow were decided according to the breathing rates and the surface areas of wire screens used.

The typical size spectrum of ^{222}Rn progeny in indoor condition ranges from 0.5 nm up to several microns with a bimodal distribution [18]. The particles of 0.5~5 nm in diameter are usually called unattached or ultrafine particles. The particles with diameters larger than 5 nm are generally called attached particles, and they account for a portion of over 90% in general environmental conditions. The attached fraction is usually described by a log-normal distribution with AMD of 200 nm for typical home condition and of 250 nm for typical mine condition. In this study, the analysis for the attached mode was restricted to particle sizes ranging from 100 to 300 nm for home condition and from 120 to 350 nm for mine condition, respectively.

2.3 Reference fractions of ^{222}Rn progeny deposited in the respiratory tract

A standard computational software package LUDEP© 2.06 was used to calculate the deposition fractions in the respiratory tract as reference values. LUDEP© is a PC-based user-friendly respiratory tract deposition and dose evaluation program developed by National Radiological Protection Board (NRPB), UK. It employs the new human respiratory tract model (ICRP 66) for calculating deposition fractions in different regions of the respiratory tract for well defined intake scenarios. The values of parameters and equations contained in LUDEP© have been systematically testified against ICRP Publication 66.

3 Results and discussion

3.1 Deposition fraction in the T-B region and its simulation

Previous study has shown that the tracheobronchial (T-B) region is one of the most radiosensitive regions in the respiratory tract [12], and the natural radiation dose in this region is mainly contributed from the deposition of attached ^{222}Rn progeny. On the other hand, as shown in Fig.1, theoretical calculation reveals that the collection efficiencies of wire screens depend on the mesh numbers of generally used wire screens (listed as Table 1). The values are generally lower than 2% in a particle size ranging from 100 to 500 nm. Therefore, for most effective collection of the attached ^{222}Rn progeny, the mesh number of 635 was selected in this study.

Table 1 Parameters of commonly used wire screens

Mesh number	Wire diameter / μm	Screen thickness/ μm	Solid volume fraction (SVF)
635	20	50	0.345
400	24	53	0.302
200	40	89	0.231
100	108	249	0.308

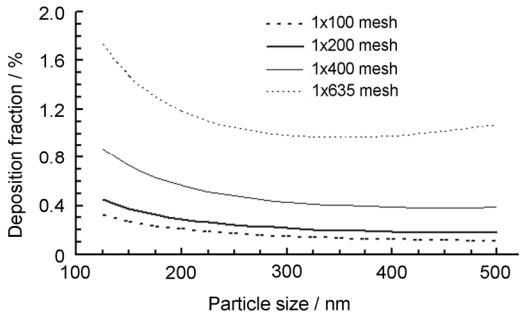

Fig.1 Collection efficiencies of different mesh numbers of wire screens at a face velocity of 12 cm·s^{-1}.

As shown in Fig.2, at the suggested sampling face velocity of 12 cm·s^{-1}, it was found that the collection efficiencies of attached ^{222}Rn progeny on four 635-mesh wire screens are in most concordance with the deposition fractions in the T-B region calculated with LUDEP©. In the particle size ranging from 100 to 350 nm, the average deviation of the deposition fractions calculated with the two methods is only –1.5%, with a range of –5.11%~2.50%. While for the previous configuration of wire screens[7] in the same range of particle sizes, the deviation ranged from –41%~–32%, with an average of –39%.

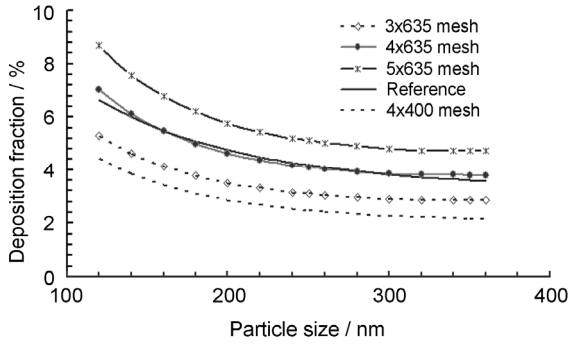

Fig.2 Collection efficiencies of wire screens in different configurations in a sampling velocity of 12 cm·s^{-1} for attached ^{222}Rn progeny. The deposition fractions in T-B region calculated with LUDEP© are used as references.

3.2 Deposition fraction in the E-T region and its simulation

Based on the calculation with LUDEP©, it is known that the deposition fraction of attached ^{222}Rn progeny in the extra-thoracic (E-T) region is negligible. Furthermore, even though most of the unattached ^{222}Rn progeny deposits in the E-T region from nose-breathing, the total amount of unattached ^{222}Rn progeny deposited in the E-T region is quite small because the fraction of unattached ^{222}Rn progeny is generally less than 10% in general environments. However, in some special indoor environments, such as green houses, the ultrafine particles are far more than the attached particles, the deposition fraction of the ultrafine particles in the E-T region should be considered.

As shown in Fig.3, it is quite difficult to completely simulate the deposition characteristics of unattached ^{222}Rn progeny in the E-T region by using wire screen. However, taking a typical size distribution of unattached ^{222}Rn progeny (AMD:1.0 nm, GSD:1.4) in general environments into account [16], it is considered that one 100-mesh or one 200-mesh wire screen is relatively suitable for simulating the deposition characteristics of unattached ^{222}Rn progeny in the E-T region. Based on the model calculation, it is known that one 100-mesh wire screen will collect 80.8% of ultrafine particles with an AMD=1.0 nm and GSD=1.4, while one 200-mesh wire screen will collect 87.0% of the particles in the same conditions. Compared with the reference value of 83.0% calculated with LUDEP©, one 100-mesh wire screen was selected to simulate the deposition of unattached ^{222}Rn progeny in the E-T region in this study.

3.3 Configuration of the sampler

Based on the above analyses, a new sampling system was designed for simulating aerosol deposition in the respiratory tract. The schematic diagram of the

new sampler is shown in Fig.4. It consists of three sampling heads in different configurations. Head A houses only one backup filter for collecting the total airborne ^{222}Rn progeny. Head B contains one 100-mesh wire screen and a backup filter paper for simulating collection of ^{222}Rn progeny passing through the E-T region. In head C are installed one 100-mesh wire screen, four 635-mesh wire screens and a backup filter paper for simulating collection of ^{222}Rn progeny passing through both the E-T and T-B regions. By considering the wall deposition effect, the three sampling heads were designed as the same size.

The following equations can be used to evaluate the deposition fractions of particles deposited in the E-T ($DEP_{E\text{-}T}$) and T-B ($DEP_{T\text{-}B}$) regions,

$$DEP_{E\text{-}T} = 100 \times (C_A - C_B)/C_A \quad (3)$$

$$DEP_{T\text{-}B} = 100 \times (C_B - C_C)/C_A \quad (4)$$

where C_A, C_B and C_C are the aerosol concentrations collected by the filters installed in the sampling heads A, B and C, respectively.

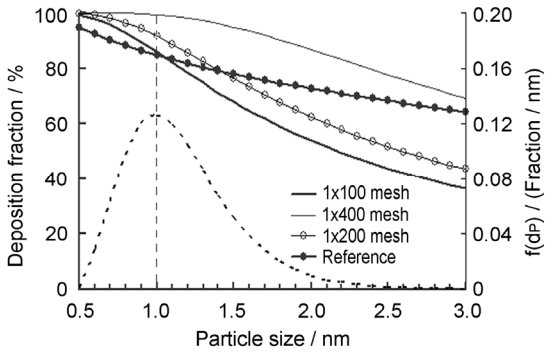

Fig. 3 Collection efficiencies of different meshes of wire screen in a sampling velocity of 12 cm·s^{-1} for unattached ^{222}Rn progeny. The deposition fractions in E-T region calculated with LUDEP are used as references. The dashed curve is a typical frequency distribution of unattached ^{222}Rn progeny with AMD=1.0 nm and GSD=1.4.

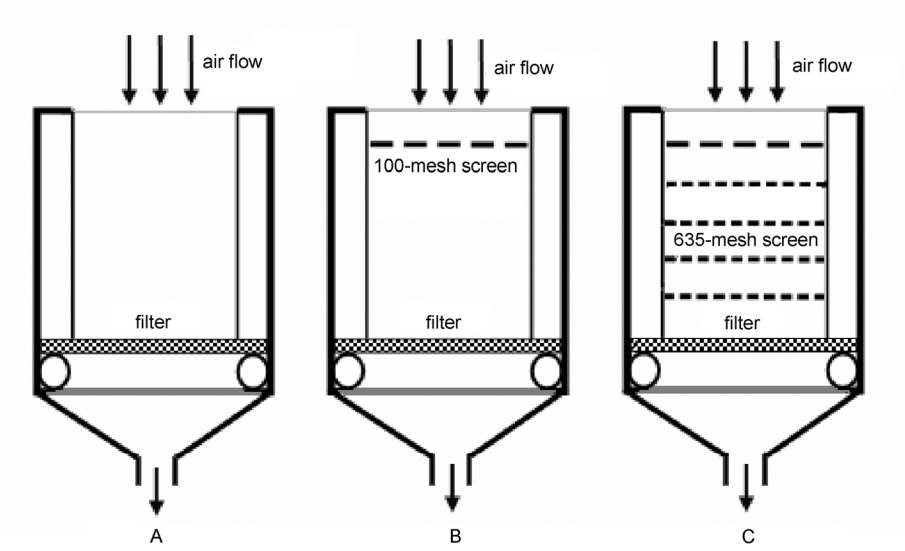

Fig.4 Schematic diagram of the sampler for simulating aerosols deposition in the respiratory tract.

4 Conclusions

A new sampler consisting of three different configurations of sampling heads was developed for simulating the deposition characteristics of aerosol deposited in the E-T and T-B regions of human respiratory tract. Compared with the previous designed samplers, the new sampler can simulate the characteristics of aerosol deposition in the T-B region with much better accuracy. It implies that the lung dose from radon exposure could be more accurately estimated. However, further studies are still needed for more accurate simulation of the deposition of ultrafine particles deposited in the E-T region, especially in the environments with a large fraction of ultrafine particles.

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