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Long-term determination of airborne radon progeny concentrations using LR 115 solid-state nuclear track detectors

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ABSTRACT

This paper described the establishment of lognormal distributions for the Jacobi room model parameters with a view to improve an existing method for long-term passive measurements of the equilibrium factor using LR 115 solid-state nuclear track detectors, namely, through the proxy equilibrium factor (F_p) method. F_p is defined as $(C_1 + C_3)/C_0$ where C_0, C_1 and C_3 are the concentrations of ^{222}Rn, and the airborne concentrations of ^{218}Po and ^{218}Po (or ^{214}Bi), respectively. The studied Jacobi room model parameters included the ventilation rate λ_v, the aerosol attachment rate λ_a, the deposition rate $\lambda_d{}^u$ of unattached progeny and the deposition rate $\lambda_d{}^a$ of attached progeny. The lognormal distributions generated more realistic distributions for the equilibrium factor F and the unattached fraction f_p of the potential alpha energy concentration, and a much tighter relationship between F and F_p, when compared with the traditionally used uniform distributions. With the new relationship between F and F_p, the accuracy of the F_p method to determine F from F_p is significantly improved.

1. Introduction

The radon-related absorbed dose in the lung is mainly due to short-lived radon progeny, i.e., ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po, but not the radon (^{222}Rn) gas itself. Accordingly, long-term measurements of the concentrations of radon progeny or the equilibrium factor F, among other information such as the unattached fraction f_p of the potential alpha energy concentration and the size distribution of radon progeny, are needed to accurately assess the health hazards contributed by radon progeny.

A common practice for radon hazard assessment nowadays is to first determine the radon gas concentration and then to apply an assumed F with a typical value of about 0.4 (UNSCEAR, 2009). However, in reality, F varies significantly with time and place, and an assumed F cannot reflect the actual conditions (Nikezic and Yu, 2005; Yu et al., 1996a). This problem cannot be solved through active measurements based on air filtering (Yu et al., 1996b, 1997, 1999), since they only give short-term determinations. Methods based on long-term measurements of radon progeny concentrations or F using solid-sate nuclear track detectors (SSNTDs) have been reviewed (Amgarou et al., 2003; Nikezic and Yu, 2004; Yu et al., 2005). Our group has previously proposed a feasible method for long-term measurements of F through the so-called "proxy equilibrium factor" (F_p) (Nikezic et al., 2004; Yu et al., 2005), which will be briefly described in section 2. However, for particular values of F_p, the ranges of F could be large, which could adversely affect the accuracy of the method to determine F from F_p. A method is proposed in section 3 to improve the relationship between F and F_p by establishing more realistic distributions of the Jacobi room model parameters, and the results and discussion will be presented in section 4.

2. Proxy equilibrium factor F_p

We denote C_0, C_1, C_2, C_3 and C_4 as the concentrations of ^{222}Rn, and the airborne concentrations of the first (^{218}Po), second (^{214}Pb), third (^{214}Bi) and fourth (^{214}Po) radon progeny, respectively (which are short-lived radon progeny). It is well established that ^{214}Bi and ^{214}Po are always in equilibrium due to the very short half life of ^{214}Po (164 μs), so we will simply use C_3 (=C_4) to denote both the airborne concentrations of ^{214}Bi and ^{214}Po. The equilibrium factor F is defined as

$$F = 0.105 f_1 + 0.515 f_2 + 0.380 f_3 \quad (1)$$

where $f_i = C_i/C_0$ (i = 1,2,3).

We proposed the use of bare LR 115 SSNTDs to determine F_p and showed that this gave good estimates of F (Nikezic et al., 2004; Yu et al., 2005). The LR 115 SSNTD has an upper energy threshold for track formation, which is well below the energy of alpha particles

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emitted by the radon progeny plate out on the detector. The responses of the bare LR 115 detector to ^{222}Rn, ^{218}Po and ^{214}Po were expressed by the partial sensitivities ε_i of the detector to these species (i.e., the number of tracks per unit area per unit exposure) with the unit (m^{-2})/(Bqm^{-3}s) or just (m). The partial sensitivities ε_i were found to be the same for ^{222}Rn, ^{218}Po and ^{214}Po (Nikezic et al., 2004; Yu et al., 2005). With equal partial sensitivities, the total track density ρ (in track m^{-2}) on the detector due to airborne ^{222}Rn, ^{218}Po and ^{214}Po was given by $\rho = \varepsilon_i(C_0 + C_1 + C_3)\times t$, where t was the exposure time. The "proxy equilibrium factor" F_p was defined as (Nikezic et al., 2004):

$$F_p = f_1 + f_3 = \rho/(\varepsilon_i C_0 t) - 1 \qquad (2)$$

The quantities on the right hand side of Eq. (2) are known: ρ is total track density on LR 115 detector, C_0 may be obtained from the separate measurements, t is exposure time, and ε_i are subjects of calculations—they may also be determined experimentally from the calibration experiment with the known radon and progeny concentrations.

By using the Jacobi room model (Jacobi, 1972), and by randomly varying the associated parameters λ_v, λ_a, $\lambda_d{}^u$ and $\lambda_d{}^a$, in the ranges given in Table 1, where λ_v is the ventilation rate, λ_a is the aerosol attachment rate, $\lambda_d{}^u$ is the deposition rate of unattached progeny and $\lambda_d{}^a$ is the deposition rate of attached progeny, F was plotted with F_p as shown in Fig. 1 (gray + black areas; see also Yu et al., 2005). These ranges were used previously by Amgarou et al. (2003), Nikezic et al. (2004) and Yu et al. (2005), and uniform sampling was employed from these ranges. We observed a relatively good correlation between F and F_p, and as such, we could determine F from F_p. As a result, the F_p method was successfully deployed for various applications (Leung et al., 2006, 2007; Yu et al., 2008).

3. Revisiting the distributions for Jacobi room model parameters

From Fig. 1, we could see that for particular values of F_p, the ranges of F could be large. In particular, the dispersion of F values became large where F_p was around unity. When compared to more extreme F_p values (i.e., those which are much smaller than or much larger than unity), more different combinations of Jacobi room model parameters could combine to generate a particular F_p value around unity, and these combinations of model parameters would generate a larger range of F values. This could adversely affect the accuracy of the method to determine F from F_p. A closer study of the problem revealed that the relatively large range of F corresponding to a value of F_p was a consequence of the wide ranges of Jacobi room model parameters as shown in Table 1 and the adopted uniform sampling of these parameters employed for the computer simulations. With such an approach, we discarded the information provided by the best-estimated values of these Jacobi room model parameters and ignored the fact it was unlikely to obtain parameters far away from their best-estimated values.

According to the Jacobi room model, a set of parameters generate an F value and an f_p value. As such, realistic distributions of the Jacobi room model parameters should also be able to generate

Table 1
Ranges for Jacobi room model parameters employed for the computer simulations.

Parameter	Lower limit	Upper limit
Ventilation rate λ_v (s^{-1})	0.2	2.1
Aerosol attachment rate λ_a (s^{-1})	5	500
Deposition rate of unattached progeny $\lambda_d{}^u$ (s^{-1})	5	110
Deposition rate of attached progeny $\lambda_d{}^a$ (s^{-1})	0.05	1.1

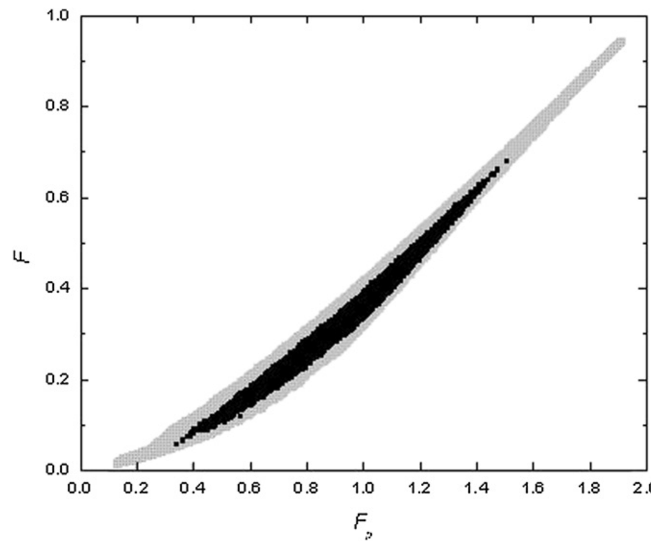

Fig. 1. The relationship between the equilibrium factor F and the proxy equilibrium factor F_p, obtained by sampling the Jacobi room model parameters from uniform distributions (gray + black areas), and from lognormal distributions (black area).

realistic distributions of F and f_p. Fig. 2 shows the distribution of f_p values determined by sampling the Jacobi room model parameters from uniform distributions. The arithmetic and geometric means for the f_p values were 4.4 and 2.6%, respectively, and the probabilities of getting f_p values larger than 30% were 1.96%. For a comparison, the nominal f_p value used for an average dwelling site is 8% (Marsh and Birchall, 2000). Fig. 3 shows the distribution of F values determined by sampling the Jacobi room model parameters from uniform distributions. The arithmetic and geometric means were 0.29 and 0.26, respectively. For a comparison, the typical value of F for radon indoors was 0.4 (UNSCEAR, 2009). As such, uniform distributions of Jacobi room model parameters did not generate very satisfactory distributions of F and f_p.

In this paper, we attempted to improve the distributions for Jacobi room model parameters, in such a way that the probabilities of getting parameters at their best-estimated values were the

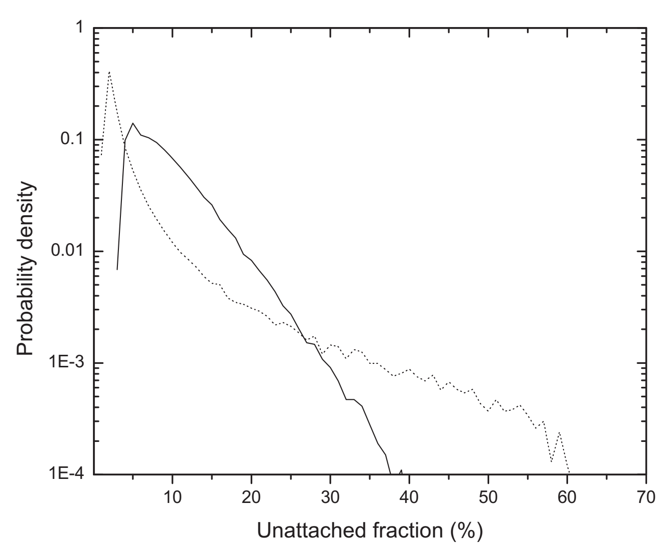

Fig. 2. Distribution of f_p values determined by sampling the Jacobi room model parameters from lognormal distributions (solid line) and uniform distributions (dotted line).

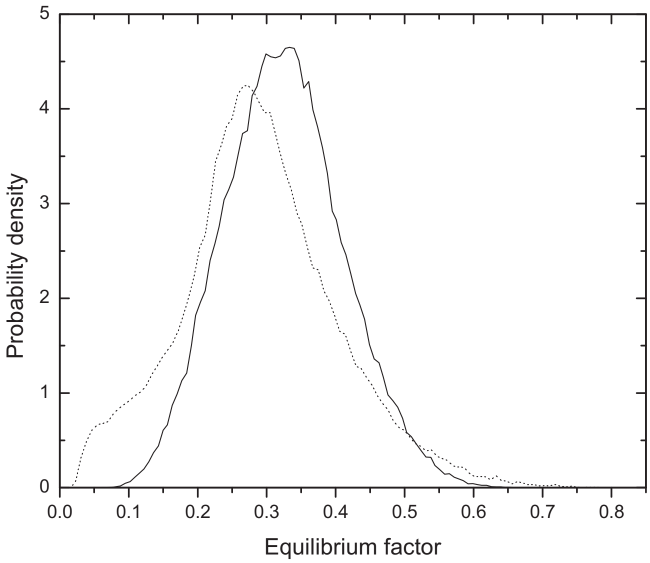

Fig. 3. Distribution of F values determined by sampling the Jacobi room model parameters from lognormal distributions (solid line) and uniform distributions (dotted line).

largest, and that the probabilities of getting parameters far away from their best-estimated values were small. Without better information, we adopted the best-estimated values of the Jacobi room model parameters as $\lambda_v = 0.55$, $\lambda_a = 50$, ${\lambda_d}^u = 20$ and ${\lambda_d}^a = 0.2\ \mathrm{h}^{-1}$ (Yu et al., 2005). These best-estimated values were skewed towards the lower limits of the ranges as shown in Table 1, so we proposed to adopt lognormal distributions for the parameters. In trying to establish the lognormal distributions, we used the best-estimated values as the median values. We further needed the geometric standard deviations (σ_g) for the lognormal distributions. We imposed that both the probabilities getting parameters below the lower limits and the probabilities getting parameters above the upper limits to be $\leq 10^{-4}$ to give estimates for σ_g. If better information on the parameters becomes available in the future, this criterion can be revised accordingly. Of course, lognormal distributions with other parameters (medians and geometric standards deviations) or even other types of distributions can be used if they are found to generate more realistic scenarios.

4. Results and discussion

By imposing that both the probabilities getting Jacobi room model parameters below the lower limits and the probabilities getting parameters above the upper limits to be $\leq 10^{-4}$, we found the values of σ_g as 1.3, 1.8, 1.4 and 1.4 for λ_v, λ_a, ${\lambda_d}^u$ and ${\lambda_d}^a$, respectively.

We first examined whether these lognormal distributions for the Jacobi room model parameters with the determined values of σ_g generated more realistic distributions of f_p. Fig. 2 shows the distribution of f_p values determined by sampling the Jacobi room model parameters from the newly established lognormal distributions. The arithmetic and geometric means were now 8.6 and 7.6%, respectively, compared to the previously determined 4.4 and 2.6%, respectively. Furthermore, the probability of getting f_p values larger than 30% now became as low as 0.318%, compared to the previously determined 1.96%. Porstendorfer (1994) stated that for typical indoor aerosol conditions f_p ranged from 5 to 20%. The nominal f_p value used for an average dwelling site was 8% (e.g., Marsh and Birchall, 2000). Therefore, we concluded that the lognormal distributions generated more realistic f_p values than the uniform distributions.

Table 2
Comparisons between the mean values and the ranges of the equilibrium factor F determined from different proxy equilibrium factors (F_p) obtained by sampling the Jacobi room model parameters from uniform distributions and lognormal distributions. The ranges of F were directly read from the graphs shown in Fig. 1 and the mean values were obtained as the averages between the maximum and minimum values.

F_p	F (from uniform distributions)	F (from lognormal distributions)
0.4	0.10 ± 0.04	0.08 ± 0.01
0.6	0.18 ± 0.06	0.17 ± 0.02
0.8	0.27 ± 0.07	0.25 ± 0.02
1.0	0.38 ± 0.07	0.37 ± 0.04
1.2	0.50 ± 0.05	0.49 ± 0.02
1.4	0.62 ± 0.04	0.62 ± 0.01

We then examined whether lognormal distributions for the Jacobi room model parameters generated more realistic distributions of F. Fig. 3 shows the distribution of F values determined by sampling the Jacobi room model parameters from the newly established lognormal distributions. The arithmetic and geometric means were now both 0.32, compared to the previously determined 0.29 and 0.26, respectively. UNSCEAR (2009) commented that the typical value of F for radon indoors was 0.4. Therefore, we again observed that the lognormal distributions generated more realistic F values.

Fig. 1 (black area only) shows the relationships between F and F_p obtained by sampling the Jacobi room model parameters from lognormal distributions. We observed that the relationships became tighter by sampling from the lognormal distributions. For the convenience of discussion in this section, we referred to the equilibrium factors determined from an F_p value obtained by sampling the Jacobi room model parameters from uniform and lognormal distributions as F_1 and F_2, respectively. Table 2 shows the comparisons between the mean values and the ranges of F_1 and F_2 determined from different F_p values. For F_p values from 0.4 to 1.4, the ranges for F_1 values were from ±0.04 to ±0.07, while the ranges for F_2 values were from ±0.01 to ±0.04. The percentage uncertainties for the F_1 values were in general about 2–3 times larger than those for the F_2 values. The percentage uncertainties were in general larger for smaller F_p values (and thus also smaller F_1 and F_2 values). For example, when $F_p = 0.4$, the percentage uncertainty was 40% for F_1 while it dropped to only about 13% for F_2. With the tighter relationship between F and F_p obtained by sampling the Jacobi room model parameters from lognormal distributions, it became meaningful to obtain a best-fit relationship between F and F_p. The best third-order polynomial fit was:

$$F = -0.02453 + 0.20522F_p + 0.17528F_p^2 - 0.00621F_p^3 \quad (3)$$

Another observation from Table 2 was that the F_2 values were in general slightly smaller than the F_1 values). However, the differences were small and the resulting effect might not be significant.

5. Conclusions

This paper described the establishment of lognormal distributions for the Jacobi room model parameters to improve the proxy equilibrium factor (F_p) method for long-term passive measurements of the equilibrium factor using LR 115 SSNTDs. The lognormal distributions generated more realistic distributions of F and f_p, and much tighter relationship between F and F_p, when compared with the traditionally used uniform distributions.

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