Inhalation of $^{222}\text{Rn}$ progeny has been recognized as a health risk, primarily as a cause of human lung cancer. $^{222}\text{Rn}$ progeny in the domestic environment contributes the greatest fraction of the natural radiation exposure to the public. The ultrafine activity of these progeny amounts up to about 10 percent of the total activity (attached and ultrafine), but is considered to yield about 50 percent of the total radiation dose. Therefore, measurements of ultrafine fraction are essential for the estimation of radiation dose. The current study presents measured data on the total equilibrium equivalent concentration (EEC) and ultrafine equilibrium equivalent concentration (EEC$^{uu}$), ultrafine fraction ($f_b$), and unattached activity size distributions of radon progeny in the low ventilated room at Minia University, Minia City, Egypt. A screen diffusion battery was used for collection the ultrafine fraction and measuring the total activity concentration of radon progeny. The EEC of radon progeny was varied between 1.3 and 18.9 Bq m$^{-3}$ with a mean value of 5.2 ± 0.48 Bq m$^{-3}$. The mean activity thermodynamic diameter (AMTD) of ultrafine of radon progeny was determined to be 1.26 nm with relative mean geometric standard deviations (GSD) of 1.3. The ultrafine fraction of radon progeny, $f_b$, has a range 0.01 to 0.21 with an average of 0.08 ± 0.03. Based on the above experimental results, the deposition fractions have been evaluated in each air way generation through the human lung by applying a lung deposition model. The effect of radon progeny deposition by adult male has been also studied for various levels of physical exertion. The dose conversion factor has been discussed as a function of $f_b$. Finally, the annual dose was calculated to be 0.36 mSv.

**Keywords:** radon progeny; equilibrium equivalent concentration; unattached activity size distributions of radon progeny; Deposition fractions; annual dose

**INTRODUCTION**

Over the past 50 y, there has been a considerable and increasing interest in natural radiation to which the people are exposed. The measurement of short-lived $^{222}\text{Rn}$ progeny ($^{218}\text{Po}, 214\text{Pb}, 214\text{Bi}$ and $214\text{Po}$) in air has become a routine procedure for controlling the radiation exposure by inhalation. In general, the concentration of $^{222}\text{Rn}$ and its progeny in indoor air is on average 2–10 times higher than outdoor.[1- 4]. This is due to low rates of air exchange and the dynamic collection into closed space, with additional contributions from $^{222}\text{Rn}$ sources such as building
materials. The high concentrations of these radionuclides in indoor air coupled with the prolonged exposure periods related to indoor habitation make indoor $^{222}\text{Rn}$ decay products a potential health hazard.

A large fraction of $^{218}\text{Po}$ (80-82%) is positively charged after their formation [5]. These atoms attach ambient water molecules or react with trace gases and $\text{H}_2\text{O}$, $\text{NO}_2$, and $\text{NO}$ vapors, grow by cluster formation, and become neutralized by the recombination with negative ions in the air and charge transfer processes (this is define as ultrafine or unattached fraction of radon progeny, they have a size range 0.5 to 5 nm [6-8]. These clusters attach to aerosol particles which suspended in the air and have a size range 1 nm up to 100 µm [9], forming radioactive aerosol or attached fraction of radon progeny [10]. The basic processes of $^{222}\text{Rn}$ progeny behavior in the air are shown in Figure 1.

![Figure 1. Basic processes of Rn progeny behaviour in air defining ultrafine and aerosol-attached activities](image)

The inhalation of radon progeny in the environment yields the greatest amount of natural radiation exposure of the human public. [11-14]. [15-17]. In all dosimetric models, the ultrafine and attached activities of radon progeny are among the most important parameters for estimating the radiation exposure. The ultrafine atoms may be deposited in the trachea and bronchial region, while the attached atoms are deposited in different parts of the pulmonary region due to different sizes of aerosol particles [18]. Epidemiological studies have established that enhanced levels of radon and its progeny in dwellings can cause health hazards and may lead to serious diseases, such as lung cancer [19, 20, 8]. Since it is difficult to measure the deposited activity in the respiratory system of the human being, the absorbed doses are calculated from models which need information about the equilibrium equivalent concentrations (EEC), ultrafine or unattached fraction, $f_u$, and activity size distribution of ultrafine and attached radon progeny.

Wire screens are commonly used to estimate ultrafine radon progeny in ambient and mine atmospheres. The use of wire screens for the separation of the ultrafine fraction was first studied by James et al., [21-23]. Measurements of activity size distribution of ultrafine and attached radon progeny show that the ultrafine fraction can well be separated from the aerosol particle attached activities [24-27].

The activity size distribution of radon progeny has been determined by tagging the natural aerosol particles with radon progeny. However, some measurements of radon progeny (for attached and ultrafine fraction) have been performed in indoor air [24], [28], [29-39], [8].

Most of the observed data of above literatures have shown that the size distribution consisted of ultrafine clusters with median diameters between 0.5 and 5 nm (unattached activity)
and progenies associated with ambient aerosol particles in sizes ranging between 100 and 500 nm (attached activity). The ultrafine fraction is deposited nearly completely in the respiratory tract during inhalation, whereas 80 percent of the attached are exhaled without deposition [40]. The amount of unattached activities up to about 10 percent of the total activity, but is considered to yield about 50 percent of the total radiation dose [40].

The decay products of $^{222}$Rn in air are ordinarily not given by individual activity concentration, but rather by equilibrium equivalent concentration (EEC). The EEC is the total activity concentration (attached and ultrafine) of $^{222}$Rn in radioactive equilibrium (equal activities) with its short lived progeny which has the same potential alpha energy concentration as the non-equilibrium mixture. The EEC of radon progeny is given by ICRP and UNSCEAR as [16], [41].

$$\text{EEC} = 0.105C_1 + 0.516C_2 + 0.379C_3$$  \hspace{1cm} (1)

where $C_1$, $C_2$ and $C_3$ are the total activity concentrations (Bq/m$^3$) of $^{218}$Po, $^{214}$Pb and $^{214}$Bi, respectively. For ultrafine equilibrium equivalent concentration, EEC$^{\text{un}}$, is given by

$$\text{EEC}^{\text{un}} = 0.105C_{1}^{\text{un}} + 0.516C_{2}^{\text{un}} + 0.379C_{3}^{\text{un}}$$ \hspace{1cm} (2)

where $C_{1}^{\text{un}}$, $C_{2}^{\text{un}}$ and $C_{3}^{\text{un}}$ are the ultrafine activity concentrations (Bq/m$^3$) of $^{218}$Po, $^{214}$Pb and $^{214}$Bi, respectively.

The ultrafine fraction of radon progeny, $f_b$, has much higher motilities in the air and can more effectively deposit in the respiratory system. Thus, for a long time the ultrafine fraction has been given extra importance in estimating health effects of radon progeny. The ultrafine fraction, $f_b$, of radon progeny is given by:

$$f_b = \frac{\text{EEC}^{\text{un}}}{\text{EEC}}$$  \hspace{1cm} (3)

Several observations have been carried out in indoor, and the value of $f_b$ in most cases was found to be varied from 0.03 to 0.4[10] [26], [29], [42-48], [33]. However, most of these measurements were performed in low ventilation rooms with additional aerosol sources such as cigarette smoke, cooking, burning candle, stove heating and air cleaner.

Deposition theoretical modeling of radon containing aerosol in human lung represents a useful tool for interpret health effects from inhaled particular and for study the effectiveness of different inhalation procedure. Deposition is the process that determines what fraction of the inspired particles is caught in the respiratory tract and, thus, fails to exit with expired air. It is likely that all particles that touch a wet surface are deposited, thus, the site of contact is the site of initial deposition. Distinct physical mechanisms operate on inspired particles move them toward respiratory tract surfaces. Major mechanisms are inertial forces, gravitational sedimentation, Brownian diffusion, interception and electrostatic forces.

A major factor governing the effectiveness of the deposition mechanisms is the parameters of the ultrafine and attached activity size distributions (active median thermodynamic diameter, AMTD, geometric standard deviation, GSD, and ultrafine fraction, $f_b$). Based on these parameters, the deposition fraction in each airway generation through the human lung has been calculated by using a lung deposition model.

The present work summarizes the experimental data on EEC, EEC$^{\text{un}}$ and ultrafine fraction, $f_b$, of radon progeny in different low-ventilated living room. Also, based on the obtained parameters of ultrafine and attached activity size distributions of radon progeny (AMTD, GSD),
MATERIALS AND METHOD

Ultrafine Activity Size Distribution

To measure unattached activity size distribution of short-lived radon progeny, a wire screen diffusion battery similar to that employed and calibrated by Cheng et al. [53] was used. It was constructed with the same screen characteristics to determine the size distribution of ultrafine radon progeny. It consisted of five stainless-steel screens with 24, 35, 50, 200, and 635 mesh numbers. The screens were calibrated with monodisperse silver aerosol particles. The measured 50% cut-off diameters of the screens are 0.9, 1.3, 1.9, 4.0 and 7.9 nm.

To determine the ultrafine activities of radon progeny, the aerosol attached and total radon progeny concentrations were measured. Each measurement consisted of two parallel samples: one with a single screen and the other as a reference sample without screen (this procedure was repeated with different screens, see Figure 2).

The screen was used only for collecting the ultrafine activities. The activities penetrating the screen (mostly attached to aerosol particle) and that of the reference sample were collected on membrane filters (Sartorius membrane filters type SM, 1.2 mm pore size, 25 mm diameter and an efficiency reaching about 100%) and the alpha activities were detected during and after air
sampling by a surface barrier detector. According to the Ruffle method [54] and through utilizing $^{241}$Am as a radioactive source of alpha rays, the counting efficiency of the detector was found to be $17.0 \pm 0.5\%$. The detector has an active area of $300 \text{ mm}^2$ and the separation between the filter and detector is $6 \text{ mm}$. With an energy resolution of about $300 \text{ keV}$, it was possible to distinguish the alpha particle energies emitted during the decay of $^{218}\text{Po}$ ($6 \text{ MeV}$) and that of $^{214}\text{Po}$ ($7.69 \text{ MeV}$). In order to determine the activity concentrations of radon progeny ($^{219}\text{Po}$, $^{214}\text{Pb}$ and $^{214}\text{Bi}$), the measurements were performed in two steps. Firstly, the alpha particle spectrum was collected during a sampling period of $30 \text{ min}$. Secondly, after waiting for a time period of $30 \text{ min}$ without sampling, the alpha particle spectrum was measured again (during decay) for a time period of $30 \text{ min}$. From the measured alpha counts of $^{218}\text{Po}$ and $^{214}\text{Po}$ during the sampling period and the $^{214}\text{Po}$ counts during the decay period, the activity concentrations of $^{219}\text{Po}$, $^{214}\text{Pb}$ and $^{214}\text{Bi}$ could be calculated according to a method described by Wicke, [55]. The attached activities were derived from the sample obtained with the screen. The collected ultrafine activity on the screen is the difference between the measurements of the reference sample (without screen) and the screen sample.

The measurements of radon progeny concentrations were performed on different days. During the measurements the aerosol particle concentration was monitored by a condensation nuclei counter (General electric TSI, Model 3020). The counter can be used for determining aerosol particle concentration in the range from below $10^3$ up to $10^7 \text{ cm}^3$. The parameters of ultrafine activity size distributions (AMTD and GSD) were obtained from the lognormal distribution method (William, 1999) as

$$\ln(AMD) = \frac{\sum n_i \ln d_i}{\sum n_i}$$

$$\ln(GSD) = \left[ \frac{\sum n_i (\ln d_i - \ln AMD)^2}{\sum n_i} \right]^{1/2}$$

(4)

where $n_i$, $d_i$ are the fraction and the cut-off diameter in the stage $i$, respectively. Also, these parameters can be obtained by a graphical cumulative method. The cumulative attached activities were plotted versus the cut-off diameter of the impactor stages. The AMTD is defined as the diameter at 50% cumulative fractions. The GSD of the size distribution is defined as the diameter at 84% cumulative activity divided by the diameter obtained at 50%.

Deposition Calculation

Deposition of inhaled aerosols in any given region of the human respiratory tract depends upon particle size, shape, density and subject breathing pattern. In the present work, deposition calculations were based on the following set of aerosol characteristics pattern. Each component or mode of the radon progeny aerosol was assumed to be represented by a log normal distribution, in which the geometric standard deviation (GSD) is related to the activity median diameter (AMD) by NRC [56].

$$GSD = 1 + 1.5[1 - (100AMD^{1.5} + 1)]^{-1}$$

(5)

In the present investigation, the AMD of ultrafine fraction was $1.26 \text{ nm}$. Deposition fractions represent aerosol mass fraction deposited within specified regions during a complete breathing cycle normalized to the mass entering the trachea.

A total lung volume $3000 \text{ cm}^3$, a tidal volume $1000 \text{ cm}^3$ and a spherical particles having a density equal $1 \text{ g cm}^{-3}$ were considered. Airway geometry was selected randomly and a deposition
fraction in each airway generation of the human lung was calculated deterministically by using the deposition formulas which were described by Koblinker and Hofmann [49]. Ventilation rates were taken as 0.54 and 1.5 m$^3$ h$^{-1}$ for rest and light exercise, respectively. These values have been substituted in the stochastic deposition model to calculate the amounts of radon progeny deposited in each airway generation, as function of aerosol size and breathing rate, for each subject.

In radon dosimetry, dose conversion factor (DCF) is defined as the ratio between the weighted equivalent doses to EEC of radon progeny. DCF values may be obtained either based on results of epidemiologic studies or calculated applying dosimetric models [57]. Based on the obtained values of the $f_b$, DCF have been calculated by using an empirical formula proposed by Porstendörfer [43].

$$DCF_{bb} = 101xf_b + 6.7x(1-f_b) \text{ for mouth breathing}$$
$$DCF_{bn} = 23xf_b + 6.2x(1-f_b) \text{ for nasal breathing}$$

The annual inhalation dose due to radon and its progeny is estimated according to the following formula [17], [58].

$$D_a(\text{msv}) = T \left[ 0.17C_{\text{Rn}} + 9EEC \right] \times 10^{-6}$$

where $T$ is the time in hours a person spends at a particular location and $C_{\text{Rn}}$ is the concentration of radon gas in units of Bq m$^{-3}$. The factors of 0.17 and 9 are the effective dose coefficients (nSv/Bq h m$^{-3}$) for radon and EEC, respectively. An average person spends time indoors with an occupancy factor of 0.8 averaged over 1 year [16], this gives $T = 7008$ h. In the present study, $C_{\text{Rn}}$ is estimated according to the following relation:

$$C_{\text{Rn}} = \frac{EEC}{F}$$

**RESULTS AND DISCUSSIONS**

About forty samples have been carried out in different low ventilated room at Minia University, Minia city, Egypt. From the measured of activity concentrations, EEC, EEC$^{\text{un}}$ and $f_b$ of radon progeny have been calculated. The obtained values of EEC varied from 1.3 to 18.9 Bq m$^{-3}$ with an average value of 5.2± 0.48 Bq m$^{-3}$. Fig. 3 shows the frequency distributions of total equilibrium equivalent concentration, EEC. This distribution looks log-normal and has also been observed by many other authors during the measurements of radon progeny [58-63]. This log normal distribution indicates the dynamic behavior of radon progeny concentrations with either time or space. The parameters which responsible for temporal variations are temperature, moisture content, ventilation of the different parts of the building, $^{238}$U concentration and radon exhalation rate from the soil and building materials [58].

The frequency distributions of ultrafine fraction, $f_b$, are shown in Figure.4 where $f_b$ varied between 0.01 and 0.21 with a mean value of 0.08 ± 0.03. The present mean value of $f_b$ (0. 08) is about three times higher than proposed in the literature, $f_b = 0.03$, [64], [57], [41] [32] and lower than the mean value of 0.19 given by Kranrod et al [8].

The parameters of unattached activity size distributions and ultrafine fraction (EEC$^{\text{un}}$) of radon progeny as obtained from the measurements with diffusion battery are summarized in Table 1.
Figure 3. Frequency distribution of EEC

Figure 4. Frequency distribution of $f_b$

Table 1. The activity size distribution parameters of unattached EEC of short lived radon progeny

<table>
<thead>
<tr>
<th>AMTD (nm)</th>
<th>GSD</th>
<th>EEC$^{un}$ (Bq m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.26</td>
<td>1.3</td>
<td>0.4 ±0.08</td>
</tr>
</tbody>
</table>

(1.06 – 1.5) (1.2 – 2.0) (0.04 – 1.8)
Fig. (5) presents the activity size distribution of ultrafine (EEC\textsuperscript{ul}) fraction of radon progeny. The EEC of ultrafine fraction plotted verses the cut-off diameter of the screen diffusion battery. The mean active median thermodynamic diameter (AMTD) of ultrafine fraction of EEC\textsuperscript{ul} is 1.26 nm (1.06 – 1.5) with corresponding average geometric standard deviation of 1.3. The present AMTD (1.26 nm) is considered to be relatively higher than the values obtained (around 0.8 nm) by [33], [36], [67].

Based on the obtained experimental parameters, the deposition fraction in each airway generation for adult male has been calculated by applying Mont Carlo deposition model of Koblinker and Hofmann [49].

Figure 6 represents the deposition fraction that is predicted for each airway generation of the adult male lung over the size range of concern for deposition of radon progeny. This Figure relates the number of particles deposited in each airway generation to the number that enter the trachea on inhalation. It can be seen that the deposition fraction of particles with diameter of 1.26 nm are calculated to be uniformly high throughout the bronchi (generation 1 to 8). By the time the inspired air reaches the bronchioles (generation 9-15), the number of ultrafine airborne particles available for deposition was low. Therefore, deposition is found to be decrease rapidly in succeeding generations of the bronchiolar airways.

The bronchial deposition fraction of particles in the size range of attached radon progeny were found to be about two orders of magnitude lower than those of unattached progeny. This clears that the disproportionately largely contributions to the dose from exposure to small fraction of radon progeny in the unattached state. The attached or so-called accumulation mode of the radon progeny aerosol has a median size in ambient air that ranges from about 150 to 400 nm diameter [68], [36]. However, the carrier aerosol particles are considered to be partially hygroscopic and grow in the respiratory tract to about double their ambient size.

Another significant factor that must be accounted for the calculating of deposition profile of radon progeny within the respiratory tract is the typical variability or dispersion in size of the aerosol particles. Ultrafine radon progeny have a relatively narrow distribution of particle size,
whereas the activity-size distribution of progeny attached to ambient aerosol particles is typically broad.

Figure 6. Deposition fraction calculated with varying particle diameters.

Figure 7. Effect of exercise on fraction of particles deposited in each airway generation at two levels of physical activity for an adult male (resting, 0.54 m$^3$ h$^{-1}$ and light work, 1.5 m$^3$ h$^{-1}$).

Figure 7 illustrates how the deposition profiles of ultrafine and attached progeny are expected to be influenced by subject’s breathing rate. An increase in the breathing rate (from rest to light work) is found to decrease the deposition fraction with which inhaled progeny were deposited in the bronchi. As the ventilation rate increased from 0.54 to 1.5 m$^3$ h$^{-1}$, the average deposition fraction of airway generations 1 through 8 were expected to decrease by 22% for 1.26 nm particles and by about 38% for 350 nm particles.

Based on the obtained $f_b$, the DCF has been evaluated [69], [48] by applying lung models [43]. The calculated DCF (for mouth and nasal) are plotted versus $f_b$ as in Figure 8. It is clear from
this figure that the DCF is affected where the inhalation is through the nasal or mouth.

![Figure 8. DCF as a function of unattached fraction](image)

Due to equation 7 ($$\text{EEC}= 5.21 \text{ Bq m}^{-3}$$ and equilibrium factor $$F = 0.4$$), the annual dose was calculated to be 0.36 mSv.

**CONCLUSIONS**

The following conclusions can be drawn from the results of the present work:

1. A significant factor that must be accounted for calculating the deposition profile of radon progeny within the respiratory tract is the typical variability or dispersion in size of the aerosol particles. Unattached radon progeny have a relatively narrow distribution of particle size, whereas the activity size distribution of progeny attached to ambient aerosol particles is typically broad.

2. The obtained parameters of the activity size distribution (AMTD and GSD) are necessary to calculate the deposition and dose in the human lungs. For best estimation of doses, accurate data on these parameters are necessary. Simultaneous measurements of short lived radon progeny in different environments (indoor, outdoor, mine) are necessary in order to model the time-dependent behavior, deposition and attachment and to determine the particle size distribution.

**REFERENCES**


النشاط الإشعاعي بالنسبة للنوعة من نوائح الرادون

في الهواء داخل الغرف

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يتمثل استنشاق نوائح الرادون-222 خطراً صحياً كسبب لسرطان الرئة في الإنسان. وفي البيئة المنزلية، يُسمى نوائح الرادون في الجزء الأكبر من التعرض الإشعاعي للإنسان. النشاط الإشعاعي فائق النوعة لهذه النوائح يمثل حوالي 10% من النشاط الإشعاعي الكلي (المنتصف و فائق النوعة)، إلا أنه يُنجم حوالي 50% من الجرعة الإشعاعية الكلية. بذلك فإن قياسات النشاط فائق النوعة هامة لتقدير الجرعة الإشعاعية وتعمق دراسة حالات اللمفاضة لتركيزات الإشعاع الكهرومغناطيسي، تركيزات الإشعاع الكهرومغناطيسي (ECF) في النوائح، وتركيزات الإشعاع الكهرومغناطيسي (ECF) في النوائح.

الحاجة للنشاط الإشعاعي غير المنصف للنوائح الرادون في غرفة غير جيدة التهوية في جامعة المنها، مدينة المنها، مصر.

استخدمت بطارية إنشارة حبيبية لجمع الجرعة فائق النوعة وقياس تركيزات النشاط الإشعاعي الكلي لنوائح الرادون. تراوحت قيم نوائح الرادون بين 1.3 و 18.9 كريزيون/متر مكعب، بقيمة متوسطة 5.2 ± 0.8 كريزيون/متر. تم تحديد متوسط الطور النادياني كهروضولي (AMTD) النوائح الرادون فائق النوعة ليكون 1.22 نانومتر بمتوسط الجرعة معنويات هنسي نسب (GSD) (ECF) في النوائح الرادون (ECF) كانت ذات مدى 0.10 إلى 0.20، بمتوسط معنويات هنسي نسب (GSD) (ECF) في النوائح الرادون (ECF) كانت ذات مدى 0.10 إلى 0.20، بمتوسط معنويات هنسي نسب (GSD) (ECF) في النوائح الرادون (ECF) كانت ذات مدى 0.10 إلى 0.20، بمتوسط معنويات هنسي نسب (GSD) (ECF) في النوائح الرادون (ECF) كانت ذات مدى 0.10 إلى 0.20، بمتوسط معنويات هنسي نسب (GSD) (ECF) في النوائح الرادون (ECF) كانت ذات مدى 0.10 إلى 0.20، بمتوسط معنويات هنسي نسب (GSD) (ECF) في النوائح الرادون (ECF) كانت ذات مدى 0.10 إلى 0.20، بمتوسط معنويات هنسي نسب (GSD) (ECF) في النوائح الرادون (ECF) كانت ذات مدى 0.10 إلى 0.20، بمتوسط معنويات هنسي نسب (GSD) (ECF) في النوائح الرادون (ECF) كانت ذات مدى 0.10 إلى 0.20، بمتوسط معنويات هنسي نسب (GSD) (ECF) في النوائح الرادون (ECF) كانت ذات مدى 0.10 إلى 0.20، بمتوسط معنويات هنسي نسب (GSD) (ECF) في النوائح الرادون (ECF) كانت ذات مدى 0.10 إلى 0.20، بمتوسط معنويات هنسي Nسب (GSD) (ECF) في النوائح الرادون (ECF) كانت ذات مدى 0.10 إلى 0.20، بمتوسط معنويات Hنسي Nسب (GSD) (ECF) في النوائح الرادون (ECF) كانت ذات مدى 0.10 إلى 0.20، بمتوسط معنويات Hنسي Nسب (GSD) (ECF) في النوائح الرادون (ECF) كانت ذات مدى 0.10 إلى 0.20، بمتوسط معنويات Hنسي Nسب (GSD) (ECF) في النوا...