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Estimation of the Effective Dose Rates from Radon and Thoron during the Chemical Processing of the Black Sand Minerals

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Abstract: The additive effective dose rates from the radioactive gases radon and thoron and their decay products were evaluated at the laboratories of the minerals; ilmenite, zircon, monazite and rutile. Two types of concentration-effective dose conversion factors were employed; factors resulted from epidemiological studies and those obtained by the Human Respiratory Tract Model (HRTM). Based on HRTM, the additive effective dose rates from radon and thoron gases were found to be 5.84×10^{-9} and 1.58×10^{-9} ($Sv.h^{-1}.kBq^{-1}$), respectively. No significant difference found between the additive effective doses received from thoron gas estimated by the two methods while the value of the additive effective dose rate estimated for radon gas by HRTM factors is almost twice that obtained by the epidemiological factor. The additive effective dose rates received from the radioactive gases radon and thoron and their individual progenies are constants and they are used to estimate the effective dose rates at the environments of these gases directly from the known activity of the processed mineral. On the average, the additive effective dose rate received from each of the three radon decay products ^{218}Po, ^{214}Pb and ^{214}Bi is 1.95×10^{-9} ($Sv.h^{-1}.kBq^{-1}$) at the common ventilation rate 1 (h^{-1}).

Keywords: Effective dose rate, Equilibrium factor, Biokinetic models, Radon.

1 Introduction

Epidemiological studies of occupational exposures of miners and domestic exposures of the public have provided strong and complementary evidence of the risks of lung cancer following inhalation of radon and its progeny. In the large cohorts of underground miners, annual occupational exposures were considered for the whole working period of each individual. Consequently, these studies are able to analyze dose–response relationships taking account of time-dependent modifying factors, such as age at exposure and time since exposure. The risk of lung cancer associated with domestic exposures to radon has been evaluated in a large number of case–control studies, requiring estimates of radon exposure in houses over a period of 30 years preceding lung cancer diagnosis. A weakness of such studies is that measurements made during the study period are assumed to apply throughout the whole period of exposure [1].

The control of domestic exposures can be based directly on lung cancer risk estimates per unit exposure derived from epidemiological data; that is, in terms of radon concentrations in homes. However, for the purpose of control of occupational exposures using dose limits and constraints, estimates of dose per unit exposure are required. The effective dose per unit exposure to radon and its progeny was obtained using the so-called 'dose conversion convention' [2,3]. This approach compared the detriment per unit exposure to radon and its progeny with the total detriment associated with unit effective dose, estimated largely on the basis of studies of Japanese atomic bomb survivors [2]. The values given were 5 mSv per WLM [1.4 mSv per (mJh/m^3)] for workers and 4 mSv per WLM [1.1 mSv per (mJh/m^3)] for members of the public.

Doses from radon and its progeny can also be calculated using different dosimetric models. A review of published data on the effective dose per unit exposure to radon progeny obtained using dosimetric models is included in several reports [1]. Values of effective dose range from about 6 to 20 mSv per WLM [1.7–5.7 mSv per (mJh/m^3)], with results using the Human Respiratory Tract Model, HRTM [3] in the range from approximately 10 to 20 mSv per WLM [3–6 mSv per (mJh/m^3)] depending on the

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exposure scenario.
The International Commission on Radiological Protection, ICRP, has concluded that radon and its progeny should be treated in the same way as other radionuclides within the system of protection. That is, doses from radon and its progeny should be calculated using ICRP biokinetic and dosimetric models, including the HRTM and ICRP systemic models. In the near future, ICRP will provide dose coefficients per unit exposure to radon and its progeny for different reference conditions of domestic and occupational exposure, with specified equilibrium factors and aerosol characteristics. It should be recognized, however, that these dose coefficients will be larger by about a factor of two or more [1].
The black sand minerals; monazite, zircon, ilmenite and rutile may have elevated concentrations of the radioactive elements uranium and thorium. During the chemical treatment of these minerals, radiation exposures arise to the occupational workers due to the existence of these radioactive elements and their decay chains [4].
Many efforts were done to propose the suitable measures to control the radiation exposures during the treatment of the radioactive materials [5-8]. This study estimates the additive effective dose rates from radon and thoron gases, as a control measure, during the chemical treatments of the radioactive minerals monazite, zircon, ilmenite and rutile.

2 Materials and methods

2.1 Exposure sources and environment

The measurements to estimate radiation effective doses were carried out at the black sands laboratories at the Nuclear Materials Authority (NMA), Egypt. One laboratory uses sulphoric acid to solve monazite mineral to get the rare earth elements (REEs). Another laboratory attacks ilmenite mineral by sulphoric acid to obtain titanium oxides. The third laboratory treats zircon mineral using sodium hydroxide to get zirconia. Rutile mineral is separated from the ore black sands by physical methods in different grades. Concentration of rutile can be upgraded using sulphoric acid to minimize the impurities of other minerals.
The source of black sand minerals is the beach deposits at Abu Khashaba, northern Nile coast, Egypt. Black sand minerals (Ilmenite, Zircon, Monazite and Rutile) were concentrated from the beach deposits at the project of concentration and separation of black sands, Egypt. The purity of the studied minerals is almost 50%. Monazite and zircon are classified as radioactive minerals while ilmenite and rutile have impurities from the other two minerals.
However, the activity A of the processed quantity from each mineral is abstracted from another study, Table (1), [9,10]. Sources of radiation exposure are restricted to the internal exposure represented by the inhalation of radon, thoron gases.

2.2 Background

The background of each physical quantity was measured for 20 hr (3 working days) at the working area inside each laboratory before interfering the area with the mineral to be processed. SARAD device was adjusted to display the concentrations C_{Rn} and C_{Tn} each quarter an hour. During the chemical processing of the mineral, the physical quantities were measured in the same manner for the necessary time at each processing stage. The average value of the background of a physical quantity at the working area is subtracted from the average value of this quantity during each stage and the incremental value is tabulated.

Table (1): Mass m (kg), activity concentration S_A (Bq.g^{-1}) and Activity A (kBq) of the processed minerals.

Mineral	m (kg)	S_A (Bq.g^{-1})	A (kBq)
monazite	0.2	9.23	1.85
ilmenite	2.5	1.45	3.63
rutile	10	1.15	11.50
zircon	2,5	7.06	17.65

2.3 Calculation of the concentrations of radon and thoron progenies

Radon and thoron decay products are responsible for the most part of the radiation doses delivered by these gases. However, the concentration of a gas is generally considered as a surrogate for the concentrations of its decay products. This is achieved using a value of the equilibrium factor, F_{eq}, between the concentration of the gas and the concentrations of its decay products.
The equilibrium state between radon or thoron gas and their progenies is affected by the ventilation rate λ (h^{-1}). Most studies calculate the effective doses received from the decay products of these gases at a value of 1(h^{-1}) for λ which sets the equilibrium factor F_{eq} at a value of 0.4 between radon and its decay products and at a value of 0.03 between thoron and its decay products(11).
Figures (1&2) represent the variation of the value of F_{eq} between both gases and their progenies with the age of each gas. Also, these figures show the ratio R_p of the concentration of each progeny to its maximum value at F_{eq}=1, i.e., when the concentration of the progeny equals that of the parent gas. The values of the concentration ratios R_p of radon and thoron decay products at the desired values of F_{eq} are represented in Table (2).
On the other hand, the gases measurements are preferred to decay products measurements because of their simplicity and cost effectiveness [12].

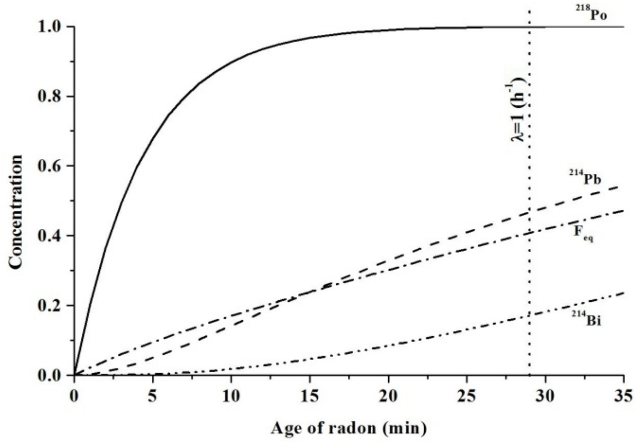

Figure 1. Variation of the concentrations of radon progenies and the equilibrium factor F_{eq} with time.

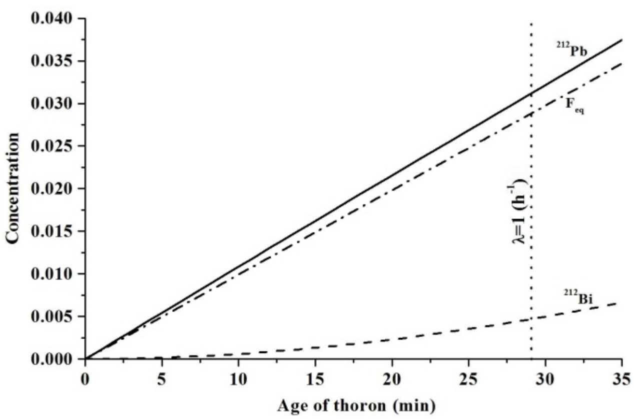

Figure 2. Variation of the concentrations of thoron progenies and the equilibrium factor F_{eq} with time.

3 Results and Discussion

During the chemical treatments of the black sands minerals radon and thoron gases emanate from the minerals grains as well as from the liquid compounds of solved radioactive minerals. These gases along with the gamma rays emitted from the studied minerals represent a potential elevation in the radiation exposures at the working areas.

3.1 Radon and thoron concentrations

Table (2) represents the values of each of the measured radiation quantities; concentrations of radon gas C_{Rn} and thotron gas C_{Tn} (Bq.m^{-3}) at the studied laboratories of chemical treatment of monazite, rutile, zircon and monazite.

The average value of C_{Rn} and C_{Tn} change over a range with its upper value is one order magnitude higher than its lower value. This reflects the same manner of the variation of the activity A of the studied minerals which changes from 1.85 to 17.65 (kBq), Table (1).

Table (2): Average incremental concentrations of the radioactive gases radon C_{Rn} and thoron C_{Tn} at the laboratories of chemical treatment of the black sands minerals.

Mineral	C_{Rn} (Bq.m^{-3})	C_{Tn} (Bq.m^{-3})
Monazite	1.04±0.16	2.37±0.36
Ilmenite	2.51±0.38	3.13±0.47
Rutile	9.52±1.43	17.50±2.63
Zircon	12.50±1.88	20.63±3.09

Figure (3) shows the variation of the average incremental value of each of the quantities; C_{Rn}, and C_{Tn} with the activity A of the studied minerals. From the figure, two straight lines represent the linear proportionality between each of the measured quantities and the activity of the processed radioactive minerals.

The slope of the two lines quantify the 'additive' concentrations (Bq.m^{-3}.kBq^{-1}) of radon gas C_{SRn} and thoron gas C_{STn} due to 1 (kBq) of mineral activity. The values of C_{SRn} and C_{STn} arise due to the processing of 1 (kBq) are 0.75 and 1.27 ((Bq.m^{-3}).kBq^{-1}) respectively.

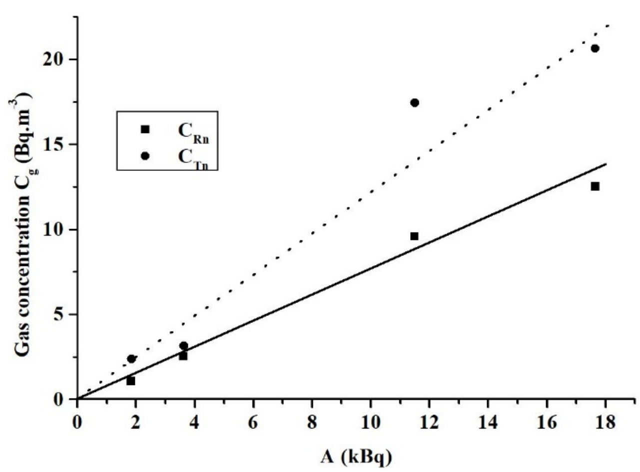

Figure 3. Variation of the concentrations of the gases radon C_{Rn} and thoron C_{Tn} with the activity A of the studied minerals.

Thorium is the head of the radioactive series responsible for the emanation of thoron gas. On the other hand, the studied minerals have high concentrations of thorium to be classified as thorium minerals. This explains the doubled value of C_{STn} compared to the value of C_{SRn}.

3.2 Effective dose rate

The effective dose rate received due to the inhalation of radon and thoron decay products can be estimated via two approaches.

3.2.1 Epidemiological factors

The first approach uses epidemiological data and risk estimates for lung cancer derived directly from the miner cohort studies. These studies resulted in coefficients to estimate the doses from the inhalation of radioactive gases. UNSCEAR reported two factors; $9x10^{-9}$ and $40x10^{-9}$ $(Sv.(Bq.m^{-3})^{-1})$ for radon and thoron respectively. This approach yields two relations to get the effective dose rate resulting from the inhalation of radon and its decay products E_{Rn} at F_{eq}=0.4 and the effective dose rate resulting from the inhalation of thoron and its decay products E_{Tn} at F_{eq}=0.03. These relations are [11]:

$$E_{Rn}\ (Sv.h^{-1}) = C_{Rn}\ (Bq.m^{-3})\ .\ 0.4\ .\ 9x10^{-9}\ (Sv.\ Bq^{-1}.h^{-1}.m^{3}) \quad (1)$$

$$E_{Tn}\ (Sv.h^{-1}) = C_{Tn}\ (Bq.m^{-3})\ .\ 0.03\ .\ 40x10^{-9}\ (Sv.\ Bq^{-1}.h^{-1}.m^{3}) \quad (2)$$

where C_{Rn} and C_{Tn} are the average values of the incremental concentrations of radon and thoron, respectively, Table (2).
The effective dose rates E_{Rn} and E_{Tn} during the processing of the studied minerals based on the epidemiological coefficients are represented in Table (3).

Table (3): Incremental effective dose rates from radon E_{Rn} and thoron E_{Tn} at the studied laboratories of chemical treatment of the blach sands minerals using the epidemiological coefficients.

Mineral	E_{Rn} $(Sv.h^{-1})$	E_{Tn} $(Sv.h^{-1})$
monazite	$3.74x10^{-09}$	$2.84x10^{-09}$
ilmenite	$9.00x10^{-09}$	$3.76x10^{-09}$
rutile	$3.44x10^{-08}$	$2.09x10^{-09}$
zircon	$4.5x10^{-08}$	$2.48x10^{-08}$

The values of the effective dose rate from radon gas E_{Rn} received due to the processing of a mineral are comparable to that from thoron gas E_{Tn}.

Equation (3) can be reformulated as follows:

$$E_{Rn}\ (Sv.h^{-1}) = \xi_{Rn}\ .\ C_{Rn}\ (Bq.m^{-3}) \quad (3)$$

where C_{Rn} is the radon gas concentration and ξ_{Rn} is a constant such that:

$$\xi_{Rn} = 3.6x10^{-9}\ \ (Sv.\ Bq^{-1}.h^{-1}.m^{3}) \quad (4)$$

Now we can define the additive effective dose rate E_{SRn} $(Sv.h^{-1}.kBq^{-1})$ received by the workers from radon gas during the processing of an additional 1kBq of a radioactive mineral to be:

$$E_{SRn} = \xi_{Rn}\ .\ C_{SRn} \quad (5)$$

Since C_{SRn} is a constant, so, E_{SRn} is a constant equals 2.7 $(Sv.h^{-1}.kBq^{-1})$.

Similarly

$$\xi_{Tn} = 1.2x10^{-9}\ \ (Sv.\ Bq^{-1}.h^{-1}.m^{3}) \quad (6)$$

and E_{STn} is a constant equals 1.52 $(Sv.h^{-1}.kBq^{-1})$.

3.2.2 Human Respiratory Tract Model (HRTM)

The other approach to calculate the effective dose rate received from radon and thoron decay products applies the available scientific information on the health effects attributed to the studied gases and their decay products. The ICRP proposed that the same approach should be applied to exposure to radon and thoron gases and their progenies as that applied to other radionulcides using reference biokinetic and dosimetric models [12-14]
Radon and thoron progenies are deposited in the respiratory tract. According to the Human Respiratory Tract Model (HRTM), aerosol deposition fraction in the respiratory tract depends on the inhaled particle sizes and the human physiological parameters. The measured aerosol particle sizes have been proved to follow a lognormal distribution. In the present work, aerosols with activity median aerodynamic diameter AMAD of 5µm are assumed to represent the attached particles in the working areas. The values of the dose conversion coefficients K_p $(Sv.Bq^{-1})$ of radon and thoron decay products at the 5µm size are collected from the tables published by the International Atomic Energy Agency [1]. However, the values of the needed factors and parameters are summarized in Table (4).
The effective dose rate E_p $(Sv.h^{-1})$ due to the inhalation of 1Bq of any decay product p is calculated as follows:

$$E_p = C_g\ .\ R_p\ .\ K_p\ .\ B \quad (7)$$

where
C_g = the average concentration of the gas $(Bq.m^{-3})$ released from a mineral, Table (2),
g = radon (Rn) or thoron (Tn) gas,
R_p = concentration ratio between the progeny p at $\lambda=1(h^{-1})$ and its maximum value at F_{eq}=1, Table (4),
K_p = conversion coefficient of the progeny p [4],
B = 1.2 $(m^{3}.h^{-1})$, breathing rate [15].

The terms K_p and B are constants and R_p is constant at a chosen value of the equilibrium factor F_{eq}. Accordingly, a constant $\varkappa_p$ $(Sv.Bq.m^{3}.h^{-1})$ can be introduced to simplify the calculation of the effective dose rate from the decay product p as follows:

$$\varkappa_p = R_p\ .\ K_p\ .\ B \quad (8)$$

Equation (5) is modified to be as follows:

$$E_p = \varkappa_p \cdot C_g \quad (9)$$

Table (4) represents the values of $\varkappa_p$ for radon and thoron progenies while Table (5) represents the value of the effective dose rate E_p received from each progeny at the studied laboratories based on the HRTM.

Table (4): Ratios of the concentrations of radon thoron gases R_p at the chosen values of F_{eq} and the values of the dose conversion coefficients of the progenies K_p based on the HRTM. The values of the constant $\varkappa_p$ are represented.

p	R_p	K_p (Sv.Bq^{-1})	$\varkappa_p$ (Sv.Bq^{-1}.h^{-1}.m^3)
Radon decay products F_{eq}=0.4			
^{218}Po	1	2.2x10^{-9}	2.64x10^{-9}
^{214}Pb	0.467	4.8x10^{-9}	2.69x10^{-9}
^{214}Bi	0.171	1.2x10^{-8}	2.46x10^{-9}
Thoron decay products F_{eq}=0.03			
^{212}Pb	0.031	3.3x10^{-8*}	1.23x10^{-9}
^{212}Bi	0.0047	1.5x10^{-8}	8.46x10^{-11}

*AMAD=2.5µm[12]

The additive effective dose rate E_{Sp} (Sv.h^{-1}.kBq^{-1}) from each progeny which is the incremental effective dose received from the progeny p due the processing of an additional 1kBq of a radioactive mineral can be calculated as follows:

$$E_{Sp} = \varkappa_p \cdot C_{Sg}, \quad (10)$$

where $C_{Sg}=C_{SRn}$ or C_{STn}.

Since $\varkappa_p$ and C_{Sg} are constants, the values of E_{Sp} for radon and thoron decay products are constants. The values of the additive effective dose rates E_{Sp} are represented in Table (5). It is recognized that no important differences between the values of E_{Sp} for the three radon decay products since the increasing values of K_p are compensated by the decreasing values of R_p, Equation (5) and Table (4). Referring to thoron decay products, the value of E_{Sp} for ^{212}Pb is one order magnitude higher than the value of ^{212}Bi. This is ascribed to the very low value of R_p for ^{212}Bi at the chosen value of F_{eq}.

Table (5): Incremental effective dose rates E_p and the additive effective dose rates E_{Sp} from radon and thoron progenies during the processing of the black sands minerals based on the HRTM.

Mineral	E_p (Rn) (Sv.h^{-1})			E_p (Tn) (Sv.h^{-1})	
	^{218}Po	^{214}Pb	^{214}Bi	^{212}Pb	^{212}Bi
monazite	2.29x10^{-9}	2.33x10^{-9}	2.13x10^{-9}	2.42x10^{-9}	1.67x10^{-10}
ilmenite	5.50x10^{-9}	5.60x10^{-9}	5.13x10^{-9}	3.20x10^{-9}	2.21x10^{-10}
rutile	2.10x10^{-8}	2.14x10^{-8}	1.96x10^{-8}	1.78x10^{-8}	1.23x10^{-9}
zircon	2.75x10^{-8}	2.80x10^{-8}	2.57x10^{-8}	2.11x10^{-8}	1.45x10^{-9}
E_{Sp} (Sv.h^{-1}.kBq^{-1})	1.98x10^{-9}	2.02x10^{-9}	1.85x10^{-9}	1.48x10^{-9}	1.02x10^{-10}

In general, the average value of the additive effective dose rate E_{Sp} received by the workers from each of the three radon decay products ^{218}Po, ^{214}Pb and ^{214}Bi due to the processing of an additional 1kBq from a radioactive mineral is 1.95x10^{-9} (Sv.h^{-1}.kBq^{-1}) at the common ventilation rate of 1 (h^{-1}).

To compare the effective dose rate obtained by the epidimiological approach with that obtained by HRTM, the effective dose rates E_p from the progenies of each gas should be summed. However, the summation effective dose rate E_{Rn} (Sv.h^{-1}) received from radon decay products is:

$$E_{Rn} = \sum E_p \quad (11)$$

or

$$E_{Rn} = \varkappa_{Rn} \cdot C_{Rn} \quad (12)$$

where $\varkappa_{Rn}$ is a constant such that:

$$\varkappa_{Rn} = \sum \varkappa_p = 7.79\text{x}10^{-9} \text{ (Sv. Bq}^{-1}\text{.h}^{-1}\text{.m}^3) \quad (13)$$

p= ^{218}Po, ^{214}Pb and ^{214}Bi, while the summation effective dose rate E_{Tn} (Sv.h^{-1}) from thoron decay products is:

$$E_{Tn} = \sum E_p \quad (14)$$

or

$$E_{Tn} = \varkappa_{Tn} \cdot C_{Tn} \quad (15)$$

where

$$\varkappa_{Tn} = \sum \varkappa_p = 1.31\text{x}10^{-9} \text{ (Sv. Bq}^{-1}\text{.h}^{-1}\text{.m}^3) \quad (16)$$

p= ^{212}Pb and ^{212}Bi.

Table (6) represents the values of the incremental effective dose rates E_{Rn} and E_{Tn} received at the studied laboratories based on the HRTM. From Tables 3 and 6, it is clear that the values of E_{Rn} based on the HRTM due to the processing of the studied minerals are almost twice that obtained epidemiologically. This difference is explained considering that the radiation weighting factor used for alpha particles is 20 in the biokintic models while the relative biological effectiveness of alpha particles based on the epidemiology is closer to 10 than 20 [12,16-18].

Figure (4) compares the variation of the resultant incremental effective dose rate E_{Rn} from radon gas obtained by the epidemiological coefficient to that obtained by the biokinetic models with the activity A (kBq) of the processed radioactive minerals. The slopes of the two lines represent the additive effective dose rate E_{SRn} (Sv.h^{-1}.kBq^{-1}) received from radon progenies due to the processing of 1 (kBq) of the radioactive minerals. Again, it is obvious that the value of E_{SRn} obtained by the biokinetic models is almost twice the value obtained epidemiologically.

Fortunately, it seems that no significant difference between the value of the incremental effective dose rate from thoron gas E_{Tn} (Sv.h^{-1}) obtained by both methods as represented in Tables (3&6) and accordingly no significant difference between the values of the additive effective dose rate E_{STn} (Sv.h^{-1}.kBq^{-1}) as clarified in Fig. (5).

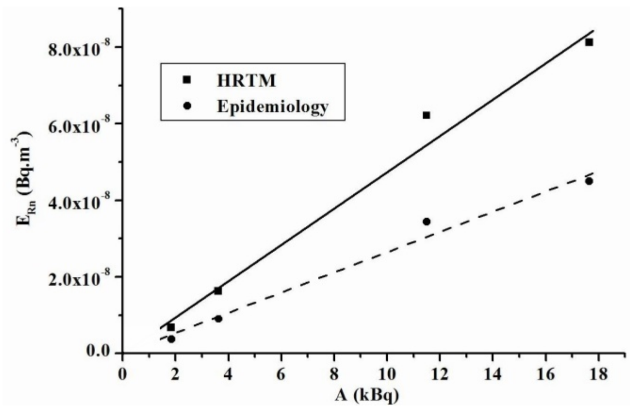

Figure 4. Variation of the effective dose rate from radon obtained epidemiologically and by HRTM with the activity of the studied minerals.

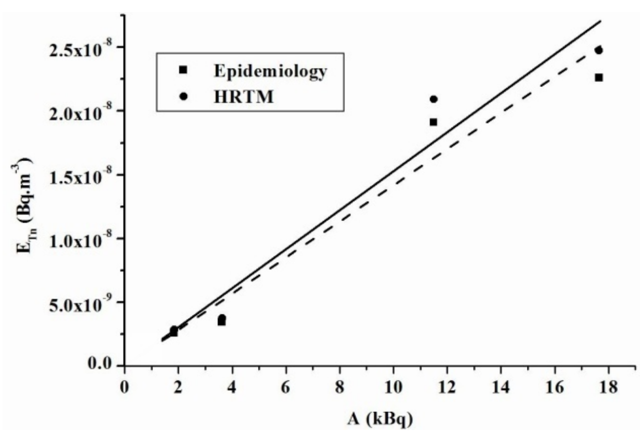

Figure 5. Variation of the effective dose rate from thoron obtained epidemiologically and by HRTM with the activity of the studied minerals.

It is seldom that the value of the additive effective dose rate received from radon gas E_{SRn} due to the processing of 1 (kBq) from a radioactive mineral is represented by the summation of the values of the additive effective dose rates E_{Sp} of the radon decay products ^{218}Po, ^{214}Pb and ^{214}Bi while the specific dose rate from thoron gas E_{STn} is the summation of the values of E_{Sp} of thoron decay products ^{212}Pb and ^{212}Bi as represented in Table (6).

Table (6): Incremental effective dose rate from radon E_{Rn} and from thoron E_{Tn} based on HRTM coefficients at the laboratories of chemical treatment of the studied minerals. The additive effective dose rates E_{Sg} are represented.

Mineral	$E_{Rn} = \sum E_p$ (Sv.h^{-1})	$E_{Tn} = \sum E_p$ (Sv.h^{-1})
monazite	6.75x10^{-9}	2.59x10^{-9}
ilmenite	1.62x10^{-8}	3.42x10^{-9}
rutile	6.21x10^{-8}	1.91x10^{-8}
zircon	8.12x10^{-8}	2.26x10^{-8}
	$E_{SRn} = \sum E_{Sp}$	**$E_{STn} = \sum E_{Sp}$**
E_{Sg} (Sv.h^{-1}.kBq^{-1})	5.84x10^{-9}	1.58x10^{-9}

Indeed, the comparison between the epidemiological and HRTM approaches is basically a comparison between the values of ξs and ϰs. No important difference between the values of ξ_{Tn} and $\varkappa_{Tn}$ for thoron gas while $\varkappa_{Rn}$ is more than twice the value of ξ_{Rn} for radon gas. This is reflected on the values of the additive effective dose rates estimated for radon or thoron gas E_{sg}.

Now, it is easy to calculate the effective dose rate received from a gas or from any individual decay product directly using the activity of the processed mineral as follows:

$$\mathbf{E_g\ (Sv\ .\ h^{-1}) = E_{sg}\ (Sv.h^{-1}.kBq^{-1})\ .\ A\ (kBq)} \quad (17)$$

$$\mathbf{E_p\ (Sv\ .\ h^{-1}) = E_{sp}\ (Sv.h^{-1}.kBq^{-1})\ .\ A\ (kBq)} \quad (18)$$

where A (kBq) is the activity of the mineral.

4 Conclusions

The additive effective dose rates received from radon and thoron gases along with their decay products at the laboratories of chemical treatments of the black sands minerals are useful constants to obtain the effective dose rates directly from the known activities of these materials. The additive effective dose rate received from radon gas estimated using the dose conversion coefficients resulting from the Human Respiratory Tract Model (HRTM) was found to be twice that obtained using the epidemiological factors. The additive effective dose rate received from thoron gas proved the equality of the two approaches. Previously, it was explained considering that the radiation weighting factor used for alpha particles is 20 in the biokintic models while the relative biological effectiveness of alpha particles based on the epidemiology is closer to 10 than 20. Based on HRTM, the additive effective dose rates from radon and thoron gases were found to be 5.84x10^{-9} and 1.58x10^{-9} (Sv.h^{-1}.kBq^{-1}), respectively. Accordingly, the average value of the additive effective dose rate received from each of the three radon decay products ^{218}Po, ^{214}Pb and ^{214}Bi is 1.95×10^{-9} ($Sv.h^{-1}.kBq^{-1}$) at the common ventilation rate 1 (h^{-1}).

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