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Assessment of Beta Radiation Doses to the Respiratory Tract and Heart of Spa Workers Due to the Inhalation of ^{214}Pb and ^{214}Bi Radon Progeny

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Abstract

Radon and its progeny are present in dwellings, caves, mines, and workplaces. They disintegrate by emitting alpha and beta minus particles as well as gamma photons. Due to their longer ranges, beta minus particles emitted by the attached and unattached fractions of the ^{214}Pb and ^{214}Bi radon progeny from the inhalation of air in spa rooms may lose their energies in lung tissues as well as in neighbouring organs such as heart, spinal cord, larynx and esophagus. In order to assess the dose to spa workers due to inhalation, concentrations of radon (^{222}Rn), and the attached and unattached fractions of the ^{214}Pb and ^{214}Bi radon beta minus-emitting progeny have been measured in different spas by means of CR-39 and LR-115 type II nuclear track detectors. Committed equivalent doses due to beta minus particles emitted by the attached and unattached fractions of ^{214}Pb and ^{214}Bi radon daughters were assessed in different tissues of the respiratory tract of female and male spa workers. It has been shown that committed equivalent doses to the tissues of the respiratory system of spa workers due to the emitted beta minus particles depend on the activity of the attached and unattached fractions of ^{214}Pb and ^{214}Bi radon progeny in spa rooms and the mass of the tissue. The annual committed effective doses to the respiratory tract due to the attached and unattached fractions of ^{214}Pb and ^{214}Bi radon progeny have been determined: a maximum value of 1.25 mSv $y^{-1}$was found for female workers spending 8 h per day during one year in spas (2,080 hours). A new dosimetric method was developed for assessing doses to the heart of spa workers due to beta minus particles emitted by ^{214}Pb and ^{214}Bi radon daughters present in BB compartment of the respiratory tract from inhalation of air. It has been shown that committed equivalent dose to the heart tissues of spa workers due to beta minus particles in heart tissues depend on the activity of the attached and unattached fractions of ^{214}Pb and ^{214}Bi radon progeny present in BB compartment (bronchi) of the respiratory tract and the heart surface of spa workers.

Keywords: ^{214}Pb and ^{214}Bi radon progeny; attached and unattached fractions; spa atmosphere; lung; heart; beta radiation dose assessment.

1.INTRODUCTION

The radon (^{222}Rn) radioactive inert gas belongs to the ^{238}U natural radioactive series. It is produced by disintegration of ^{226}Ra. ^{222}Rn and its decay products are alpha, beta minus and gamma emitting radionuclides. The inhalation of these radionuclides, which occurs in outdoor air [1] and, at higher concentrations, in indoor air is the main source of exposure to radiations of individuals in their homes and workplaces[2-6].In previous works, we showed that the total concentrations (attached and unattached fractions) of radon, and its daughters are significantly enhanced in the presence of different pollutants in indoor air such as cigarette smoke [7,8], fly ashes from coal burning [9], thermal water [10], marble dusts [11] and vehicle exhaust fumes [6]. We have recently determined concentrations of the attached and unattached fractions of the ^{218}Po and ^{214}Po radon progeny [12] and assessed radiation doses to the respiratory tract of workers in marble factories due to alpha-particles emitted by ^{218}Po and ^{214}Po radon progeny in the air of these locations: it has been shown that the concentrations of radon (^{222}Rn) and ^{218}Po and ^{214}Po radon progeny increase with the ventilation rate and the presence of pollutants. According to the anatomy of the human body, many organs such as heart, spinal cord, larynx and oesophagus are surrounded by lung tissues[13, 14]. So, due to their ranges in lung tissues (2 to 7 mm) beta minus particles emitted by both attached and unattached fractions of ^{214}Pb and ^{214}Bi radon progeny present in lung compartments from the inhalation of air may reach and lose their energies in neighbouring organs. The number of spas has significantly increased during the last decade in the tourist city of Marrakech in which national and foreign bathers received massages, body treatments, and aromatherapy and hair services, among others. The main aim of conducting this research work is to assess radiation doses to the respiratory system, and heart of spa workers due to beta minus particles emitted by ^{214}Pb and ^{214}Bi radon progeny from the inhalation of air.

In the work described here, a nuclear track detector technique was used for measuring the concentration of radon as well as those of the attached and unattached fractions of ^{214}Pb and ^{214}Bi radon progeny in the air of spas.Beta radiation doses due to the inhalation of the attached and unattached ^{214}Pb and ^{214}Bi radon progeny by workers inside spas were assessed in the lungs. A new dosimetric model was developed for determining radiation dose deposited in the heart of spa workers by beta particles emitted by ^{214}Pb and ^{214}Biradon progeny present in the bronchi BB compartment of the respiratory tract from the inhalation of air.The composition data for lung and heart given in the ICRP Publication 89 (ICRP 2002) for adults were used.

2. METHODS OF STUDY

a. Description of the spas studied

The spas that were the subjects of this investigation are located in the tourist city of Marrakech (Morocco); they are all built by cement and bricks.Spa workers spent 8 hours per day (six days per week) inside the considered spa rooms. The volume of the studied spa rooms varies between 26.25 m^3 and 40.50 m^3. Temperature and pressure inside the considered spa rooms are respectively equal to 40 °C and 968.70hPa.

b. Determination of the concentrations of ^{222}Rn, and its progeny in the air of spas

The concentrations of ^{222}Rn (radon), its progeny were measured in the air of various spas using the following types of nuclear track detectors:

(a) CR-39 discs of 2 cm in radius and 500µm thickness manufactured by Pershore Mouldings Ltd, United Kingdom;

(b) Kodak LR-115 type II discs of 2 cm in radius comprising 12 µm of cellulose nitrate on a 100 µm thick polyester base manufactured by Kodak Pathé, France, and marketed by Dosirad, France.

The detectors were hung 80 cm from ceiling and 220 cm from floor in different spa rooms for 24 hours in February 2019 according to the procedure described by Misdaq and Ouguidi[15]. During the exposure time, alpha particles emitted by the radionuclides of the ^{222}Rn and ^{220}Rn series in the air of a spa room bombarded the nuclear track films. After this irradiation, the exposed LR-115 II detectors were etched for 2 h at 60°C in a sodium hydroxide (NaOH) solution of 2.5 normality and CR-39 films were etched for 7 h at 70°C in a NaOH solution of 6.25 normality [16]. After chemical treatment, the track densities were determined using microscope at 40x magnification. Background levels for the nuclear track detectors were established by placing five unexposed films inside small, well closed plastic pockets for 24 h at each spa room and determining the resulting track densities. For testing the reproducibility of the method six pairs of CR-39 and LR-115 type II films were hung in the studied spa rooms for 24 hours. The distance between the pairs of detectors is of 25 cm. The average track density rates registered on the six couples of detectors were determined. The standard deviation of the average track density rate determination is of 1%. For the chosen optimal etching conditions, the LR-115 type II film is sensitive to alpha-particles of residual energy comprises between E_{min} = 1.6 MeV and E_{max} = 4.7 MeV reaching its surface under an angle lower than its critical angle of etching $\theta_c^{'}$ while the CR-39 detector is sensitive to alpha particles of residual energy situated between 0 and 20 MeV reaching its surface under an angle smaller than its critical angle of etching θ_c. The critical angles of etching $\theta_c^{'}$ and θ_c were calculated using a method described in detail by Misdaq et al. [17].

The global (G) track density rates (tracks cm^{-2} s^{-1}) due to alpha particles emitted by ^{222}Rn and its progeny (three alpha emitters) and ^{220}Rn and its progeny (four alpha emitters) in the air of spa room, registered on the CR-39 (ρ_G^{CR}) and LR-115 II (ρ_G^{LR}) detectors, after subtracting the corresponding background levels, were obtained as follows [18, 19]:

$$\rho_G^{CR} = \left[\sum_{j=1}^{3} A_c(j) k_j P_j^{CR} R_j + \sum_{j=1}^{4} A_c(j) k'_j P_j^{CR} R_j \right] \quad (1)$$

And

$$\rho_G^{LR} = \left[\sum_{j=1}^{3} A_c(j) k_j P^{LR} \Delta R + \sum_{j=1}^{4} A_c(j) k'_j \, P^{LR} \, \Delta R \right] \quad (2)$$

Where, $A_c(j)$ (Bq cm^{-3}) is the activity of a jth alpha emitter, R_j and R'_j are the ranges in air of an alpha particle of index j and initial energy E_j emitted by the nuclei of the ^{222}Rn and ^{220}Rn series inside the air of the studied spa rooms, respectively, k_j and k'_j are respectively, the banching ratios corresponding to the alpha disintegration of the radionuclides of the ^{222}Rn and ^{220}Rn series, and $\Delta R = R_{max} - R_{min}$. R_{min} and R_{max} are the alpha particle ranges in air which correspond to the lower (E_{min}) and upper (E_{max}) ends of the energy window ΔE, P_j^{CR} represents the probability for an alpha particle of initial energy E_j and index j to reach and be registered on the CR-39 detector, and $\boldsymbol{P}^{LR}$ represents the probability for an alphaparticle to reach and be registered on the LR-115 II detector[18, 19].Ranges of the emitted alpha particles in air and solid state nuclear track detectors utilized were calculated by using a SRIM programme [20].

The activity concentrations of the unattached fraction $A_{c,u}(j-1)$ and attached fraction $A_{c,a}(j-1)$ of a (j-1)th radionuclide and those of its jth unattached progeny $A_{c,u}(j)$ and attached progeny $A_{c,a}(j)$ are related by the following relationships [21]:

$$A_c(j) = A_{c,a}(j) + A_{c,u}(j) \quad (3)$$

$$A_{c,u}(j) = \frac{\lambda_j A_{c,u}(j-1) + r_{j-1}\lambda_j A_{c,a}(j-1)}{V + \lambda_j + q^u + X} \quad (4)$$

and

$$A_{c,a}(j) = \frac{(1-r_{j-1})\lambda_j A_{c,a}(j-1) + X A_{c,u}(j)}{V + \lambda_j + q^a} \quad (5)$$

Where $\lambda_j(s^{-1})$ is the radioactive decay constant of the jth ^{222}Rn or ^{220}Rn progeny, r_j is the recoil factor of the aerosol-attached radon or thoron progeny j, V (h^{-1}) is the ventilation rate, measured by using a CO_2 tracer method, inside a spa room (Table 1), q^a is the plate-out rate of the aerosol-attached radon or thoron progenies, q^u is the plate-out rate of the unattached radon or thoron daughters, and X is the mean attachment rate.

The values of j for ^{222}Rn and its daughters and for ^{220}Rn and its progeny are given in Reference [12].

Since ^{222}Rn and ^{220}Rn are gaseous, all of the activity is unattached, that is:

- $A_{c,u}(0) = A_c(0)$;
- $A_{c,a}(0) = 0$.

Values of recoil factors for attached ^{222}Rn and ^{220}Rn progeny (r_1, r_2, r_3 and r_4) have been previously determined[22].

c. *Determination of annual betacommitted effective doses due to the inhalation of ^{214}Pb and ^{214}Bi radon decay products in the respiratory tract of spa workers*

In terms of the International Commission on Radiological Protection model [13, 14], the human respiratory tract is divided into two major regions: the thoracic region TH and the extrathoracic ET region. The thoracic region is divided into four subregions (alveolar interstitium AI, bronchioles bb, bronchi BB and lymphatics LN_{TH}), while the extrathoracic region is dividedinto three subregions (anterior nasal ET_1, posterior nasal passage, larynx, pharynx and mouth ET_2 and lymphatics LN_{ET}). There are ten compartments in the thoracic region, numbered 1 to 10: AI_1, AI_2, AI_3, bb_1, bb_2, bb_{seq}, BB_1, BB_2, BB_{seq} and LN_{TH}, respectively. The extrathoracic region contains four compartments numbered 11 to 14: ET_2, ET_{seq}, LN_{ET}, and ET_1, respectively.

Inhaled radon daughters are attached to particles of an activity median aerodynamic diameter (AMAD) of 300nm with a geometric standard deviation σ_g=2.47 in workplaces [21].

The resulting beta-equivalent dose rate (Sv s^{-1}) in a tissue T of the respiratory tract of a spa worker from the inhalation of the attached fraction of a j'th ^{222}Rn decay progeny is given by:

$$\dot{H}_T^a(j')(t) = A_{c,a}^T(j')(t)D_{SP}^T(j')\, W_R \qquad (6)$$

Where $A_{c,a}^T(j')(t)$ (Bq) is the activity of the attached fraction of the j'th ^{222}Rn daughter in tissue T of the respiratory tract, $D_{SP}^T(j')$ is the specific beta dose (Gy) deposited by beta particles emitted by 1 Bq of a j'th ^{222}Rn daughter inside tissue T and $W_R = 1$ is the radiation weighting factor for beta particles [23].

The $D_{SP}^T(j')$ specific beta dose is given by [2, 24]:

$$D_{SP}^T(j') = k\,\frac{K_{j'}R_{j'}S_{j'}}{m_T} \qquad (7)$$

Where m_T is the mass of the target tissue T, $K_{j'}$ is the branching ratio for beta disintegration, $R_{j'}$ is the range in lung of the beta particle emitted by a j'th ^{222}Rn daughter, $S_{j'}$ is the stopping power of the tissue T for the emitted beta particle and k=1.6 10^{-10} is a conversion factor. The ranges of the emitted beta minus particles in lung were calculated by using ESTAR code [25].

The equivalent dose in the tissue T of the respiratory tract for the attached fraction of the j'th ^{222}Rn decay progeny is given by:

$$H_T^a(j') = \int_0^{t'_e} \dot{H}_T^a(j')(t)dt \qquad (8)$$

Where t'_e is the exposure time of the tissue T.

The resulting beta equivalent dose rate (Sv s^{-1}) in a tissue T of the respiratory tract of a spa worker from the inhalation of the unattached fraction of a j'th ^{222}Rn decay progeny is given by:

$$\dot{H}_T^u(j')(t) = A_{c,u}^T(j')(t)D_{SP}^T(j')\, W_R \qquad (9)$$

Where $A_{c,u}^T(j')(t)$ (Bq) is the activity of the unattached fraction of a j'th ^{222}Rn decay progeny in the tissue T of the respiratory tract.

The equivalent dose in a tissue T of the respiratory tract for the unattached fraction of a j'th ^{222}Rn decay progeny is given by:

$$H_T^u(j') = \int_0^{t'_e} \dot{H}_T^u(j')(t)dt \qquad (10)$$

Committed equivalent doses for the thoracic H_{TH} (j') and extrathoracic H_{ET} (j') regions obtained by summation of regional doses weighted with factors assigned for the partition of radiation detriment are given by:

$$H_{TH}(j') = A_{BB}(H_{BB}^a(j') + H_{BB}^u(j')) + A_{bb}(H_{bb}^a(j') + H_{bb}^u(j')) + A_{AI}(H_{AI}^a(j') + H_{AI}^u(j')) + A_{LN_{TH}}(H_{LNTH}^a(j') + H_{LNTH}^u(j')) \qquad (11)$$

and

$$H_{ET}(j') = A_{ET_1}(H_{ET1}^a(j') + H_{ET1}^u(j')) + A_{ET2}(H_{ET2}^a(j') + H_{ET2}^u(j')) + A_{LNET}(H_{LNET}^a(j') + H_{LNET}^u(j')) \qquad (12)$$

where $H_{BB}^a(j'), H_{BB}^u(j'), H_{bb}^a(j'), H_{bb}^u(j'), H_{AI}^a(j'), H_{AI}^u(j'), H_{LNTH}^a(j')$ and $H_{LNTH}^u(j')$ are respectively the equivalent doses due to the attached and unattached fractions of a j'th ^{222}Rn decay progeny in the BB, bb, AI and LN_{TH} tissues of the thoracic region, $H_{ET1}^a(j'), H_{ET1}^u(j'), H_{ET2}^a(j'), H_{ET2}^u(j'), H_{LNET}^a(j')$ and $H_{LNET}^u(j')$ are respectively the equivalent doses due to the attached and unattached fractions of a j'th ^{222}Rn decay progeny in the ET_1, ET_2 and LN_{ET} tissues of the extrathoracic region, A_{BB}=0.333, A_{bb}, A_{AI} and $A_{LN_{TH}}$ are respectively the weighting factors for the partition of radiation detriment for the BB, bb and AI tissues of the thoracic region and A_{ET_1}, A_{ET_2} and $A_{LN_{ET}}$ are the weighting factors for the partition of radiation detriment for the ET_1, ET_2 and LN_{ET} extrathoracic region [13].

The committed effective dose (Sv y^{-1} per hour of exposure) due to the unattached and attached fractions of the ^{214}Pb and ^{214}Bi radon decay products from the inhalation of air by working personnel inside spas is given by:

$$E = E^u + E^a \qquad (13)$$

where

$$E^u = 0.12\left[H_{TH}^u(^{214}Pb) + H_{TH}^u(^{214}Bi)\right] + 0.025\left[H_{ET}^u(^{214}Pb) + H_{ET}^u(^{214}Bi)\right] \qquad (14)$$

is the committed effective dose due to the unattached fractions of the ^{214}Pb and ^{214}Bi radon progeny and

$$E^{a} = 0.12\left[H_{TH}^{a}(^{214}Pb) + H_{TH}^{a}(^{214}Bi)\right] + 0.025\left[H_{ET}^{a}(^{214}Pb) + H_{ET}^{a}(^{214}Bi)\right] \quad (15)$$

is the committed effective dose due to the attached fractions of the ^{214}Pb and ^{214}Bi radon progeny.

d. A new dosimetric model for determining radiation dose to the heart of spa workers due to beta minus-particles emitted by ^{214}Pb and ^{214}Bi radon progeny present in the BB compartment of lung

There are five beta minus emitting radionuclides belonging to the radon (^{222}Rn) series: ^{214}Pb with a half-life of 26.8 min, ^{214}Bi with a half-life of 19.7 min, ^{210}Pb with a half-life of 22 y which is longer than the half-life of radon (3.82 d), ^{210}Tl with a half-life of 1.32 min, and ^{206}Tl with a half-life of 4.3 min [26]. The activities due to both attached and unattached fractions of ^{210}Tl and ^{206}Tl radionuclides are negligible because their half-lives are too short compared to the exposure time (24 hours) of the CR-39 and LR-115 type II track detectors inside the studied spa rooms. So, we consider only contributions of ^{214}Pb and ^{214}Bi radon progeny in our investigations. According to the anatomy of the human body, the heart is surrounded by the lungs as shown in Fig. 1. So, due to their longer ranges in lung tissues (2 to 7 mm) beta minus particles emitted by ^{214}Pb and ^{214}Bi radon progeny present in the BB compartment of the respiratory tract may reach and lose their energies in the heart tissues of workers (Fig. 2).

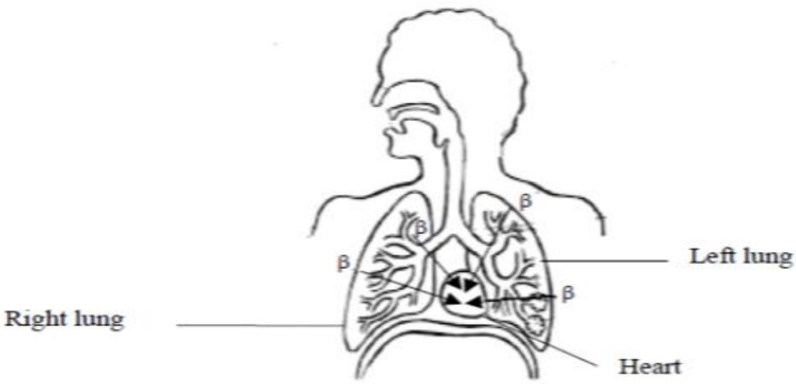

Fig. 1. Scheme showing the human heart receiving beta minus particles coming from the lungs due to the disintegration of ^{214}Pb and ^{214}Bi radon progeny.

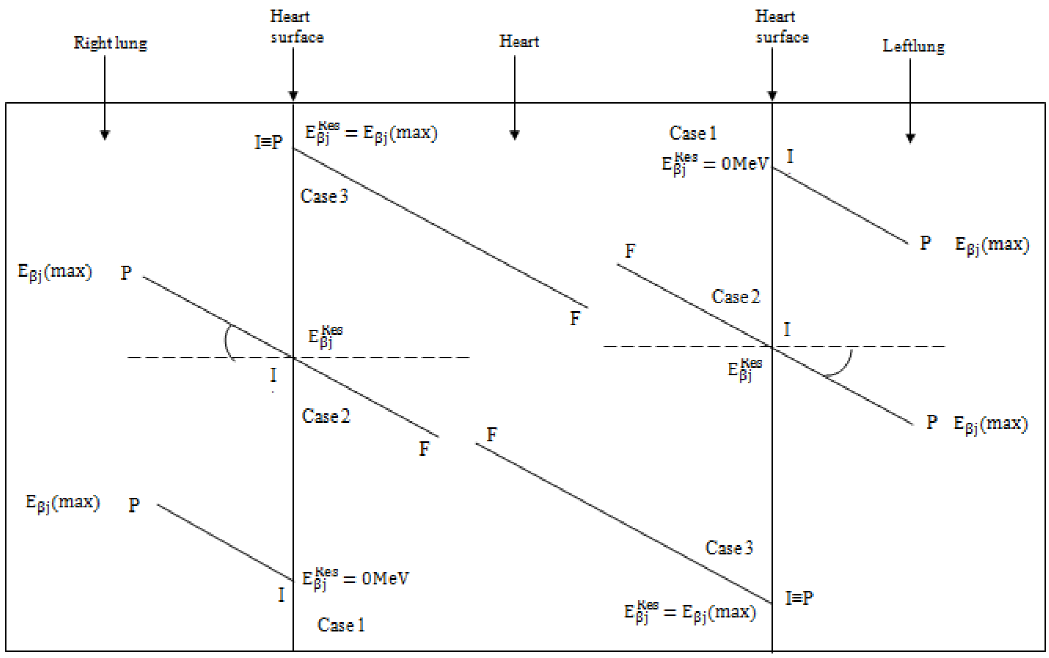

Fig.2. Ranges of beta-particles emitted by a the ^{214}Pb and ^{214}Bi radon progeny inside lungs ($\overline{PI} = x_j$) and heart ($\overline{IF} = R_j^{Heart}$): $E_{\beta j}$(max)is the initial beta-particle energy and $E_{\beta j}^{Res}$ its residual energy on the point I.

Indeed, a beta particle (β^-) of index j and initial energy $E_{\beta j}$ (max), emitted by a radionuclide, belonging to the ^{222}Rn series, localized at the point P inside the lungs (Fig. 2) has a range, $\overline{PF}$,

$$\overline{PF} = x_j + R_{\beta_j}^{Heart} \tag{16}$$

where x_j is the distance between the point of emission P and the heart surface (point I)(Fig. 2) and $R_{\beta_j}^{Heart}$ is the range of the beta particle in heart ($\overline{IF}$). x_j is smaller or equal to the range of the beta particle in lung (R_{β_j}).

By fitting the curve representing variation of beta particle range versus beta particle energy in lung (Fig. 3(a)) one can get the relationship between energy and range of beta particles in lung. The residual energy $E_{\beta_j}^{Res}$ of a beta particle of initial energy $E_{\beta j}$ (max) is obtained by using the correspondence with the (R_{β_j} - x_j) range (Fig. 3(a)). By exploiting the energy–range relationship between the energy and range of beta particles in the heart (obtained by fitting the curve represented in Fig. 3(b)) one can determine the range of the beta particle in heart $R_{\beta_j}^{Heart}$. According to Fig. 2 one can distinguish three situations. For $x_j = R_{\beta_j}$, $E_{\beta_j}^{Res} = 0\ MeV$; there is no energy loss of beta particles in heart (case 1 of Fig. 2). For a beta particle emitted at the surface of the heart $x_j = 0\ \mu m$, $E_{\beta_j}^{Res} = E_{\beta_j}(\max)$; the energy loss of beta particles in skin is maximum ($R_{\beta_j}^{Skin}$ maximum) (case 3 of Fig. 2). For $x_j < R_{\beta_j}$, $E_{\beta_j}^{Res} < E_{\beta_j}(\max)$; the ranges of beta particles in heart are lower than those corresponding to $x_j = 0\ \mu m$ (case 2 of Fig. 2).

The ESTAR code [25](Berger et al. 2005) and composition data for lung and heart[23](ICRP 2007) were utilized for calculating the ranges of beta particles emitted by the ^{214}Pb and ^{214}Bi radon progeny in heart and lung (Fig. 3).$E_{\beta j}$ (max) is equal to 1.52 MeV for beta minus particles emitted by ^{214}Pb radon progeny and to 0.65 MeV for beta minus emitted by ^{214}Bi radon progeny [26].

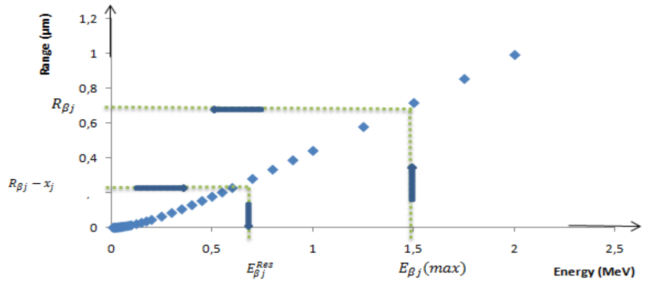

Fig.3(a)

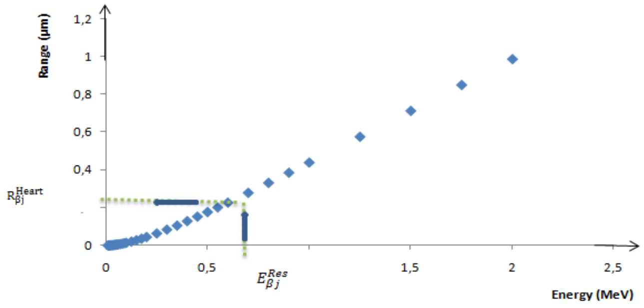

Fig.3(b)

Fig. 3. Variation of beta-particle range as a function of beta-particle energy in lungs (a) and heart (b).

Equivalent dose rates (Sv s^{-1}) to the human heart due to the energy loss of beta particles emitted by the attached fraction of a radionuclide of index j belonging to the ^{222}Rn series (^{214}Pb or ^{214}Bi) present in lung from the inhalation of air are given by:

$$\dot{H}_{Heart}(j,t) = A_{c,a}^{Heart}(j,t) D_{sp}^{Heart}(j) W_R \tag{17}$$

where $A_{c,a}^{Heart}(j,t)$ (Bq) is the activity, at time t, in 1 cm^3 of heart due to the attached fraction of a beta emitting radionuclide of index j belonging to the ^{222}Rn series, $D_{Sp}^{Heart}(j)$ is the specific beta dose (Gy) deposited by 1Bq of the attached fraction of a beta emitting radionuclide of index j belonging to the ^{222}Rn series in heart, and W_R is the radiation weighting factor which is equal to 1 for beta particles [23].

The $A_{c,a}^{Heart}(j,t)$ activity is given by:

$$A_{c,a}^{Heart}(j,t) = A_{c,a}^{BB}(j,t) e^{-\lambda_{\beta j} t}\ x1cm^3 \tag{18}$$

Where $A_{c,a}^{BB}(j,t)$ (Bq cm^{-3}) is the activity due to the attached fraction of a beta emitting radionuclide of index j belonging to the ^{222}Rn series present in the BB compartment of the respiratory tract of a spa worker, $\lambda_{\beta j}$ is the beta radioactive decay constant of a radionuclide of index j belonging to the ^{222}Rn series.

The $D_{Sp}^{Heart}(j)$ specific beta dose is expressed by:

$$D_{sp}^{Heart}(j) = k \frac{k_{\beta j}}{\rho_{Heart} S_{Heart}} \frac{E_{\beta j}^{Res}}{R_{\beta j}^{Heart}} \tag{19}$$

where $k_{\beta j}$= 1is the branching ratio corresponding to the beta disintegration of the radionuclides of the ^{222}Rn series (^{214}Pb and ^{214}Bi), ρ_{Heart} is the density of heart (1.00 g cm^{-3}), S_{Heart} is the heart surface (cm^2), k = 1.6.10^{-13} (J MeV^{-1}) is a conversion factor, $R_{\beta_j}^{Heart}$ is the range, in heart, of a beta particle of index j and residual energy $E_{\beta_j}^{Res}$ emitted by a radionuclide belonging to the ^{222}Rn series (Fig. 3(b)). S_{Heart} has been calculated by exploiting data given for the human heart dimensions given in the ICRP publication 23 [27]. S_{Heart} was found equal to 166.70 cm^2 for adult males and to 130.68 cm^2 for adult females.

By integrating Eq. (17) over time, equivalent doses (Sv) to the heart due to a beta particle of residual energy $E_{\beta_j}^{Res}$ emitted by a radionuclide of index j belonging to the ^{222}Rn series is given by:

$$H_{Heart}(j) = \frac{D_{sp}^{Heart}(j)\ W_R}{\lambda_{\beta j}} A_{c,a}^{BB}(j,t)\left(1 - e^{-\lambda_{\beta j} t_e}\right) \quad (20)$$

where t_e is the exposure time.

Equivalent doses to heart (Sv) due to all residual energies of a beta particle of index j and initial energy $E_{\beta j}$(max) belonging to the ^{222}Rn series is given by:

$$H_{heart}(j) = \frac{k\, k_{\beta j} A_{c,a}^{BB}(j,t)(1-e^{-\lambda_{\beta j} t_e})}{2\,\lambda_{\beta j} \rho_{Heart} S_{Heart} \Delta E_{\beta j}^{Res}} \int_0^{E_{\beta j}(max)} \frac{E_{\beta j}^{Res}}{R_{\beta j}^{skin}(E_{\beta j}^{Res})} dE_{\beta j}^{Res} \quad (21)$$

where t_e is the exposure time and $\Delta E_{\beta_j}^{Res}$ a chosen step on the [0-$E_{\beta j}$(max)] energy interval.

Total annual equivalent dose to surface heart of 1cm^2 during an exposure time equals 1 year (Sv y^{-1} cm^{-2}), due to beta particles emitted by the attached fractions of ^{214}Pb and ^{214}Bi radon short-lived decay products from the inhalation of air by spa workers is expressed by:

$$H_a^{heart}(Tot) = \sum_{j=1}^{2} H_{heart}(j) \quad (22)$$

Similarly,equivalent dose rates (Sv s^{-1}) to the human heart due to the energy loss of beta particles emitted by the unattached fraction of a radionuclide of index j belonging to the ^{222}Rn series present in lung from the inhalation of air are given by:

$$\dot{H}_{Heart}(j,t) = A_{c,u}^{Heart}(j,t) D_{sp}^{Heart}(j) W_R \quad (23)$$

where $A_{c,u}^{Heart}(j,t)$ (Bq) is the activity, at time t, in 1 cm^3 of heart due to the unattached fraction of a beta emitting radionuclide of index j belonging to the ^{222}Rn series, $D_{Sp}^{Heart}(j)$ is the specific beta dose (Gy) deposited by 1Bq of the unattached fraction of a beta emitting radionuclide of index j belonging to the ^{222}Rn series in heart, and W_R is the radiation weighting factor which is equal to 1 for beta particles [23].

The $A_{c,u}^{Heart}(j,t)$ activity is given by:

$$A_{c,u}^{Heart}(j,t) = A_{c,u}^{BB}(j,t) e^{-\lambda_{\beta j} t}\ x1cm^3 \quad (24)$$

Where $A_{c,u}^{BB}(j,t)$ (Bq cm^{-3}) is the activity due to the unattached fraction of a beta emitting radionuclide of index j belonging to the ^{222}Rn series present in the BB compartment of the respiratory tract of a spa worker, $\lambda_{\beta j}$ is the beta radioactive decay constant of a radionuclide of index j belonging to the ^{222}Rn series.

By integrating Eq. (23) over time, equivalent doses (Sv) to the heart due to a beta particle of residual energy $E_{\beta_j}^{Res}$ emitted by a radionuclide of index j belonging to the ^{222}Rn series is given by:

$$H_{Heart}(j) = \frac{D_{sp}^{Heart}(j)\ W_R}{\lambda_{\beta j}} A_{c,u}^{BB}(j,t)\left(1 - e^{-\lambda_{\beta j} t_e}\right) \quad (25)$$

where t_e is the exposure time.

Equivalent doses to heart (Sv) due to all residual energies of a beta-particle of index j and initial energy $E_{\beta j}$(max) belonging to the ^{222}Rn series is given by:

$$H_{heart}(j) = \frac{k\, k_{\beta j} A_{c,u}^{BB}(j,t)(1-e^{-\lambda_{\beta j} t_e})}{2\,\lambda_{\beta j} \rho_{Heart} S_{Heart} \Delta E_{\beta j}^{Res}} \int_0^{E_{\beta j}(max)} \frac{E_{\beta j}^{Res}}{R_{\beta j}^{Heart}(E_{\beta j}^{Res})} dE_{\beta j}^{Res} \quad (26)$$

where t_e is the exposure time and $\Delta E_{\beta_j}^{Res}$ is a chosen step on the [0-$E_{\beta j}$(max)] energy interval.

Total annual equivalent dose to surface heart of 1cm^2 during an exposure time equals 1 year (Sv y^{-1} cm^{-2}), due to beta particles emitted by the by the unattached fractions of the^{214}Pb and ^{214}Bi radon short-lived decay products from the inhalation of air by spa workers is expressed by:

$$H_u^{heart}(Tot) = \sum_{j=1}^{2} H_{heart}(j) \quad (27)$$

e. Statistical analysis

Analyses of variance were by Origin Pro 8.1 statistical software. The Tukey's test was applied, and σ = 1 indicated that the difference of the means is significant at the 0.05 level.

3. RESULTS AND DISCUSSION

a. Concentrations of ^{222}Rn, and its progeny in the air of spas

Radon (^{222}Rn) concentrations (A_c (^{222}Rn)) as well as those of the attached ($A_{c,a}$(^{214}Pb) and $A_{c,a}$(^{214}Bi)) and unattached ($A_{c,u}$(^{214}Pb) and $A_{c,u}$(^{214}Bi))fractions of the ^{214}Pb and ^{214}Bi radon progenywere measured in February 2019 in the air of spassituated in the tourist city of Marrakech (Morocco) by using Eqs.(1)-(5). Results obtained are given in Table 1. From the statistical error on the track counting, the error associated with the track density rate measurements could be determined, from which a relative uncertainty smaller than 8% was established for ^{222}Rn and its progeny concentrations. The reproducibility of the experimental method was checked by measuring radon concentration six times in each spa room.

Spa atmosphere	V (h^{-1})	A_c (^{222}Rn) ($Bq\ m^{-3}$)	$A_{c,u}$(^{214}Pb) ($Bq\ m^{-3}$)	$A_{c,a}$(^{214}Pb) ($Bq\ m^{-3}$)	$A_{c,u}$(^{214}Bi) ($Bq\ m^{-3}$)	$A_{c,a}$(^{214}Bi) ($Bq\ m^{-3}$)
Spa 1	0.34	103.12±8.08	1.08±0.08	54.18±4.06	0.021±0.001	43.34±3.25
Spa 2	0.58	65.89±5.16	0.68±0.05	34.11±2.56	0.013±0.001	27.28±2.05
Spa 3	0.53	66.75±5.01	0.69±0.05	34.59±2.57	0.013±0.001	27.67±2.08
Spa 4	0.46	72.88±5.20	0.73±0.05	36.45±2.73	0.014±0.001	29.16±2.19

Table 1. Data obtained for the radon activity A_c (^{222}Rn), activities of the unattached $A_{c,u}$(^{214}Pb), and attached $A_{c,a}$(^{214}Pb) fractions of ^{214}Pb and activities of the unattached $A_{c,u}$(^{214}Bi), and attached $A_{c,a}$(^{214}Bi) fractions of ^{214}Bi. V is the ventilation rate inside spas.

One can note that since the studied spas were built by the same building materials (cement and bricks) and their temperature and pressure are constant (40 °C and 968.70hPa),the concentrations of radon (^{222}Rn) and the attached and unattached fractions of its ^{214}Pb and ^{214}Bi progeny increase when the ventilation rate (V) inside the studied spa rooms decreases.One can note that the ratio of the activity of the attached fraction ($A_{c,a}$(^{214}Pb) to the activity of the unattached fraction ($A_{c,u}$(^{214}Pb) of ^{214}Pb is about 50 whereas the ratio of the activity of the attached fraction $A_{c,a}$(^{214}Bi)) to the activity of unattached fraction $A_{c,u}$(^{214}Bi)) of ^{214}Bi is about 2060 for the spa rooms studied. Indeed, one gets the same values of these rations by calculating $\frac{A_{c,a}(214\text{Pb})}{A_c^{Tot}\ (214\text{Pb})}$, $\frac{A_{c,u}(214\text{Pb})}{A_c^{Tot}\ (214\text{Pb})}$, $\frac{A_{c,a}(214\text{Bi})}{A_c^{Tot}\ (214\text{Bi})}$, and $\frac{A_{c,u}(214\text{Bi})}{A_c^{Tot}\ (214\text{Bi})}$ ratios for each spa room. A_c^{Tot} (214Pb)and A_c^{Tot} (214Bi) are respectively the total activities due to both attached and unattached fractions of ^{214}Pb and ^{214}Bi.

For instance for Spa1, we have:

$$\frac{A_{c,a}(214\text{Pb})}{A_c^{Tot}\ (214\text{Pb})} = 0.98, \frac{A_{c,u}(214\text{Pb})}{A_c^{Tot}\ (214\text{Pb})} = 0.0195\ ,$$
$$\frac{A_{c,a}(214\text{Bi})}{A_c^{Tot}\ (214\text{Bi})} = 0.99\ ,and\ \frac{A_{c,u}(214\text{Bi})}{A_c^{Tot}\ (214\text{Bi})} = 4.84\text{x}\ 10^{-4}.$$

So, we get:

$$\frac{A_{c,a}(214\text{Pb})}{A_{c,u}(214\text{Pb})} = 50.25 \text{ and } \frac{A_{c,a}(214\text{Bi})}{A_{c,u}(214\text{Bi})} = 2065$$

The difference between these ratios is due to the small value of $\frac{A_{c,u}(214\text{Bi})}{A_c^{Tot}\ (214\text{Bi})}$ ratio compared to $that\ of\ the$ $\frac{A_{c,u}(214\text{Pb})}{A_c^{Tot}\ (214\text{Pb})}$ $one.$

It is to be noted that the concentrations of the attached fractions are clearly higher than those of the unattached fractions of the ^{214}Pb and ^{214}Bi radon progeny inside spa rooms studied. This means that the majority of ^{214}Pb and ^{214}Bi atoms attach themselves to the aerosols in the studied spas.

b. Committed effective doses due to the energy loss of beta-particles emitted by ^{214}Pb and ^{214}Bi radon daughters in the lung of spa workers from the inhalation of air

The annual committed equivalent doses due to the attached and unattached fractions of ^{214}Pband ^{214}Bi radon progeny from inhalation of air have been determined in the respiratory tract tissues of male and female spa workers by using Eqs. (8) and (10). Data obtained are shown in Table 2(a) and Table 2 (b) for male spa workers and Table 3 (a) and Table 3 (b) ($H_T^a(^{214}Pb)$ and ^{214}Pb ($H_T^u(^{214}Pb)$) and ^{214}Bi ($H_T^a(^{214}Bi)$ and $H_T^u(^{214}Bi)$) radon progeny were determined for male and female workers in different spa rooms. Data obtained are shown in Tables 2 and 3. The statistical relative uncertainty of the annual committed equivalent dose determination was lower than 10%.

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Spa atmosphere	^{214}Pb					^{214}Bi				
	Thoracic region			Extrathoracic region		Thoracic Region			Extrathoracic Region	
	H^{a}_{AI} (x10^{10} Sv y^{-1})	H^{a}_{bb} (x10^{8} Sv y^{-1})	H^{a}_{BB} (x10^{8} Sv y^{-1})	H^{a}_{ET2} (x10^{8} Sv y^{-1})	H^{a}_{ET1} (x10^{7} Sv y^{-1})	H^{a}_{AI} (x10^{10} Sv y^{-1})	H^{a}_{bb} (x10^{8} Sv y^{-1})	H^{a}_{BB} (x10^{8} Sv y^{-1})	H^{a}_{ET2} (x10^{5} Sv y^{-1})	H^{a}_{ET1} (x10^{8} Sv y^{-1})
Spa 1	2.10±0.20	2.40±0.23	1.00±0.09	5.00±0.46	2.07±0.21	4.15±0.40	4.62±0.45	1.75±0.17	1.76±0.16	3.60±0.34
Spa 2	1.20±0.11	1.43±0.13	0.60±0.05	3.10±0.31	1.3±0.12	2.53±0.25	3.00±0.28	1.03±0.10	1.02±0.10	2.19±0.20
Spa 3	1.32±0.12	1.44±0.13	0.61±0.05	3.20±0.31	1.32±0.12	2.56±0.25	3.00±0.28	1.04±0.10	1.04±0.10	2.20±0.20
Spa 4	1.40±0.13	1.52±0.14	0.70±0.06	3.35±0.33	1.39±0.13	2.72±0.26	3.20±0.31	1.11±0.11	1.10±0.10	2.33±023

Table 2(a). Data obtained for annual beta minus committed equivalent doses due to the attached fractions of the ^{214}Pb and ^{214}Bi radon short-lived progeny in the respiratory tract of male spa workers from the inhalation of air.

Spa atmosphere	^{214}Pb					^{214}Bi				
	Thoracic region			Extrathoracic region		Thoracic Region			Extrathoracic Region	
	H^{u}_{AI} (x10^{13} Sv y^{-1})	H^{u}_{bb} (x10^{9} Sv y^{-1})	H^{u}_{BB} (x10^{9} Sv y^{-1})	H^{u}_{ET2} (x10^{8} Sv y^{-1})	H^{u}_{ET1} (x10^{9} Sv y^{-1})	H^{u}_{AI} (x10^{15} Sv y^{-1})	H^{u}_{bb} (x10^{11} Sv y^{-1})	H^{a}_{BB} (x10^{11} Sv y^{-1})	H^{u}_{ET2} (x10^{8} Sv y^{-1})	H^{u}_{ET1} (x10^{11} Sv y^{-1})
Spa 1	1.00±0.12	1.80±0.17	2.20±0.22	4.60±0.46	2.15±0.22	5.42±0.54	8.2±0.82	9.76±0.97	4.20±0.42	9.70±0.97
Spa 2	0.70±0.07	1.10±0.11	1.30±0.13	3.00±0.30	1.30±0.13	2.63±0.26	4.00±0.40	4.76±0.48	2.03±0.20	4.77±0.47
Spa 3	0.71±0.07	1.11±0.11	1.32±0.13	3.00±0.30	1.32±0.13	2.63±0.26	4.00±0.40	4.76±0.48	2.03±0.20	4.77±0.47
Spa 4	0.76±0.07	1.20±0.12	1.30±0.13	3.10±0.31	1.40±0.14	2.63±0.26	4.00±0.40	4.76±0.48	2.03±0.20	4.77±0.47

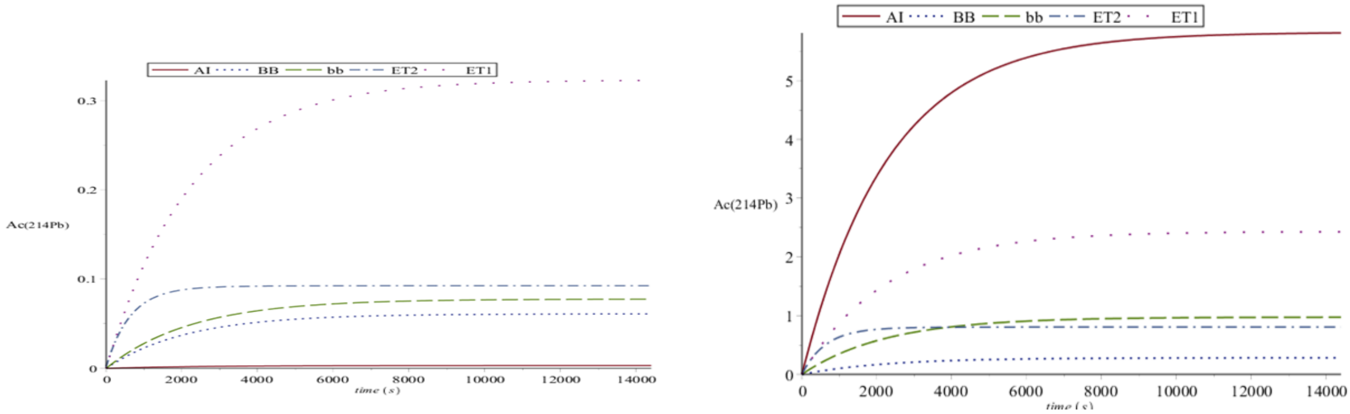
Table 2(b). Data obtained for annual beta minus committed equivalent doses due to the unattached fractions of the ^{214}Pb and ^{214}Bi radon short-lived progeny in the respiratory tract of male spa workers from the inhalation of air.

Spa atmosphere	^{214}Pb					^{214}Bi				
	Thoracic region			Extrathoracic region		Thoracic Region			Extrathoracic Region	
	H^{a}_{AI} (x10^{10} Sv y^{-1})	H^{a}_{bb} (x10^{8} Sv y^{-1})	H^{a}_{BB} (x10^{8} Sv y^{-1})	H^{a}_{ET2} (x10^{7} Sv y^{-1})	H^{a}_{ET1} (x10^{8} Sv y^{-1})	H^{a}_{AI} (x10^{10} Sv y^{-1})	H^{a}_{bb} (x10^{8} Sv y^{-1})	H^{a}_{BB} (x10^{8} Sv y^{-1})	H^{a}_{ET2} (x10^{5} Sv y^{-1})	H^{a}_{ET1} (x10^{8} Sv y^{-1})
Spa 1	2.70±0.26	2.40±0.23	1.06±0.10	5.63±0.56	2.20±0.21	5.12±0.51	4.65±0.46	2.07±0.20	2.10±0.20	4.30±0.40
Spa 2	1.61±0.16	1.43±0.14	0.62±0.06	3.46±0.34	1.30±0.12	3.14±0.31	3.00±0.29	1.16±0.11	1.23±0.12	2.51±0.25
Spa 3	1.63±0.16	1.44±0.14	0.63±0.06	3.51±0.35	1.32±0.12	3.20±0.31	3.00±0.29	1.30±0.12	1.25±0.12	2.55±0.25
Spa 4	1.72±0.17	1.52±0.15	0.67±0.06	3.71±0.37	1.41±0.13	3.40±0.33	3.12±0.31	1.35±0.13	1.33±0.13	3.00±0.29

Table 3(a). Data obtained for annual beta minus committed equivalent doses due to the attached fractions of the ^{214}Pb and ^{214}Bi radon short-lived progeny in the respiratory tract of female spa workers from the inhalation of air.

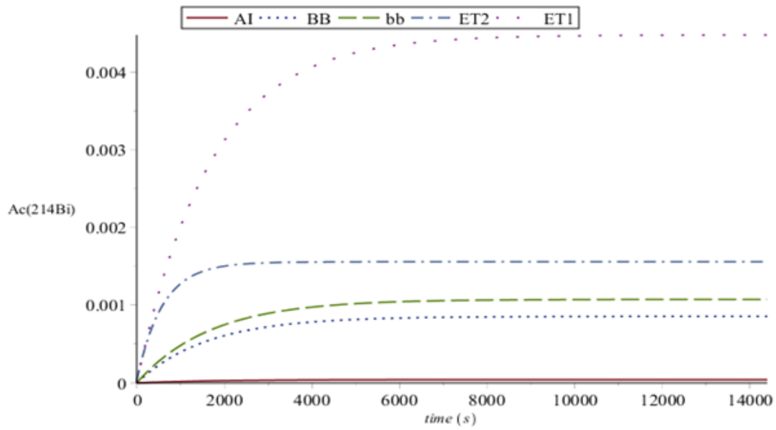
Spa atmosphere	^{214}Pb					^{214}Bi				
	Thoracic region			Extrathoracic region		Thoracic Region			Extrathoracic Region	
	H^{u}_{AI} (x10^{13} Sv y^{-1})	H^{u}_{bb} (x10^{9} Sv y^{-1})	H^{u}_{BB} (x10^{9} Sv y^{-1})	H^{u}_{ET2} (x10^{8} Sv y^{-1})	H^{u}_{ET1} (x10^{9} Sv y^{-1})	H^{u}_{AI} (x10^{15} Sv y^{-1})	H^{u}_{bb} (x10^{11} Sv y^{-1})	H^{u}_{BB} (x10^{11} Sv y^{-1})	H^{u}_{ET2} (x10^{8} Sv y^{-1})	H^{u}_{ET1} (x10^{11} Sv y^{-1})
Spa 1	1.36±0.12	1.70±0.14	2.31±0.20	5.30±0.51	2.49±0.21	6.61±0.65	8.10±0.80	10.94±1.06	5.00±0.49	11.60±1.13
Spa 2	0.80±0.07	1.01±0.08	1.40±0.12	3.25±0.30	1.50±0.13	3.20±0.31	4.05±0.40	5.27±0.51	2.00±0.18	5.60±0.52
Spa 3	0.81±0.07	1.03±0.08	1.41±0.13	3.30±0.30	1.50±0.12	3.21±0.30	4.05±0.40	5.27±0.50	2.00±0.18	5.60±0.52
Spa 4	0.90±0.08	1.10±0.09	1.50±0.13	3.50±0.31	1.60±0.14	3.21±0.31	4.05±0.40	5.27±0.51	2.00±0.17	5.60±0.51

Table 3(b). Data obtained for annual beta minus committed equivalent doses due to the unattached fractions of the ^{214}Pb and ^{214}Bi radon short-lived progeny in the respiratory tract of female spa workers from the inhalation of air.

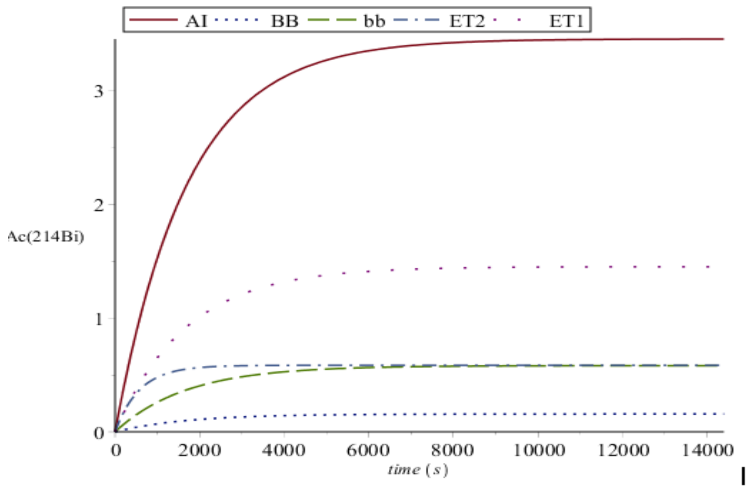


(a) (b)

Fig.4. Variation of the activity due to the unattached fraction of ^{214}Pb (a) and attached fraction of ^{214}Pb (b) as a function of time in different tissues of the respiratory tract from the inhalation of air by spa workers



(a)



(b)

Fig.5. Variation of the activity due to the unattached fraction of ^{214}Bi (a) and attached fraction of ^{214}Bi (b) as a function of time in different tissues of the respiratory tract from the inhalation of air by spa workers.

It is to be noted that annual committed equivalent doses due to the attached fractions of ^{214}Pb ($H_T^a(^{214}Pb)$) and ^{214}Bi ($H_T^a(^{214}Bi)$) and unattached fractions of ^{214}Pb ($H_T^u(^{214}Pb)$) and ^{214}Bi ($H_T^u(^{214}Bi)$) are influenced by the integral of activity–time curves (the activity integrals)(Eqs. (8) and (10)) of ^{214}Pb and ^{214}Bi in a given tissue of the respiratory tract, the mass of the target tissue (m_T) and the weighting factor for the partition of radiation detriment (Eqs. (11) and (12)). Variation of the activities of ^{214}Pb and ^{214}Bi as functions of time in various tissues of the respiratory tract from the inhalation of air by spa workers are shown in Figs. 4 and 5.

The following observations can be made from data shown in Tables 2 and 3:

- The annual committed equivalent doses from the attached and unattached fractions of ^{214}Pb and ^{214}Bi were higher in the extrathoracic region ET than in the thoracic region TH. This was because, after inhalation, ^{214}Pb and ^{214}Bi are deposited in the extrathoracic region ET and thoracic region TH of the lung of spa workers. According to the ICRP compartmental model [13], some ^{214}Pb and ^{214}Bi atoms are transferred from the TH region to the ET region, since these radionuclides have half-lives of 26.8 min and 19.7 min, respectively [26].

- **The annual committed equivalent doses due to the attached and unattached fractions of ^{214}Pb and ^{214}Bi radon progeny are clearly higher in the bb and BB tissues than in the AI tissue of the thoracic region even though the latter tissue shows higher activity integral than the former ones (Figs.4 and 5). This is due to the predominance of the mass tissue: the former tissues show lower masses than the latter [13].**

- The annual committed equivalent doses from the attached and unattached fractions of ^{214}Pb and ^{214}Bi radon progenyare higher in the ET_2 tissue than in the ET_1 tissue of the extrathoracic region even though the latter tissue has a smaller mass and a higher activity integral. This is because the ET_2 tissue shows a higher weighting factor for the partition of radiation detriment than the ET_1 tissue [13].

One can note that annual committed equivalent doses to the TH and ET regions from the attached fractions of ^{214}Pb and ^{214}Bi radon progeny are clearly higher than those due to the unattached fractions of these radionuclides. This is due to the fact that the activities of the attached fractions are higher than those of the unattached fractions inside the studied spa rooms (Table 1).

The committed effective doses per hour of exposure due to the attached E^a and unattached E^u fractions of the ^{214}Pb and ^{214}Bi radon daughters and global committed effective doses E from the inhalation of air by male and female workers inside the studied spa rooms were evaluated by using Eqs. (13)-(15) and the obtained results are presented in Table 4. The statistical relative uncertainty of the committed effective dose determination was smaller than 10 %.

	Committed effective dose (μSv y^{-1} h^{-1} exposure)					
Spa atmosphere	Male worker			Female worker		
	E^u	**E^a**	**E**	**E^u**	**E^a**	**E**
Spa1	(2.32±0.21) x10^{-3}	0.51±0.05	0.51±0.05	(3.06 ±0.28) x10^{-3}	0.60±0.05	0.60±0.05
Spa2	(1.11±0.10) x10^{-3}	0.31±0.03	0.31±0.03	(1.69 ±0.16) x10^{-3}	0.36±0.03	0.36±0.03
Spa3	(1.13±0.10) x10^{-3}	0.32±0.03	0.32±0.03	(1.70±0.16) x10^{-3}	0.36±0.03	0.36±0.03
Spa4	(1.21±0.11) x10^{-3}	0.33±0.03	0.33±0.03	(1.78 ±0.17) x10^{-3}	0.40±0.03	0.40±0.03

Table 4. Dataobtained for the beta minus committed effective dose per hour of exposure due to the attached E^a and unattached E^u fractions of the ^{214}Pb and ^{214}Bi radon decay products and global committed effective dose E from the inhalation of air by male and female workers in spas.

One can note that the majority of ^{214}Pb and ^{214}Bi atoms attach themselves to aerosols inside spa rooms studied. So, the global committed effective dose per hour of exposure received by spa workers isessentially due to attached fractions of the ^{214}Pb and ^{214}Bi radon progeny. The annual committed effective doses due to the attached and unattached radon progeny were calculated for male and female workers working 8 hours per day (2,080 hours per year) in the studied spa rooms. The obtained values range between 0.64 and 1.25 mSv y^{-1}.

c. Determination of committed equivalent doses to the heart of spa workers due to beta particles emitted by ^{214}Pb and ^{214}Bi present in BB compartment of lung from the inhalation of air

The activities (expressed in Bq) due to the attached and unattached fractions of ^{214}Pb and ^{214}Bi radon progeny have been evaluated in the AI, bb, BB, ET1 and ET2 compartments of the respiratory system of male and female adults from the inhalation of air. Data obtained are shown in Tables 5 and

6.The relative uncertainty on the activities of the attached and unattached fractions of the ^{214}Pb and ^{214}Bi radon progeny was about 8 %.

Spa atmosphere	^{214}Pb					^{214}Bi				
	Thoracic region			Extrathoracic region		Thoracic Region			Extrathoracic Region	
	A^a_{AI} (Bq)	A^a_{bb} (Bq)	A^a_{BB} (Bq)	A^a_{ET2} (Bq)	A^a_{ET1} (Bq)	A^a_{AI} (Bq)	A^a_{bb} (Bq)	A^a_{BB} (Bq)	A^a_{ET2} (Bq)	A^a_{ET1} (Bq)
Spa 1	2.70±0.20	0.50±0.04	0.14±0.01	0.13±0.01	14.44±1.10	2.00±0.15	0.39±0.03	0.15±0.01	11.90±0.90	10.18±0.82
Spa 2	1.70±0.13	0.31±0.02	0.12±0.01	0.12±0.01	9.11±0.70	1.20±0.09	0.21±0.01	0.12±0.01	7.50±0.60	6.32±0.52
Spa 3	1.70±0.13	0.32±0.02	0.12±0.01	0.12±0.01	9.24±0.72	1.28±0.09	0.23±0.01	0.12±0.01	7.60±0.60	6.41±0.52
Spa 4	1.80±0.14	0.34±0.02	0.12±0.01	0.12±0.01	9.65±0.73	1.31±0.10	0.24±0.01	0.13±0.01	8.01±0.64	6.75±0.53

Table5.Data obtained for the activities of the attached fractions of the ^{214}Pb and ^{214}Bi radionuclides in the compartments of the respiratory tract of spa workers from the inhalation of air.

Spa atmosphere	^{214}Pb					^{214}Bi				
	Thoracic region			Extrathoracic region		Thoracic Region			Extrathoracic Region	
	A^u_{AI} (x10^{3}Bq)	A^u_{bb} (x10^{2}Bq)	A^u_{BB} (x10^{2}Bq)	A^u_{ET2} (x10^2 Bq)	A^u_{ET1} (x10 Bq)	A^u_{AI} (x10^5 Bq)	A^u_{bb} (x10^4 Bq)	A^u_{BB} (x10^3 Bq)	A^u_{ET2} (x10^2 Bq)	A^u_{ET1} (x10^{3}Bq)
Spa 1	1.49±0.11	3.80±0.30	3.13±0.24	7.57±0.55	1.60±0.12	2.43±0.18	6.30±0.49	5.10±0.37	2.57±0.19	2.60±0.26
Spa 2	0.90±0.07	2.40±0.18	1.94±0.14	4.75±0.34	1.02±0.08	1.20±0.09	3.13±0.24	2.53±0.19	1.30±0.10	1.29±0.13
Spa 3	0.90±0.07	2.44±0.18	2.01±0.16	4.82±0.35	1.03±0.08	1.20±0.09	3.13±0.24	2.53±0.19	1.30±0.10	1.29±0.13
Spa 4	1.02±0.08	2.60±0.19	2.10±0.16	5.11±0.36	1.09±0.08	1.20±0.09	3.13±0.24	2.53±0.19	1.30±0.10	1.29±0.13

Table6. Data obtained for the activities of the unattached fractionsof the ^{214}Pb and ^{214}Bi radionuclides in the compartments of the respiratory tract of spa workers from the inhalation of air.

One can note that the activities of the attached fractions of ^{214}Pb and ^{214}Bi radon progeny in the compartments of lungs are clearly higher than those of the unattached fractions of these radionuclides. This is because the activities of the attached fractions of these radionuclides are higher than those of the unattached fractions inside the studied spa rooms. Indeed, knowing the activities of ^{214}Pb and ^{214}Bi radon progeny in the bronchi BB compartment of the lung one can determine committed equivalent dose in the heart tissues of female and male spa workers due to the attached and unattached fractions of these radionuclides by using Eqs.(22) and (27). Results obtained are given in Tables 7 and 8. The relative error on the determination of committed equivalent dose is smaller than 10 %.

Spa atmosphere	H_{heart}^{Tot} (10^{-11} Sv cm^{-2} per hour of exposure)						
	H_{heart}^{a}(^{214}Pb)	H_{heart}^{u}(^{214}Pb)	H_{heart}^{Tot}(^{214}Pb)	H_{heart}^{a}(^{214}Bi)	H_{heart}^{u}(^{214}Bi)	H_{heart}^{Tot}(^{214}Bi)	H_{heart}^{Tot}
Spa1	2.54±0.32	0.54±0.07	3.08±0.35	2.12±0.28	(12±1.56)x10^{-2}	2.24±0.28	5.32±0.59
Spa2	1.52±0.20	0.33±0.04	1.86±0.22	1.24±0.16	(5±0.63) x10^{-2}	1.29±0.17	3.15±0.37
Spa3	1.52±0.21	0.33±0.04	1.86±0.22	1.44±0.18	(5±0.63) x10^{-2}	1.49±0.18	3.35±0.37
Spa4	1.69±0.23	0.36±0.05	2.06±0.26	1.44±0.18	(5±0.63) x10^{-2}	1.49±0.18	3.55±0.37

Table 7. Data obtained for beta minus committed equivalent doses due to the attached and unattached fractions of the ^{214}Pb and ^{214}Bi radon progeny in the heart of female spa workers from the inhalation of air.

Spa atmosphere	**H_{heart}^{Tot} (10^{-11} Sv cm^{-2} per hour of exposure)**						
	H_{heart}^{a}(^{214}Pb)	**H_{heart}^{u}(^{214}Pb)**	**H_{heart}^{Tot}(^{214}Pb)**	**H_{heart}^{a}(^{214}Bi)**	**H_{heart}^{u}(^{214}Bi)**	**H_{heart}^{Tot}(^{214}Bi)**	**H_{heart}^{Tot}**
Spa 1	2.12±0.27	0.45±0,06	2.57±0.33	1.77±0.23	(10±1.3) x10^{-2}	1.87±0.24	4.44±0.57
Spa 2	1.27±0.17	0.28±0.03	1.55±0.20	1.03±0.13	(4.2±0.53) x10^{-2}	1.07±0.18	2.62±0.38
Spa 3	1.27±0.18	0.28±0.03	1.55±0.20	1.2±0.15	(4.2±0,53) x10^{-2}	1.24±0.20	2.79±0.40
Spa 4	1.41±0.19	0.3±0.04	1.71±0.23	1.2±0.15	(4.2±0,53) x10^{-2}	1.24±0.20	2.95±0.43

Table 8. Data obtained for beta minus committed equivalent doses due to the attached and unattached fractions of the ^{214}Pb and ^{214}Bi radon progeny in the heart of male spa workers from the inhalation of air.

It is to be noted that H_{Heart}^{Tot} is higher for female than for male spa workers. This is because females havelower heart surface than males (Eq.29) [27]. One can note that almost 82 % of the total committed equivalent dose from ^{214}Pb (H_{heart}^{Tot}(^{214}Pb))is due to the attached fraction of^{214}Pb (H_{heart}^{a}(^{214}Pb)) while about 96 % of the total committed equivalent dose from ^{214}Bi (H_{heart}^{Tot}(^{214}Bi)) is due to the attached fractions of^{214}Bi (H_{heart}^{a}(^{214}Bi)).It is to be noted that total committed equivalent dose to the heart of spa workers due to both ^{214}Pb and ^{214}Bi radionuclides (H_{heart}^{Tot})is higher in Spa 1 than in the other spas. This is because Spa1 shows higher activities of the attached and unattached fractions of ^{214}Pb and ^{214}Bi than in the other spas (Table 1). The maximum value of the annual committed equivalent dose was found equal to 0.11 10^{-6} Sv y^{-1}cm^{-2} for female and to 0.09 10^{-6} Sv y^{-1}cm^{-2} for male spa workers spending 2,080 hours per year in Spa 1.

4. CONCLUSION

In the present study, activity concentrations of radon (^{222}Rn) as well as those of the attached and unattached fractions of its ^{214}Pb and ^{214}Biradon progeny were evaluated in the air of spas by using CR-39 and LR-115 type II nuclear track detectors. This measurement method has the advantage of being inexpensive, accurate, and sensitive, without the need for standard calibration sources.A new dosimetric model was developed for assessing committed equivalent doses to tissues of the respiratory tract of male and female spa workers due to beta minus-particles emitted by ^{214}Pb and ^{214}Bi radon progeny from inhalation of air. It has been shown that beta radiation dosesto the tissues of the respiratory system due to the attached and unattached fractions of^{214}Pb and ^{214}Bi radon daughters increase with increasing airborne activity concentration and with decreasing tissue mass. It has been concluded that beta radiation doses to the lung of male and female spa workers are essentially due to the attached fractions of the ^{214}Pb and ^{214}Bi radon progeny from inhalation of air.Due to their longer ranges in lung tissues, beta minus particles emitted by ^{214}Pb and ^{214}Bi radon progeny present in bronchi BB compartment of the respiratory system from inhalation of air may reach and lose their energies in the heart of individuals. Indeed, a new dosimetric method was developed for estimating beta radiation doses to the heart of spa workers due to the attached and unattached fractions of ^{214}Pb and ^{214}Bi radon progeny present in bronchi BB compartment of the respiratory tract from inhalation of air. This new dosimetric model could be applied for assessing beta minus doses to other human organs such as spinal cord, larynx and oesophagus from inhalation of ^{214}Pb and ^{214}Bi radon progeny.It has been shown that heart tissues of spa workers received small beta radiation doses from inhalation of small amounts of^{214}Pb and ^{214}Bi radon progeny. But in high radon concentration atmospheres such as marble factories (Misdaq et al. 2019) or mines, workers may receive higher beta doses to the heart from inhalation of ^{214}Pb and ^{214}Bi radon progeny.The new dosimetric methods developed in this study are good tools for evaluating beta radiation doses in different organs of the human body from inhalation of other beta emitting radionuclides.

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