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# $^{238}$U and $^{232}$Th concentrations measured in different medical drugs by using solid-state nuclear track detectors and resulting radiation doses to the skin of patients

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**Abstract** Urban populations in Morocco receive free medical drugs as prescribed by doctors in district health centres. To explore the exposure pathway of $^{238}$U and $^{232}$Th and their decay products on the skin of patients, these radionuclides were measured in various medical drugs by using solid-state nuclear track detectors (SSNTDs).The measured concentrations range of $^{238}$U and $^{232}$Th in the medical drug samples of interest vary from (4.3 ± 0.3) to (11.1 ± 0.7) mBq l$^{-1}$ and (0.49 ± 0.03) to (1.3 ± 0.1) mBq l$^{-1}$, respectively. A new dosimetric model, based on the concept of specific alpha-dose and alpha-particle residual energy, was developed for evaluating radiation doses to skin following the application of different medical drugs by patients. The maximum total equivalent effective dose to skin due to the $^{238}$U and $^{232}$Th series from cutaneous application of different medical drugs by patients was found to be 2.8 mSv year$^{-1}$ cm$^{-2}$.

**Keywords** Nuclear track detectors · Medical drugs · $^{238}$U and $^{232}$Th concentrations · Radiation dose assessment to skin

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## 1 Introduction

The skin is the largest organ of the human body, with a total area of about 20 square feet. It protects individuals from microbes, helps regulate body temperature, and limits the sensation of touch, heat, and cold. The skin has three layers: (1) the epidermis, the outermost layer of skin which provides a waterproof barrier and creates the skin tone; (2) the dermis, beneath the epidermis which contains tough connective tissue, hair follicles, and sweat glands, and (3) the deeper subcutaneous tissue (hypodermis) which is made of fat and connective tissue. The critical cells in the skin are in the basal layer of the epidermis. There are considerable variations in the thickness of human epidermis with respect to body site [1]. On the face and trunk, the median thickness of the epidermis was 20–40 μm. In general, on the arms and legs, it was 40–60 μm, although there were some considerably thicker areas on the hands and feet [1]. A more detailed evaluation of the hands showed fingertips to have the greatest thickness, greater than 160 μm [1]. The degree of undulation of the basal layer was found to increase with increasing epidermal thickness. Naturally occurring radionuclides of terrestrial origin are present in various degrees in all media of the environment and contribute significantly to external and internal doses of the population [2]. Among them, important radionuclides of interest belong to the $^{238}$U and $^{232}$Th series. These radionuclides emit alpha- and beta-particles, as well as gamma rays. The different forms of emitted radiation have different energies and penetrating power and, thus, have different effects on living beings. Once the radionuclides of the $^{238}$U and $^{232}$Th series are placed on the skin, they emit alpha-particles with a range of several tens of microns (between 20 and 100 μm). This is comparable

with the depth of the basal layer of the epidermis. Due to their presence in soil and phosphate fertilizers, primordial radionuclides and their progeny are transferred via water from soil to plant flowers and medicinal plants to medical drugs. Thus, it is necessary to measure the radionuclide contents of medical drugs to assess the potential radiation doses, and if necessary, to take action to reduce the exposure of patients to radiation. $^{238}$U and $^{232}$Th concentrations have been measured in various medicinal plants by using solid-state nuclear track detectors [3]. $^{238}$U and $^{232}$Th have also been analysed in aerial parts and roots of the Peperomia pellucida medicinal plant using alpha spectrometry after radiochemical separation by ionic exchange resins and measurement with a silicon surface-barrier detector [4]. However, this technique is both destructive (chemical agents are added to the material sample) and expensive. $^{238}$U and $^{232}$Th have been analysed in different food samples using inductively coupled plasma mass spectrometry (ICP-MS), which is also destructive [5]. Committed effective doses due to the $^{238}$U and $^{232}$Th radioisotopes following the ingestion of various foodstuffs by individuals have been determined [6]. In previous works, we evaluated committed effective doses to skin due to only three alpha-emitting nuclei ($^{238}$U, $^{232}$Th, and $^{222}$Rn) from the application of Moroccan black soap [7] and olive oil [8] samples without taking into account the residual energies of the emitted alpha-particles.

In the present work, CR-39 and LR-115 type II solid-state nuclear track detectors (SSNTDs) were used for measuring $^{238}$U and $^{232}$Th alpha-activities per unit volume in different medical drugs. During the full course of medical drug application to different age groups of patients, the committed effective doses to the skin were evaluated due to alpha-particles emitted by the radionuclei of the $^{238}$U and $^{232}$Th series.

## 2 Methods of study

### 2.1 Description of the medical drugs studied

Medical drugs are cutaneously prescribed by doctors for patients in dermatology, cardiology, gastro-enterology, anaesthesia–resuscitation, gynaecology, pneumology, and rheumatology. The properties and dosages of the considered medical drugs are shown in Table 1.

**Table 1** Description of the studied medical drugs

| Medical drugs | Properties | Dosage | Medical speciality |
|---|---|---|---|
| P1 | Used for surface anaesthesia (skin and mucosa) | 1 g maximum per 10 cm$^2$ during 20–30 min | Anaesthesia |
| P2 | Vascular protective and veinotonic | 2 applications per day during 1 month | Cardiology |
| P3 | Dermocorticoid | 1–2 applications per day during 15 days | Dermatology |
| P4 | Antibacterial agent | 1 application per day during 7–15 days | Dermatology |
| P5 | Antifungal agent | 2 applications per day during 1 month | Dermatology |
| P6 | Antiparasitic agent | 2 applications per day during 8 days | Dermatology |
| P7 | Used for antiseptic skin | 1 application per day during 7 days | Dermatology |
| P8 | Antiherpetic agent | 5 applications per day during 5–10 days | Dermatology |
| P9 | Used for antiacne treatment | 1–2 applications per day during 3 months | Dermatology |
| P10 | Used for antipruritic treatment | 2–3 applications per day during 3–5 days | Dermatology |
| P11 | Used for local treatment of skin ulcers | 1–2 applications per day during 7 days | Dermatology |
| P12 | Used for the treatment of haemorrhoids | 2–3 applications per day during 7 days | Gastroenterology |
| P13 | Estrogen agent | 1 application per day 24–28 days per month during 5 years | Gynaecology |
| P14 | Progestin agent | 1 application per day during 1 month | Gynaecology |
| P15 | Used in adjunctive therapy and as decongestant in respiratory diseases | 2 applications per day during 3 days | Pneumology |
| P16 | Non-steroidal anti inflammatory | 3–4 applications per day during 2 weeks | Rheumatology |
| P17 | Used for the treatment of psoriasis | 1–2 applications per day during 2 months | Dermatology |
| P18 | Keratolytic agent | 1 application per day during 3 month | Dermatology |
| P19 | Used for the treatment of hyperpigmented lesions | 2 applications per day during 3 month | Dermatology |
| P20 | Used for rosacea treatment | 2 applications per day during 3–4 months | Dermatology |
| P21 | Used for local treatment of painful muscle contractures | 2 applications per day during 2 weeks | Rheumatology |

### 2.2 Determination of $^{238}$U and $^{232}$Th alpha-activities per unit volume in medical drugs

The alpha-activities of $^{238}$U and $^{232}$Th were measured using the following types of solid-state nuclear track detectors (SSNTDs):

- CR-39 discs, 2 cm in radius and 500 µm thick, manufactured by Pershore Mouldings Ltd, United Kingdom;
- LR-115 type II discs, 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 separately placed in close contact with different medical drugs in hermetically sealed (using glue and a cellophane tape) HDPE (high-density polyethylene) cylindrical plastic containers for 30 days (Fig. 1). During this period of time, alpha-particles emitted by the nuclei of $^{238}$U, $^{232}$Th, and their daughters inside the medical drug samples exposed the SSNTD films. After irradiation, the exposed SSNTDs were etched in two NaOH solutions: one was 2.5 mol l$^{-1}$ at 60 °C for 2 h for the LR-115 II films and the other was 6.25 mol l$^{-1}$ at 70 °C for 7 h for the CR-39 detectors [9]. After chemical treatment, the track densities registered on the CR-39 and LR-115 II SSNTDs were determined by an ordinary microscope. Backgrounds on the CR-39 and LR-115 II SSNTDs were evaluated by placing these films in sealed plastic containers, containing ambient air, identical to those used for analysing the medical drug samples, for 30 days and counting the resulting track densities. This operation was repeated ten times, and it was found that the track densities registered on the CR-39 and LR-115 II detectors were identical within the statistical uncertainties. The reproducibility of the method was checked by analysing a set of ten samples of the same medical drug. Track density production rates registered on the CR-39 and LR-115 II detectors were evaluated for the P13 medical drug sample. Data obtained, for instance, for the P13 medical drug sample was: $\rho_{\mathrm{G}}^{\mathrm{CR}} = (2.41 \pm 0.01) \times 10^{-5}$ and $\rho_{\mathrm{G}}^{\mathrm{LR}} = (9.25 \pm 0.05) \times 10^{-5}$ tracks cm$^{-2}$ s$^{-1}$, respectively. The relative uncertainty of the average track density rate determination is smaller than 1 %.

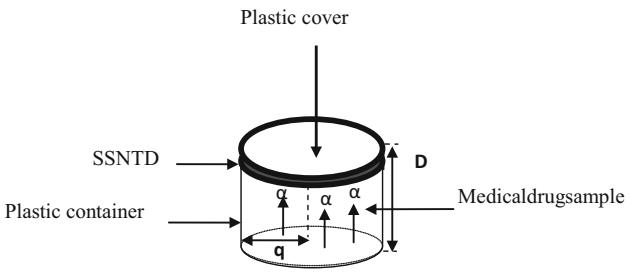


**Fig. 1** Arrangement of a solid-state nuclear track detector (SSNTD) on a medical drug material sample in a well-sealed plastic container with a radius of $q = 2$ cm, depth of $D = 1$ cm, and thickness of $t = 0.5$ cm. Glue is put between the plastic cover and plastic container and both are covered by a cellophane tape with a 0.2-cm thickness

There are three main factors which disturb the radioactive secular equilibrium between $^{238}$U and its progeny and between $^{232}$Th and its daughters: (a) the addition of any chemical compounds to the medical drug sample, (b) any escape of radon and thoron gases, and (c) the exposure time if it is shorter than 25 days. As the detection system used was well-sealed (i.e., there was no escape of radon and thoron) and the exposure time was 30 days, a radioactive secular equilibrium is established between $^{238}$U and each of its decay products and between $^{232}$Th and each of its daughters. For the experimental etching conditions, the residual thickness of the LR-115 type II detectors measured by means of a mechanical comparator is 5 µm. This thickness defines the lower ($E_{\mathrm{min}} = 1.6$ MeV) and upper ($E_{\mathrm{max}} = 4.7$ MeV) energy limits for the registration of tracks of alpha-particles in LR-115 type II films [10]. All alpha-particles emitted by the $^{238}$U and $^{232}$Th series that reach the LR-115 II detector at an angle smaller than its critical angle of etching, $\theta_{\mathrm{c}}^{'}$, with a residual energy between 1.6 and 4.7 MeV are registered as bright track-holes. The CR-39 detector is sensitive to all alpha-particles reaching its surface at an angle smaller than its critical angle of etching, $\theta_{\mathrm{c}}$. The critical angles of etching, $\theta_{\mathrm{c}}^{'}$ and $\theta_{\mathrm{c}}$, were calculated using the method described in detail by Misdaq et al. [11].

The global track density rates (tracks cm$^{-2}$ s$^{-1}$), due to alpha-particles emitted by the $^{238}$U and $^{232}$Th series inside a material sample, registered on the CR-39 ($\rho_{\mathrm{G}}^{\mathrm{CR}}$) and LR-115 II ($\rho_{\mathrm{G}}^{\mathrm{LR}}$) detectors, after subtracting the corresponding backgrounds, are, respectively, given by [9]:

$$\rho_{\mathrm{G}}^{\mathrm{CR}} = \frac{\pi q^2}{2\,S_{\mathrm{d}}} A_{\mathrm{c}}\left(^{238}\mathrm{U}\right)\left[\sum_{j=1}^{8} k_j \varepsilon_j^{\mathrm{CR}} R_j + \frac{A_{\mathrm{c}}\left(^{232}\mathrm{Th}\right)}{A_{\mathrm{c}}\left(^{238}\mathrm{U}\right)} \sum_{j=1}^{7} k_j^{'} \varepsilon_j^{'\mathrm{CR}} R_j^{'}\right], \quad (1)$$

and

$$\rho_{\mathrm{G}}^{\mathrm{LR}} = \frac{\pi q^2}{2S_{\mathrm{d}}^{'}} A_{\mathrm{c}}\left(^{238}\mathrm{U}\right)\left[\sum_{j=1}^{8} k_j \varepsilon_j^{\mathrm{LR}} R_j + \frac{A_{\mathrm{c}}\left(^{232}\mathrm{Th}\right)}{A_{\mathrm{c}}\left(^{238}\mathrm{U}\right)} \sum_{j=1}^{7} k_j^{'} \varepsilon_j^{'\mathrm{LR}} R_j^{'}\right], \quad (2)$$

where $A_{\mathrm{c}}(^{238}\mathrm{U})$, expressed in Bq cm$^{-3}$, is the activity per unit volume of $^{238}$U inside a medical drug sample. $A_{\mathrm{c}}(^{232}\mathrm{Th})$, expressed in Bq cm$^{-3}$, is the activity per unit volume of $^{232}$Th inside a medical drug sample. $S_{\mathrm{d}}$ and $S_{\mathrm{d}}^{'}$

are, respectively, the surface areas of the CR-39 and LR-115 II films. $R_j$ and $R_j^{'}$ are the ranges, in the medical drug sample, of an alpha-particle of index $j$ and initial energy $E_{\alpha_j}$ emitted by the nuclei of the $^{238}$U and $^{232}$Th series, respectively. $k_j$ and $k_j^{'}$ are, respectively, the branching ratios corresponding to the disintegration of the nuclei of the $^{238}$U and $^{232}$Th series. $\varepsilon_j^{CR}$, $\varepsilon_j^{'CR}$, $\varepsilon_j^{LR}$ and $\varepsilon_j^{'LR}$ are, respectively, the detection efficiencies of the CR-39 and LR-115 II detectors for the emitted alpha-particles [9].

**Table 2** Ranges of alpha-particles emitted by the $^{238}$U and $^{232}$Th series inside skin

| Nuclide | $E_{\alpha_j}$ (MeV) | $k_j$ | $R_j$ (μm) |
|---|---|---|---|
| (a) Uranium family | | | |
| $^{238}$U | 4.19 | 1 | 25.64 |
| $^{230}$Th | 4.62 | 1 | 29.52 |
| $^{234}$U | 4.77 | 1 | 30.93 |
| $^{226}$Ra | 4.78 | 1 | 31.03 |
| $^{210}$Po | 5.3 | 1 | 36.16 |
| $^{222}$Rn | 5.49 | 1 | 38.13 |
| $^{218}$Po | 6.00 | 1 | 43.64 |
| $^{214}$Po | 7.68 | 1 | 64.19 |
| Nuclide | $E_{\alpha_j}$ (MeV) | $k_j^{'}$ | $R_{j'}$ (μm) |
| (b) Thorium family | | | |
| $^{232}$Th | 4.01 | 1 | 24.09 |
| $^{228}$Th | 5.42 | 1 | 37.39 |
| $^{224}$Ra | 5.71 | 1 | 40.46 |
| $^{212}$Bi | 6.05 | 0.36 | 44.19 |
| $^{220}$Rn | 6.29 | 1 | 46.93 |
| $^{216}$Po | 6.78 | 1 | 52.73 |
| $^{212}$Po | 8.78 | 0.64 | 79.62 |

Combining Eqs. (1) and (2), we obtain the following relationship between the track density rates and $^{232}$Th to $^{238}$U ratios:

$$\frac{A_c(^{232}\mathrm{Th})}{A_c(^{238}\mathrm{U})} = \frac{\frac{S_d^{'}}{S_d}\sum_{j=1}^{8} k_j \varepsilon_j^{CR} R_j - \frac{\rho_G^{CR}}{\rho_G^{LR}}\sum_{j=1}^{8} k_j \varepsilon_j^{LR} R_j}{\frac{\rho_G^{CR}}{\rho_G^{LR}}\sum_{j=1}^{7} k_j^{'} \varepsilon_j^{'CR} R_j^{'} - \frac{S_d^{'}}{S_d}\sum_{j=1}^{7} k_j^{'} \varepsilon_j^{'LR} R_j^{'}}. \quad (3)$$

The $^{238}$U alpha-activity per unit volume of a medical drug sample is given by (Eq. 2):

$$A_c(^{238}\mathrm{U}) = \frac{2S_d^{'}\rho_G^{LR}}{\pi q^2\left[\sum_{j=1}^{8} k_j \varepsilon_j^{LR} R_j + \frac{A_c(^{232}\mathrm{Th})}{A_c(^{238}\mathrm{U})}\sum_{j=1}^{7} k_j^{'} \varepsilon_j^{'LR} R_j^{'}\right]}. \quad (4)$$

By measuring the $\rho_G^{CR}$ and $\rho_G^{LR}$ track density rates and calculating the $\varepsilon_j^{CR}$,$\varepsilon_j^{'CR}$,$\varepsilon_j^{LR}$, and $\varepsilon_j^{'LR}$ detection efficiencies [9] we evaluate the $\frac{A_c(^{232}\mathrm{Th})}{A_c(^{238}\mathrm{U})}$ ratio (Eq. 3) and, consequently, the $^{238}$U and $^{232}$Th alpha-activities per unit volume in a given medical drug sample (Eq. 4).

The ranges of the emitted alpha-particles in medical drugs and SSNTDs were calculated by using the TRIM (Transport of Ions in Materials) program [12].

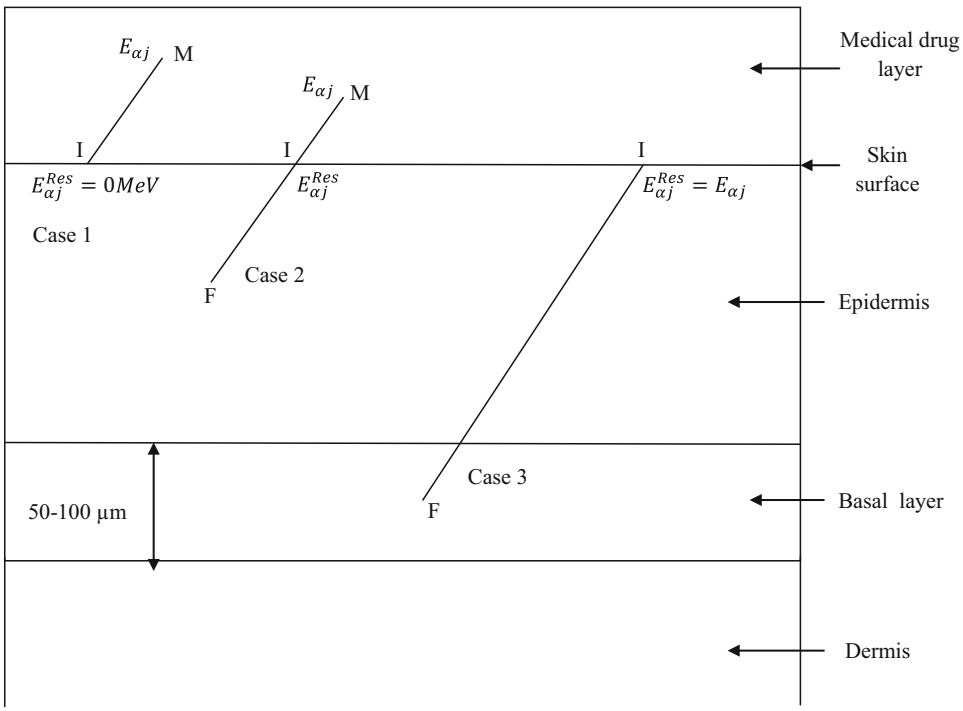


**Fig. 2** Ranges of an alpha-particle inside the medical drug layer ($\overline{MF} = x_j$) and epidermis ($IF = R_j^{skin}$). $E_{\alpha_j}$ is the initial alpha-particle energy and $E_{\alpha_j}^{Res}$ its residual energy on the point I. The medical drug layer has a depth of about 500 μm

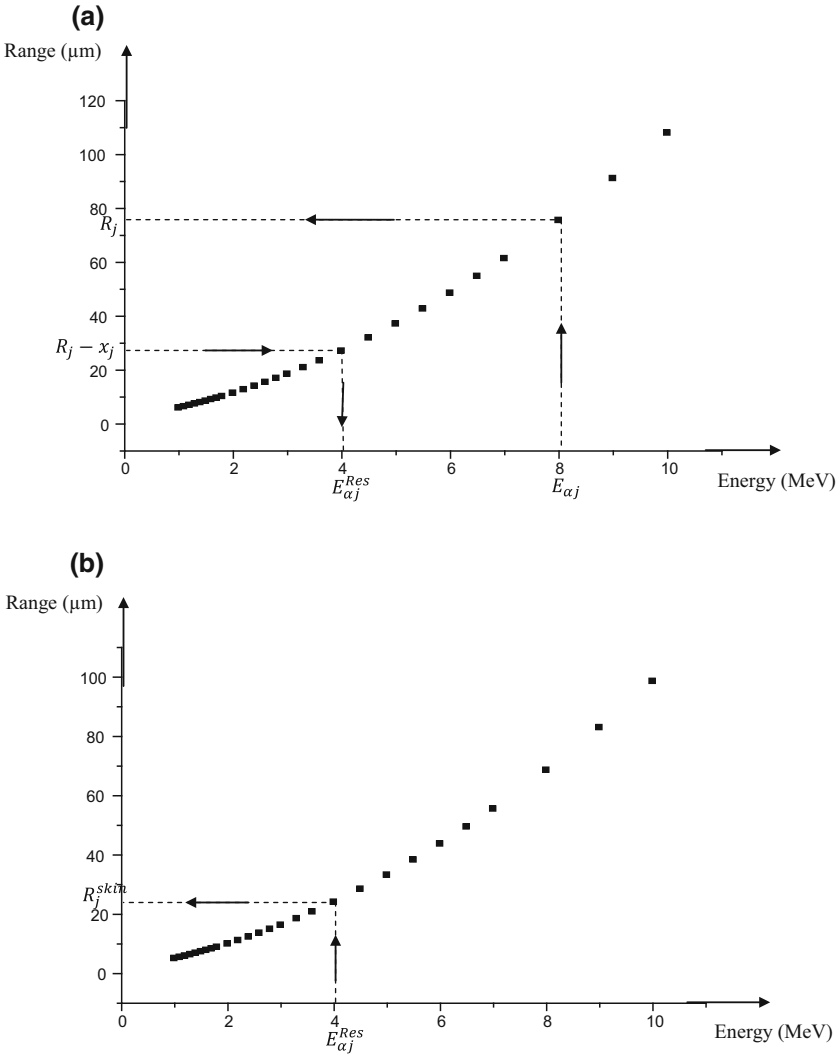


**Fig. 3** Alpha particle range–energy relation for a medical drug material sample (**a**) and skin (**b**)

### 2.3 A new dosimetric model for evaluating annual committed equivalent doses to skin due to alpha-particles emitted by the nuclei of the $^{238}$U and $^{232}$Th series from cutaneous application of medical drugs

The epidermis of the human skin is divided into several clearly defined zones [13]. Indeed, when a medical drug layer is placed on the skin of a patient, the nuclei of the $^{238}$U and $^{232}$Th series emit alpha-particles with a range of several tens of microns (20–100 μm) (Table 2). This is comparable with the depth of the basal layer of the epidermis, which is more sensitive (50–100 μm) [14].

An alpha-particle with an index of $j$ and initial energy of $E_{\alpha_j}$ emitted from a nucleus localized on the point $M$ inside the medical drug layer (Fig. 2) has a range:

$$\overline{MF} = x_j + R_j^{\text{Skin}}, \tag{5}$$

where $x_j$ ($x_j \leq R_j$, $R_j$ is the range of the alpha-particle inside the medical drug layer) is the distance between the emission point and the skin surface (Fig. 2) and $R_j^{\text{skin}}$ is the range of the alpha-particle in skin.

The alpha-particle residual energy, $E_{\alpha_j}^{\text{Res}}$, which corresponds to the $(R_j - x_j)$ range is determined by using the energy–range relation in the medical drug (Fig. 3a). By using the energy–range relation in skin, one can determine the range of the alpha-particle in skin, $R_j^{\text{skin}}$(Fig. 3b). For $x_j = R_j$ and $E_{\alpha_j}^{\text{Res}} = 0$ MeV, there is no energy loss of alpha-particles in skin (case 1 of Fig. 2). For $x_j = 0$ μm and $E_{\alpha_j}^{\text{Res}} = E_{\alpha_j}$, the energy loss of alpha-particles in the skin is at a maximum ($R_j^{\text{skin}}$ maximum) (case 3 of Fig. 2).

For $x_j \prec R_j$ and $E_{\alpha_j}^{\mathrm{Res}} \prec E_{\alpha_j}$, the range of alpha-particle in the skin is lower than those corresponding to $x_j = 0$ μm (case 2 of Fig. 2).

Alpha-equivalent dose rates ($\mathrm{Svs}^{-1}$) to the human skin due to a radionuclide of index of $j$ belonging to the $^{238}$U series and a radionuclide of index of $j'$ belonging to the $^{232}$Th series from the application of medical drugs by patients are, respectively, given by:

$$\dot{H}_{\mathrm{skin}}(j)(t) = A_{\mathrm{c}}^{\mathrm{skin}}(j)(t) D_{\mathrm{sp}}^{\mathrm{skin}}(j) W_{\mathrm{R}}, \tag{6}$$

and

$$\dot{H}_{\mathrm{skin}}\left(j'\right)(t) = A_{\mathrm{c}}^{\mathrm{skin}}\left(j'\right)(t) D_{\mathrm{sp}}^{\mathrm{skin}}\left(j'\right) W_{\mathrm{R}}, \tag{7}$$

where $A_{\mathrm{c}}^{\mathrm{skin}}(j)(t)$ (Bq) is the alpha-activity, at time $t$, in skin due to a radionuclide of index $j$ belonging to the $^{238}$U series $A_{\mathrm{c}}^{\mathrm{skin}}(j')(t)$ (Bq) is the alpha-activity, at time $t$, in skin due to a radionuclide of index $j'$ belonging to the $^{232}$Th series. $D_{\mathrm{Sp}}^{\mathrm{skin}}(j)$ is the specific alpha-dose (Gy) deposited by 1 Bq of a radionuclide of index $j$ belonging to the $^{238}$U series in skin. $D_{\mathrm{Sp}}^{\mathrm{skin}}(j')$ is the specific alpha-dose (Gy) deposited by 1 Bq of a radionuclide of index $j'$ belonging to the $^{232}$Th series in skin. $W_{\mathrm{R}}$ is the radiation weighting factor, which is equal to 20 for alpha-particles [13].

The $A_{\mathrm{c}}^{\mathrm{skin}}(j)(t)$ and $A_{\mathrm{c}}^{\mathrm{skin}}(j')(t)$ alpha-activities are, respectively, given by:

$$A_{\mathrm{c}}^{\mathrm{skin}}(j)(t) = \frac{1}{2} A_{\mathrm{c}}^{\mathrm{sample}}\left(^{238}\mathrm{U}\right) \mathrm{e}^{-\lambda_j t} \times 1\,\mathrm{cm}^3, \tag{8}$$

and

$$A_{\mathrm{c}}^{\mathrm{skin}}\left(j'\right)(t) = \frac{1}{2} A_{\mathrm{c}}^{\mathrm{sample}}\left(^{232}\mathrm{Th}\right) \mathrm{e}^{-\lambda_{j'} t} \times 1\,\mathrm{cm}^3, \tag{9}$$

where $A_{\mathrm{c}}^{\mathrm{sample}}(^{238}\mathrm{U})$ (Bq $\mathrm{cm}^{-3}$) is the alpha-activity due to $^{238}$U inside a medical drug sample. $A_{\mathrm{c}}^{\mathrm{sample}}(^{232}\mathrm{Th})$ (Bq $\mathrm{cm}^{-3}$) is the alpha-activity due to $^{232}$Th inside a medical drug sample. $\lambda_j$ is the radioactive decay constant of a radionuclide of index $j$ belonging to the $^{238}$U series and $\lambda_{j'}$ is the radioactive decay constant of a radionuclide of index $j'$ belonging to the $^{232}$Th series. The term ½ means that only half of the emitted alpha-particles inside a medical drug sample may lose their energies inside the skin.

The $D_{\mathrm{Sp}}^{\mathrm{skin}}(j)$ and $D_{\mathrm{Sp}}^{\mathrm{skin}}(j')$ specific alpha-doses are, respectively, given by:

**Table 3** Data obtained for the $^{238}$U and $^{232}$Th contents in different medical drug samples

| Medical drug samples | $\rho_{\mathrm{G}}^{\mathrm{LR}}$ ($10^{-5}$ tr $\mathrm{cm}^{-2}$ $\mathrm{s}^{-1}$) | $\rho_{\mathrm{G}}^{\mathrm{CR}}$ ($10^{-5}$ tr $\mathrm{cm}^{-2}$ $\mathrm{s}^{-1}$) | This method | | | | IDMS | |
|---|---|---|---|---|---|---|---|---|
| | | | C ($^{238}$U) (ppm) | C ($^{232}$Th) (ppm) | $A_c$($^{238}$U) (mBq $l^{-1}$) | $A_c$($^{232}$Th) (mBq $l^{-1}$) | C ($^{238}$U) (ppm) | C ($^{232}$Th) (ppm) |
| P1 | 2.29 ± 0.16 | 8.74 ± 0.61 | 0.74 ± 0.05 | 0.28 ± 0.02 | 9.1 ± 0.6 | 1.15 ± 0.07 | | |
| P2 | 1.08 ± 0.09 | 4.13 ± 0.33 | 0.35 ± 0.02 | 0.15 ± 0.01 | 4.3 ± 0.3 | 0.62 ± 0.04 | 0.36 ± 0.01 | 0.14 ± 0.01 |
| P3 | 2.33 ± 0.20 | 8.89 ± 0.8 | 0.76 ± 0.05 | 0.28 ± 0.02 | 9.3 ± 0.7 | 1.16 ± 0.07 | | |
| P4 | 1.85 ± 0.13 | 7.05 ± 0.49 | 0.61 ± 0.04 | 0.21 ± 0.01 | 7.5 ± 0.5 | 0.86 ± 0.05 | 0.60 ± 0.03 | 0.20 ± 0.01 |
| P5 | 2.48 ± 0.2 | 9.36 ± 0.75 | 0.81 ± 0.06 | 0.23 ± 0.01 | 9.9 ± 0.7 | 0.95 ± 0.06 | 0.82 ± 0.04 | 0.24 ± 0.01 |
| P6 | 1.29 ± 0.10 | 4.93 ± 0.37 | 0.42 ± 0.03 | 0.17 ± 0.01 | 5.2 ± 0.3 | 0.70 ± 0.05 | | |
| P7 | 1.41 ± 0.11 | 5.39 ± 0.44 | 0.45 ± 0.03 | 0.19 ± 0.01 | 5.5 ± 0.4 | 0.78 ± 0.06 | | |
| P8 | 2.02 ± 0.14 | 7.69 ± 0.54 | 0.67 ± 0.05 | 0.21 ± 0.01 | 8.2 ± 0.5 | 0.86 ± 0.06 | 0.66 ± 0.04 | 0.20 ± 0.01 |
| P9 | 2.24 ± 0.18 | 8.54 ± 0.71 | 0.73 ± 0.05 | 0.26 ± 0.02 | 9.0 ± 0.7 | 1.07 ± 0.07 | 0.74 ± 0.04 | 0.25 ± 0.01 |
| P10 | 2.50 ± 0.19 | 9.51 ± 0.78 | 0.83 ± 0.06 | 0.24 ± 0.01 | 10.2 ± 0.8 | 0.98 ± 0.07 | 0.82 ± 0.04 | 0.25 ± 0.01 |
| P11 | 1.69 ± 0.12 | 6.42 ± 0.45 | 0.56 ± 0.04 | 0.15 ± 0.01 | 6.9 ± 0.4 | 0.62 ± 0.04 | | |
| P12 | 2.17 ± 0.17 | 8.27 ± 0.66 | 0.71 ± 0.05 | 0.24 ± 0.01 | 8.7 ± 0.6 | 0.98 ± 0.07 | | |
| P13 | 2.42 ± 0.21 | 9.24 ± 0.76 | 0.78 ± 0.06 | 0.30 ± 0.02 | 9.6 ± 0.7 | 1.23 ± 0.07 | 0.79 ± 0.05 | 0.32 ± 0.01 |
| P14 | 1.68 ± 0.12 | 6.37 ± 0.45 | 0.57 ± 0.04 | 0.120 ± 0.006 | 7.0 ± 0.5 | 0.49 ± 0.03 | 0.58 ± 0.03 | 0.125 ± 0.004 |
| P15 | 2.07 ± 0.15 | 7.88 ± 0.63 | 0.68 ± 0.05 | 0.21 ± 0.01 | 8.4 ± 0.6 | 0.86 ± 0.06 | 0.67 ± 0.04 | 0.20 ± 0.01 |
| P16 | 1.95 ± 0.13 | 7.42 ± 0.61 | 0.64 ± 0.04 | 0.19 ± 0.01 | 7.9 ± 0.6 | 0.78 ± 0.05 | | |
| P17 | 2.53 ± 0.18 | 9.64 ± 0.67 | 0.84 ± 0.06 | 0.28 ± 0.02 | 10.2 ± 0.7 | 1.15 ± 0.07 | | |
| P18 | 2.58 ± 0.23 | 9.85 ± 0.89 | 0.85 ± 0.06 | 0.32 ± 0.02 | 10.3 ± 0.8 | 1.3 ± 0.1 | | |
| P19 | 2.05 ± 0.14 | 7.80 ± 0.55 | 0.68 ± 0.05 | 0.20 ± 0.01 | 8.4 ± 0.5 | 0.82 ± 0.05 | | |
| P20 | 2.71 ± 0.18 | 10.30 ± 0.52 | 0.90 ± 0.06 | 0.24 ± 0.01 | 11.1 ± 0.8 | 0.98 ± 0.06 | 0.92 ± 0.04 | 0.26 ± 0.01 |
| P21 | 1.22 ± 0.10 | 4.66 ± 0.37 | 0.39 ± 0.03 | 0.16 ± 0.01 | 4.8 ± 0.3 | 0.66 ± 0.04 | | |

**Table 4** Committed equivalent doses to the epidermis of skin (Sv year$^{-1}$ cm$^{-2}$) due to all residual energies of an alpha-particle of index $j$ and initial energy $E_{\alpha_j}$ belonging to the $^{238}$U series from cutaneous application of different medical drugs by (a) adult female and (b) adult male

| Medical drug samples | H ($^{238}$U) ($10^{-8}$ Sv year$^{-1}$ cm$^{-2}$) | H($^{230}$Th) ($10^{-8}$ Sv year$^{-1}$ cm$^{-2}$) | H($^{234}$U) ($10^{-8}$ Sv year$^{-1}$ cm$^{-2}$) | H ($^{226}$Ra) ($10^{-8}$ Sv year$^{-1}$ cm$^{-2}$) | H ($^{210}$Po) ($10^{-8}$ Sv year$^{-1}$ cm$^{-2}$) | H ($^{222}$Rn) ($10^{-8}$ Sv year$^{-1}$ cm$^{-2}$) | H ($^{218}$Po) ($10^{-9}$ Sv year$^{-1}$ cm$^{-2}$) | H ($^{214}$Po) ($10^{-12}$ Sv year$^{-1}$ cm$^{-2}$) | H(U)(EP) (μSv year$^{-1}$ cm$^{-2}$) |
|---|---|---|---|---|---|---|---|---|---|
| (a) | | | | | | | | | |
| P1 | 1.97 | 2.2 | 2.79 | 2.23 | 2.43 | 2.49 | 3.96 | 4.20 | 0.14 ± 0.01 |
| P2 | 1347 | 1471 | 1513 | 1516 | 1567 | 314 | 1.88 | 2 | 77 ± 6 |
| P3 | 1461 | 1596 | 1641 | 1644 | 1747 | 638 | 4.07 | 4.32 | 76 ± 6 |
| P4 | 1172 | 1280 | 1317 | 1319 | 1402 | 512 | 3.3 | 3.5 | 70 ± 6 |
| P5 | 3113 | 3400 | 3497 | 3503 | 3620 | 724 | 4.34 | 4.59 | 179 ± 16 |
| P6 | 431 | 471 | 484 | 485 | 522 | 289 | 2.25 | 2.4 | 27 ± 2 |
| P7 | 404 | 441 | 453 | 454 | 490 | 290 | 2.41 | 2.56 | 25 ± 1 |
| P8 | 858 | 937 | 964 | 966 | 1036 | 503 | 3.59 | 3.80 | 57 ± 4 |
| P9 | 8421 | 9196 | 9459 | 9476 | 8782 | 656 | 3.91 | 4.14 | 460 ± 41 |
| P10 | 532 | 581 | 598 | 599 | 648 | 444 | 4.45 | 4.71 | 34 ± 3 |
| P11 | 502 | 549 | 564 | 565 | 610 | 361 | 3 | 3.2 | 32 ± 3 |
| P12 | 637 | 695 | 715 | 717 | 773 | 458 | 3.8 | 4 | 40 ± 3 |
| P13 | 33,608 | 36,702 | 37,751 | 37,813 | 23,428 | 701 | 4.2 | 4.4 | 1700 ± 153 |
| P14 | 2191 | 2393 | 2461 | 2466 | 2548 | 510 | 3 | 3.23 | 126 ± 11 |
| P15 | 2610 | 2850 | 2930 | 2940 | 3200 | 652 | 3.64 | 3.85 | 170 ± 15 |
| P16 | 1230 | 1343 | 1381 | 1384 | 1471 | 537 | 3.43 | 3.63 | 73 ± 6 |
| P17 | 6389 | 6977 | 7177 | 7189 | 7032 | 747 | 4.45 | 4.72 | 355 ± 31 |
| P18 | 9687 | 10,578 | 10,881 | 10,900 | 10,102 | 757 | 4.50 | 4.77 | 529 ± 47 |
| P19 | 7839 | 8561 | 8806 | 8821 | 8175 | 611 | 3.64 | 3.86 | 428 ± 38 |
| P20 | 13,840 | 15,115 | 15,547 | 15,574 | 13,690 | 809 | 4.82 | 5.11 | 895 ± 80 |
| P21 | 750 | 819 | 842 | 844 | 897 | 327 | 2.1 | 2.2 | 45 ± 4 |
| (b) | | | | | | | | | |
| P1 | 1.72 | 1.92 | 2.44 | 1.94 | 2.12 | 2.18 | 3.46 | 3.67 | 0.12 ± 0.01 |
| P2 | 1177 | 1285 | 1322 | 1324 | 1368 | 274 | 1.64 | 1.74 | 68 ± 6 |
| P3 | 1461 | 1394 | 1434 | 1437 | 1527 | 557 | 3.56 | 3.70 | 76 ± 6 |
| P4 | 1024 | 1119 | 1150 | 1152 | 1225 | 447 | 2.82 | 3.02 | 61 ± 5 |
| P5 | 2720 | 2970 | 3055 | 3061 | 3163 | 633 | 3.79 | 4.017 | 156 ± 14 |
| P6 | 377 | 411 | 423 | 424 | 465 | 252 | 1.96 | 2.08 | 23 ± 2 |
| P7 | 353 | 385 | 396 | 397 | 428 | 254 | 2.11 | 2.23 | 22 ± 2 |
| P8 | 750 | 819 | 842 | 844 | 905 | 440 | 3.14 | 3.32 | 46 ± 4 |
| P9 | 7357 | 8034 | 8264 | 8279 | 8672 | 573 | 3.42 | 3.62 | 402 ± 36 |
| P10 | 465 | 507 | 522 | 523 | 566 | 388 | 3.88 | 4.12 | 30 ± 2 |

**Table 4** continued

| Medical drug samples | H ($^{238}$U) ($10^{-8}$ Sv year$^{-1}$ cm$^{-2}$) | H($^{230}$Th) ($10^{-8}$ Sv year$^{-1}$ cm$^{-2}$) | H($^{234}$U) ($10^{-8}$ Sv year$^{-1}$ cm$^{-2}$) | H ($^{226}$Ra) ($10^{-8}$ Sv year$^{-1}$ cm$^{-2}$) | H ($^{210}$Po) ($10^{-8}$ Sv year$^{-1}$ cm$^{-2}$) | H ($^{222}$Rn) ($10^{-8}$ Sv year$^{-1}$ cm$^{-2}$) | H ($^{218}$Po) ($10^{-9}$ Sv year$^{-1}$ cm$^{-2}$) | H ($^{214}$Po) ($10^{-12}$ Sv year$^{-1}$ cm$^{-2}$) | H(U)(EP) (μSv year$^{-1}$ cm$^{-2}$) |
|---|---|---|---|---|---|---|---|---|---|
| P11 | 439 | 479 | 493 | 494 | 533 | 316 | 2.62 | 2.78 | 28 ± 2 |
| P12 | 556 | 607 | 624 | 626 | 675 | 400 | 3.32 | 3.52 | 35 ± 2 |
| P13 | 29,363 | 32,066 | 32,982 | 33,036 | 20,468 | 613 | 3.66 | 3.87 | 1485 ± 133 |
| P14 | 1914 | 2091 | 2150 | 2154 | 2226 | 455 | 2.67 | 2.82 | 110 ± 9 |
| P15 | 2280 | 2490 | 2560 | 2570 | 2790 | 540 | 3.18 | 3.37 | 150 ± 9 |
| P16 | 1074 | 1174 | 1207 | 1209 | 1285 | 469 | 3 | 3.17 | 64 ± 5 |
| P17 | 5582 | 6096 | 6270 | 6281 | 6143 | 652 | 3.89 | 4.12 | 31 ± 2 |
| P18 | 8463 | 9242 | 9506 | 9523 | 8826 | 659 | 3.93 | 4.16 | 462 ± 41 |
| P19 | 6849 | 7480 | 7693 | 7707 | 7143 | 534 | 3.18 | 3.37 | 374 ± 33 |
| P20 | 12,092 | 13,206 | 13,583 | 13,607 | 11,961 | 707 | 4.21 | 4.46 | 789 ± 71 |
| P21 | 655 | 716 | 736 | 738 | 784 | 286 | 1.83 | 1.94 | 39 ± 3 |

$$D_{\mathrm{sp}}^{\mathrm{Skin}}(j) = k\frac{k_j}{d_{\mathrm{Skin}}S_{\mathrm{Skin}}}\frac{E_{\alpha_j}^{\mathrm{Res}}}{R_j^{\mathrm{Skin}}}, \tag{10}$$

and

$$D_{\mathrm{sp}}^{\mathrm{Skin}}\left(j'\right) = k\frac{k_{j'}}{d_{\mathrm{Skin}}S_{\mathrm{Skin}}}\frac{E_{\alpha_{j'}}^{\mathrm{Res}}}{R_{j'}^{\mathrm{Skin}}}, \tag{11}$$

where $d_s$ is the density of skin (g cm$^{-3}$). $S_{\mathrm{skin}}$ is the surface skin (cm$^2$). $k = 1.6 \times 10^{-13}$ (J MeV$^{-1}$) is a conversion factor. $R_j^{\mathrm{skin}}$ is the range, in skin, of an alpha-particle of index $j$ and a residual energy, $E_{\alpha_j}^{\mathrm{Res}}$, belonging to the $^{238}$U series. $R_j^{\mathrm{skin}}$ is the range, in skin, of an alpha-particle of index $j$ and a residual energy, $E_{\alpha_{j'}}^{\mathrm{Res}}$, belonging to the $^{232}$Th series (Fig. 3).

By integrating Eqs. 6 and 7, committed equivalent doses (Sv) to skin due to an alpha-particle of residual energy, $E_{\alpha_j}^{\mathrm{Res}}$, emitted by a radionuclide of index $j$ belonging to the $^{238}$U series and an alpha-particle of residual energy, $E_{\alpha_{j'}}^{\mathrm{Res}}$, emitted by a radionuclide of index $j'$ belonging to the $^{232}$Th series from the application of a medical drug sample are, respectively, given by:

$$H_{\mathrm{skin}}(j) = \frac{D_{\mathrm{sp}}^{\mathrm{skin}}(j)W_{\mathrm{R}}}{2\lambda_j}A_{\mathrm{c}}^{\mathrm{sample}}\left(^{238}\mathrm{U}\right)\left(1-\mathrm{e}^{-\lambda_j t_{\mathrm{a}}}\right), \tag{12}$$

and

$$H_{\mathrm{skin}}\left(j'\right) = \frac{D_{\mathrm{sp}}^{\mathrm{skin}}\left(j'\right)W_{\mathrm{R}}}{2\lambda_{j'}}A_{\mathrm{c}}^{\mathrm{sample}}\left(^{232}\mathrm{Th}\right)\left(1-\mathrm{e}^{-\lambda_{j'} t_{\mathrm{a}}}\right), \tag{13}$$

where $t_a$ is the application time.

Committed equivalent doses to the epidermis (EP) of the skin (Sv) due to all residual energies of an alpha-particle of index $j$ and initial energy $E_{\alpha_j}$ belonging to the $^{238}$U series and an alpha-particle of index $j'$ and initial energy $E_{\alpha_{j'}}$ belonging to the $^{232}$Th series are, respectively, given by:

$$H(j)(\mathrm{EP}) = \frac{kk_jA_{\mathrm{c}}^{\mathrm{Sample}}\left(^{238}\mathrm{U}\right)\left(1-e^{-\lambda_j t_{\mathrm{a}}}\right)}{2\lambda_j d_{\mathrm{skin}}S_{\mathrm{Skin}}E_{\alpha_j}^{\mathrm{Res}}}\int_0^{E_{\alpha_j}}\frac{E_{\alpha_j}^{\mathrm{Res}}}{R_j^{\mathrm{Skin}}\left(E_{\alpha_j}^{\mathrm{Res}}\right)}\mathrm{d}E_{\alpha_j}^{\mathrm{Res}}, \tag{14}$$

and

$$H\left(j'\right)(\mathrm{EP}) = \frac{kk_{j'}A_{\mathrm{c}}^{\mathrm{Sample}}\left(^{232}\mathrm{Th}\right)\left(1-e^{-\lambda_{j'} t_{\mathrm{a}}}\right)}{2\lambda_{j'}d_{\mathrm{skin}}S_{\mathrm{Skin}}E_{\alpha_{j'}}^{\mathrm{Res}}}\int_0^{E_{\alpha_{j'}}}\frac{E_{\alpha_{j'}}^{\mathrm{Res}}}{R_{j'}^{\mathrm{Skin}}\left(E_{\alpha_{j'}}^{\mathrm{Res}}\right)}\mathrm{d}E_{\alpha_{j'}}^{\mathrm{Res}}, \tag{15}$$

where $\Delta E_{\alpha_j}^{\mathrm{Res}}$ and $\Delta E_{\alpha_{j'}}^{\mathrm{Res}}$ are the chosen steps.

Committed equivalent doses (Sv year$^{-1}$ cm$^{-2}$) to the skin surface of 1 cm$^2$ of the epidermis during an exposure time is equal to 1 year due to the alpha-particles emitted by the $^{238}$U (eight alpha-emitting nuclei) and $^{232}$Th (seven alpha-emitting nuclei) series from the application of a

**Table 5** Committed equivalent doses to the epidermis of skin (Sv year$^{-1}$ cm$^{-2}$) due to all residual energies of an alpha-particle of index $j'$ and initial energy $E_{\alpha j'}$ belonging to the $^{232}$Th series from cutaneous application of different medical drugs by (a) adult female and (b) adult female

| Medical drug samples | H ($^{232}$Th) ($10^{-8}$ Sv year$^{-1}$ cm$^{-2}$) | H($^{228}$Th) ($10^{-8}$ Sv year$^{-1}$ cm$^{-2}$) | H($^{224}$Ra) ($10^{-8}$ Sv year$^{-1}$ cm$^{-2}$) | H ($^{212}$Bi) ($10^{-9}$ Sv year$^{-1}$ cm$^{-2}$) | H ($^{220}$Rn) ($10^{-9}$ Sv year$^{-1}$ cm$^{-2}$) | H ($^{216}$Po) ($10^{-12}$ Sv year$^{-1}$ cm$^{-2}$) | H ($^{212}$Po) ($10^{-18}$ Sv year$^{-1}$ cm$^{-2}$) | H(Th)(EP) (μSv year$^{-1}$ cm$^{-2}$) |
|---|---|---|---|---|---|---|---|---|
| (a) | | | | | | | | |
| P1 | 1.89 | 2.47 | 2.58 | 8.26 | 1.24 | 3.77 | 6.85 | 0.080 ± 0.006 |
| P2 | 1294 | 1664 | 1755 | 13.5 | 0.6 | 1.78 | 3.25 | 47 ± 4 |
| P3 | 1403 | 1818 | 1908 | 29.3 | 1.27 | 3.9 | 7.04 | 45 ± 4 |
| P4 | 1125 | 1458 | 1531 | 23.5 | 1.02 | 3.11 | 5.65 | 41 ± 3 |
| P5 | 2989 | 3845 | 4056 | 31.2 | 1.35 | 4.13 | 7.50 | 109 ± 9 |
| P6 | 414 | 538 | 563 | 16.2 | 0.7 | 2.14 | 3.89 | 15 ± 1 |
| P7 | 388 | 505 | 528 | 17.4 | 0.8 | 2.3 | 4.17 | 14 ± 1 |
| P8 | 824 | 1071 | 1122 | 25.8 | 1.12 | 3.4 | 6.2 | 30 ± 2 |
| P9 | 8086 | 10,099 | 10,847 | 28.1 | 1.22 | 3.72 | 6.76 | 291 ± 26 |
| P10 | 511 | 665 | 696 | 32 | 1.4 | 4.2 | 7.69 | 19 ± 1 |
| P11 | 482 | 628 | 657 | 21.6 | 0.9 | 2.85 | 5.19 | 18 ± 1 |
| P12 | 611 | 795 | 832 | 27.4 | 1.2 | 3.6 | 6.57 | 22 ± 2 |
| P13 | 32,273 | 35,850 | 41,847 | 30 | 1.3 | 4 | 7.23 | 1100 ± 9 |
| P14 | 2104 | 2706 | 2855 | 22 | 0.9 | 2.9 | 5.28 | 77 ± 6 |
| P15 | 251 | 3270 | 3420 | 26 | 1.1 | 3.5 | 6.30 | 9.0 ± 0.8 |
| P16 | 1181 | 1530 | 1606 | 24.7 | 1.07 | 3.26 | 5.92 | 43 ± 3 |
| P17 | 6135 | 7775 | 8288 | 32 | 1.4 | 4.2 | 7.70 | 22 ± 1 |
| P18 | 9302 | 11,617 | 12,509 | 32 | 1.4 | 4.3 | 7.78 | 334 ± 30 |
| P19 | 7528 | 9402 | 10,123 | 26.2 | 1.14 | 3.5 | 6.30 | 271 ± 24 |
| P20 | 13,291 | 16,359 | 17,794 | 34.7 | 1.5 | 4.6 | 8.34 | 474 ± 42 |
| P21 | 720 | 933 | 980 | 15 | 0.7 | 2 | 3.61 | 26 ± 2 |
| (b) | | | | | | | | |
| P1 | 1.66 | 2.16 | 2.26 | 7.22 | 1.08 | 3.3 | 5.99 | 0.070 ± 0.006 |
| P2 | 1130 | 1453 | 1534 | 11.8 | 0.5 | 1.56 | 2.84 | 41 ± 3 |
| P3 | 1226 | 1588 | 1667 | 25.6 | 1.11 | 3.39 | 6.15 | 45 ± 3 |
| P4 | 983 | 1274 | 1337 | 20.5 | 0.89 | 2.72 | 4.96 | 36 ± 3 |
| P5 | 2612 | 3359 | 3544 | 27.3 | 1.18 | 3.61 | 6.55 | 95 ± 8 |
| P6 | 361 | 470 | 492 | 14.2 | 0.6 | 1.87 | 3.40 | 13 ± 1 |
| P7 | 339 | 441 | 461 | 15.2 | 0.66 | 2 | 4.17 | 12 ± 1 |
| P8 | 720 | 935 | 980 | 22.5 | 1 | 2.98 | 5.42 | 26 ± 2 |
| P9 | 7065 | 8823 | 9500 | 24.6 | 1.07 | 3.25 | 5.91 | 254 ± 22 |
| P10 | 446 | 581 | 608 | 27.9 | 1.21 | 3.7 | 6.72 | 16 ± 1 |

**Table 5** continued

| Medical drug samples | H ($^{232}$Th) ($10^{-8}$ Sv year$^{-1}$ cm$^{-2}$) | H($^{228}$Th) ($10^{-8}$ Sv year$^{-1}$ cm$^{-2}$) | H($^{224}$Ra) ($10^{-8}$ Sv year$^{-1}$ cm$^{-2}$) | H ($^{212}$Bi) ($10^{-9}$ Sv year$^{-1}$ cm$^{-2}$) | H ($^{220}$Rn) ($10^{-9}$ Sv year$^{-1}$ cm$^{-2}$) | H ($^{216}$Po) ($10^{-12}$ Sv year$^{-1}$ cm$^{-2}$) | H ($^{212}$Po) ($10^{-18}$ Sv year$^{-1}$ cm$^{-2}$) | H(Th)(EP) (μSv year$^{-1}$ cm$^{-2}$) |
|---|---|---|---|---|---|---|---|---|
| P11 | 421 | 548 | 574 | 18.9 | 0.82 | 2.5 | 4.53 | 15 ± 1 |
| P12 | 534 | 695 | 727 | 23.9 | 1.04 | 3.2 | 5.74 | 20 ± 1 |
| P13 | 28,196 | 31,321 | 36,561 | 26.3 | 1.14 | 3.5 | 6.32 | 961 ± 84 |
| P14 | 1838 | 2364 | 2494 | 19.2 | 0.8 | 2.5 | 4.61 | 67 ± 6 |
| P15 | 2190 | 2860 | 2980 | 25.1 | 1 | 3 | 5.50 | 81 ± 7 |
| P16 | 1032 | 1337 | 1403 | 21.5 | 0.9 | 2.8 | 5.18 | 38 ± 3 |
| P17 | 5360 | 6793 | 7241 | 28 | 1.2 | 3.7 | 6.67 | 194 ± 17 |
| P18 | 8127 | 10,149 | 10,929 | 28.3 | 1.22 | 3.74 | 6.80 | 292 ± 26 |
| P19 | 6577 | 8214 | 8845 | 23 | 1 | 3 | 5.50 | 236 ± 21 |
| P20 | 11,612 | 14,292 | 15546 | 30.3 | 1.31 | 4.01 | 7.28 | 414 ± 37 |
| P21 | 629 | 815 | 856 | 13.1 | 0.6 | 1.7 | 3.16 | 23 ± 2 |

medical drug sample by patients are, respectively, given by:

$$H(\mathrm{U})(\mathrm{EP}) = \sum_{j=1}^{8} H(j)(\mathrm{Tot}), \tag{16}$$

and

$$H(\mathrm{Th})(\mathrm{EP}) = \sum_{j'=1}^{7} H\left(j'\right)(\mathrm{Tot}). \tag{17}$$

## 3 Results and discussion

### 3.1 $^{238}$U and $^{232}$Th alpha-activities per unit volume in medical drugs

The $^{238}$U ($A_c(^{238}\mathrm{U})$) and $^{232}$Th ($A_c(^{232}\mathrm{Th})$) alpha-activities per unit volume were measured in various medical drugs prescribed by doctors for different age groups of patients. Data obtained is shown in Table 3. Since the track detectors utilized were etched in two NaOH solutions at optimal conditions of etching, ensuring good sensitivities of the SSNTDs and a good reproducibility of the registered track density rates determined by means of the same optical microscope with a magnification of 40x, only the statistical uncertainty on track counting is predominant. From the statistical uncertainty on track counting, the uncertainty on track density production per unit time was determined, and then the uncertainty of the measured $^{238}$U and $^{232}$Th concentrations was determined, which gave values of about 8 %. Natural uranium is formed by $^{238}$U, $^{235}$U, and $^{234}$U radioisotopes with isotopic abundances equal to 99.27, 0.72, and 0.0055 %, respectively. So, the contribution of alpha-particles emitted by the $^{235}$U series to the global track densities registered on the SSNTDs utilized is negligible because they induce a relative uncertainty smaller than 1 %, which is included in the uncertainty on the $^{238}$U and $^{232}$Th concentration determination (8 %). The data shown in Table 3 demonstrates that all medical drug samples studied contain more $^{238}$U than $^{232}$Th. This is probably due to the fact that raw materials used for the preparation of these medical drugs contain more $^{238}$U than $^{232}$Th. It is to be noted that the $^{238}$U contents of the P1, P3, P5, P9, P10, P12, P13, P17, P18, and P20 medical drugs are clearly higher than those of the P2, P4, P6, P7, P11, P14, and P21 medical drug samples (Table 3). We also noted that the $^{232}$Th contents of the P2, P6, P7, P11, P14, and P21 medical drug samples are clearly higher than those of the P1, P3, P9, P13, P17, and P18 samples (Table 3). The minimum detection activities (MDA) for $^{238}$U and $^{232}$Th were found to be equal to (0.81 ± 0.05) and (0.11 ± 0.01) mBq l$^{-1}$, respectively.

**Table 6** Data obtained for the annual committed equivalent doses to the epidermis of the skin due to the $^{238}$U (H(U)(EP)) and $^{232}$Th (H(Th)(EP)) series from the application of different medical drugs by 15-year-old children

| Medical drug samples | Annual committed equivalent doses (μSv year$^{-1}$ cm$^{-2}$) | | | |
|---|---|---|---|---|
| | 15 years (female) | | 15 years (male) | |
| | H(U)(EP) | H(Th)(EP) | H(U)(EP) | H(Th)(EP) |
| P1 | 0.16 ± 0.01 | 0.0085 ± 0.0007 | 0.152 ± 0.01 | 0.0081 ± 0.0007 |
| P4 | 76 ± 6 | 44 ± 3 | 73 ± 6 | 42 ± 3 |
| P5 | 191 ± 17 | 117 ± 10 | 183 ± 16 | 112 ± 10 |
| P6 | 29 ± 2 | 16 ± 1 | 28 ± 2 | 16 ± 1 |
| P9 | 493 ± 44 | 311 ± 27 | 471 ± 42 | 230 ± 20 |
| P10 | 37 ± 3 | 20 ± 1 | 35 ± 3 | 19 ± 1 |
| P11 | 34 ± 3 | 19 ± 1 | 33 ± 2 | 18 ± 1 |

**Table 7** Data obtained for the annual committed equivalent doses to the epidermis of skin due to the $^{238}$U (H(U)(EP)) and $^{232}$Th (H(Th)(EP)) series from the application of different medical drugs by 10-year-old and 5-year-old children

| Medical drug samples | Annual committed equivalent doses (μSv year$^{-1}$ cm$^{-2}$) | | | |
|---|---|---|---|---|
| | 10 years | | 5 years | |
| | H(U)(EP) | H(Th)(EP) | H(U)(EP) | H(Th)(EP) |
| P1 | 0.22 ± 0.01 | 0.012 ± 0.001 | 0.32 ± 0.02 | 0.017 ± 0.001 |
| P4 | 105 ± 9 | 61 ± 5 | 151 ± 13 | 88 ± 7 |
| P5 | 270 ± 24 | 161 ± 14 | 380 ± 34 | 232 ± 20 |
| P6 | 40 ± 3 | 23 ± 2 | 58 ± 5 | 32 ± 3 |
| P10 | 51 ± 4 | 28 ± 2 | 73 ± 6 | 40 ± 3 |
| P11 | 47 ± 4 | 26 ± 2 | 68 ± 6 | 38 ± 3 |

In order to validate this method, 10 medical drugs were analysed using isotope dilution mass spectrometry (IDMS). Isotope dilution mass spectrometry is based on the addition of a known amount of enriched isotope (called the spike) to a medical drug sample. After equilibrium of the spike with the natural isotope of the element in the sample, mass spectrometry is used to measure the altered isotopic ratio(s). Data obtained by the two methods, for the $^{238}$U and $^{232}$Th contents, are in good agreement with each other (Table 3).

### 3.2 Committed equivalent doses to skin due to the radionuclides of the $^{238}$U and $^{232}$Th series from the application of medical drugs by patients

Committed equivalent doses to the epidermis of skin due to the alpha-emitting nuclei of the $^{238}$U (H(U)(EP)) and $^{232}$Th (H(Th)(EP)) series from the application of medical drugs by different age groups of patients have been evaluated by means of Eqs. 16 and 17, and the results are shown in Tables 4, 5, 6, and 7. The statistical relative uncertainty of the committed dose determination is 9 %. It should be noted that H(U)(EP) and H(Th)(EP) increase with an increase in the application time of medical drugs by adults (Tables 1, 4, 5).

It is to be noted from the data shown in Tables 4, 5, 6, and 7 that H(U)(EP) and H(Th)(EP) due to cutaneous application of the medical drug P1 are negligible compared to those due to the other medical drugs for adults and children. This is because the application time for medical drug P1, used for surface anaesthesia, is shorter than those for the other medical drugs (Table 1). It is to be noted from the results shown in Table 4 that committed equivalent doses to the epidermis of the skin due to alpha-particles emitted by $^{214}$Po (H($^{214}$Po)) and $^{218}$Po (H($^{218}$Po)) are negligible compared to those corresponding to the other alpha-emitters of the $^{238}$U series. This is because they have smaller half-lives, $1.6 \times 10^{-4}$ s and 3.05 min, respectively, than the other radionuclides. Also, one can note that committed equivalent doses to the epidermis due to $^{212}$Po (H($^{212}$Po)) and $^{216}$Po (H($^{216}$Po)) are negligible compared to those corresponding to the other alpha-emitters of the $^{232}$Th series (Table 5). This is due to the fact that these radionuclides possess smaller half-lives, $3.7 \times 10^{-7}$ s and 0.158 s, respectively, than the other alpha-emitters of the $^{232}$Th series. It is to be noted that total committed

equivalent doses due to the $^{238}$U and $^{232}$Th series from cutaneous application of P1, P4, P5, P6, P10, and P11 medical drugs are higher for 5-year-old children than for the other age groups of patients (Tables 4, 5, 6, 7). This is because 5-year-old children possess smaller skin surface area than the other age groups of patients [1]. The maximum total committed equivalent dose to skin due to the $^{238}$U and $^{232}$Th series was found to be equal to 2.8 mSv year$^{-1}$ cm$^{-2}$, obtained for women applying the P13 medical drug (Tables 4a, 5a), which is significantly smaller than the dose limit for members of the public, which is of 50 mSv year$^{-1}$ cm$^{-2}$ [1].

## 4 Conclusion

In this study, it has been shown that the use of CR-39 and LR-115 type II solid-state nuclear track detectors (SSNTDs) allows for the evaluation of $^{238}$U and $^{232}$Th alpha-activities per unit volume in various medical drug samples. A new dosimetric model was developed for evaluating radiation doses to skin due to the alpha-emitting nuclei of the $^{238}$U and $^{232}$Th series from the application of medical drugs by patients. The committed equivalent doses to the epidermis of the skin due to the alpha-emitting nuclei of the $^{238}$U and $^{232}$Th series increase with the application time of medical drugs. It has been shown that only nine alpha-emitting nuclei belonging to the $^{238}$U and $^{232}$Th series significantly contribute to the global radiation dose to the epidermis of skin from the application of medical drugs by patients. It has also been shown that the committed effective dose due to the $^{238}$U and $^{232}$Th series increases when the skin surface area of the patients decreases. Thus, there is no radiation risk to the epidermis from cutaneous application of the studied medical drugs by patients. The SSNTD method used has the advantage of being inexpensive, accurate, sensitive, and does not require the use of standard sources for its calibration. It is a useful tool for measuring $^{238}$U and $^{232}$Th concentrations in medical drugs, as well as essential oils extracted from aromatic and medicinal plants.

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