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Determination of Alpha Radiation Dose to Skin Due to Artificial and Natural Radionuclides from the Deposition of Different Material Samples

M. A. Misdaq[1] and H. Harrass

Nuclear Physics and Techniques Laboratory, Faculty of Sciences Semlalia, BP. 2390, University of Cadi Ayyad, Marrakech, Morocco (URAC-15 Research Unit Associated to the CNRST, Rabat, Morocco).

Abstract

Artificial alpha-emitting radionuclides are significantly utilized in nuclear medicine. So, the skin of practitioners as well as patients in nuclear medicine and workers in the industry of radiopharmaceuticals may be accidentally contaminated even for a very short time by these radionuclides. Natural alpha-emitting radioisotopes such as those belonging to the uranium and thorium series are deposited on the human skin from the application of various natural material samples. The mean absorbed dose in skin due alpha-particles emitted by natural and artificial radionuclides was calculated by using a Monte Carlo computer code based on determining residual energies of the emitted alpha-particles. Alpha-activities were determined for radiopharmaceutical and natural material samples. A new dosimetric model based on exploiting data obtained for alpha-activities and mean alpha absorbed doses due to artificial and natural material samples for evaluating committed equivalent doses to skin of workers was developed. The influence of the application time, alpha-disintegration ratio, half-life of the radionuclide, and contaminated skin surface on committed equivalent dose was investigated. Maximum values of the committed equivalent dose to skin were found equal to 0.552 mSv cm^{-2} y^{-1} for alpha-particles emitted by artificial radionuclides and 0.16 mSv cm^{-2} y^{-1} for those emitted by ^{238}U, ^{232}Th and ^{222}Rn natural radioisotopes, respectively.

Keywords: Artificial and natural alpha-emitting radionuclides; Monte Carlo simulation; Radiation dose assessment to skin

1. INTRODUCTION

With a surface area of about 2 m^2 and a weight of about 2.1 kg, the skin is the largest organ of the human body. It protects individuals from the hazards of the environment, regulates body temperature and limits sensation of touch, heat and cold. The skin is composed of a series of three layers: The epidermis, dermis and hypodermis. The critical cells in the skin are in the basal layer of the epidermis [1]. Alpha-particles are helium nuclei made up of two protons and two neutrons which have short range and high linear energy transfer. Alpha-particle emitting radionuclides are of great interest in alpha-radioimmunotherapy and targeted therapy for the treatment of malignant diseases [2-7]. Patients and practitioners in nuclear medicine as well as workers in the industry of radiopharmaceuticals may be accidentally contaminated by alpha-emitting radiopharmaceuticals. Natural radioisotopes belonging to the ^{238}U and ^{232}Th series are deposited on the skin of individuals from the application of various material samples such as building materials [8], olive oil [9], black soap [10], thermal waters [11], and medical drugs [12]. It is then necessary to assess alpha-radiation dose to the skin of workers to avoid any radiation dose enhancement.

In the present work, mean absorbed dose in skin was calculated by using a Monte Carlo computer code based on generating uniformly alpha-particles in a material layer deposited on skin and determining the residual energy of these particles. Alpha-activities of the deposited material samples were evaluated. Committed equivalent doses to skin due to artificial and natural alpha-emitting radionuclides from the application of different material samples were determined.

2. MATERIAL AND METHODS

a. Calculation of the mean absorbed dose to skin due to alpha-particles

The epidermis of the human skin is divided into several clearly defined zones [13]. Indeed, when a material layer of 1 mm depth is placed on the skin of an individual (Fig. 1), the emitted alpha-particles have ranges of several tens of microns (20 to 100µm). This is comparable with the depth of the basal layer of the epidermis which is more sensitive (50 to 100µm) [14].

An alpha-particle of index j and initial energy E_{α_j} emitted from a nucleus localized on the point P inside a material layer (Fig. 1) has a range:

$$\overline{PF} = x_j + R_j^{skin} \tag{1}$$

where x_j ($x_j \le R_j$, R_j is the range of the alpha-particle inside the material layer) is the distance between the emission point and the skin surface (Fig. 1) and R_j^{skin} is the range of the alpha-particle in skin. The ranges of alpha-particles in the material layer and skin were calculated using a TRIM programme [15].

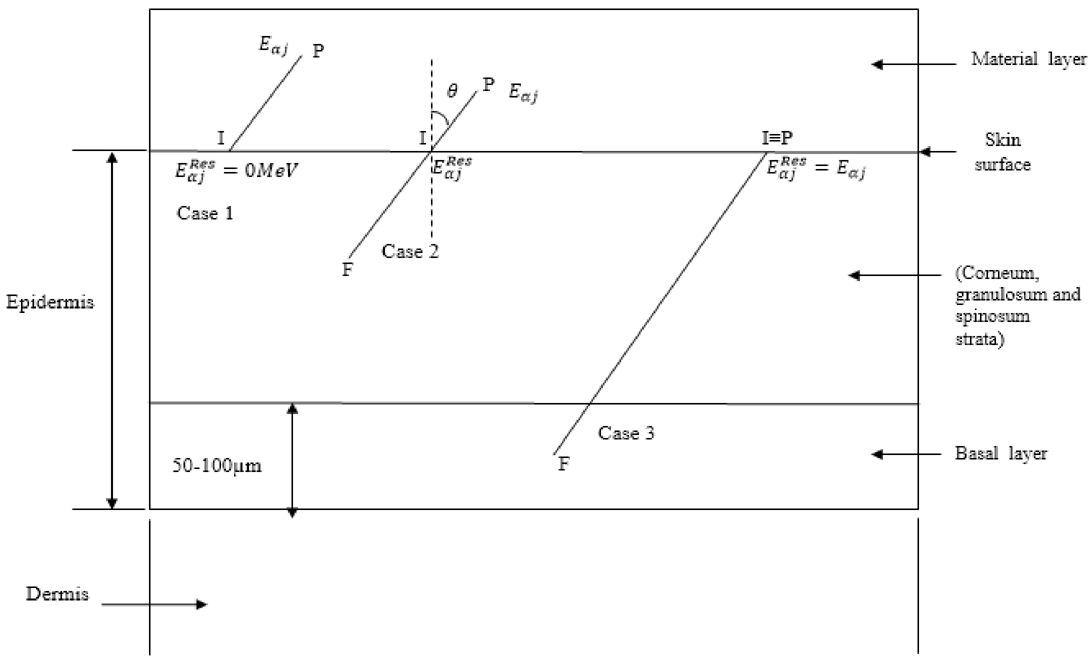


Fig. 1. Ranges of an alpha-particle inside a material layer ($\overline{PI} = x_j$) and epidermis ($\overline{IF} = R_j^{skin}$). $E_{\alpha j}$ is the initial alpha-particle energy and $E_{\alpha j}^{Res}$ its residual energy on the point I. The deposited material layer has a depth of about 1mm.

The alpha-particle residual energy $E_{\alpha_j}^{\mathrm{Res}}$ which corresponds to the (R_j-x_j) range is determined by using the energy-range relation in the material sample (an example is given in Fig. 2a for alpha-particles in a radiopharmaceutical sample). By using the energy–range relation in skin one can determine the range of the alpha-particle in skin R_j^{skin} (Fig. 2b). For $x_j = R_j$, $E_{\alpha_j}^{\mathrm{Res}} = 0\ MeV$; there is no energy loss of alpha-particles in skin (case 1 of Fig. 1). For $x_j = 0\ \mu m$, $E_{\alpha_j}^{\mathrm{Res}} = E_{\alpha_j}$; the energy loss of alpha-particles in skin is maximum (R_j^{skin} maximum) (case 3 of Fig. 1). For $x_j \prec R_j$, $E_{\alpha_j}^{\mathrm{Res}} \prec E_{\alpha_j}$; the ranges of alpha-particles in skin are lower than those corresponding to $x_j = 0\ \mu m$ (case 2 of Fig. 1).

Let us consider a cylindrical material layer of 1 cm^2 basis surface and 1 mm depth deposited on the skin surface of an individual as shown in Fig. 3. An alpha-particle of index j and initial energy E_{α_j} generated at point P (Fig. 3) at a distance x_j from the skin which reaches the skin has a range R_j^{skin} in skin. Since the deposited material layer has a depth of 1 mm which is greater than the radon diffusion length in the considered materials, alpha-particles emitted by radon in ambient air cannot reach the skin of individuals (Fig. 1).

The distance x_j is given by (Fig. 3):

$$x_j = \frac{t}{\cos\theta} \text{ if } \quad q > \overline{O_1^{'}Q_1} \tag{2}$$

where

$$\overline{O_1^{'}Q_1}^2 = r^2 + t^2 tg^2(\theta) + 2r\, t tg(\theta) \cos(\psi) \tag{3}$$

q is the radius of the cylindrical material layer.

The calculation of the absorbed dose in skin due to the emitted alpha-particles consists firstly on generating random numbers by using a programme called random subroutine, based on a congruential method [16], and calculating the x_j distances and, R_j and R_j^{skin} ranges by using a programme called AMADS (Alpha Mean Absorbed Dose in Skin) which is represented schematically in Fig. 4.

The uniform random sampling of the emission point P and emission direction is achieved by computing the distance from the center axis r, the depth t, cos θ (θ between 0 and $\frac{\pi}{2}$) and Ψ (Fig. 3) with four uniform random numbers [16-18]:

$$\begin{aligned} r &= q\sqrt{\xi_1} && , 0 \le \xi_1 < 1 \\ t &= R_j \xi_2 && , 0 \le \xi_2 < 1 \\ \cos\theta &= \xi_3 && , 0 \le \xi_3 < 1 \\ \psi &= 2\pi\xi_4 && , 0 \le \xi_4 < 1 \end{aligned} \tag{4}$$

where R_j is the range of an alpha-particle of index j and initial energy E_{α_j} in the material sample.

The absorbed dose (Gy) in a cylinder of 1cm^2 basis surface and $R_j^{skin}\cos\theta$ depth of skin due to an alpha-particle of index j and residual energy $E_{\alpha_j}^{\mathrm{Res}}$ is:

$$D_j = \frac{k\,E_{\alpha j}^{\mathrm{Res}}}{m} \tag{5}$$

where $m = d_{Skin} R_j^{Skin} \cos\theta \times 1\mathrm{cm}^2$ is the mass of the cylindrical volume of skin, d_{Skin} is the density of skin and k = 1.6 x 10^{-13} J MeV^{-1} is a conversion factor.

Eq. (5) can be rewritten:

$$D_j = \frac{k\,E_{\alpha j}^{\mathrm{Res}}}{d_{Skin} R_j^{Skin} \cos\theta \times 1\mathrm{cm}^2} \tag{6}$$

For a large number N_r^j of α-particles of index j reaching the surface skin with a residual energy $E_{\alpha_j}^{\mathrm{Res}}$ the mean absorbed dose in skin is:

$$\langle D_j(\mathrm{skin})\rangle = \frac{\sum D_j}{N_r^j} \tag{7}$$

An alpha-particle of index j and initial energy E_{α_j} reaches the basal layer of the human skin when:

$$x_j < R_j \ \text{ and } \ R_j^{Skin} > (50\mu\mathrm{m}/\cos\theta) \tag{8}$$

The mean absorbed dose in the basal layer of an individual is given by:

$$\langle D_j(BL)\rangle = \frac{\sum D_j}{N_{BL}^j} \tag{9}$$

where N_{BL}^j is the number of alpha-particles reaching the basal layer of skin with a residual energy $E_{\alpha_j}^{\mathrm{Res}}(BL)$.

The mean absorbed dose per fluence in the basal layer of the epidermis is given by:

$$\frac{\langle D_j(BL)\rangle}{\phi} = \frac{\sum D_j}{N_{BL}^j} \times 1\ \mathrm{cm}^2 \tag{10}$$

b. Committed equivalent dose to skin due to alpha-particles from the deposition of different material samples

Alpha-equivalent dose rates (Sv s^{-1}) to the skin of individuals due to an alpha-particle emitted by a radionuclide j from the application of a material sample is given by:

$$\overset{*}{H}_{skin}(j)(t) = \langle D_j(Skin) \rangle \mathrm{K}_j \; A_C^{skin}(j)(t) W_R \tag{11}$$

where $A_c^{skin}(j)(t)$ (Bq) is the alpha-activity, at time t, in skin due to a radionuclide j,W_R is the radiation weighting factor which is equal to 20 for alpha-particles [13], and K_j is the alpha-disintegration branching ratio.

The $A_c^{skin}(j)(t)$ alpha-activity is given by:

$$\mathrm{A_c^{skin}(j)(t) = \frac{1}{2} A_c^{sample}(j) e^{-\lambda_j t} \text{ x } 1cm^2 \text{ x }} R_j \tag{12}$$

where $A_c^{sample}(j)$ in Bq cm^{-3} is the alpha-activity due to a radionuclide j inside a material sample, λ_j is the radioactive decay constant of a radionuclide j and R_j (in cm) is the range of an alpha-particle of index j in the material sample. The term ½ means that only half of the emitted alpha-particles inside a material sample may lose their energies inside the skin.

By integrating Eq. (11), committed equivalent dose (Sv) to skin due to an alpha-particle of residual energy $E_{\alpha_j}^{Res}$ emitted by a radionuclide j from the application of a material sample is given by:

$$\mathrm{H_{skin}(j) = \frac{\langle D_j(Skin) \rangle K_j \; W_R}{2\lambda_j} A_C^{sample}(j)\left(1 - e^{-\lambda_J t_a}\right) \text{x } 1cm^2 \text{ x }} R_j \tag{13}$$

where t_a is the application time of the material sample on skin.

Similarly committed equivalent dose to the basal layer of the epidermis from the application of a material sample is given by:

$$\mathrm{H_{BL}(j) = \frac{\langle D_j(BL) \rangle K_j \; W_R}{2\lambda_j} A_C^{sample}(j)\left(1 - e^{-\lambda_J t_a}\right) \text{x } 1cm^2 \text{ x }} R_j \tag{14}$$

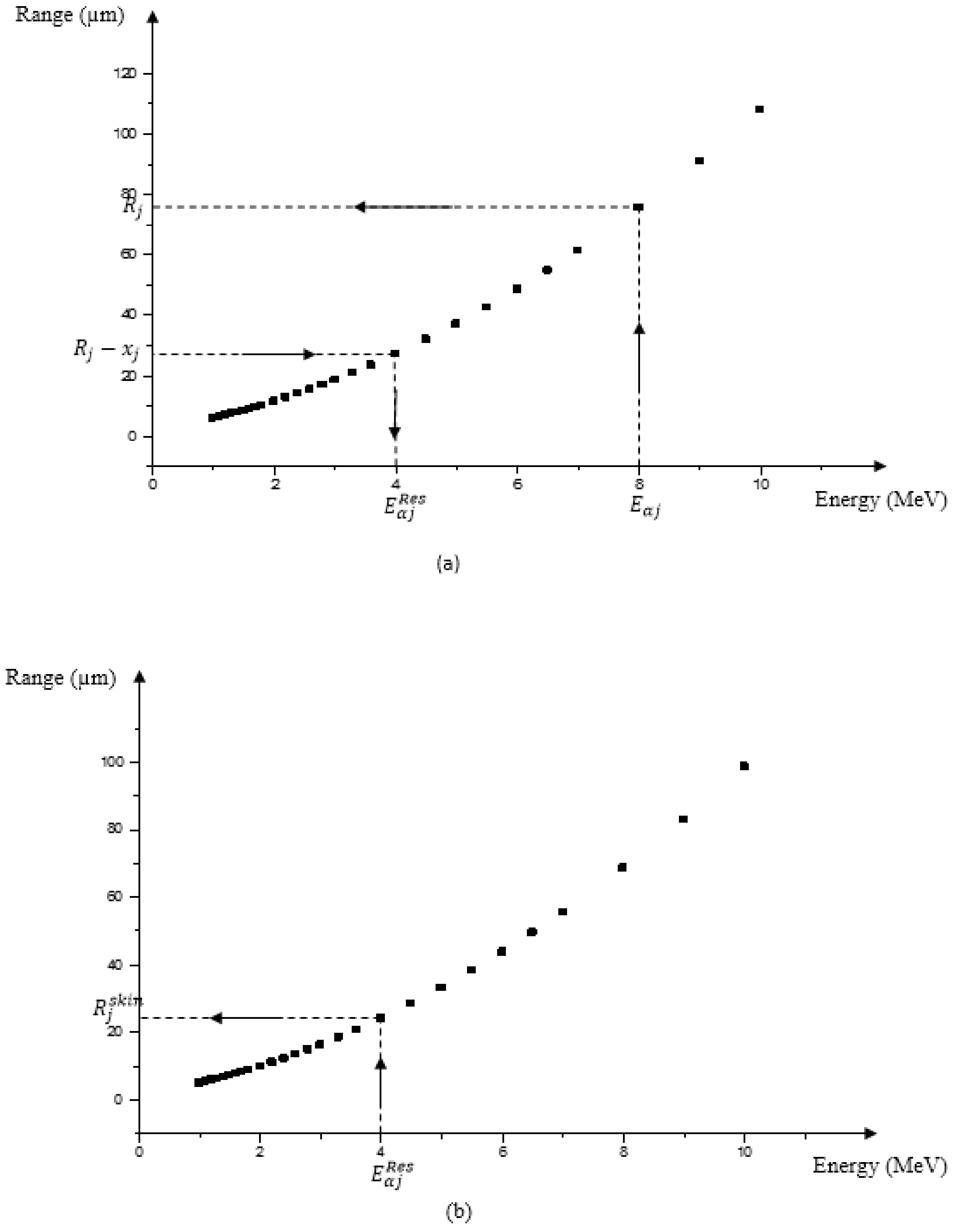


Fig. 2. Alpha-particle range-energy relationship for a material sample (a) and skin (b).

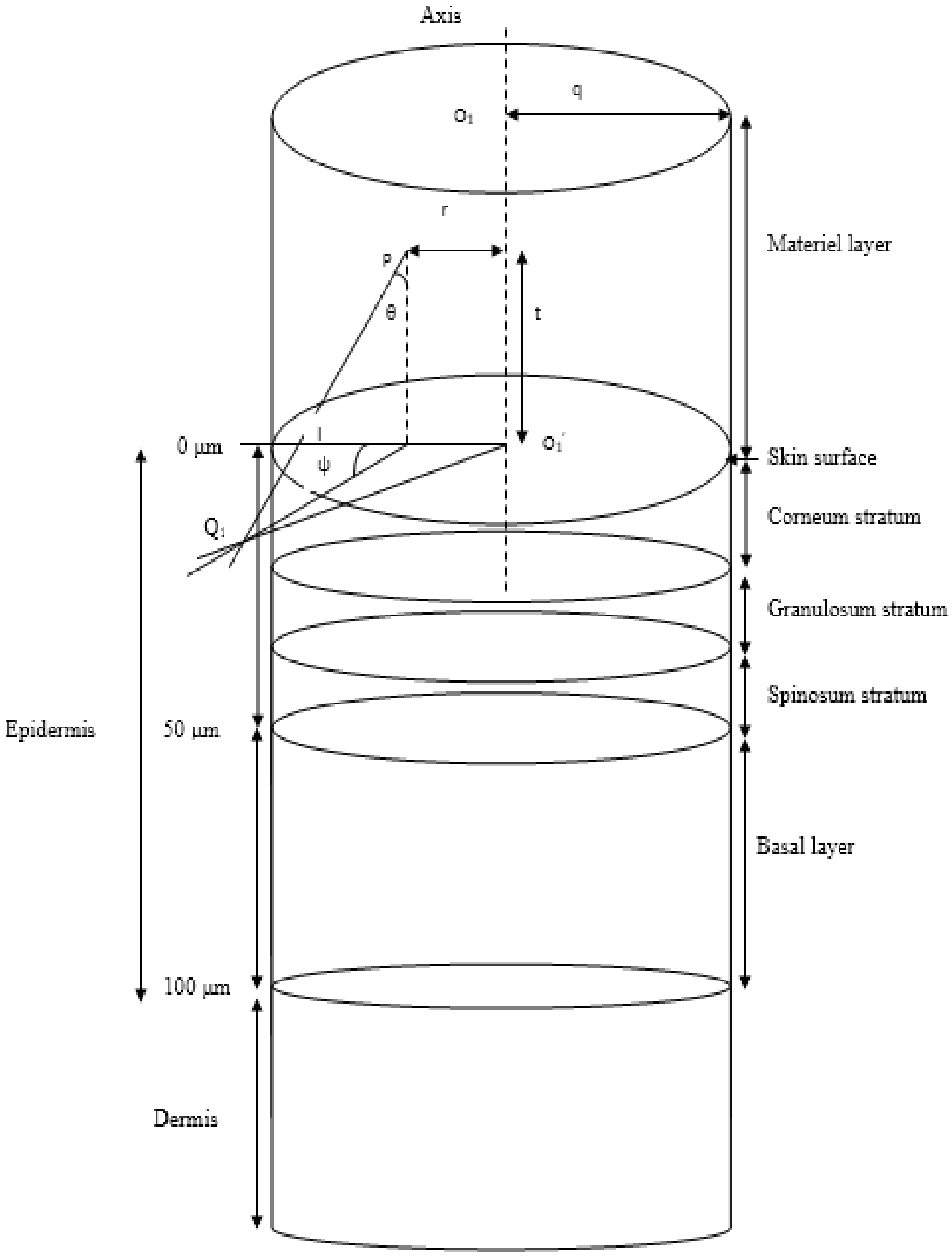


Fig. 3. Arrangement of a cylindrical material layer of 1 cm^2 surface and 1 mm depth deposited on the skin surface of an individual. q is the radius of the material layer. $\overline{PI} = x_j$

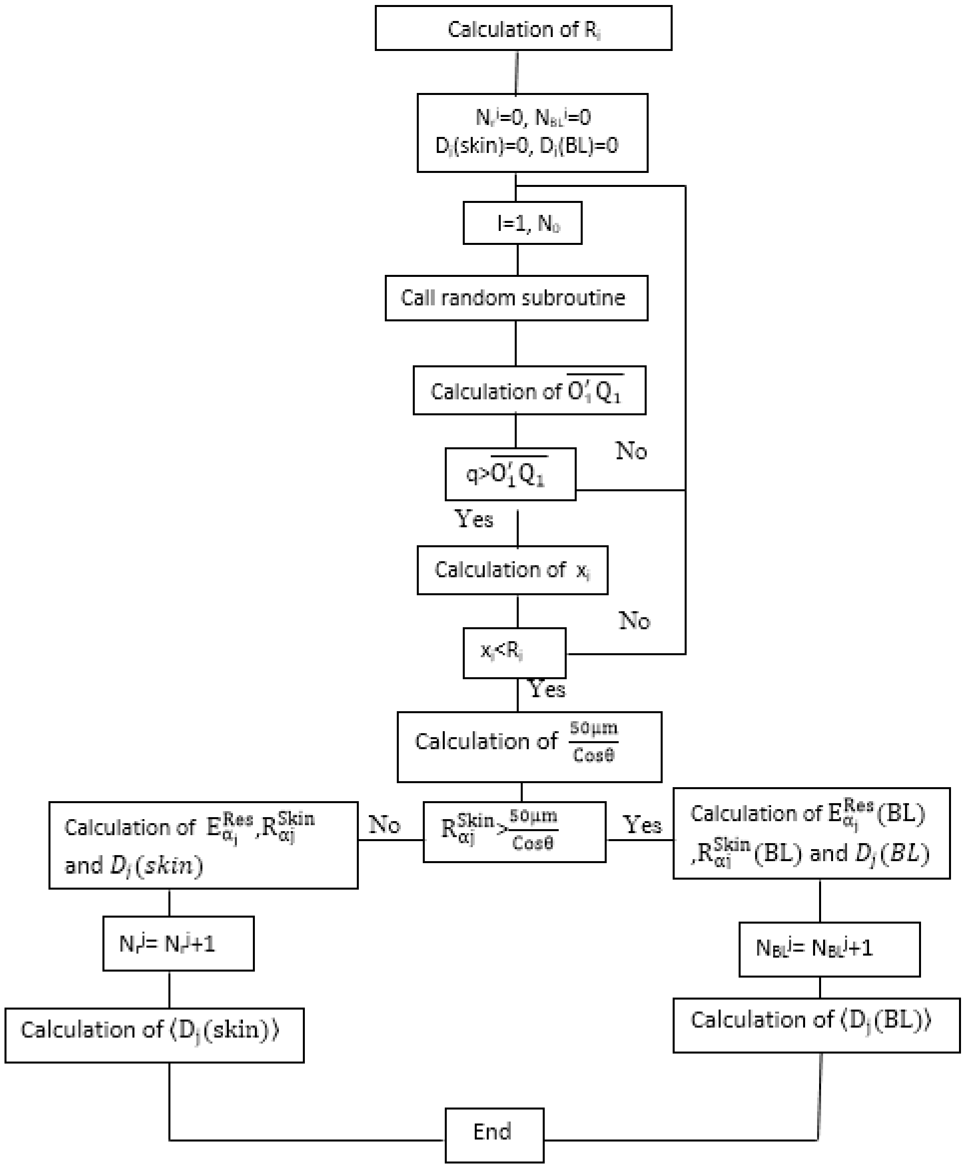


Fig. 4. Flow chart of the AMADS Fortran programme which is used to calculate the mean absorbed dose in skin of individuals from deposition of alpha-emitting radionuclides. We employ the same symbols as in the text. It is therefore self-explanatory. $N_0 = 10^6$ alpha-particles.

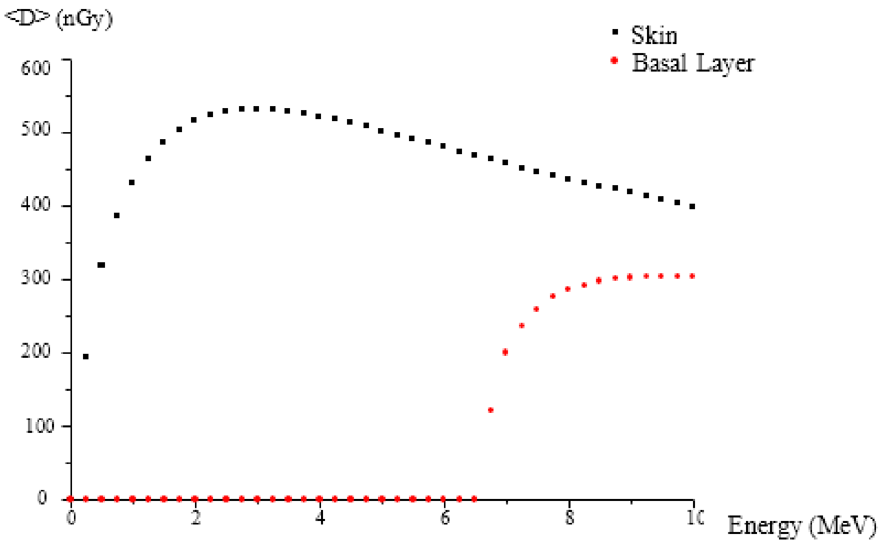


Fig. 5. Variation of the mean absorbed dose in the corneum, granulosum and spinosum strata (skin) and basal layer of the epidermis as a function of alpha-particle initial energy.

RESULTS AND DISCUSSION

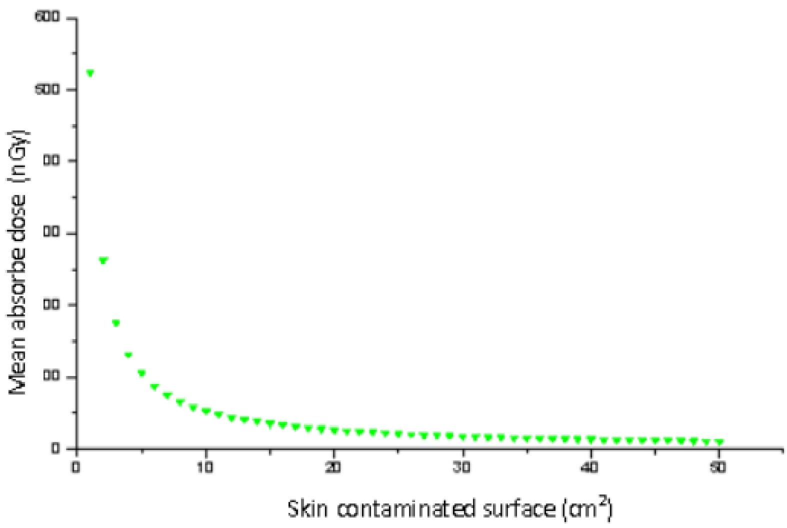
a. Mean absorbed dose to skin from the deposition of alpha-emitting radionuclides

Mean absorbed dose in skin due to alpha-particles generated in a material layer deposited on the skin of an individual was evaluated by using the AMADS (Alpha mean absorbed dose in skin) Monte Carlo code. Data obtained are represented in Fig. 5. The statistical uncertainty of the mean absorbed dose determination is of 0.5 %. It is to be noted that the mean absorbed dose in skin increases, reaches a maximum at E_{α_j} = 3 MeV and decreases when E_{α_j} increases. This is due to the fact that the stopping power of skin for the incident alpha-particles ($E_{\alpha_j}^{\mathrm{Res}}/R_j^{skin}$) (Eq. (6)) increases in the [0-3MeV] energy interval and then decreases for energies larger than 3 MeV. One can also note that only alpha-particles of initial energy greater than 6.75 MeV can reach the sensitive basal layer of the epidermis. Mean absorbed dose in skin was calculated for alpha-particles emitted by different artificial radionuclides used in nuclear medicine. Data obtained are shown in Table 1. Only alpha-particles emitted by ^{212}Po can reach the basal layer of the epidermis (Table 1). Mean absorbed dose was calculated for different contaminated skin surfaces belonging to the [1-50 cm^2]

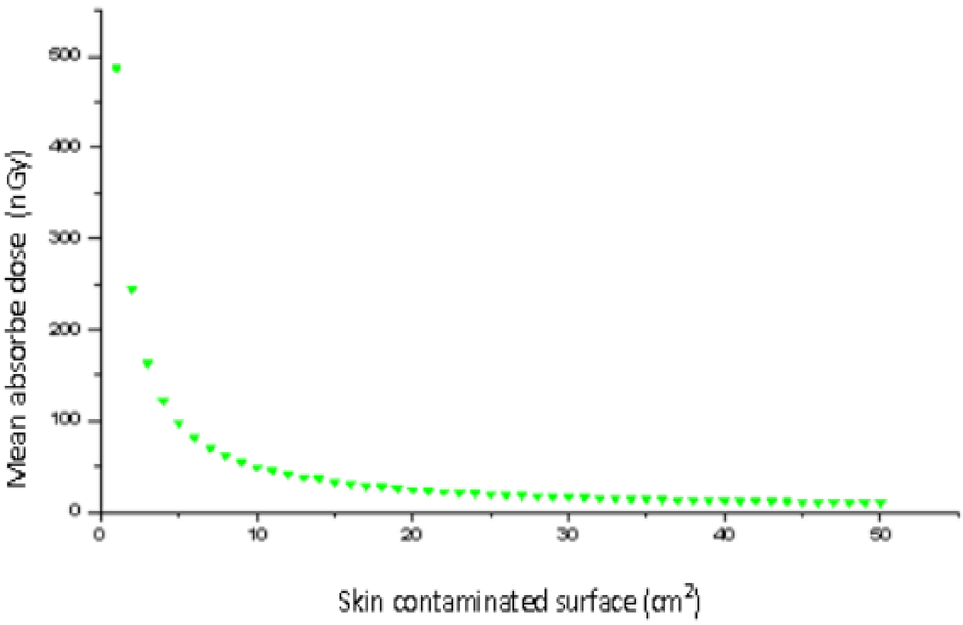
interval from accidental application of various radiopharmaceuticals. An example is given in figure 6 for the ^{149}Tb and ^{225}Ac radionuclides. It is to be noted that the mean absorbed dose decreases when the contaminated skin surface increases.

Table 1. Data obtained for mean absorbed dose in the corneum, granulosum and spinosum strata ($\langle D_j(\text{skin})\rangle$) and basal layer ($\langle D_j(\text{BL})\rangle$) of the epidermis from the application of different alpha-emitting radionuclides.

Radionuclide (j)	$E_{\alpha j}$ (MeV)	Branching ratio (%)	λ_j (s^{-1})	$\langle D_j(\text{skin})\rangle$ (nGy)	$\langle D_j(\text{BL})\rangle$ (nGy)
^{224}Ra	5.68	100	2.2 x 10^{-6}	488.2±0.7	0
^{212}Bi	6.05	35.94	190.63 x 10^{-6}	479.8±0.7	0
^{213}Bi	5.87	2	253.34 x 10^{-6}	483.9±0.7	0
^{225}Ac	5.73	100	0.80 x 10^{-6}	487.1±0.7	0
^{211}At	5.87	41.80	26.74 x 10^{-6}	483.9±0.7	0
^{230}U	5.80	100	0.386 x 10^{-6}	485.5±0.7	0
^{210}Po	5.30	100	0.058 x 10^{-6}	496.8±0.7	0
^{223}Ra	5.979	100	0.704 x 10^{-6}	481.4±0.7	0
^{212}Po	8.78	100	2310490	423.1±0.6	300±1
^{149}Tb	4.00	22.6	46.961 x 10^{-6}	523.5±0.8	0



(a) Terbium 149



(b) Actinium 225

Fig. 6. Variation of the mean absorbed dose in skin as a function of skin contaminated surface from accidental application of ^{149}Tb (a) and ^{225}Ac (b) radionuclides.

Mean absorbed doses in skin due to natural radionuclides (^{238}U, ^{232}Th and ^{222}Rn) from the application of various building material samples were determined. Data obtained are shown in Table 2.

Table 2. Data obtained for the mean absorbed dose in skin ($\langle D_j(\text{skin})\rangle$) due to ^{238}U, ^{232}Th and ^{222}Rn from the application of different building material samples by workers.

Material sample	$\langle D_j(\text{Skin})\rangle$ (10^{-7}Gy)		
	^{238}U	^{232}Th	^{222}Rn
Cement	5.22±0.01	5.25±0.01	4.87±0.01
Marble	5.23±0.01	5.26±0.01	4.96±0.01
Plaster	5.21±0.01	5.24±0.01	4.95±0.01
Clay	5.23±0.01	5.26±0.01	4.97±0.01

In order to validate our calculation method, alpha-particles reaching the surface skin with residual energies given in Annex G of the ICRP Publication 116 [14] and normally incident on skin have been considered. Data obtained by the two methods for the absorbed dose per fluence to the basal layer of skin were found in good agreement with each other (Table 3).

Table 3. Values of mean absorbed dose per fluence in the basal layer of the epidermis obtained by this method and those given by the ICRP [14], for mono-energetic alpha-particles normally incident on skin.

E_{α_j} (MeV)	Mean absorbed dose per fluence (μGy.cm^2)	
	This method	ICRP dose coefficient
6.5	-	0.00111
6.8	0.0201	0.0256
7.0	0.0403	0.0420
7.5	0.0697	0.0752
8.0	0.098	0.103
8.5	0.109	0.128
9.0	0.142	0.150
9.5	0.136	0.140
10.0	0.173	0.180

b. Alpha committed equivalent dose to skin from the application of different material samples

When injecting radiopharmaceutical solutions containing alpha-emitting nuclei to patients some drops may be deposited on their skin. Workers in radiopharmaceutical industry may also be contaminated by alpha-emitting radioisotopes. Committed equivalent dose to skin was determined for different alpha-emitting radiopharmaceuticals from accidental application during 5, 10 and 20 minutes per year for a deposited activity of 20 Bq cm^{-3} (20 drops). Data obtained are shown in Table 4. It is to be noted that committed equivalent dose to skin increases with the application time of radiopharmaceuticals. Even if ^{212}Po emits alpha-particles with energy higher than those emitted by the other radionuclides, committed equivalent dose to skin due this radionuclide is negligible compared with those due to the other radionuclides. This is because ^{212}Po has a half-life lower than those of the other radionuclides (Table 1). One can note that committed equivalent dose due to ^{213}Bi is clearly lower than those due to the other radionuclides. This is due to the fact that ^{213}Bi has a lower alpha disintegration branching ratio (2%) than the other radionuclides. It is obvious, according to Eq. (13) that committed equivalent dose to skin due to a radionuclide j increases when the corresponding deposited activity increases. The maximum committed equivalent dose to skin was found equal to 0.552 mSv cm^{-2} y^{-1}, obtained for accidental application of ^{223}Ra during 20 minutes per year for a deposited activity of 20 Bq cm^{-3} (Table 4), which is smaller than the dose limit for workers which is of 500 mSv cm^{-2} y^{-1} [1].

Table 4. Data obtained for the committed equivalent dose to the corneum, granulosum and spinosum strata ($H_{skin}(j)$) and basal layer ($H_{BL}(j)$) of the epidermis from accidental application, during 5, 10 and 20 minutes, of various radiopharmaceuticals. We considered a volume of 20 drops placed on the skin of individuals corresponding to an activity of 20 Bq/cm^3. The relative uncertainty is of 0.5 %.

Radionuclide (j)	$H_{Skin}(j)$ (µSv/cm^2/y) t_A=5 min	$H_{Skin}(j)$ (µSv/cm^2/y) t_A=10 min	$H_{Skin}(j)$ (µSv/cm^2/y) t_A=20 min	$H_{BL}(j)$ (µSv/cm^2/y) t_A=5 min	$H_{BL}(j)$ (µSv/cm^2/y) t_A=10 min	$H_{BL}(j)$ (µSv/cm^2/y) t_A=20 min
^{224}Ra	129.4±0.2	258.7±0.4	517.02±1.03	0	0	0
^{212}Bi	49.0±0.1	95.2±0.2	180.19±0.36	0	0	0
^{213}Bi	2.60±0.01	5.00±0.01	9.31±0.02	0	0	0
^{225}Ac	130.8±0.3	261.7±0.5	523.26±1.05	0	0	0
^{211}At	56.2±0.1	111.9±0.2	222.07±0.44	0	0	0
^{230}U	133.0±0.3	265.8±0.5	531.48±1.06	0	0	0
^{210}Po	118.5±0.2	236.9±0.5	473.89±0.95	0	0	0
^{223}Ra	138.1±0.3	276.2±0.5	552.34±1.10	0	0	0
^{149}Tb	18.49±0.04	36.72±0.05	72.42±0.14	0	0	0
^{212}Po	(3.23±0.01)10^{-7}	(3.23±0.01)10^{-7}	(3.23±0.01)10^{-7}	(2.29±0.01)10^{-7}	(2.29±0.01)10^{-7}	(2.29±0.01)10^{-7}

Alpha-activities per unit volume due to ^{238}U, ^{232}Th and ^{222}Rn were measured inside different building material samples by using a method based on using CR-39 and LR-

115 II solid state nuclear track detectors (SSNTDs) [19]. Data obtained are shown in Table 5. The uncertainty of the ^{238}U, ^{232}Th and ^{222}Rn concentrations determination is of the order of 8 %. Committed equivalent doses to the skin of individuals due to ^{238}U, ^{232}Th and ^{222}Rn from the application of different building material samples by workers were evaluated. Data obtained are shown in Table 5. The uncertainty of the committed equivalent doses determination is of 9 %. It is to be noted that committed equivalent doses to skin due to ^{238}U, ^{232}Th and ^{222}Rn from the application of clay are clearly higher than those resulting from the application of the other building material samples. This is because clay shows higher ^{238}U, ^{232}Th and ^{222}Rn alpha-activities than the other building material samples. One can also note that committed equivalent dose to skin due to ^{222}Rn is clearly lower than those due to ^{238}U and ^{232}Th from the application of the studied building material samples. This is due to the fact that ^{222}Rn has a lower half-life (3.82 d) than those of ^{238}U and ^{232}Th (Eq. (13)). A maximum value of the total committed equivalent dose to skin due to ^{238}U, ^{232}Th and ^{222}Rn was found equal to 0.16 mSv cm^{-2} y^{-1}, obtained from the application of clay by workers (2016 hours per year) (Table 5), which is smaller than the dose limit for workers which is of 500 mSv cm^{-2} y^{-1} [1].

Table 5. Table 5. Committed equivalent doses to the epidermis of skin due to ^{238}U,^{232}Th and ^{222}Rn from the application of different building material samples.

Building material sample (application time)	$A_c(^{238}U)$ (Bq.m^{-3})	$A_c(^{232}Th)$ (Bq.m^{-3})	$A_c(^{222}Rn)$ (Bq.m^{-3})	$H_{Skin}(^{238}U)$ (μSv.cm^{-2}.y^{-1})	$H_{Skin}(^{232}Th)$ (μSv.cm^{-2}.y^{-1})	$H_{Skin}(^{222}Rn)$ (μSv.cm^{-2}.y^{-1})
Cement (8h/day)	165±10	165±10	165±10	7.90± 0.48	7.48±0.45	0.78±0.05
Marble (8h/day)	235±14	205±13	235±12	13.78± 0.82	11.39±0.72	1.26±0.06
Plaster (8h/day)	82±5	53±4	82±5	11.36±0.69	6.95±0.52	1.03±0.06
Clay (8h/day)	998±60	647±39	998±60	91.86±5.52	56.42±3.40	8.42±0.51

4. CONCLUSION

It has been shown by this study that by using a Monte Carlo computer code, one can determine mean absorbed dose in skin due to alpha-emitting radionuclides from the application of various artificial and natural material samples. A new dosimetric model was described for determining committed equivalent dose to skin due to alpha-emitting nuclei from the application of various radiopharmaceutical and building material samples. It is concluded that committed equivalent dose to skin is influenced by the disintegration branching ratio, half-life of the radionuclide, deposited activity, contaminated skin surface and application time of the material samples. Therefore, medical personnel in hospitals as well as workers in the radiopharmaceutical industry should avoid any contamination by alpha-emitting radionuclides when handling radiopharmaceuticals. Also workers in building material factories should protect their skin from building material dusts to avoid any enhancement of exposure to alpha radiation. This dosimetric method is a good tool for assessing alpha radiation doses due to the cutaneous application of diverse products such as creams, medical drugs, plant oils…

5. ACKNOWLEDGMENTS

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REFERENCES

[1] International Commission on Radiological Protection, 1990, “Recommendations of the International Commission on Radiological Protection”, Publication 60, Ann. ICRP 21 (1-3).

[2] Akudugu, J. M., and Howell, R. W., 2012, “A method to predict response of cell populations to cocktails of chemotherapeutics and radiopharmaceuticals: Validation with daunomycin, doxorubicin, and the alpha particle emitter ^{210}Po”, Nucl. Med. Biol., 39, pp. 954-961.

[3] Sgouros, G., 2008, “Alpha-particles for targeted therapy”, Adv. Drug. Delivery Rev., 60, pp. 1402-1406.

[4] Wesley, J. N., McGee, E. C., Garmestani, K., Brechbiel, M. W., Yordanov, A. T., Wu, C., Gansow, O. A., Eckelman, W. C., Bacher, J. D., Flyn, M., Goldman, C. K., McLin, M., Schwartz, U. P., Jackson-White, T., Phillip, C. M., Decker, J., and Waldmann, T. A., 2004, “Systemic radioimmunotherapy using a monoclonal antibody, anti-Tac directed toward the alpha subunit of the IL-2 receptor armed with the α-emitting radionuclides ^{212}Bi or ^{211}At”, Nucl. Med. Biol., 31, pp. 357-364.

[5] McDevitt, M. R., Barendswaard, E., Ma, D., Lai, L., Curcio, M. J., Sgouros, G., Ballangrud, A. M., Yang, W. H., Finn, R. D., Pelligrini, V., Geerlings, M. W., Lee, Jr. M., Brechbiel, M. W., Bander, N. H., Cordon-Cardo, C., and

Scheinberg, D., 2000, "An α-particle emitting antibody ([^{213}Bi] J591) for radioimmunotherapy of prostate cancer", Cancer Res., 60, pp. 6095-60100.

[6] Miederer, M., Sceinberg, D. A., and McDevitt, M. R., 2008, "realizing the potential of the actinium-225 radionuclide generator in targeted alpha particle therapy applications", Adv. Drug. Delivery Rev., 60, pp. 1371-1382.

[7] Supiot, S., Thillays, F., Rio, E., Mahé, M. A., Barbet, F. J., Kraeber-Bdéré, F., and Chérel, M., 2007, "Le point sur les avancées récentes de la radio-immunothérapie alpha. Alpha-radioimmunotherapy: a review of recent developments", Can. Rad., 11, pp. 252-259.

[8] Misdaq, M. A., and Amghar, A., 2005, "Radon and thoron from various marble materials: impact on the workers", Rad. Meas., 39, pp. 421-430.

[9] Misdaq, M.A, and Touti, R., 2012, "Annual Committed effective dose from olive oil (due to ^{238}U, ^{232}Th and ^{222}Rn) estimated for members of the public from ingestion and skin application", Health Phys., 102 (3), pp. 335-345.

[10] Misdaq, M. A., and Outeqablit, K., 2010, "Determination of committed effective doses to skin due to ^{238}U, ^{232}Th and ^{222}Rn from the application of various Moroccan black soap (Saboun Beldi) samples by members of the general public", Radiat. Prot. Dosim. 142 (2), pp. 136-145.

[11] Misdaq, M. A., Ghilane, M., Ouguidi, J., and Outeqablit, K., 2012, "Radiation doses to individuals due to ^{238}U, ^{232}Th and ^{222}Rn from the immersion in thermal waters and to radon progeny from the inhalation of air inside thermal stations", Radiat. Environ. Biophys., 51, pp. 375-389.

[12] Misdaq, M. A., and Matrane, A., 2016, "^{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", Nucl. Sci. Tech., 27: 51, pp. 30-41.

[13] International Commission on Radiological Protection, 2007, "Recommendations of the International Commission on Radiological Protection", ICRP Publication 103, Ann. ICRP 37 (2-4).

[14] International Commission on Radiological Protection, 2010, "Recommendations of the International Commission on Radiological Protection", ICRP Publication 116, Ann ICRP 40 (2-5).

[15] Biersack, J. P., and Ziegler, J. F., 1998, IBM Research, *TRIM* Version 98.

[16] Rzama, A., Erramli, H., Misdaq, M. A., 1994, "A new calculation method adapted to the experimental conditions for determining samples ɤ-activities

induced by 14 MeV neutrons", Nucl. Instr. Meth. Phys. Res., B 93, pp. 464-468.

[17] Misdaq, M. A., and Merzouki, A., 2002, "Determination of the gamma-ray effective dose from different cylindrical radioactive solution sources in a biological tissue by using Monte Carlo calculations", Radiopro., 37 (2), pp. 149-160.

[18] Rzama, A., Misdaq, M. A., Erramli, H., Blondiaux, G., Isabelle, D. B., and Bajard, J. C., 1994, "Study of gamma-photon self-absorption in stainless steel samples by experimental and calculational methods", J. Radioanal. Nucl. Chem. 183 (2), pp. 409-420.

[19] Misdaq, M. A., Khajmi, H., Aitnouh, F., Berrazzouk, S., and Bourzik, W., 2000, "A new method for evaluating uranium and thorium contents in different natural material samples by calculating the CR-39 and LR-115 type II SSNTD detection efficiencies for the emitted α-particles", Nucl. Instr. Meth. Phys. Res. B171 (3), pp. 350-359.