MONTE CARLO CALCULATION OF DOSE RATE CONVERSION FACTORS FOR EXTERNAL EXPOSURE TO PHOTON EMITTERS IN SOIL

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***Abstract*—The dose rate conversion factors $\dot{D}_{CF}$ (absorbed dose rate in air per unit activity per unit of soil mass, nGy h^{-1} per Bq kg^{-1}) are calculated 1 m above ground for photon emitters of natural radionuclides uniformly distributed in the soil. Three Monte Carlo codes are used: 1) The MCNP code of Los Alamos; 2) The GEANT code of CERN; and 3) a Monte Carlo code developed in the Nuclear Technology Laboratory of the Aristotle University of Thessaloniki. The accuracy of the Monte Carlo results is tested by the comparison of the unscattered flux obtained by the three Monte Carlo codes with an independent straightforward calculation. All codes and particularly the MCNP calculate accurately the absorbed dose rate in air due to the unscattered radiation. For the total radiation (unscattered plus scattered) the $\dot{D}_{CF}$ values calculated from the three codes are in very good agreement between them. The comparison between these results and the results deduced previously by other authors indicates a good agreement (less than 15% of difference) for photon energies above 1,500 keV. Antithetically, the agreement is not as good (difference of 20–30%) for the low energy photons.**

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Key words: Monte Carlo; dose, external; gamma radiation; dose, absorbed

INTRODUCTION

Dose rate conversion factors for external gamma exposure to photon emitters from contaminated soil are very important for radiation physicists and therefore have been studied for more than three decades. The literature on the subject is extensive and in the following discussion only some of the relevant references are considered. The first calculations have been performed by Beck and de Planque (1968) and Beck et al. (1972). They used the polynomial expansion matrix equation method for solving the soil/air transport problem to calculate the exposure rates 1 m above ground level for distributed sources of γ emitters in soil. The dose rates in air were calculated for γ energies (from 0.25 to 2.75 MeV) for radionuclides commonly found in the natural environment. Conversion factors have also been calculated by Kocher and Sjoreen (1985) using the point-kernel integration method, in which it is assumed that soil is an infinite scattering medium for photons, and employed buildup factors to account for doses from uncollided and scattered photons. Soil properties, including the photon cross-sectional data, were approximated by those of concrete. All dose conversion factors were calculated as usual for a point receptor located 1 m above the ground. In the present decade Monte Carlo techniques have been used almost exclusively in order to calculate absorbed dose rate in air. Chen (1991) developed a Monte Carlo algorithm to track the photon transport equation in the soil/air medium. One of the most complete studies of air kerma rate per unit of soil mass for natural sources uniformly distributed in the ground is performed by Saito and Jacob (1995). The photon transport calculations were carried out using the Monte Carlo program YURI (Saito and Moriuchi 1985), which has been verified through comparison with various experimental and theoretical data. The results obtained from this work are considered as reference values (ICRU 1994).

A question which has to be answered is whether this research and in particular the accuracy of the calculations performed up to now need any further investigation. It is our view that the theoretical calculations of air kerma rates have reached a very mature stage. However, the development of new personal computers with always increasing computation capabilities makes possible the use by small research groups of "heavy" general purpose Monte Carlo codes like the MCNP code or the GEANT code of CERN. This becomes extremely helpful in cases where published data do not match the situation of interest absolutely. To our knowledge, the only calculations with these codes of air kerma rates are the following: The MCNP code has been used by Saito and Jacob (1995) for calculations of air kerma rates for a plane surface source and also for a plane source at a depth where the air kerma is attenuated by one order of

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magnitude compared with that for the surface plane source. The GEANT code has been used very recently by Likar et al. (1998) for calculations of absorbed dose rates in air 1 m above soil for uniform distribution of photon emitters in soil. As will be discussed in the following sections, the geometry used in that work is not the most appropriate for the determination of the dose rate coefficients due to the "huge detector" used. It is understandable, that a smaller "detector" needs much more computing time, a problem that we had to face in the present work. The use of such codes gives also the possibility to test them in relative simple health physics problems.

In the present work we calculated the gamma absorbed dose rate in air 1 m above ground for uniform distribution of natural radionuclides in soil with three different Monte Carlo codes: 1) The MCNP code (Briesmeister 1993); 2) the GEANT code of CERN (GEANT 1993); and 3) a Monte Carlo code developed in the Nuclear Technology Laboratory of the Aristotle University of Thessaloniki, the so-called "MC" code. The aim of the present work is to compare and validate the results reached from the three different Monte Carlo codes.

CALCULATION PROCEDURE

The absorbed gamma dose rate in air $\dot{D}$ (nGy h^{-1}) at a point 1 m above soil for uniform distribution of a gamma-ray emitter of photon energy E_0 can be calculated easily, as it will be shown in the following chapter, if the photon flux energy distribution $\phi(E)$ is known at the given position. The photon flux is comprised by two parts: 1) The unscattered flux which is due to photons of energy E_0 reaching the given position without any interaction with the soil and the air above; and 2) The scattered flux which is due to photons of energies $0 < E < E_0$ reaching the given position after scattering mainly in soil. Although the calculation of the unscattered flux is straightforward, the calculation of the scattered flux is more complex and needs the solution of the transport equation or use of Monte Carlo transport codes. A short description of the Monte Carlo codes and the implementations of the simulations used are given below.

The MCNP code

The Los Alamos National Laboratory MCNP code is a general purpose Monte Carlo radiation transport code that can numerically simulate neutron, photon, and electron transport. For photons, the code takes account of incoherent and coherent scattering, the possibility of fluorescent emission after photoelectric absorption, absorption in pair production with local emission of annihilation radiation, and bremsstrahlung. The user supplied information required by MCNP contains information about specific items such as the geometry and the materials characterizing the environment that will be simulated, the source distribution of the radiation, and finally the type of the answers desired (e.g., energy distribution of photon flux in a given position).

The geometry of our calculation using the MCNP code is simple and is shown in Fig. 1. The different components incorporated in the simulation are

- *Air:* Simulated as a cylinder of 40 m radius and 1.5 m height with atomic composition of 79% N and 21% O and a density of 0.00129 g cm^{-3};
- *Soil:* Simulated as a cylinder of 40 m radius and 1 m depth with atomic composition of 7.3% Al, 2.1% C, 1.4% Ca, 3.9% Fe, 0.9% K, 0.5% Mg, 0.1% N, 0.6% Na, 50.1% O, 32.7% Si, 0.4% Ti and a density of 1.3 g cm^{-3} (Lindsay 1979). As it will be shown in the next chapter the radius of 40 m and the soil depth of 1 m are sufficient in order to consider the emission photon geometry as half space geometry. In addition, it is known (Saito and Jacob 1995) that the atomic composition of soil is not a critical parameter of the flux energy distribution. We obtained practically the same results for two different atomic compositions: the atomic composition presented here and the one given by Beck et al. (1972).

The source distribution of radiation incorporated in the MCNP code is photon emitters uniformly distributed in the soil with 8 different photon energies between 200 and 3,000 keV. The number of photons emitted in each of these 8 simulations was fifty million.

For the determination of the photon flux energy distribution at 1 m above soil two virtual detectors were used: 1) The point detector, which is a standard tally of the MCNP code, gives the energy distribution of the photon flux directly, normalized per starting photon; and 2) A sphere of radius of 40 cm with its center located at 1 m above soil. The MCNP code counts the number of photons as a function of their energy crossing the surface of the sphere and calculates the photon fluence energy distribution, normalized per starting photon, which can be easily transformed into flux per unit activity per unit of soil mass (γ cm^{-2} s^{-1} per Bq kg^{-1}). Both virtual detectors are located on the Z axis of the cylinder of radius of 40 m. Special detectors were also used in some cases where the deposited energy of photons per unit mass of air is directly computed.

The GEANT code

The GEANT code was developed by the Application Software Group at CERN. The GEANT program describes the passage of elementary particles through matter. The principal applications of the code are 1) the

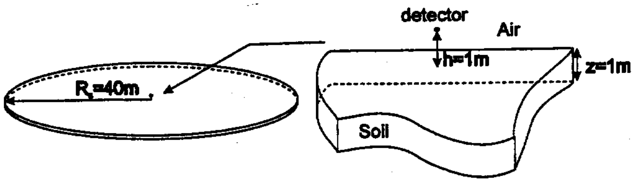

Fig. 1. Simulated geometry by the MCNP code.

RESULTS AND DISCUSSION

Photon flux energy distribution

A typical simulated photon flux energy distribution per 10 keV step as calculated by the point detector of the MCNP code for photons of energy 1,500 keV emitted from the soil is shown in Fig. 2a. The photon emitters are uniformly distributed in the soil and the photon flux is normalized per starting photon and per second. The simulated photon flux as calculated by the volume detector (sphere of radius 40 cm) is presented in Fig. 2b. In both spectra the flux due to unscattered photons (peak) and the continuum due to the photon flux energy distribution of the scattered photons can be clearly observed. The comparison between the two simulated fluxes indicates that both detectors give about the same results, the statistics, however, obtained with the point detector seem to be much better than those of the volume detector. This is due to the fact that a point detector does not rely on particle simulation by random walk as the volume detector. Point detector is a Monte Carlo method wherein the simulation of particle transport from one place to another is deterministically short-circuited (Briesmeister 1993).

In order to check if the emission photon geometry is a half space geometry the unscattered flux was calculated with the MCNP code for different photon energies, soil radii, and soil depth combinations. Fig. 3 presents the unscattered flux per unit activity and per soil mass (Bq kg^{-1}) (assuming a fractional yield equal to 1) as function of the soil depth and in Fig. 4 as function of the soil radius. From these two figures it is clear that the emission photon geometry can be considered as a half space geometry.

A test of the accuracy of our Monte Carlo results is the comparison of the unscattered flux obtained by the three Monte Carlo codes with the numerical solution of eqn (3) (Beck et al. 1972) calculating the unscattered flux 1 m above soil per activity per unit mass for photon emitters uniformly distributed in the ground (Fig. 5):

$$\phi = -S_0 \times \frac{1}{2 \cdot \rho_s \cdot \left(\frac{\mu_s}{\rho_s}\right)} \times \int_0^1 e^{-\left(\frac{\mu_a}{\rho_a}\rho_a\right)\frac{h}{\omega}} \times \left(e^{-\left(\frac{\mu_a}{\rho_a}\rho_a\right)\frac{z}{\omega}} - 1\right) d\omega \quad (3)$$

where S_0 the intensity of the source in photons $\text{cm}^{-3}\ \text{s}^{-1}$;

z the depth beneath the surface, where the source is distributed;

$\omega = \cos\theta$;

ρ_s = soil's density;

μ_s/ρ_s = mass attenuation coefficient in soil;

ρ_a = air's density;

μ_a/ρ_a = mass attenuation coefficient in air; and

h = detector's distance from the soil.

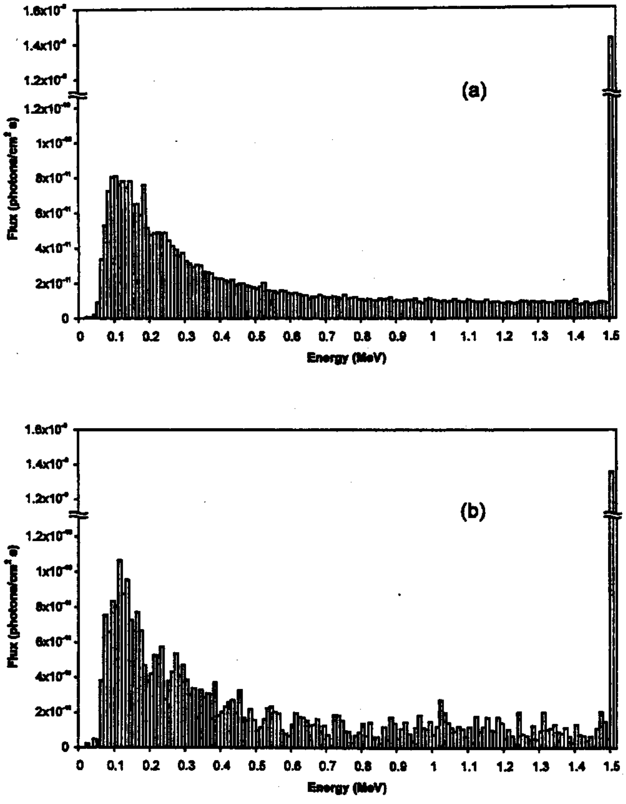

Fig. 2. Photon flux at 1 m above soil surface as deduced by the MCNP code with (a) a point detector and (b) a volume one for photon emitter of energy of 1,500 keV uniformly distributed in the soil. The flux is normalized per emitted photon per second.

Eqn (3) can be solved numerically; in the present work it was solved with Mathcad 7[‡] package using Romberg's algorithm. Table 1 presents the results of the unscattered flux 1 m above soil per activity per unit mass for different photon energies (assuming a fractional yield equal to 1), calculated by the three Monte Carlo codes, by Beck et al. (1972) and by Mathcad 7 package. The comparison between the results indicates that all Monte

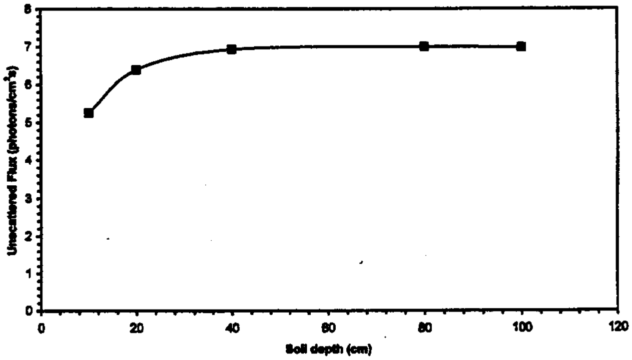

Fig. 3. Unscattered flux normalized per emitted photon of energy of 1,500 keV (per cm³ and per second) as a function of soil's depth.

[‡] Mathcad 7, Mathsoft, Inc., 101 Main Street, Cambridge, MA 02142-1521, USA.

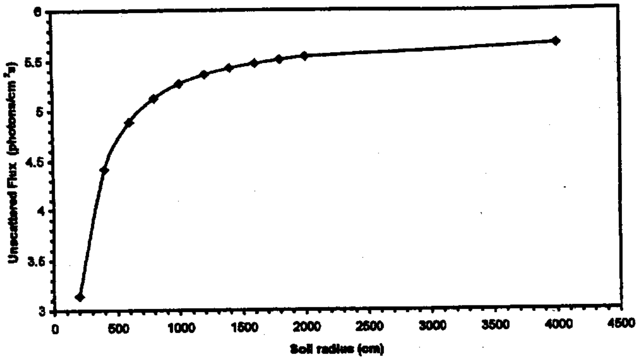

Fig. 4. Unscattered flux normalized per emitted photon of energy of 1,000 keV (per cm^3 and per second) as a function of soil's radius.

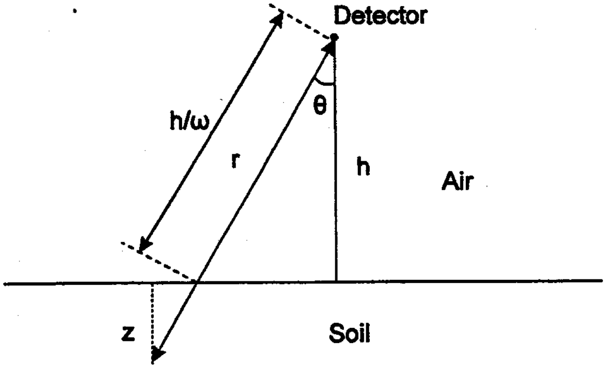

Fig. 5. Theoretical model (eqn 3) used in calculating unscattered flux.

Carlo codes calculate very well the unscattered radiation, and in particular the difference between the results obtained with the MCNP code and by the Mathcad 7 package is less than 2%. It is worth mentioning that the unscattered flux was calculated using Mathcad in order to achieve a better accuracy than Beck did. The good agreement between the unscattered flux calculated by MCNP and by Mathcad indicates that the simulation parameters used (geometry, tallies, materials) by MCNP are correct.

Dose rate conversion factors

Knowing the photon flux energy distribution, the dose rate conversion factor $\dot{D}_{CF}$ (absorbed dose rate in air per unit activity per unit of soil mass, nGy h^{-1} per Bq kg^{-1}) for a photon emitter of energy E_0 uniformly distributed in the ground can be calculated easily by

$$\dot{D} = \sum_{i=1}^{n} \frac{\mu_\alpha}{\rho}(E_i)\, E_i \phi_i(E_i)\,, \tag{4}$$

where E_i is the average energy of band i, $\phi_i(E_i)$ is the photon flux per unit activity per unit of soil mass in energy band i, and $\mu_\alpha/\rho(E_i)$ is the mass absorption coefficient for air at energy band i. The summation starts at the energy band $i = 1$ (10–20 keV) proceeds with a step of 10 keV and ends at the energy band $i = n$ containing the photon energy of E_0.

The MCNP code offers the possibility of using a detector that calculates directly the energy deposition in a given volume. For photon emitters uniformly distributed in the ground of photon energy 1,500 keV the dose rate conversion factor $\dot{D}_{CF}$ was found to be 0.369 nGy h^{-1} per Bq kg^{-1} (assuming a fractional yield equal to 1). Calculating first the photon flux and then using eqn (4), $\dot{D}_{CF}$ was found equal to 0.354 nGy h^{-1} per Bq kg^{-1}. The comparison between the two values (difference of about 4%) indicate that, as it should, the dose rate conversion factors are independent of the method used for their extraction.

Table 2 presents the dose rate conversion factor $\dot{D}_{CF}$ calculated by the three Monte Carlo codes for different photon energies. In the same table for comparison reasons, previous results as deduced from the work of Kocher and Sjoreen (1985), Chen (1991), Likar et al. (1998), and Saito and Jacob (1995) are presented. It is clear that the differences between the results obtained from the three Monte Carlo codes of the present work are small (between 1% and 9%) for all photon energies. It is our view that from the three codes the most accurate results are obtained by the MCNP code. This is strongly supported by Table 1 where the best agreement between the results obtained for the unscattered radiation by the

Table 1. Unscattered flux obtained by the Monte Carlo codes of the present work, numerical solution of the eqn (3) and as calculated by Beck et al. (1972)

	γ cm^{-2} s^{-1} per emitted photon g^{-1} s^{-1}				
Energy (keV)	GEANT	MCNP	MC	Mathcad	Beck
200	4.33	3.63	4.31	3.67	3.91
400	5.14	4.86	5.86	4.92	4.93
800	7.22	6.67	6.91	6.81	6.74
1,000	8.18	7.45	7.59	7.56	7.53
1,500	9.94	9.21	9.84	9.36	9.27
2,000	10.95	10.72	10.75	10.90	10.81
2,500	12.66	12.10	12.10	12.03	12.17
3,000	13.74	13.21	13.08	13.44	13.74

Table 2. Conversion factors obtained by the Monte Carlo codes of the present work and as deduced by Kocher and Sjoreen (1985), Chen (1991), Likar et al. (1998), Saito and Jacob (1995).

	nGy h^{-1} per emitted photon kg^{-1} s^{-1}						
Energy (keV)	MCNP	GEANT	MC	Kocher	Chen	Likar	Saito
200	0.0282	0.0308	0.0304	0.0363	0.0380	0.0414	0.0420
400	0.0743	0.0768	0.0791	0.1015	0.0997	0.0985	
800	0.1733	0.1841	0.1790	0.2205	0.2135	0.2070	
1000	0.2228	0.2364	0.2317	0.2765	0.2614	0.2660	0.2793
1500	0.3539	0.3740	0.3559	0.4139	0.4053	0.3970	0.4128
2000	0.4857	0.5018	0.4779	0.5498	0.5662	0.5410	0.5792
2500	0.6271	0.6557	0.6212			0.6590	
3000	0.7554	0.7911	0.7460	0.8071	0.7979	0.7370	0.8603

three Monte Carlo codes and the direct calculation with the Mathcad 7 package is for the MCNP code. This is probably due to the use of the point detector by the MCNP. The point detector uses the most complicated variance reduction techniques, which are partially deterministic methods. These techniques circumvent the normal random walk process by using deterministic-like techniques such as next event estimators. However, they must be used with caution and particularly in cases where there is a source or high scattering medium near the detector. This is not our case where the point detector is surrounded by air.

The comparison between the results obtained in the present work by the three codes with the results obtained by other authors indicates a good agreement (less than 15% of difference) for photon energies above 1,500 keV. However, the agreement is not as good (difference of 20–30%) for the low energy photons. Moreover, it can be seen that the values proposed in the current research are always lower than the ones proposed by the other authors. A possible explanation for that could be the use of different energy bining in the calculation of the flux spectrum. The energy bin in the present work, as mentioned before, was selected to be 10 keV—A value that is considered to be fairly low and can estimate accurately the absorbed dose rate afterwards. Unfortunately, there are no data for the bining used by other authors in order to be positive that this is the reason of the difference among the results. Bad statistics could be another reason for this discrepancy although it does not justify the bias of the values. In our case we traced 50 × 10^6 photons while others (e.g., Chen) traced only 10,000 photons. The precision of the results given in this work is more than 95% for each energy bin of the flux spectrum. That means much better precision for absorbed dose rate estimations. It has to be mentioned that precision refers to the error or uncertainty estimates for the results of Monte Carlo and not to the accuracy. Also, the materials used in the present research are different from the ones other authors used. For example, Kocher and Sjoreen used concrete instead of soil for their computations. Moreover, the computation methods used are different. Kocher and Sjoreen used the point kernel method while Beck used a polynomial solution to Boltzman's transfer equation. Finally, it is interesting to compare the results deduced from the present work by the GEANT code with those obtained by the recent work of Likar et al. (1998) using the above mentioned code. Despite the fact that they use a completely different geometry with a huge detector (2 km), which probably makes some problems in their calculation (their value at 3 MeV is underestimated in comparison with the extrapolation at this energy deduced from their values of 0.2 MeV-2 MeV), the difference between the results is 7%–26%.

Table 3 presents the dose rate conversion factors (absorbed dose rate in air per unit activity per unit of soil mass, nGy h^{-1} per Bq kg^{-1}) 1 m above ground, due to natural radionuclides and to ^{137}Cs (from the Chernobyl accident) distributed uniformly in the ground, as extracted from the three Monte Carlo codes. The intensity (photon emission probability per 100 decays) is also presented for the photopeaks of each radionuclide. Although the most important peaks (intensities larger than 1%) are presented in this table, the total dose rate conversion factor for each series takes into account all known peaks [approximately 300 peaks for each series (Chu et al. 1999)]. As expected (from Table 2), the differences between the dose rate conversion factors obtained from the three codes are small (less than 5%).

In Table 4 the dose rate conversion factors of specific radionuclides presented in Table 3 are compared with previous results of Saito and Jacob (1995) and Beck et al. (1972). The differences between the results of this research and the results obtained by other researchers are 18% for uranium series, 15% for thorium series, and 10% for ^{40}K.

CONCLUSION

The dose rate conversion factors (absorbed dose rate in air per unit activity per unit of soil mass, nGy h^{-1} per Bq kg^{-1}) were calculated 1 m above ground for photon emitters of natural radionuclides uniformly distributed in the soil. Three Monte Carlo codes were used: 1) the MCNP code of Los Alamos; 2) the GEANT code of CERN; and 3) a Monte Carlo code developed in the Nuclear Technology Laboratory of the Aristotle University of Thessaloniki. All codes and particularly the MCNP calculate very well the absorbed dose rate in air due to the unscattered radiation. The difference between

Table 3. Conversion factors for different radionuclides estimated by the Monte Carlo codes of the present work. Only the most important peaks are presented here. However all the known peaks are taken into account for the computation of the total conversion factor of the series.

Nuclide	Energy	Percentage per disintegration	nGy h^{-1} per Bq kg^{-1}		
			MCNP	MC	GEANT
^{232}Th series					
^{228}Ac	129.1	3.03	0.00036	0.00040	0.00044
^{228}Ac	154.2	1.02	0.00018	0.00020	0.00021
^{228}Ac	209.4	4.71	0.00143	0.00154	0.000155
^{228}Ac	270.3	3.9	0.00173	0.00185	0.00183
^{228}Ac	328	3.48	0.00201	0.00214	0.00210
^{228}Ac	338.4	12.4	0.00746	0.00795	0.00777
^{228}Ac	409.4	2.31	0.00177	0.00188	0.00183
^{228}Ac	463	4.8	0.00430	0.00455	0.00450
^{228}Ac	562.3	1.02	0.00116	0.00122	0.00123
^{228}Ac	755.2	1.14	0.00185	0.00191	0.00196
^{228}Ac	794.8	5.01	0.00862	0.00891	0.00915
^{228}Ac	835.6	1.88	0.00342	0.00354	0.00364
^{228}Ac	840.2	1.02	0.00187	0.00193	0.00199
^{228}Ac	911.1	30	0.06024	0.06249	0.06395
^{228}Ac	964.6	5.64	0.01207	0.01254	0.01281
^{228}Ac	968.9	18.1	0.03894	0.04046	0.04132
^{228}Ac	1,459.2	1.08	0.00371	0.00373	0.00392
^{228}Ac	1,495.8	1.09	0.00385	0.00387	0.00406
^{228}Ac	1,587.9	3.84	0.01448	0.01449	0.01522
^{228}Ac	1,620.6	1.51	0.00582	0.00582	0.00611
^{228}Ac	1,630.4	2.02	0.00784	0.00783	0.00823
^{212}Bi	727.3	6.66	0.01031	0.01071	0.01096
^{212}Bi	785.5	1.11	0.00188	0.00195	0.00200
^{212}Bi	1,620.5	1.49	0.00575	0.00574	0.00603
^{224}Ra	241	3.7	0.00139	0.00150	0.00149
^{208}Tl	377.4	2.34	0.00162	0.00172	0.00168
^{208}Tl	510.7	8.1	0.00818	0.00865	0.00863
^{208}Tl	583.1	31	0.03673	0.03870	0.03903
^{208}Tl	860.5	4.32	0.00813	0.00842	0.00864
^{208}Tl	2,614.5	36	0.23635	0.23391	0.24721
^{212}Pb	238.6	44.6	0.01657	0.01777	0.01771
^{212}Pb	300.1	3.42	0.00175	0.00187	0.00184
Total			0.51678	0.52389	0.54373
^{238}U series					
^{214}Pb	241.9	7.6	0.00288	0.00309	0.00308
^{214}Pb	295.2	18.9	0.00948	0.01013	0.00996
^{214}Pb	352	36.3	0.02297	0.02448	0.02388
^{226}Ra	186	3.9	0.00098	0.00105	0.00108
^{214}Bi	609.4	42.8	0.05348	0.05625	0.05691
^{214}Bi	665.6	1.4	0.00195	0.00204	0.00207
^{214}Bi	768.4	4.8	0.00793	0.00822	0.00843
^{214}Bi	806.2	1.1	0.00192	0.00199	0.00204
^{214}Bi	934	3.1	0.00640	0.00664	0.00679
^{214}Bi	1,120.4	15	0.03816	0.03924	0.04043
^{214}Bi	1,155.3	1.7	0.00448	0.00459	0.00475
^{214}Bi	1,238.2	6.1	0.01740	0.01774	0.01842
^{214}Bi	1,281	1.5	0.00445	0.00452	0.00471
^{214}Bi	1,377.7	4.3	0.01384	0.01400	0.01463
^{214}Bi	1,401.6	1.5	0.00492	0.00497	0.00520
^{214}Bi	1,408	2.6	0.00857	0.00866	0.00907
^{214}Bi	1,509.3	2.2	0.00784	0.00788	0.00828
^{214}Bi	1,661.4	1.16	0.00460	0.00459	0.00482
^{214}Bi	1,729.8	3.2	0.01326	0.01318	0.01385
^{214}Bi	1,764.6	16.7	0.07074	0.07021	0.07375
^{214}Bi	1,847.6	2.3	0.01025	0.01014	0.01065
^{214}Bi	2,118.7	1.3	0.00675	0.00665	0.00700
^{214}Bi	2,204.3	5.3	0.02880	0.02843	0.02993
^{214}Bi	2,448	1.65	0.01011	0.01000	0.01056
Total			0.38092	0.38668	0.39996
^{137}Cs	661.6	85.1	0.11761	0.12084	0.12424
^{40}K	1,460.8	11	0.03780	0.03808	0.03995

Table 4. Conversion factors for different radionuclides deduced by the Monte Carlo codes of the present work and as deduced by Saito and Jacob (1995) and Beck et al. (1972).

	nGy h^{-1} per Bq kg^{-1}				
Nuclide	MCNP	MC	GEANT	Saito	Beck
^{232}Th series					
^{228}Ac	0.18526	0.19120	0.19594	0.22100	0.27800
^{212}Bi	0.02256	0.02305	0.02383	0.02720	0.02120
^{224}Ra	0.00156	0.00167	0.00167	0.00214	
^{208}Tl	0.28944	0.28871	0.30312	0.32600	0.32100
^{212}Pb	0.01796	0.01926	0.01917	0.02770	0.02120
Total	0.51678	0.52389	0.54373	0.60400	0.66600
^{238}U series					
^{214}Pb	0.04150	0.04413	0.04342	0.05460	0.04720
^{226}Ra	0.00092	0.00099	0.00100	0.00125	
^{214}Bi	0.33849	0.34156	0.35554	0.40100	0.37800
Total	0.38092	0.38668	0.39996	0.46300	0.43000
^{40}K	0.03780	0.03808	0.03995	0.04170	0.04220

the values deduced by the MCNP code and the precise solution of the corresponding integral (eqn 3) is less than 2%. For the total radiation (unscattered plus scattered) the results obtained from the three codes are in very good agreement between them. The comparison between the results obtained in the present work by the three codes and the results obtained previously by other authors indicate a good agreement (less than 15% of difference) for photon energies above 1,500 keV. However, the agreement is not as good (difference of 20–30%) for the low energy photons (e.g., 200 keV). The very good agreement of the dose rate conversion factors calculated by the three independent Monte Carlo codes used in the present work indicates that the corresponding values reported in ICRU (1994) may be reexamined.

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