Radiation Protection Dosimetry (2013), Vol. 156, No. 1, pp. 7–24 doi:10.1093/rpd/nct045
Advance Access publication 29 March 2013

EXTERNAL DOSE-RATE CONVERSION FACTORS OF RADIONUCLIDES FOR AIR SUBMERSION, GROUND SURFACE CONTAMINATION AND WATER IMMERSION BASED ON THE NEW ICRP DOSIMETRIC SETTING

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Received September 6 2012, revised January 4 2013, accepted February 24 2013

For the assessment of external doses due to contaminated environment, the dose-rate conversion factors (DCFs) prescribed in Federal Guidance Report 12 (FGR 12) and FGR 13 have been widely used. Recently, there were significant changes in dosimetric models and parameters, which include the use of the Reference Male and Female Phantoms and the revised tissue weighting factors, as well as the updated decay data of radionuclides. In this study, the DCFs for effective and equivalent doses were calculated for three exposure settings: skyshine, groundshine and water immersion. Doses to the Reference Phantoms were calculated by Monte Carlo simulations with the MCNPX 2.7.0 radiation transport code for 26 mono-energy photons between 0.01 and 10 MeV. The transport calculations were performed for the source volume within the cut-off distances practically contributing to the dose rates, which were determined by a simplified calculation model. For small tissues for which the reduction of variances are difficult, the equivalent dose ratios to a larger tissue (with lower statistical errors) nearby were employed to make the calculation efficient. Empirical response functions relating photon energies, and the organ equivalent doses or the effective doses were then derived by the use of cubic-spline fitting of the resulting doses for 26 energy points. The DCFs for all radionuclides considered important were evaluated by combining the photon emission data of the radionuclide and the empirical response functions. Finally, contributions of accompanied beta particles to the skin equivalent doses and the effective doses were calculated separately and added to the DCFs. For radionuclides considered in this study, the new DCFs for the three exposure settings were within $\pm$10 % when compared with DCFs in FGR 13.

INTRODUCTION

For the assessment of public and radiation worker's doses due to radionuclides released into the environment from nuclear facilities either during the normal operation or under accident situations, dose-rate conversion factors (DCFs), i.e. the organ equivalent DCFs or the effective DCFs due to a unit concentration of radionuclides in the environmental media, are needed for both external and internal exposure pathways. For external exposure pathways, those DCFs provided by United States Environmental Protection Agency in the Federal Guidance Report 12 (FGR 12)[(1)] and FGR 13[(2)] have been widely employed. Both of them provide DCFs for an individual standing either in contaminated air or on contaminated ground, or in contaminated water. The MIRD-type stylised phantom based on the Reference Man[(3)] was used to model the exposed individual.

Recently, there are significant changes in the dosimetric models, procedures and even in radionuclide decay data. First, the International Commission on Radiological Protection (ICRP) developed new voxel phantoms[(4)] representing the Reference Male and the Reference Female for use in dosimetric calculations. The body sizes of adult Reference Phantoms are a little larger than those defined previously and the location and the size of each organ or tissue became much more realistic. Secondly, the ICRP modified the tissue weighting factors needed in the calculation of the effective dose in the 2007 recommendations[(5)]. Thirdly, there are changes in the process of calculating the effective dose; sex averaging of organ equivalent doses before weighting the tissue weighting factors. Finally, the radiation decay data of radionuclides interested in radiological assessments also were updated and published in ICRP publication 107[(6)]. All of these changes should affect the values of

DCFs. Therefore, it is necessary to investigate the effect of such recent changes on the DCFs.

In this study, the DCFs for external exposure with all those changes being taken into account were calculated. The environmental compositions and settings for external exposure are similar to those used in FGR 12.

Impact of recent changes may be more significant in the case of internal exposure because those changes in geometrical models of the Reference Phantoms directly and sensitively affect the *S*-values, the specific equivalent dose of radionuclides. Moreover, there are additional changes in the internal dosimetric models, e.g. the human alimentary tract model (ICRP 100, 2006)[7] replacing the simple ICRP 30 model[8].

However, only the DCFs for external exposure were calculated in this study. Tissue-equivalent DCFs and effective DCFs were calculated for three exposure settings, i.e. the skyshine doses from contaminated air, the groundshine doses from contaminated ground surface and the immersion doses from contaminated water.

MATERIALS AND METHODS

Computational models and data

The computational models for the skyshine, groundshine and water immersion exposures are shown in Figures 1 and 2. The phantoms being exposed are the Reference Male or Female Phantoms prescribed in ICRP publication 110 (2009). For calculating the dose rates for the skyshine and groundshine models, the earth is modelled down to 4.0-m depth to take into account the albedo effect. For the groundshine model, it is assumed that the contaminants exist on the ground surface only. For these three models, radionuclides are assumed to distribute uniformly over the entire volume of air or water and over the entire area of ground surface.

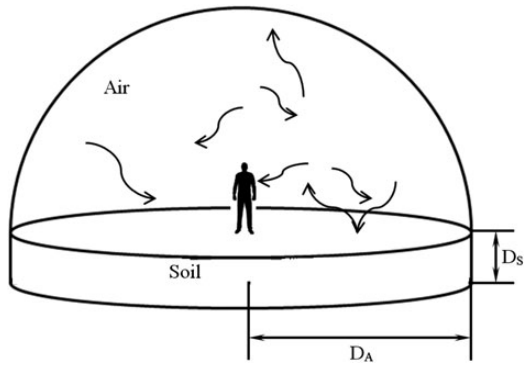

Figure 1. The computational model for calculating dose rates due to skyshine and groundshine. D_A is the cut-off distance presenting the maximum range practically contributing to dose rates and D_S is the soil depth to account the albedo effect.

The material composition data of air, soil and water are given in Table 1[1]. For the phantoms, the material composition data of organs or tissues given in Tables B1 and B2 of ICRP publication 110 (2009)[3] were used.

Radionuclides having a potentially wide range in the environment as a result of planned or unplanned releases from nuclear facilities were considered in this study. Hence, they are largely fission products or activation products expected to be generated during the operation of nuclear facilities. The radiation production data of radionuclides were extracted from those given in ICRP publication 107. Since nuclides interested in this study do not include ones with the capacity for neutron production, and since alpha particles are not relevant to external exposure, gamma rays, X-rays and beta particles are selected as the sources emitted from the radionuclides.

The Monte Carlo particle transport code MCNPX is used together with the cross-section library MCNPLIB04[9] and El03[10] in the calculation of absorbed dose to the organs of Reference Phantoms due to unit source intensity of specified energies of photons. For the specified photon energies, 26 energy points are used for the range of 0.01–10 MeV. Absorbed doses for organs and tissues have been calculated by applying F6 tally in the MCNPX code[11].

Simplifications and approximations for computation

Cut-off distances

Ideally, the source media are semi-infinite. However, it is evident that radiation particles produced

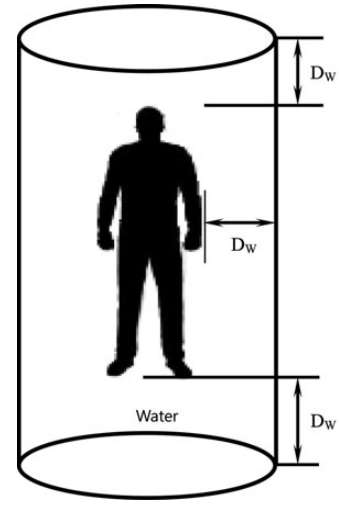

Figure 2. The computational model for calculating dose rates due to water immersion. D_w is the maximum distance practically contributing to dose rates.

extremely far from the receptor phantoms do not contribute to the resulting dose, while they increase computation time and relative errors significantly. To avoid this inefficacy, appropriate cut-off distances (CODs) are employed for this computation.

In order to determine the CODs for photons having different energies, trial calculations were made with a simplified receptor model. As the simplified receptor, a tissue-equivalent sphere of 1 m in diameter centred at 1.5 m above the ground surface or deep in water was used. With repeated calculations by increasing the distance from 1 mean-free-path (MFP), the resulting absorbed doses were monitored to check their convergences. An analysis indicating whether the resulting dose had been increased <1 % for the additional distance of 1 MFP, was performed, and these final distances were then selected as the CODs.

The CODs were 2.5–6 MFPs depending on the photon energies in the cases of skyshine and groundshine, and $\sim$7 MFPs in the case of water immersion, respectively. Figure 3 shows the resulting CODs (in meters) as a function of photon energy. Successive calculations with the Reference Phantoms were carried out up to these CODs.

As a test, the weighted equivalent doses using ICRP 110 Reference Male only were calculated at the CODs, and then compared with those calculated up to the CODs+0.5 MFP at the same energy point. There were no significant differences in the resulting doses.

Table 1. Material compositions and densities of air, soil and water.

Element	Mass fraction		
	Air	Soil (Silt)	Water
H	0.00064	0.021	0.112
C	0.00014	0.016	
N	0.75086		
O	0.23555	0.577	0.888
Ar	0.01281		
Al		0.050	
Si		0.271	
K		0.013	
Ca		0.041	
Fe		0.011	
Density	1.2 kg m^{-3}	1600 kg m^{-3}	1000 kg m^{-3}

Equivalent dose ratio method

Some organs or tissues in the Reference Phantoms, e.g. the thymus and the lymph nodes, are very small and accordingly the statistical variances in the dose estimates remain large even with extremely large numbers of histories. The situation becomes worse when the source volume increases, because the geometrical efficiency decreases roughly with the inverse square of the distance from the source point to the receptor volume, particularly in the case of the air contamination setting.

To overcome this problem in the air contamination setting, scaling factors for such small organs were employed. This is the equivalent dose ratio method

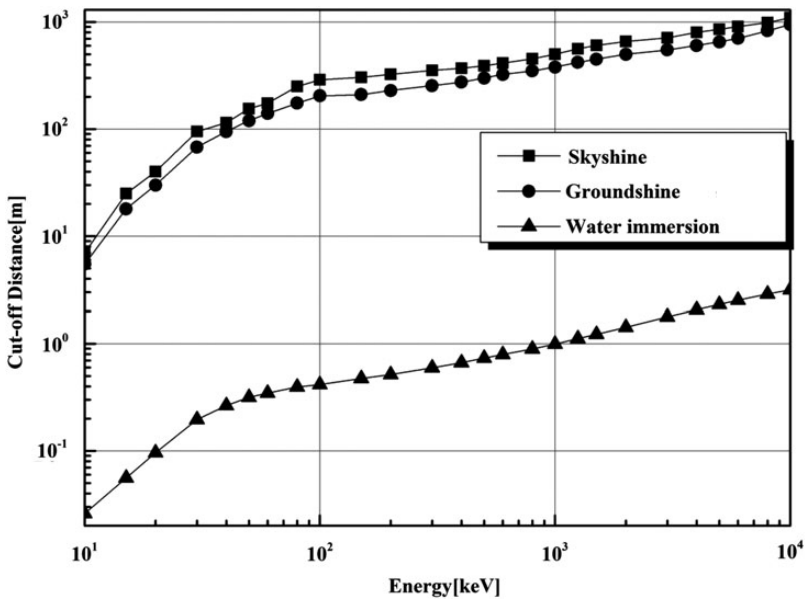

Figure 3. Cut-off distances (CODs) for different photon energies.

(EDRM). For the other settings (groundshine and water immersion), the statistical errors were satisfactorily reduced by increasing the histories.

The EDRM is based on the inference that the energy spectrum of photons incident to the receptor body would not significantly change with the geometrical range beyond a few MFPs because the particle fluence at the receptor position is dominated by those produced for closer reference distances. Then, the ratios among different organ doses would tend to be invariant with the increasing source volume. This enables one to estimate the doses to small organs from the extended source volume by multiplying the dose to an organ with the larger volume (reference organ), where the statistical error is satisfactorily reduced, by the ratio values (K) determined with a smaller source volume. The muscle is selected as the reference organ and the dose ratios K_{ij}, where i is the index of organ of interest and j is the photon energy, were evaluated at 50 m radius. That is,

$$\left(\frac{D_{ij}}{D_{\mathrm{RO}}}\right)_{r=\mathrm{r_o}} \cong \left(\frac{D_{ij}}{D_{\mathrm{RO}}}\right)_{r=\mathrm{COD}} \cong K_{ij} \tag{1}$$

where r_o is the reference distance (50 m) and RO denotes the reference organ (MUSCLE).

As a test case, Figure 4 shows the K factors of various organs calculated for 1250-keV photons at some different sizes of the source volume. It is confirmed that K factors deviate within 10 %, while the radius of the air volume varies from 50 m to the COD (565 m).

For validating K factors, the equivalent dose rates for $r = \mathrm{COD}$ $[H_i^{\mathrm{COD}}]$ can be calculated as

$$\dot{H}_i^{\mathrm{COD}} \cong \dot{H}_{\mathrm{RO}}^{\mathrm{COD}} \times K_i \tag{2}$$

where $[\dot{H}_{\mathrm{i}}^{\mathrm{COD}}]$ is the equivalent dose to organ i at COD and $[\dot{H}_{\mathrm{RO}}^{\mathrm{COD}}]$ is the equivalent dose to the reference organ at the reference distance (50 m). And, K factors are applied for organs having the relative errors of 10 % or more resulted in MCNP simulations at each energy bin.

K factors for different organs at different photon energies are given in Appendix A.

Calculation of DCFs

Photon DCFs

For each exposure setting, the equivalent doses to all the organs/tissues contributing to the effective ones were calculated for both the Reference Male and Female Phantoms for the 26 fixed energy points. Then, sex-averaged organ equivalent doses were calculated by simple averaging of the organ equivalent doses of the Reference Male and Female. The effective doses were calculated by weighting and averaging the sex-averaged organ equivalent doses over all the organs for which the tissue weighting factors are given in ICRP 103. This procedure provides dose coefficients for photon sources having unit emission intensity at the fixed energy points.

In order to apply the dose coefficients (for equivalent doses and effective doses) to the source spectra

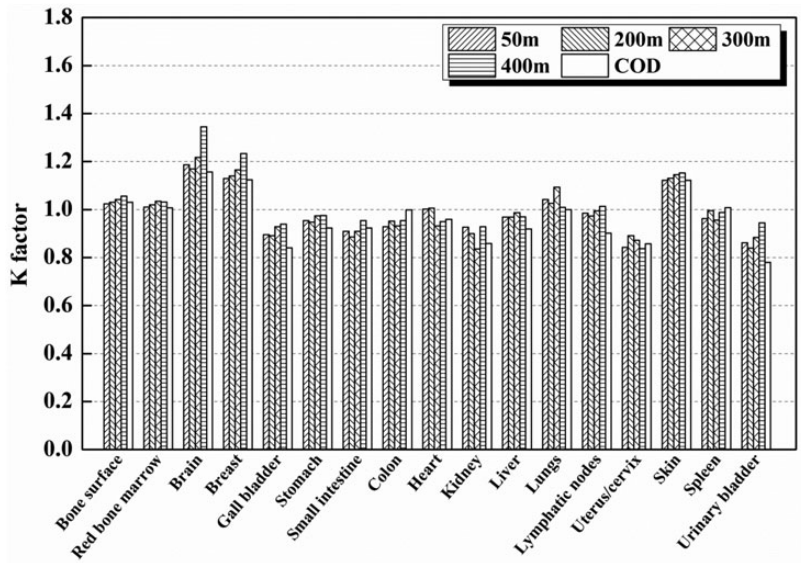

Figure 4. K factors for different organs of ICRP 110 Reference Male evaluated for different air volumes at 1250 keV.

of radionuclides, they fit to mathematical functions of energy[12]. Finally, the photon DCFs for all radionuclides were calculated by

$$\mathrm{DCF_p} = \sum_i y_i \mathrm{DC}(E_i) \quad (3)$$

where y_i is the yield of photon energy E_i per disintegration of the given radionuclide, DC is the dose coefficient calculated using the fitted equations and the subscript p indicates photon DCF.

Beta particle contribution

Beta particles emitted from the radionuclides having the maximum energies of a few MeV contribute to the equivalent doses to superficial tissues, typically the skin and the lens of eyes. Currently, no tissue weighting factor is assigned for the lens and consequently the skin equivalent doses only contribute to the effective doses. Since there are no changes in the calculation of electron dosimetry, the contribution of beta radiation to the DCFs can be determined by the conventional approach except for any changes in source emission data.

Therefore, the skin equivalent dose for beta particles are used data at table III.1, table III.2 and table III.3 in FGR 12 in this study.

RESULTS AND DISCUSSION

Photon dose coefficients

Figures 5–7 show the calculated equivalent dose coefficients, which are compared with the FGR 12 values, of 1-MeV photon to selected organs for the three exposure settings. In spite of those changes in the Reference Phantoms and in the tissue weighting factors, the DCFs for the three cases do not deviate significantly from the values of FGR 12. Notable differences are in the dose equivalents to bone surface. Dose equivalents to bone surface in FGR 12 are significantly higher than those derived from this study. The differences can be attributed to the different dosimetric approaches applied. The mean dose to bone region was taken as the bone surface equivalent dose in FGR 12 because the bone surface region had not been modelled in the MIRD-type phantom. The Reference Phantoms of ICRP used in this study include the soft bone surface regions specifically defined. Typically, the bone density is higher than soft tissues, and contains high-Z elements resulting in the increased doses.

Figures 8–10 show the curves of effective dose coefficients fitted as the function of photon energies, and compared with FGR 12 values [effective dose equivalent (H_E) and effective dose (E)][13] as well.

Exposure characteristics of photons having low energies are larger in the organs of breasts, salivary

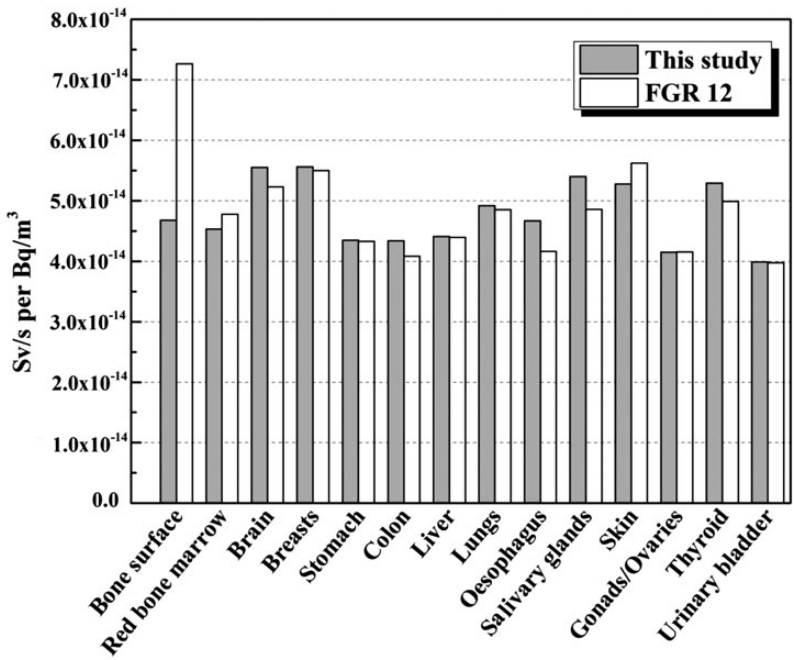

Figure 5. Equivalent DCFs for skyshine of 1-MeV photon when compared with those calculated in FGR 12.

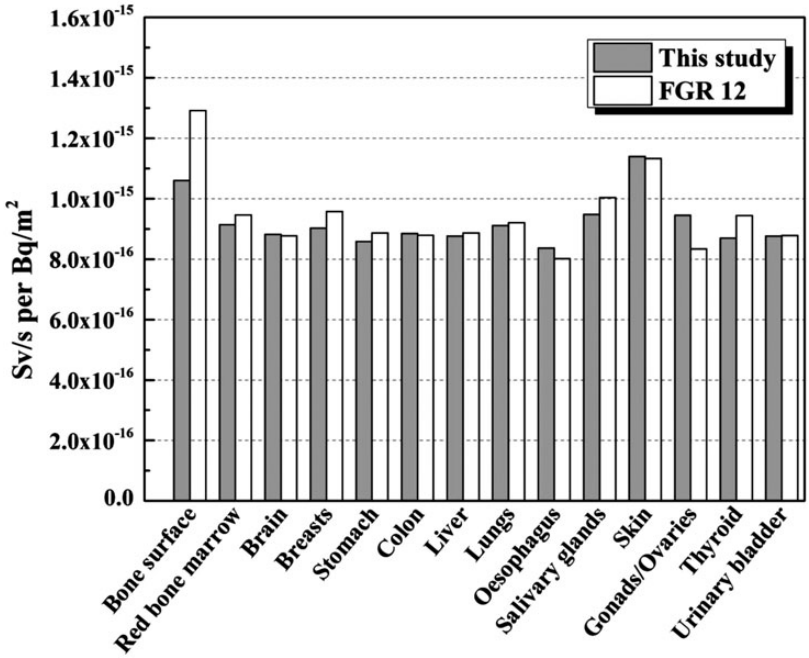

Figure 6. Equivalent DCFs for groundshine of 1-MeV photon when compared with those calculated in FGR 12.

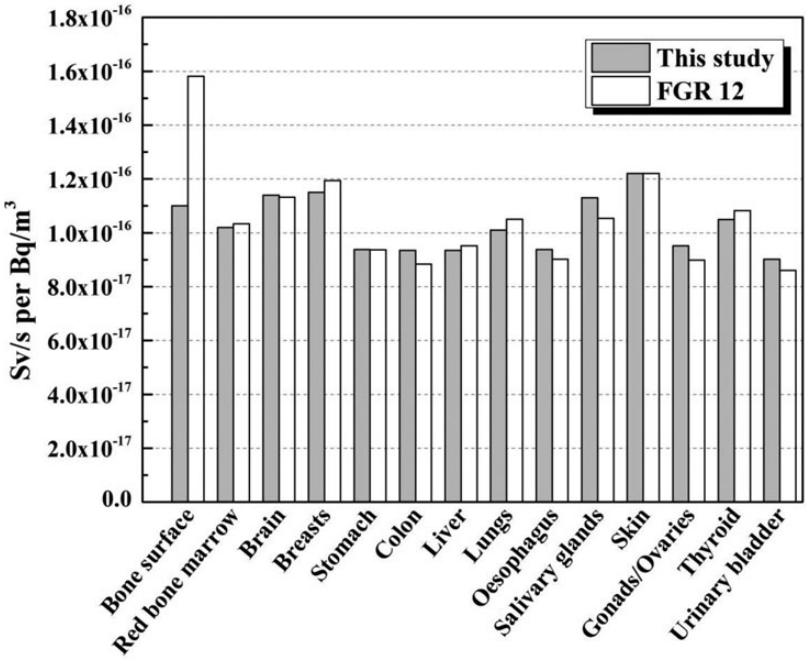

Figure 7. Equivalent DCFs for water immersion of 1-MeV photon when compared those calculated in FGR 12.

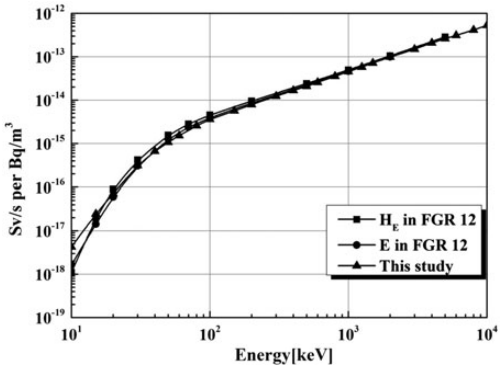

Figure 8. Effective doses vs. energy for skyshine.

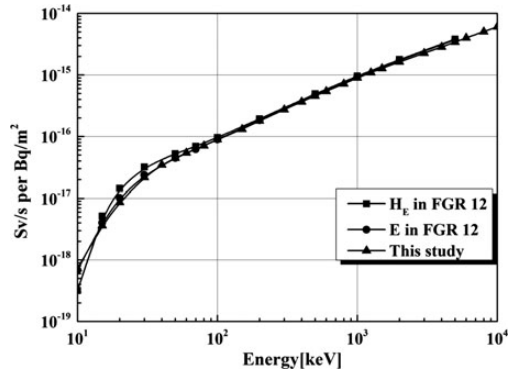

Figure 9. Effective doses vs. energy for groundshine.

glands and gonads (ovaries), which are located in the near positions from the surface of the human body, than the other organs due to their low penetrating capacities to the human body. The equivalent dose for the breasts applying new Reference Phantom have been especially turned out to be larger than one applying the existing reference phantom[4, 14]. There are some increases to effective doses due to the increase in weighting factors, 0.05–0.12, as well. From these stated reviews, effective doses for energies <30 keV have been confirmed to have than ones applying DCFs of FGR 12 and FGR 13.

The equivalent dose coefficients applied for evaluating organ equivalent doses are provided as Tables in Appendix B.

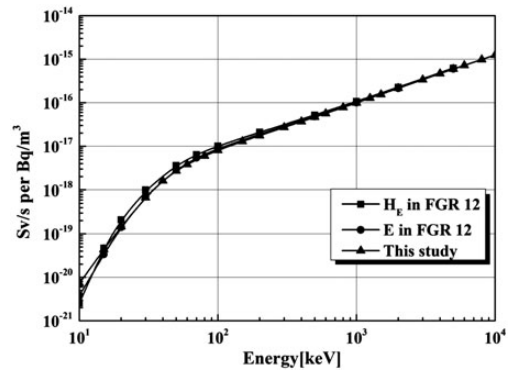

Figure 10. Effective doses vs. energy for water immersion.

DCFs

The DCFs for each nuclide are obtained by summing each photon's equivalent DCF. The skin equivalent DCF is obtained by summing equivalent dose rates from the beta particles.

New DCFs calculated in this study were compared with those summarised in FGR 12 and FGR 13 and are shown in Appendix C. External exposure from the radioactive nuclides considered in this study as environmentally important is not changed significantly by applying new DCFs.

CONCLUSION

By considering the recent changes in the dosimetric models, procedures for determining the effective dose and even the decay data of radionuclides, new DCFs needed for estimating the radiological impact of radionuclides on the environment have been calculated for three external exposure settings: skyshine, groundshine and water immersion.

The new DCFs have been compared with those provided in FGR 12 and FGR 13. Most of the calculated DCFs are within ± 10 % of the values suggested in FGR 12 and 13 except a few radionuclides due to their decay data, their contributions to organ doses and the characteristics of Reference Phantoms. Although the new DCFs do not significantly differ from the previous ones, it should be emphasised that the new DCFs are based on the current recommendations of the ICRP.

There are always underlying uncertainties in this type of dosimetric calculations. A standardising process, therefore, is needed to establish a reference set of DCFs by national authorities or an international body like the ICRP. The DCFs given in this study together with other result[15], will provide important input to the standardising process.

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Appendix A. K factors for organs/MUSCLE of the reference individuals for different photon energies in skyshine.

Table A1. K factors for organs/MUSCLE of the Reference Male.

Organ/tissue	Photon energy (MeV)								
	0.10	0.15	0.20	0.30	0.40	0.50	0.60	0.80	1.00
Adrenals	7.70E−01	8.11E−01	8.37E−01	8.35E−01	8.35E−01	8.32E−01	8.70E−01	8.56E−01	8.85E−01
Extrathoracic region	1.02E+00	1.07E+00	1.12E+00	1.13E+00	1.14E+00	1.14E+00	1.15E+00	1.13E+00	1.13E+00
Oral mucosa	9.39E−01	1.02E+00	1.05E+00	1.06E+00	1.09E+00	1.10E+00	1.09E+00	1.09E+00	1.09E+00
Bone surface	1.24E+00	1.13E+00	1.09E+00	1.05E+00	1.03E+00	1.03E+00	1.02E+00	1.02E+00	1.01E+00
Red bone marrow	1.22E+00	1.11E+00	1.06E+00	1.01E+00	9.96E−01	9.88E−01	9.84E−01	9.82E−01	9.79E−01
Brain	1.15E+00	1.16E+00	1.17E+00	1.17E+00	1.18E+00	1.18E+00	1.18E+00	1.19E+00	1.18E+00
Breast	1.06E+00	1.10E+00	1.16E+00	1.17E+00	1.17E+00	1.18E+00	1.16E+00	1.14E+00	1.14E+00
Gall bladder	8.02E−01	8.22E−01	8.15E−01	8.39E−01	8.37E−01	8.51E−01	8.60E−01	8.73E−01	8.92E−01
Stomach	8.83E−01	8.85E−01	8.78E−01	8.89E−01	8.82E−01	8.85E−01	8.90E−01	9.01E−01	9.11E−01
Small intestine	8.43E−01	8.43E−01	8.37E−01	8.28E−01	8.36E−01	8.40E−01	8.49E−01	8.63E−01	8.75E−01
Colon	8.84E−01	8.87E−01	8.79E−01	8.71E−01	8.76E−01	8.77E−01	8.76E−01	8.90E−01	8.93E−01
Heart	9.38E−01	9.43E−01	9.54E−01	9.55E−01	9.50E−01	9.50E−01	9.57E−01	9.68E−01	9.67E−01
Kidney	8.38E−01	8.47E−01	8.58E−01	8.38E−01	8.36E−01	8.39E−01	8.37E−01	8.58E−01	8.64E−01
Liver	8.91E−01	8.90E−01	8.91E−01	8.86E−01	8.87E−01	8.89E−01	8.96E−01	9.05E−01	9.16E−01
Lungs	9.83E−01	9.93E−01	1.00E+00	1.00E+00	1.01E+00	1.01E+00	1.01E+00	1.02E+00	1.02E+00
Lymphatic nodes	9.24E−01	9.31E−01	9.32E−01	9.26E−01	9.31E−01	9.34E−01	9.39E−01	9.45E−01	9.49E−01
Muscle	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Oesophagus	8.66E−01	8.99E−01	9.24E−01	9.23E−01	9.43E−01	9.46E−01	9.42E−01	9.68E−01	9.82E−01
Pancreas	7.71E−01	7.76E−01	7.97E−01	7.76E−01	7.95E−01	7.99E−01	8.07E−01	8.22E−01	8.38E−01
Prostate	7.28E−01	7.37E−01	7.43E−01	7.56E−01	7.77E−01	7.65E−01	7.84E−01	7.95E−01	8.28E−01
Salivary glands	1.05E+00	1.09E+00	1.13E+00	1.15E+00	1.13E+00	1.16E+00	1.16E+00	1.17E+00	1.15E+00
Skin	1.12E+00	1.13E+00	1.14E+00	1.15E+00	1.15E+00	1.14E+00	1.14E+00	1.13E+00	1.12E+00
Spleen	8.86E−01	9.17E−01	8.97E−01	9.02E−01	8.99E−01	8.98E−01	9.00E−01	9.11E−01	9.27E−01
Gonads male	9.45E−01	9.30E−01	9.45E−01	9.38E−01	9.25E−01	9.26E−01	9.22E−01	9.26E−01	9.31E−01
Thymus	1.02E+00	1.05E+00	1.06E+00	1.08E+00	1.08E+00	1.09E+00	1.08E+00	1.10E+00	1.07E+00
Thyroid	1.20E+00	1.15E+00	1.16E+00	1.11E+00	1.12E+00	1.13E+00	1.11E+00	1.14E+00	1.11E+00
Urinary bladder	7.89E−01	8.15E−01	8.15E−01	8.07E−01	8.08E−01	8.16E−01	8.12E−01	8.33E−01	8.43E−01
	1.25	1.50	2.00	3.00	4.00	5.00	6.00	8.00	10.0
Adrenals	9.03E−01	9.18E−01	9.10E−01	9.26E−01	9.62E−01	9.71E−01	9.61E−01	9.54E−01	9.48E−01
Extrathoracic region	1.12E+00	1.11E+00	1.12E+00	1.11E+00	1.08E+00	1.08E+00	1.08E+00	1.07E+00	1.07E+00
Oral mucosa	1.10E+00	1.11E+00	1.10E+00	1.10E+00	1.09E+00	1.09E+00	1.09E+00	1.09E+00	1.09E+00
Bone surface	1.01E+00	1.01E+00	1.01E+00	1.01E+00	1.00E+00	1.01E+00	1.00E+00	1.01E+00	1.01E+00
Red bone marrow	9.83E−01	9.85E−01	9.87E−01	9.92E−01	9.94E−01	1.00E+00	1.00E+00	1.01E+00	1.01E+00
Brain	1.18E+00	1.17E+00	1.16E+00	1.15E+00	1.14E+00	1.14E+00	1.13E+00	1.12E+00	1.13E+00
Breast	1.13E+00	1.12E+00	1.14E+00	1.13E+00	1.11E+00	1.10E+00	1.09E+00	1.07E+00	1.07E+00
Gall bladder	8.86E−01	9.16E−01	9.27E−01	9.53E−01	9.51E−01	9.41E−01	9.70E−01	9.61E−01	9.54E−01
Stomach	9.17E−01	9.27E−01	9.32E−01	9.46E−01	9.55E−01	9.55E−01	9.65E−01	9.70E−01	9.71E−01
Small intestine	8.81E−01	8.90E−01	8.99E−01	9.16E−01	9.30E−01	9.39E−01	9.45E−01	9.54E−01	9.57E−01
Colon	8.97E−01	9.05E−01	9.16E−01	9.29E−01	9.37E−01	9.38E−01	9.46E−01	9.52E−01	9.55E−01
Heart	9.76E−01	9.84E−01	9.89E−01	9.99E−01	1.00E+00	1.00E+00	1.00E+00	1.01E+00	1.01E+00
Kidney	8.80E−01	8.94E−01	9.08E−01	9.28E−01	9.29E−01	9.33E−01	9.43E−01	9.48E−01	9.51E−01
Liver	9.19E−01	9.30E−01	9.33E−01	9.49E−01	9.59E−01	9.57E−01	9.66E−01	9.70E−01	9.74E−01
Lungs	1.03E+00	1.03E+00	1.04E+00	1.04E+00	1.04E+00	1.04E+00	1.04E+00	1.04E+00	1.04E+00
Lymphatic nodes	9.49E−01	9.56E−01	9.63E−01	9.74E−01	9.79E−01	9.81E−01	9.85E−01	9.89E−01	9.93E−01
Muscle	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Oesophagus	9.80E−01	9.80E−01	9.94E−01	9.96E−01	1.01E+00	1.00E+00	9.94E−01	9.95E−01	9.90E−01
Pancreas	8.48E−01	8.60E−01	8.71E−01	8.93E−01	9.09E−01	9.12E−01	9.15E−01	9.19E−01	9.32E−01
Prostate	8.29E−01	8.40E−01	8.62E−01	8.86E−01	8.93E−01	9.15E−01	9.15E−01	9.33E−01	9.22E−01
Salivary glands	1.16E+00	1.14E+00	1.13E+00	1.12E+00	1.13E+00	1.11E+00	1.11E+00	1.10E+00	1.09E+00
Skin	1.12E+00	1.11E+00	1.09E+00	1.08E+00	1.07E+00	1.06E+00	1.06E+00	1.05E+00	1.05E+00
Spleen	9.27E−01	9.40E−01	9.39E−01	9.49E−01	9.61E−01	9.67E−01	9.66E−01	9.81E−01	9.78E−01
Gonads male	9.48E−01	9.40E−01	9.26E−01	9.44E−01	9.55E−01	9.38E−01	9.49E−01	9.62E−01	9.60E−01
Thymus	1.08E+00	1.07E+00	1.08E+00	1.06E+00	1.05E+00	1.04E+00	1.06E+00	1.05E+00	1.04E+00
Thyroid	1.10E+00	1.10E+00	1.08E+00	1.06E+00	1.04E+00	1.05E+00	1.06E+00	1.05E+00	1.03E+00
Urinary bladder	8.59E−01	8.78E−01	8.67E−01	8.95E−01	9.11E−01	9.07E−01	9.12E−01	9.31E−01	9.36E−01

Table A2. K factors for organs/MUSCLE of the Reference Female.

Tissue	Emitted photon energy (MeV)								
	0.10	0.15	0.20	0.30	0.40	0.50	0.60	0.80	1.00
Adrenals	7.59E−01	8.11E−01	8.39E−01	8.45E−01	8.49E−01	8.71E−01	8.89E−01	8.90E−01	8.88E−01
Extrathoracic region	9.37E−01	9.98E−01	1.05E+00	1.09E+00	1.10E+00	1.11E+00	1.11E+00	1.13E+00	1.11E+00
Oral mucosa	9.34E−01	1.00E+00	1.03E+00	1.07E+00	1.05E+00	1.06E+00	1.08E+00	1.08E+00	1.09E+00
Bone surface	1.28E+00	1.16E+00	1.11E+00	1.07E+00	1.05E+00	1.04E+00	1.04E+00	1.03E+00	1.02E+00
Red bone marrow	1.30E+00	1.17E+00	1.11E+00	1.06E+00	1.03E+00	1.02E+00	1.02E+00	1.01E+00	1.01E+00
Brain	1.17E+00	1.18E+00	1.19E+00	1.20E+00	1.21E+00	1.20E+00	1.20E+00	1.20E+00	1.19E+00
Breast	1.03E+00	1.09E+00	1.13E+00	1.15E+00	1.15E+00	1.15E+00	1.14E+00	1.14E+00	1.14E+00
Gall bladder	7.98E−01	8.42E−01	8.72E−01	8.66E−01	8.59E−01	8.64E−01	8.72E−01	8.86E−01	8.85E−01
Stomach	9.49E−01	9.57E−01	9.51E−01	9.51E−01	9.42E−01	9.38E−01	9.43E−01	9.42E−01	9.49E−01
Small intestine	8.70E−01	8.81E−01	8.85E−01	8.76E−01	8.83E−01	8.78E−01	8.84E−01	8.97E−01	9.05E−01
Colon	9.12E−01	9.12E−01	9.09E−01	9.10E−01	9.16E−01	9.11E−01	9.14E−01	9.23E−01	9.25E−01
Heart	9.69E−01	9.81E−01	9.86E−01	1.00E+00	9.78E−01	9.88E−01	9.87E−01	1.00E+00	1.00E+00
Kidney	8.96E−01	8.99E−01	9.07E−01	8.87E−01	9.00E−01	9.06E−01	9.14E−01	9.16E−01	9.26E−01
Liver	9.50E−01	9.43E−01	9.51E−01	9.40E−01	9.42E−01	9.41E−01	9.49E−01	9.62E−01	9.68E−01
Lungs	1.02E+00	1.03E+00	1.03E+00	1.04E+00	1.03E+00	1.04E+00	1.04E+00	1.04E+00	1.04E+00
Lymphatic nodes	9.62E−01	9.69E−01	9.71E−01	9.65E−01	9.66E−01	9.71E−01	9.70E−01	9.79E−01	9.79E−01
Muscle	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Oesophagus	9.31E−01	9.71E−01	9.78E−01	1.01E+00	9.98E−01	1.00E+00	1.00E+00	1.01E+00	1.01E+00
Pancreas	8.50E−01	8.76E−01	8.82E−01	8.92E−01	8.81E−01	8.78E−01	8.99E−01	9.15E−01	9.22E−01
Uterus female	7.19E−01	7.60E−01	7.64E−01	7.84E−01	7.81E−01	7.88E−01	8.03E−01	8.13E−01	8.18E−01
Salivary glands	1.02E+00	1.08E+00	1.12E+00	1.12E+00	1.14E+00	1.14E+00	1.14E+00	1.16E+00	1.15E+00
Skin	1.13E+00	1.14E+00	1.15E+00	1.16E+00	1.16E+00	1.15E+00	1.15E+00	1.14E+00	1.13E+00
Spleen	9.81E−01	9.79E−01	9.74E−01	9.49E−01	9.47E−01	9.65E−01	9.58E−01	9.63E−01	9.64E−01
Ovaries female	7.55E−01	8.00E−01	7.82E−01	8.09E−01	7.90E−01	8.22E−01	8.22E−01	8.67E−01	8.42E−01
Thymus	1.03E+00	1.05E+00	1.11E+00	1.10E+00	1.10E+00	1.07E+00	1.11E+00	1.11E+00	1.10E+00
Thyroid	1.20E+00	1.18E+00	1.18E+00	1.15E+00	1.15E+00	1.14E+00	1.13E+00	1.17E+00	1.15E+00
Urinary bladder	8.75E−01	8.79E−01	8.69E−01	8.63E−01	8.62E−01	8.61E−01	8.45E−01	8.57E−01	8.62E−01
	1.25	1.50	2.00	3.00	4.00	5.00	6.00	8.00	10.0
Adrenals	9.06E−01	9.06E−01	9.32E−01	9.36E−01	9.32E−01	9.31E−01	9.35E−01	9.59E−01	9.51E−01
Extrathoracic region	1.11E+00	1.10E+00	1.11E+00	1.10E+00	1.10E+00	1.09E+00	1.09E+00	1.07E+00	1.05E+00
Oral mucosa	1.10E+00	1.09E+00	1.09E+00	1.08E+00	1.08E+00	1.07E+00	1.07E+00	1.08E+00	1.08E+00
Bone surface	1.02E+00	1.02E+00	1.02E+00	1.01E+00	1.01E+00	1.01E+00	1.01E+00	1.01E+00	1.01E+00
Red bone marrow	1.01E+00	1.01E+00	1.01E+00	1.01E+00	1.01E+00	1.01E+00	1.01E+00	1.02E+00	1.02E+00
Brain	1.19E+00	1.18E+00	1.17E+00	1.16E+00	1.15E+00	1.14E+00	1.13E+00	1.12E+00	1.13E+00
Breast	1.13E+00	1.13E+00	1.12E+00	1.11E+00	1.10E+00	1.09E+00	1.08E+00	1.06E+00	1.05E+00
Gall bladder	8.95E−01	9.19E−01	9.33E−01	9.38E−01	9.37E−01	9.55E−01	9.46E−01	9.63E−01	9.30E−01
Stomach	9.54E−01	9.57E−01	9.61E−01	9.68E−01	9.70E−01	9.71E−01	9.75E−01	9.74E−01	9.73E−01
Small intestine	9.10E−01	9.20E−01	9.29E−01	9.42E−01	9.48E−01	9.52E−01	9.55E−01	9.63E−01	9.64E−01
Colon	9.29E−01	9.34E−01	9.51E−01	9.58E−01	9.60E−01	9.61E−01	9.66E−01	9.67E−01	9.65E−01
Heart	1.00E+00	9.97E−01	1.01E+00	1.00E+00	1.01E+00	1.01E+00	1.01E+00	1.00E+00	1.00E+00
Kidney	9.26E−01	9.34E−01	9.41E−01	9.57E−01	9.63E−01	9.67E−01	9.69E−01	9.75E−01	9.85E−01
Liver	9.68E−01	9.78E−01	9.76E−01	9.83E−01	9.88E−01	9.88E−01	9.92E−01	9.94E−01	9.91E−01
Lungs	1.04E+00	1.04E+00	1.04E+00	1.04E+00	1.04E+00	1.04E+00	1.04E+00	1.03E+00	1.04E+00
Lymphatic nodes	9.84E−01	9.82E−01	1.00E+00	1.00E+00	1.01E+00	1.01E+00	1.01E+00	1.01E+00	1.02E+00
Muscle	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Oesophagus	1.02E+00	1.02E+00	1.03E+00	1.02E+00	1.02E+00	1.02E+00	1.03E+00	1.03E+00	1.01E+00
Pancreas	9.12E−01	9.25E−01	9.32E−01	9.41E−01	9.48E−01	9.48E−01	9.49E−01	9.58E−01	9.61E−01
Uterus female	8.42E−01	8.38E−01	8.84E−01	9.01E−01	9.17E−01	9.25E−01	9.27E−01	9.31E−01	9.22E−01
Salivary glands	1.15E+00	1.13E+00	1.14E+00	1.12E+00	1.12E+00	1.12E+00	1.11E+00	1.11E+00	1.12E+00
Skin	1.12E+00	1.11E+00	1.10E+00	1.08E+00	1.07E+00	1.07E+00	1.06E+00	1.06E+00	1.06E+00
Spleen	9.62E−01	9.61E−01	9.83E−01	9.90E−01	9.88E−01	9.87E−01	9.97E−01	9.99E−01	9.88E−01
Ovaries female	8.95E−01	8.97E−01	9.12E−01	9.12E−01	9.37E−01	9.50E−01	9.40E−01	9.62E−01	9.43E−01
Thymus	1.10E+00	1.10E+00	1.11E+00	1.11E+00	1.10E+00	1.11E+00	1.10E+00	1.10E+00	1.09E+00
Thyroid	1.15E+00	1.15E+00	1.14E+00	1.11E+00	1.10E+00	1.09E+00	1.09E+00	1.08E+00	1.08E+00
Urinary Bladder	8.61E−01	8.78E−01	8.96E−01	9.10E−01	9.13E−01	9.24E−01	9.22E−01	9.30E−01	9.43E−01

Appendix B. Organ equivalent dose-rate factors.

Table B1. DCFs of photon for the skyshine (Sv s^{-1} per Bq m^{-3}).

Tissue	Emitted photon energy (MeV)												
	0.01	0.015	0.02	0.03	0.04	0.05	0.06	0.08	0.10	0.15	0.20	0.30	0.40
Adrenals	1.97E−26	1.97E−24	1.15E−18	1.05E−16	3.03E−16	7.69E−16	8.96E−16	1.86E−15	2.91E−15	4.73E−15	6.82E−15	1.07E−14	1.44E−14
Extrathoracic region	4.22E−18	3.43E−17	1.06E−16	3.10E−16	6.53E−16	1.04E−15	1.37E−15	2.44E−15	3.46E−15	5.93E−15	8.52E−15	1.45E−14	1.91E−14
Oral mucosa	3.52E−19	9.25E−18	3.28E−17	1.55E−16	4.09E−16	8.71E−16	1.14E−15	2.10E−15	3.60E−15	5.79E−15	8.47E−15	1.36E−14	1.83E−14
Bone surface	1.67E−19	6.18E−18	4.78E−17	3.95E−16	9.74E−16	1.65E−15	2.24E−15	3.59E−15	4.76E−15	7.02E−15	9.42E−15	1.41E−14	1.86E−14
Red bone marrow	1.97E−19	7.83E−18	5.33E−17	3.83E−16	9.32E−16	1.60E−15	2.17E−15	3.55E−15	4.81E−15	6.89E−15	9.40E−15	1.38E−14	1.81E−14
Brain	2.57E−23	1.21E−19	6.77E−18	2.03E−16	6.51E−16	1.22E−15	1.70E−15	3.02E−15	4.28E−15	6.59E−15	9.53E−15	1.48E−14	2.12E−14
Breast	1.86E−17	1.29E−16	2.94E−16	6.83E−16	9.72E−16	1.31E−15	1.66E−15	2.65E−15	3.90E−15	6.42E−15	9.10E−15	1.47E−14	1.95E−14
Gall bladder	2.54E−26	3.47E−20	3.02E−18	7.22E−17	3.59E−16	7.32E−16	9.83E−16	1.93E−15	3.05E−15	4.86E−15	6.86E−15	1.08E−14	1.45E−14
Stomach	8.87E−22	1.44E−18	2.17E−17	2.21E−16	5.23E−16	8.30E−16	1.35E−15	2.26E−15	3.38E−15	5.35E−15	7.23E−15	1.10E−14	1.62E−14
Small intestine	1.38E−22	5.14E−19	1.33E−17	1.61E−16	4.42E−16	8.37E−16	1.19E−15	2.17E−15	3.07E−15	4.69E−15	6.63E−15	1.03E−14	1.44E−14
Colon	4.10E−21	1.71E−18	2.47E−17	2.22E−16	5.57E−16	9.29E−16	1.35E−15	2.51E−15	3.22E−15	4.83E−15	7.27E−15	1.09E−14	1.52E−14
Heart	3.73E−26	4.81E−19	1.38E−17	1.86E−16	5.04E−16	9.24E−16	1.37E−15	2.48E−15	3.59E−15	5.76E−15	7.93E−15	1.19E−14	1.76E−14
Kidney	3.06E−26	1.14E−19	5.65E−18	1.28E−16	4.43E−16	8.21E−16	1.18E−15	2.06E−15	3.18E−15	5.19E−15	6.87E−15	1.07E−14	1.40E−14
Liver	5.82E−22	8.94E−19	1.61E−17	1.82E−16	5.06E−16	8.87E−16	1.31E−15	2.39E−15	3.35E−15	5.28E−15	7.29E−15	1.15E−14	1.50E−14
Lungs	4.38E−22	9.50E−19	1.94E−17	2.30E−16	5.78E−16	1.03E−15	1.49E−15	2.68E−15	3.75E−15	5.98E−15	8.12E−15	1.25E−14	1.72E−14
Lymphatic nodes	1.15E−18	2.06E−17	7.42E−17	3.06E−16	6.24E−16	1.05E−15	1.47E−15	2.45E−15	3.37E−15	5.50E−15	7.73E−15	1.14E−14	1.61E−14
Muscle	6.61E−19	1.91E−17	9.28E−17	4.11E−16	7.88E−16	1.23E−15	1.65E−15	2.69E−15	3.64E−15	5.72E−15	7.97E−15	1.26E−14	1.68E−14
Oesophagus	9.77E−22	6.21E−19	8.24E−18	1.20E−16	3.95E−16	6.95E−16	1.17E−15	2.41E−15	3.51E−15	5.37E−15	7.62E−15	1.19E−14	1.66E−14
Pancreas	2.92E−26	1.48E−20	2.09E−18	8.24E−17	3.37E−16	7.21E−16	1.13E−15	1.84E−15	3.09E−15	4.70E−15	6.88E−15	1.07E−14	1.43E−14
Prostate/uterus female	1.82E−26	1.82E−24	1.60E−18	6.04E−17	2.43E−16	5.19E−16	9.05E−16	1.79E−15	2.76E−15	4.37E−15	6.09E−15	9.78E−15	1.33E−14
Salivary glands	2.40E−18	4.69E−17	1.68E−16	4.98E−16	8.09E−16	1.13E−15	1.58E−15	2.47E−15	3.94E−15	5.97E−15	8.73E−15	1.50E−14	1.94E−14
Skin	1.78E−16	3.90E−16	5.79E−16	9.83E−16	1.30E−15	1.72E−15	2.12E−15	3.22E−15	4.28E−15	6.62E−15	9.34E−15	1.47E−14	1.97E−14
Spleen	3.73E−26	5.38E−19	1.48E−17	1.93E−16	5.14E−16	9.42E−16	1.28E−15	2.32E−15	3.57E−15	5.57E−15	7.40E−15	1.23E−14	1.65E−14
Gonads male/ovaries female	2.46E−18	1.58E−17	5.01E−17	2.44E−16	5.84E−16	8.46E−16	1.22E−15	1.80E−15	3.24E−15	5.04E−15	7.02E−15	1.11E−14	1.47E−14
Thymus	8.62E−20	8.53E−18	5.61E−17	3.59E−16	6.61E−16	1.13E−15	1.63E−15	2.34E−15	3.92E−15	6.15E−15	8.84E−15	1.38E−14	1.86E−14
Thyroid	1.47E−19	1.76E−17	1.01E−16	4.99E−16	9.93E−16	1.34E−15	2.29E−15	2.75E−15	4.57E−15	6.81E−15	9.52E−15	1.43E−14	1.94E−14
Urinary bladder	1.31E−19	8.69E−18	4.05E−17	1.87E−16	4.57E−16	8.42E−16	1.26E−15	2.23E−15	3.17E−15	4.76E−15	6.87E−15	1.06E−14	1.43E−14
Effective dose	4.33E−18	2.46E−17	7.21E−17	3.12E−16	6.63E−16	1.07E−15	1.53E−15	2.56E−15	3.70E−15	5.73E−15	8.01E−15	1.24E−14	1.68E−14

	0.5	0.6	0.8	1.0	1.25	1.50	2.0	3.0	4.0	5.0	6.0	8.0	10.0
Adrenals	1.84E−14	2.30E−14	3.14E−14	4.15E−14	5.29E−14	6.67E−14	9.19E−14	1.39E−13	1.97E−13	2.52E−13	3.01E−13	4.06E−13	5.10E−13
Extrathoracic region	2.42E−14	2.95E−14	4.08E−14	5.24E−14	6.53E−14	8.09E−14	1.11E−13	1.64E−13	2.27E−13	2.87E−13	3.45E−13	4.56E−13	5.68E−13
Oral mucosa	2.33E−14	2.83E−14	3.92E−14	5.11E−14	6.45E−14	8.03E−14	1.09E−13	1.62E−13	2.26E−13	2.86E−13	3.44E−13	4.60E−13	5.82E−13
Bone surface	2.30E−14	2.78E−14	3.71E−14	4.68E−14	6.04E−14	7.44E−14	1.02E−13	1.50E−13	2.10E−13	2.68E−13	3.20E−13	4.29E−13	5.43E−13
Red bone marrow	2.21E−14	2.69E−14	3.63E−14	4.53E−14	5.75E−14	7.18E−14	9.74E−14	1.49E−13	2.09E−13	2.67E−13	3.20E−13	4.30E−13	5.46E−13

Continued

Table B1. *Continued*

Tissue	Emitted photon energy (MeV)												
	0.5	0.6	0.8	1.0	1.25	1.50	2.0	3.0	4.0	5.0	6.0	8.0	10.0
Brain	2.53E−14	3.26E−14	4.25E−14	5.55E−14	6.82E−14	8.73E−14	1.16E−13	1.72E−13	2.38E−13	3.02E−13	3.59E−13	4.78E−13	6.05E−13
Breast	2.52E−14	3.01E−14	4.22E−14	5.56E−14	6.61E−14	8.22E−14	1.13E−13	1.66E−13	2.30E−13	2.90E−13	3.45E−13	4.54E−13	5.70E−13
Gall bladder	1.85E−14	2.27E−14	3.17E−14	4.16E−14	5.21E−14	6.71E−14	9.28E−14	1.41E−13	1.96E−13	2.52E−13	3.04E−13	4.09E−13	5.06E−13
Stomach	1.94E−14	2.46E−14	3.46E−14	4.35E−14	5.48E−14	6.89E−14	9.45E−14	1.43E−13	2.00E−13	2.56E−13	3.08E−13	4.13E−13	5.23E−13
Small intestine	1.77E−14	2.27E−14	3.16E−14	4.05E−14	5.09E−14	6.68E−14	8.90E−14	1.38E−13	1.95E−13	2.51E−13	3.02E−13	4.07E−13	5.16E−13
Colon	1.96E−14	2.37E−14	3.37E−14	4.34E−14	5.58E−14	6.81E−14	9.52E−14	1.40E−13	1.97E−13	2.52E−13	3.04E−13	4.08E−13	5.16E−13
Heart	2.04E−14	2.51E−14	3.43E−14	4.71E−14	5.67E−14	7.25E−14	9.97E−14	1.49E−13	2.09E−13	2.66E−13	3.19E−13	4.27E−13	5.41E−13
Kidney	1.83E−14	2.20E−14	3.16E−14	4.04E−14	5.28E−14	6.69E−14	9.23E−14	1.40E−13	1.97E−13	2.52E−13	3.04E−13	4.09E−13	5.21E−13
Liver	1.96E−14	2.38E−14	3.33E−14	4.41E−14	5.38E−14	6.94E−14	9.29E−14	1.44E−13	2.03E−13	2.58E−13	3.11E−13	4.17E−13	5.28E−13
Lungs	2.03E−14	2.63E−14	3.52E−14	4.92E−14	5.74E−14	7.62E−14	1.04E−13	1.55E−13	2.17E−13	2.76E−13	3.31E−13	4.41E−13	5.61E−13
Lymphatic nodes	1.94E−14	2.51E−14	3.40E−14	4.52E−14	5.51E−14	7.09E−14	9.70E−14	1.47E−13	2.06E−13	2.64E−13	3.17E−13	4.25E−13	5.40E−13
Muscle	2.10E−14	2.59E−14	3.52E−14	4.59E−14	5.85E−14	7.33E−14	9.92E−14	1.49E−13	2.08E−13	2.65E−13	3.18E−13	4.25E−13	5.38E−13
Oesophagus	2.10E−14	2.54E−14	3.57E−14	4.67E−14	5.85E−14	7.30E−14	1.01E−13	1.50E−13	2.10E−13	2.69E−13	3.21E−13	4.30E−13	5.39E−13
Pancreas	1.81E−14	2.23E−14	3.13E−14	4.12E−14	5.15E−14	6.53E−14	9.00E−14	1.37E−13	1.93E−13	2.47E−13	2.96E−13	3.99E−13	5.09E−13
Prostate/uterus female	1.68E−14	2.07E−14	2.90E−14	3.85E−14	4.89E−14	6.14E−14	8.71E−14	1.33E−13	1.88E−13	2.44E−13	2.93E−13	3.96E−13	4.96E−13
Salivary glands	2.49E−14	3.01E−14	4.20E−14	5.40E−14	6.75E−14	8.31E−14	1.14E−13	1.67E−13	2.33E−13	2.96E−13	3.53E−13	4.69E−13	5.96E−13
Skin	2.48E−14	3.00E−14	4.10E−14	5.28E−14	6.55E−14	8.13E−14	1.10E−13	1.61E−13	2.23E−13	2.83E−13	3.37E−13	4.49E−13	5.66E−13
Spleen	2.08E−14	2.43E−14	3.37E−14	4.42E−14	5.53E−14	6.96E−14	9.59E−14	1.44E−13	2.03E−13	2.59E−13	3.12E−13	4.21E−13	5.28E−13
Gonads male/ovaries female	1.89E−14	2.28E−14	3.23E−14	4.15E−14	5.39E−14	6.72E−14	9.17E−14	1.38E−13	1.97E−13	2.50E−13	3.00E−13	4.09E−13	5.11E−13
Thymus	2.33E−14	2.86E−14	3.97E−14	5.07E−14	6.36E−14	7.93E−14	1.10E−13	1.62E−13	2.24E−13	2.85E−13	3.44E−13	4.58E−13	5.72E−13
Thyroid	2.45E−14	2.93E−14	4.15E−14	5.29E−14	6.58E−14	8.24E−14	1.11E−13	1.61E−13	2.23E−13	2.84E−13	3.42E−13	4.52E−13	5.69E−13
Urinary bladder	1.81E−14	2.17E−14	3.04E−14	3.99E−14	5.03E−14	6.42E−14	8.80E−14	1.34E−13	1.90E−13	2.43E−13	2.91E−13	3.95E−13	5.05E−13
Effective dose	2.10E−14	2.58E−14	3.58E−14	4.65E−14	5.78E−14	7.28E−14	9.97E−14	1.49E−13	2.09E−13	2.66E−13	3.19E−13	4.27E−13	5.39E−13

Table B2. DCFs of photon for the groundshine (Sv s^{-1} per Bq m^{-2}).

Tissue	Emitted photon energy (MeV)												
	0.01	0.015	0.02	0.03	0.04	0.05	0.06	0.08	0.10	0.15	0.20	0.30	0.40
Adrenals	3.07E−24	3.75E−20	3.72E−19	7.20E−18	2.04E−17	2.90E−17	4.20E−17	5.35E−17	7.07E−17	9.77E−17	1.46E−16	2.47E−16	3.40E−16
Extrathoracic region	5.38E−19	4.73E−18	1.17E−17	2.26E−17	3.35E−17	3.88E−17	5.08E−17	6.60E−17	8.11E−17	1.26E−16	1.84E−16	2.86E−16	3.75E−16
Oral mucosa	4.47E−20	1.41E−18	4.64E−18	1.37E−17	2.40E−17	3.08E−17	4.64E−17	6.25E−17	8.18E−17	1.13E−16	1.85E−16	2.81E−16	3.72E−16
Bone surface	1.98E−20	6.34E−19	5.44E−18	3.22E−17	5.81E−17	7.45E−17	8.69E−17	1.05E−16	1.24E−16	1.72E−16	2.23E−16	3.30E−16	4.42E−16
Red bone marrow	2.18E−21	3.78E−19	3.37E−18	2.07E−17	4.19E−17	5.85E−17	7.14E−17	9.02E−17	1.08E−16	1.48E−16	1.90E−16	2.80E−16	3.73E−16
Brain	2.51E−24	4.36E−20	3.17E−19	8.26E−18	2.32E−17	3.54E−17	4.68E−17	6.51E−17	8.18E−17	1.27E−16	1.75E−16	2.61E−16	3.52E−16
Breast	1.28E−18	1.41E−17	2.88E−17	3.90E−17	4.21E−17	4.43E−17	4.93E−17	6.52E−17	8.60E−17	1.39E−16	1.82E−16	2.91E−16	3.85E−16
Gall bladder	5.96E−22	4.82E−21	3.61E−19	8.50E−18	2.14E−17	2.93E−17	4.04E−17	5.70E−17	7.29E−17	1.20E−16	1.68E−16	2.35E−16	3.35E−16
Stomach	1.45E−22	1.89E−19	2.90E−18	1.57E−17	3.03E−17	4.14E−17	5.13E−17	6.76E−17	8.20E−17	1.20E−16	1.75E−16	2.60E−16	3.57E−16
Small intestine	1.63E−23	1.23E−19	2.25E−18	1.55E−17	2.94E−17	4.10E−17	5.03E−17	6.67E−17	8.41E−17	1.27E−16	1.74E−16	2.65E−16	3.62E−16
Colon	1.42E−21	3.26E−19	3.71E−18	1.98E−17	3.39E−17	4.48E−17	5.29E−17	6.88E−17	8.68E−17	1.27E−16	1.80E−16	2.71E−16	3.58E−16
Heart	1.59E−23	2.27E−19	1.30E−18	1.18E−17	2.53E−17	3.59E−17	4.68E−17	6.23E−17	8.12E−17	1.19E−16	1.60E−16	2.60E−16	3.33E−16
Kidney	6.00E−22	1.37E−19	9.20E−19	1.33E−17	2.86E−17	4.10E−17	5.10E−17	6.62E−17	8.52E−17	1.30E−16	1.68E−16	2.63E−16	3.48E−16
Liver	1.43E−22	1.37E−19	2.03E−18	1.43E−17	2.91E−17	3.99E−17	4.92E−17	6.77E−17	8.39E−17	1.27E−16	1.69E−16	2.57E−16	3.45E−16
Lungs	3.85E−22	9.92E−20	1.90E−18	1.44E−17	2.77E−17	3.91E−17	4.81E−17	6.62E−17	8.46E−17	1.25E−16	1.67E−16	2.71E−16	3.57E−16
Lymphatic nodes	1.83E−19	3.95E−18	1.10E−17	2.45E−17	3.56E−17	4.61E−17	5.46E−17	7.13E−17	8.88E−17	1.33E−16	1.80E−16	2.76E−16	3.76E−16
Muscle	2.54E−19	4.40E−18	1.53E−17	3.71E−17	4.91E−17	5.79E−17	6.55E−17	8.19E−17	1.01E−16	1.52E−16	2.06E−16	3.15E−16	4.26E−16
Oesophagus	3.93E−23	2.35E−19	1.44E−18	8.51E−18	1.94E−17	3.14E−17	3.96E−17	5.41E−17	7.33E−17	1.10E−16	1.53E−16	2.38E−16	3.72E−16
Pancreas	1.50E−22	1.07E−19	4.85E−19	7.27E−18	2.02E−17	3.18E−17	4.51E−17	6.20E−17	7.63E−17	1.20E−16	1.66E−16	2.45E−16	3.57E−16
Prostate/uterus female	1.12E−22	6.45E−20	2.30E−19	6.04E−18	1.85E−17	2.57E−17	4.34E−17	5.94E−17	7.69E−17	1.18E−16	1.67E−16	2.57E−16	3.63E−16
Salivary glands	1.79E−19	6.71E−18	1.99E−17	3.59E−17	4.39E−17	4.85E−17	5.71E−17	7.34E−17	8.93E−17	1.42E−16	1.89E−16	3.05E−16	4.36E−16
Skin	4.60E−17	8.32E−17	8.88E−17	8.00E−17	7.28E−17	7.20E−17	7.55E−17	9.03E−17	1.11E−16	1.68E−16	2.30E−16	3.56E−16	4.77E−16
Spleen	4.87E−26	3.60E−19	1.93E−18	1.63E−17	3.16E−17	4.07E−17	5.32E−17	7.31E−17	8.91E−17	1.24E−16	1.85E−16	2.56E−16	3.36E−16
Gonads male/ovaries female	1.30E−18	7.19E−18	1.50E−17	2.84E−17	4.02E−17	4.83E−17	5.83E−17	7.02E−17	9.87E−17	1.36E−16	1.85E−16	3.02E−16	3.81E−16
Thymus	2.60E−20	5.42E−19	3.25E−18	1.51E−17	2.65E−17	3.32E−17	4.60E−17	6.51E−17	7.92E−17	1.17E−16	1.55E−16	2.40E−16	3.19E−16
Thyroid	7.14E−21	2.45E−18	1.25E−17	2.78E−17	4.19E−17	5.38E−17	6.47E−17	7.98E−17	9.18E−17	1.48E−16	1.97E−16	2.57E−16	3.56E−16
Urinary bladder	1.35E−20	1.65E−18	6.92E−18	1.90E−17	3.03E−17	3.95E−17	5.23E−17	7.05E−17	8.17E−17	1.28E−16	1.75E−16	2.64E−16	3.49E−16
Effective dose	7.30E−19	3.62E−18	8.64E−18	2.16E−17	3.45E−17	4.44E−17	5.42E−17	7.06E−17	8.87E−17	1.31E−16	1.79E−16	2.74E−16	3.67E−16

	0.5	0.6	0.8	1.0	1.25	1.50	2.0	3.0	4.0	5.0	6.0	8.0	10.0
Adrenals	4.38E−16	5.25E−16	6.83E−16	8.40E−16	1.01E−15	1.22E−15	1.62E−15	2.19E−15	2.76E−15	3.38E−15	3.89E−15	4.99E−15	6.07E−15
Extrathoracic region	5.18E−16	5.70E−16	7.87E−16	9.64E−16	1.12E−15	1.33E−15	1.68E−15	2.27E−15	2.82E−15	3.31E−15	3.81E−15	4.91E−15	5.90E−15
Oral mucosa	4.45E−16	5.20E−16	6.77E−16	8.26E−16	1.01E−15	1.21E−15	1.57E−15	2.10E−15	2.67E−15	3.10E−15	3.62E−15	4.75E−15	5.73E−15
Bone surface	5.47E−16	6.51E−16	8.54E−16	1.06E−15	1.27E−15	1.47E−15	1.87E−15	2.60E−15	3.26E−15	3.96E−15	4.70E−15	5.69E−15	6.71E−15
Red bone marrow	4.61E−16	5.54E−16	7.19E−16	9.14E−16	1.09E−15	1.26E−15	1.63E−15	2.28E−15	2.85E−15	3.44E−15	4.08E−15	5.21E−15	6.20E−15
Brain	4.51E−16	5.63E−16	7.03E−16	8.82E−16	1.08E−15	1.20E−15	1.56E−15	2.26E−15	2.71E−15	3.15E−15	3.64E−15	4.53E−15	5.63E−15
Breast	4.82E−16	5.66E−16	7.67E−16	9.03E−16	1.13E−15	1.26E−15	1.62E−15	2.27E−15	2.87E−15	3.33E−15	4.00E−15	4.87E−15	5.79E−15

Continued

Table B2. *Continued*

Tissue	Emitted photon energy (MeV)												
	0.5	0.6	0.8	1.0	1.25	1.50	2.0	3.0	4.0	5.0	6.0	8.0	10.0
Gall bladder	4.11E−16	4.99E−16	6.68E−16	8.05E−16	9.92E−16	1.18E−15	1.53E−15	2.13E−15	2.72E−15	3.24E−15	3.80E−15	4.88E−15	5.83E−15
Stomach	4.38E−16	5.11E−16	6.82E−16	8.58E−16	1.04E−15	1.26E−15	1.59E−15	2.17E−15	2.76E−15	3.46E−15	3.95E−15	4.91E−15	6.07E−15
Small intestine	4.43E−16	5.42E−16	7.13E−16	8.65E−16	1.06E−15	1.28E−15	1.62E−15	2.29E−15	2.97E−15	3.61E−15	4.36E−15	5.25E−15	6.22E−15
Colon	4.60E−16	5.51E−16	7.19E−16	8.85E−16	1.05E−15	1.26E−15	1.61E−15	2.21E−15	2.96E−15	3.65E−15	3.99E−15	5.16E−15	6.34E−15
Heart	4.13E−16	5.00E−16	6.66E−16	8.54E−16	1.06E−15	1.22E−15	1.58E−15	2.21E−15	2.57E−15	3.31E−15	3.73E−15	4.75E−15	5.70E−15
Kidney	4.34E−16	5.20E−16	7.23E−16	8.64E−16	1.08E−15	1.29E−15	1.67E−15	2.24E−15	2.84E−15	3.52E−15	3.90E−15	4.99E−15	6.00E−15
Liver	4.28E−16	5.24E−16	6.77E−16	8.76E−16	1.05E−15	1.20E−15	1.57E−15	2.15E−15	2.64E−15	3.36E−15	4.28E−15	5.10E−15	5.94E−15
Lungs	4.40E−16	5.34E−16	6.97E−16	9.11E−16	1.12E−15	1.29E−15	1.64E−15	2.27E−15	2.68E−15	3.22E−15	3.98E−15	5.00E−15	5.87E−15
Lymphatic nodes	4.57E−16	5.41E−16	7.36E−16	9.06E−16	1.12E−15	1.39E−15	1.80E−15	2.40E−15	3.05E−15	3.64E−15	4.10E−15	5.18E−15	6.29E−15
Muscle	5.36E−16	6.36E−16	8.38E−16	1.03E−15	1.25E−15	1.47E−15	1.88E−15	2.58E−15	3.22E−15	3.82E−15	4.44E−15	5.66E−15	6.82E−15
Oesophagus	4.48E−16	5.00E−16	6.39E−16	8.37E−16	9.93E−16	1.25E−15	1.55E−15	2.19E−15	2.69E−15	3.16E−15	3.76E−15	4.79E−15	5.76E−15
Pancreas	4.24E−16	5.14E−16	6.78E−16	8.15E−16	1.05E−15	1.23E−15	1.59E−15	2.21E−15	2.78E−15	3.26E−15	3.87E−15	4.81E−15	5.95E−15
Prostate/uterus female	4.17E−16	5.18E−16	6.86E−16	8.98E−16	1.08E−15	1.28E−15	1.70E−15	2.40E−15	2.93E−15	3.51E−15	3.99E−15	5.19E−15	6.37E−15
Salivary glands	5.08E−16	5.78E−16	7.57E−16	9.48E−16	1.12E−15	1.32E−15	1.64E−15	2.24E−15	2.76E−15	3.26E−15	3.89E−15	4.80E−15	5.75E−15
Skin	5.96E−16	7.12E−16	9.26E−16	1.14E−15	1.38E−15	1.62E−15	2.02E−15	2.75E−15	3.40E−15	4.04E−15	4.73E−15	5.90E−15	7.05E−15
Spleen	4.24E−16	5.22E−16	6.84E−16	8.74E−16	1.02E−15	1.22E−15	1.57E−15	2.16E−15	2.71E−15	3.23E−15	3.68E−15	4.84E−15	5.80E−15
Gonads male/ovaries female	4.73E−16	5.83E−16	7.64E−16	9.45E−16	1.16E−15	1.37E−15	1.74E−15	2.44E−15	3.09E−15	3.65E−15	4.25E−15	5.45E−15	6.63E−15
Thymus	4.08E−16	4.75E−16	6.48E−16	8.03E−16	9.75E−16	1.16E−15	1.50E−15	2.12E−15	2.57E−15	3.08E−15	3.62E−15	4.62E−15	5.61E−15
Thyroid	4.42E−16	5.10E−16	7.15E−16	8.70E−16	1.05E−15	1.21E−15	1.55E−15	2.08E−15	2.62E−15	3.10E−15	3.62E−15	4.67E−15	5.54E−15
Urinary bladder	4.39E−16	5.27E−16	7.26E−16	8.76E−16	1.09E−15	1.30E−15	1.68E−15	2.31E−15	2.91E−15	3.48E−15	4.06E−15	5.18E−15	6.23E−15
Effective dose	4.56E−16	5.44E−16	7.19E−16	8.95E−16	1.09E−15	1.28E−15	1.63E−15	2.26E−15	2.84E−15	3.42E−15	4.01E−15	5.05E−15	6.07E−15

Table B3. DCFs of photon for the water immersion (Sv s^{-1} per Bq m^{-3}).

Tissue	Emitted photon energy (MeV)												
	0.01	0.015	0.02	0.03	0.04	0.05	0.06	0.08	0.10	0.15	0.20	0.30	0.40
Adrenals	1.42E−26	9.24E−23	5.10E−21	2.00E−19	7.63E−19	1.56E−18	2.42E−18	4.20E−18	5.91E−18	1.00E−17	1.41E−17	2.23E−17	3.07E−17
Extrathoracic region	1.30E−20	7.48E−20	2.31E−19	8.05E−19	1.66E−18	2.69E−18	3.80E−18	6.00E−18	8.24E−18	1.36E−17	1.91E−17	3.00E−17	4.10E−17
Oral mucosa	5.48E−22	1.53E−20	8.10E−20	4.45E−19	1.19E−18	2.16E−18	3.23E−18	5.38E−18	7.53E−18	1.28E−17	1.80E−17	2.85E−17	3.92E−17
Bone surface	2.75E−22	1.01E−20	9.31E−20	8.92E−19	2.46E−18	4.23E−18	5.93E−18	8.91E−18	1.15E−17	1.72E−17	2.24E−17	3.28E−17	4.32E−17
Red bone marrow	2.82E−22	1.12E−20	9.02E−20	7.55E−19	2.11E−18	3.73E−18	5.32E−18	8.14E−18	1.06E−17	1.59E−17	2.08E−17	3.04E−17	4.00E−17
Brain	1.16E−26	1.60E−22	1.05E−20	3.52E−19	1.35E−18	2.62E−18	3.94E−18	6.45E−18	8.83E−18	1.45E−17	2.00E−17	3.11E−17	4.24E−17
Breast	2.49E−20	1.98E−19	5.34E−19	1.40E−18	2.33E−18	3.34E−18	4.38E−18	6.54E−18	8.73E−18	1.42E−17	1.98E−17	3.10E−17	4.24E−17
Gall bladder	2.75E−24	1.94E−21	6.19E−21	2.04E−19	8.18E−19	1.68E−18	2.59E−18	4.46E−18	6.21E−18	1.04E−17	1.45E−17	2.28E−17	3.12E−17
Stomach	6.68E−25	2.03E−21	4.14E−20	4.73E−19	1.33E−18	2.36E−18	3.42E−18	5.47E−18	7.41E−18	1.19E−17	1.63E−17	2.52E−17	3.42E−17
Small intestine	7.52E−26	1.01E−21	2.70E−20	3.91E−19	1.17E−18	2.14E−18	3.13E−18	5.06E−18	6.89E−18	1.12E−17	1.54E−17	2.38E−17	3.25E−17
Colon	6.55E−24	2.82E−21	5.00E−20	5.32E−19	1.43E−18	2.46E−18	3.51E−18	5.52E−18	7.41E−18	1.19E−17	1.63E−17	2.51E−17	3.41E−17
Heart	7.32E−26	6.53E−22	2.33E−20	3.68E−19	1.17E−18	2.19E−18	3.26E−18	5.33E−18	7.30E−18	1.19E−17	1.64E−17	2.54E−17	3.47E−17
Kidney	7.84E−22	2.14E−22	1.49E−20	3.40E−19	1.12E−18	2.10E−18	3.12E−18	5.07E−18	6.92E−18	1.12E−17	1.54E−17	2.38E−17	3.25E−17
Liver	6.59E−25	1.47E−21	3.33E−20	4.24E−19	1.26E−18	2.29E−18	3.35E−18	5.40E−18	7.33E−18	1.18E−17	1.62E−17	2.50E−17	3.41E−17
Lungs	1.88E−23	1.45E−21	3.60E−20	4.63E−19	1.34E−18	2.42E−18	3.52E−18	5.66E−18	7.71E−18	1.26E−17	1.73E−17	2.69E−17	3.68E−17
Lymphatic nodes	2.15E−21	4.20E−20	1.71E−19	7.23E−19	1.61E−18	2.65E−18	3.73E−18	5.81E−18	7.79E−18	1.25E−17	1.71E−17	2.64E−17	3.59E−17
Muscle	1.17E−21	3.65E−20	2.05E−19	1.01E−18	2.15E−18	3.36E−18	4.57E−18	6.86E−18	9.04E−18	1.42E−17	1.93E−17	2.95E−17	3.98E−17
Oesophagus	1.82E−25	1.15E−21	2.01E−20	2.47E−19	8.41E−19	1.68E−18	2.61E−18	4.49E−18	6.36E−18	1.08E−17	1.52E−17	2.41E−17	3.33E−17
Pancreas	6.91E−25	8.28E−22	4.41E−21	2.01E−19	8.22E−19	1.69E−18	2.63E−18	4.49E−18	6.25E−18	1.04E−17	1.44E−17	2.25E−17	3.09E−17
Prostate/uterus female	5.16E−25	1.02E−25	2.50E−21	1.52E−19	6.55E−19	1.41E−18	2.26E−18	3.98E−18	5.65E−18	9.64E−18	1.35E−17	2.15E−17	2.98E−17
Salivary glands	3.95E−21	8.82E−20	3.56E−19	1.20E−18	2.19E−18	3.25E−18	4.37E−18	6.60E−18	8.83E−18	1.43E−17	1.98E−17	3.08E−17	4.20E−17
Skin	3.34E−19	8.27E−19	1.37E−18	2.50E−18	3.68E−18	4.90E−18	6.14E−18	8.62E−18	1.11E−17	1.71E−17	2.30E−17	3.50E−17	4.71E−17
Spleen	2.25E−28	1.70E−21	3.79E−20	4.75E−19	1.38E−18	2.45E−18	3.56E−18	5.67E−18	7.63E−18	1.22E−17	1.67E−17	2.57E−17	3.49E−17
Gonads male/ovaries female	8.02E−21	6.49E−20	1.95E−19	7.37E−19	1.58E−18	2.61E−18	3.66E−18	5.70E−18	7.67E−18	1.22E−17	1.67E−17	2.56E−17	3.49E−17
Thymus	1.83E−23	1.05E−20	8.90E−20	5.56E−19	1.37E−18	2.34E−18	3.37E−18	5.43E−18	7.43E−18	1.22E−17	1.70E−17	2.67E−17	3.66E−17
Thyroid	1.06E−22	2.78E−20	1.90E−19	9.13E−19	1.98E−18	3.16E−18	4.41E−18	6.74E−18	8.99E−18	1.42E−17	1.93E−17	2.94E−17	3.96E−17
Urinary bladder	2.51E−22	1.42E−20	8.43E−20	4.87E−19	1.22E−18	2.14E−18	3.11E−18	5.02E−18	6.85E−18	1.12E−17	1.54E−17	2.39E−17	3.25E−17
Effective dose	7.23E−21	4.38E−20	1.46E−19	6.80E−19	1.61E−18	2.71E−18	3.84E−18	6.01E−18	8.07E−18	1.29E−17	1.76E−17	2.71E−17	3.68E−17

	0.5	0.6	0.8	1.0	1.25	1.50	2.0	3.0	4.0	5.0	6.0	8.0	10.0
Adrenals	3.95E−17	4.86E−17	6.72E−17	8.75E−17	1.13E−16	1.41E−16	1.96E−16	3.12E−16	4.38E−16	5.66E−16	6.90E−16	9.40E−16	1.18E−15
Extrathoracic region	5.25E−17	6.39E−17	8.73E−17	1.11E−16	1.42E−16	1.73E−16	2.38E−16	3.72E−16	5.04E−16	6.43E−16	7.80E−16	1.05E−15	1.33E−15
Oral mucosa	5.03E−17	6.12E−17	8.44E−17	1.08E−16	1.38E−16	1.69E−16	2.32E−16	3.62E−16	4.98E−16	6.29E−16	7.64E−16	1.03E−15	1.30E−15
Bone surface	5.39E−17	6.47E−17	8.68E−17	1.10E−16	1.39E−16	1.69E−16	2.30E−16	3.58E−16	4.89E−16	6.21E−16	7.54E−16	1.02E−15	1.29E−15
Red bone marrow	4.99E−17	6.00E−17	8.07E−17	1.02E−16	1.30E−16	1.58E−16	2.17E−16	3.40E−16	4.67E−16	5.96E−16	7.25E−16	9.86E−16	1.25E−15
Brain	5.38E−17	6.54E−17	8.92E−17	1.14E−16	1.45E−16	1.76E−16	2.41E−16	3.75E−16	5.11E−16	6.48E−16	7.84E−16	1.06E−15	1.34E−15
Breast	5.40E−17	6.59E−17	8.99E−17	1.15E−16	1.46E−16	1.78E−16	2.43E−16	3.77E−16	5.08E−16	6.46E−16	7.77E−16	1.05E−15	1.32E−15

Continued

Table B3. *Continued*

Tissue	Emitted photon energy (MeV)												
	0.5	0.6	0.8	1.0	1.25	1.50	2.0	3.0	4.0	5.0	6.0	8.0	10.0
Gall bladder	4.00E−17	4.92E−17	6.79E−17	8.80E−17	1.14E−16	1.41E−16	1.97E−16	3.15E−16	4.37E−16	5.59E−16	6.82E−16	9.34E−16	1.17E−15
Stomach	4.36E−17	5.32E−17	7.31E−17	9.38E−17	1.21E−16	1.48E−16	2.06E−16	3.25E−16	4.50E−16	5.78E−16	7.02E−16	9.63E−16	1.22E−15
Small intestine	4.15E−17	5.07E−17	7.01E−17	9.00E−17	1.16E−16	1.43E−16	2.00E−16	3.18E−16	4.40E−16	5.64E−16	6.90E−16	9.41E−16	1.19E−15
Colon	4.34E−17	5.30E−17	7.28E−17	9.35E−17	1.20E−16	1.48E−16	2.05E−16	3.26E−16	4.50E−16	5.75E−16	7.02E−16	9.57E−16	1.21E−15
Heart	4.42E−17	5.40E−17	7.44E−17	9.52E−17	1.23E−16	1.51E−16	2.10E−16	3.31E−16	4.58E−16	5.85E−16	7.12E−16	9.67E−16	1.23E−15
Kidney	4.15E−17	5.08E−17	7.00E−17	9.00E−17	1.16E−16	1.43E−16	1.99E−16	3.18E−16	4.41E−16	5.65E−16	6.93E−16	9.43E−16	1.20E−15
Liver	4.34E−17	5.30E−17	7.27E−17	9.35E−17	1.20E−16	1.48E−16	2.05E−16	3.26E−16	4.50E−16	5.77E−16	7.06E−16	9.60E−16	1.22E−15
Lungs	4.69E−17	5.73E−17	7.88E−17	1.01E−16	1.30E−16	1.59E−16	2.20E−16	3.46E−16	4.75E−16	6.06E−16	7.38E−16	1.00E−15	1.27E−15
Lymphatic nodes	4.56E−17	5.56E−17	7.63E−17	9.77E−17	1.25E−16	1.54E−16	2.13E−16	3.36E−16	4.63E−16	5.93E−16	7.21E−16	9.85E−16	1.25E−15
Muscle	5.04E−17	6.12E−17	8.33E−17	1.06E−16	1.35E−16	1.65E−16	2.27E−16	3.54E−16	4.85E−16	6.17E−16	7.50E−16	1.02E−15	1.29E−15
Oesophagus	4.28E−17	5.26E−17	7.29E−17	9.38E−17	1.21E−16	1.49E−16	2.07E−16	3.30E−16	4.56E−16	5.82E−16	7.10E−16	9.54E−16	1.22E−15
Pancreas	3.95E−17	4.84E−17	6.70E−17	8.65E−17	1.12E−16	1.39E−16	1.94E−16	3.11E−16	4.33E−16	5.57E−16	6.78E−16	9.28E−16	1.17E−15
Prostate/uterus female	3.82E−17	4.72E−17	6.61E−17	8.52E−17	1.11E−16	1.37E−16	1.92E−16	3.09E−16	4.29E−16	5.48E−16	6.73E−16	9.13E−16	1.17E−15
Salivary glands	5.33E−17	6.48E−17	8.85E−17	1.13E−16	1.44E−16	1.75E−16	2.38E−16	3.72E−16	5.06E−16	6.48E−16	7.84E−16	1.05E−15	1.31E−15
Skin	5.93E−17	7.16E−17	9.67E−17	1.22E−16	1.54E−16	1.87E−16	2.54E−16	3.90E−16	5.28E−16	6.67E−16	8.07E−16	1.09E−15	1.36E−15
Spleen	4.43E−17	5.41E−17	7.44E−17	9.54E−17	1.22E−16	1.50E−16	2.09E−16	3.30E−16	4.55E−16	5.83E−16	7.11E−16	9.73E−16	1.23E−15
Gonads male/ovaries female	4.42E−17	5.42E−17	7.44E−17	9.52E−17	1.22E−16	1.49E−16	2.07E−16	3.27E−16	4.52E−16	5.74E−16	6.99E−16	9.51E−16	1.20E−15
Thymus	4.66E−17	5.71E−17	7.86E−17	1.01E−16	1.30E−16	1.59E−16	2.19E−16	3.46E−16	4.81E−16	6.05E−16	7.35E−16	1.00E−15	1.26E−15
Thyroid	5.01E−17	6.10E−17	8.29E−17	1.05E−16	1.35E−16	1.65E−16	2.27E−16	3.55E−16	4.87E−16	6.14E−16	7.47E−16	1.03E−15	1.29E−15
Urinary bladder	4.17E−17	5.09E−17	7.03E−17	9.02E−17	1.16E−16	1.43E−16	2.00E−16	3.18E−16	4.41E−16	5.66E−16	6.91E−16	9.45E−16	1.19E−15
Effective dose	4.67E−17	5.69E−17	7.79E−17	9.96E−17	1.28E−16	1.56E−16	2.16E−16	3.40E−16	4.67E−16	5.96E−16	7.24E−16	9.86E−16	1.25E−15

Appendix C. A summary of DCFs for calculating effective doses due to radioactive effluents released to the environment under the normal or accidental situations of the referred nuclear power reactor.

Nuclides	Effective DCFs											
	Air submersion (Sv s^{-1} per Bq m^{-3})				Ground surface (Sv s^{-1} per Bq m^{-2})				Water immersion (Sv s^{-1} per Bq m^{-3})			
	FGR 12 (He)	FGR 13	This study	RE[7]	FGR 12 (He)	FGR 13	This study	RE[7]	FGR 12 (He)	FGR 12[9]	This study	RE[7]
^{110m}Ag	1.36E−13	1.27E−13	1.26E−13	1 %	2.65E−15	2.58E−15	2.46E−15	5 %	2.94E−16	2.79E−16	2.75E−16	1 %
^{41}Ar	6.50E−14	6.15E−14	6.01E−14	2 %	1.20E−15	1.22E−15	1.16E−15	5 %	1.41E−16	1.34E−16	1.33E−16	1 %
^{137m}Ba	2.88E−14	2.69E−14	2.60E−14	3 %	5.86E−16	5.78E−16	5.48E−16	5 %	6.26E−17	5.87E−17	5.75E−17	2 %
^{57}Co	5.61E−15	4.98E−15	4.64E−15	7 %	1.15E−16	1.09E−16	1.07E−16	2 %	1.25E−17	1.12E−17	1.02E−17	10 %
^{58}Co	4.76E−14	4.45E−14	4.34E−14	3 %	9.50E−16	9.23E−16	8.76E−16	5 %	1.03E−16	9.76E−17	9.52E−17	3 %
^{60}Co	1.26E−13	1.19E−13	1.17E−13	2 %	2.35E−15	2.30E−15	2.18E−15	6 %	2.74E−16	2.61E−16	2.58E−16	1 %
^{134}Cs	7.57E−14	7.07E−14	6.87E−14	3 %	1.52E−15	1.48E−15	1.41E−15	5 %	1.64E−16	1.55E−16	1.51E−16	3 %
^{136}Cs	1.06E−13	9.94E−14	9.65E−14	3 %	2.09E−15	2.03E−15	1.90E−15	7 %	2.31E−16	2.19E−16	2.10E−16	4 %
^{137}Cs	7.74E−18	9.28E−17	8.64E−17	7 %	2.85E−19	2.99E−18	2.75E−18	9 %	1.49E−20	9.12E−20	9.13E−20	0 %
^{138}Cs	1.21E−13	1.15E−13	1.13E−13	2 %	2.19E−15	2.26E−15	2.14E−15	6 %	2.62E−16	2.51E−16	2.47E−16	2 %
^{131}I	1.82E−14	1.69E−14	1.62E−14	4 %	3.76E−16	3.64E−16	3.52E−16	3 %	3.98E−17	3.71E−17	3.54E−17	5 %
^{132}I	1.12E−13	1.05E−13	1.02E−13	3 %	2.21E−15	2.20E−15	2.07E−15	6 %	2.43E−16	2.30E−16	2.23E−16	3 %
^{133}I	2.94E−14	2.76E−14	2.66E−14	4 %	5.97E−16	6.16E−16	5.92E−16	4 %	6.39E−17	6.03E−17	5.89E−17	2 %
^{134}I	1.30E−13	1.22E−13	1.19E−13	3 %	2.53E−15	2.52E−15	2.38E−15	6 %	2.82E−16	2.67E−16	2.59E−16	3 %
^{135}I	7.98E−14	7.54E−14	7.50E−14	1 %	1.47E−15	1.47E−15	1.40E−15	5 %	1.73E−16	1.65E−16	1.64E−16	1 %
^{85}Kr	1.19E−16	2.40E−16	2.25E−16	7 %	2.64E−18	1.05E−17	1.00E−17	5 %	2.55E−19	3.55E−19	3.49E−19	2 %
^{85m}Kr	7.48E−15	6.88E−15	6.28E−15	10 %	1.52E−16	1.57E−16	1.50E−16	5 %	1.65E−17	1.52E−17	1.39E−17	9 %
^{87}Kr	4.12E−14	3.98E−14	3.83E−14	4 %	7.32E−16	8.39E−16	7.88E−16	6 %	8.93E−17	8.56E−17	8.36E−17	2 %
^{88}Kr	1.02E−13	9.72E−14	9.55E−14	2 %	1.74E−15	1.72E−15	1.62E−15	6 %	2.21E−16	2.13E−16	2.10E−16	1 %
^{54}Mn	4.09E−14	3.83E−14	3.78E−14	1 %	8.12E−16	7.89E−16	7.50E−16	5 %	8.88E−17	8.41E−17	8.23E−17	2 %
^{99}Mo	7.28E−15	6.99E−15	6.68E−15	5 %	1.47E−16	1.78E−16	1.69E−16	5 %	1.58E−17	1.51E−17	1.45E−17	4 %
^{24}Na	2.18E−13	2.08E−13	2.01E−13	3 %	3.61E−15	3.59E−15	3.35E−15	7 %	4.73E−16	4.57E−16	4.52E−16	1 %
^{95}Nb	3.74E−14	3.49E−14	3.41E−14	2 %	7.48E−16	7.27E−16	6.88E−16	6 %	8.11E−17	7.66E−17	7.48E−17	2 %
^{147}Nd	6.19E−15	5.73E−15	5.41E−15	6 %	1.39E−16	1.40E−16	1.35E−16	4 %	1.36E−17	1.26E−17	1.20E−17	5 %
^{239}Np	7.69E−15	6.96E−15	6.92E−15	1 %	1.63E−16	1.54E−16	1.59E−16	−3 %	1.70E−17	1.55E−17	1.50E−17	3 %
^{143}Pr	2.10E−17	1.94E−16	1.76E−16	10 %	7.01E−19	2.06E−17	2.00E−17	3 %	4.04E−20	1.87E−19	1.87E−19	0 %
^{86}Rb	4.81E−15	4.95E−15	4.76E−15	4 %	9.31E−17	1.67E−16	1.59E−16	5 %	1.04E−17	1.02E−17	9.85E−18	4 %
^{88}Rb	3.36E−14	3.33E−14	3.27E−14	2 %	5.95E−16	7.40E−16	6.91E−16	7 %	7.26E−17	6.93E−17	6.93E−17	0 %
^{89}Rb	1.06E−13	1.01E−13	1.07E−13	−6 %	1.91E−15	1.97E−15	2.01E−15	−2 %	2.30E−16	2.21E−16	2.35E−16	−6 %
^{103}Ru	2.25E−14	2.09E−14	2.09E−14	0 %	4.63E−16	4.48E−16	4.53E−16	−1 %	4.89E−17	4.59E−17	4.68E−17	−2 %
^{105}Ru	3.81E−14	3.57E−14	3.28E−14	9 %	7.69E−16	7.81E−16	7.10E−16	10 %	8.27E−17	7.80E−17	7.19E−17	8 %
^{131m}Xe	3.89E−16	3.50E−16	3.51E−16	0 %	2.06E−17	1.61E−17	1.51E−17	7 %	8.93E−19	7.70E−19	7.30E−19	5 %

Continued

Appendix C. *Continued*

Nuclides	Effective DCFs											
	Air submersion (Sv s^{-1} per Bq m^{-3})				Ground surface (Sv s^{-1} per Bq m^{-2})				Water immersion (Sv s^{-1} per Bq m^{-3})			
	FGR 12 (He)	FGR 13	This study	RE[7]	FGR 12 (He)	FGR 13	This study	RE[7]	FGR 12 (He)	FGR 12[9]	This study	RE[7]
^{133}Xe	1.56E−15	1.34E−15	1.23E−15	9 %	4.61E−17	3.96E−17	3.94E−17	1 %	3.54E−18	3.04E−18	2.81E−18	8 %
^{133m}Xe	1.37E−15	1.29E−15	1.23E−15	5 %	4.07E−17	3.53E−17	3.37E−17	5 %	3.04E−18	2.79E−18	2.57E−18	9 %
^{135}Xe	1.19E−14	1.11E−14	1.04E−14	7 %	2.42E−16	2.50E−16	2.43E−16	3 %	2.61E−17	2.41E−17	2.23E−17	8 %
^{135m}Xe	2.04E−14	1.90E−14	1.79E−14	6 %	4.24E−16	4.18E−16	3.95E−16	6 %	4.45E−17	4.18E−17	3.99E−17	5 %

(1) RE (relative error) $= \dfrac{(\text{FGR 13} - \text{this study})}{\text{this study}}$.

(2) FGR 12* : Effective DCFs have been calculated based on those of the organs suggested in Table II-4 of FGR 12, tissue weighting factors in ICRP 60[14] and nuclide information in ICRP 38, respectively.

Daughter radionuclide(s) for each of any radionuclide's DCFs have not been taken into account in this table (e.g. ^{137}Cs).