Dose Coefficients for Industrial Radiography Sources Calculated with Mesh-type Computational Phantoms in Different Body Sizes

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1. Introduction

Accidents by industrial radiography sources have been commonly reported, which usually involve powerful gamma-emitting sources and could result in very high radiation doses to workers, leading to serious injuries or even death. The International Atomic Energy Agency (IAEA) reported that accidents by industrial radiography sources accounts for approximately half of all reported accidents in nuclear-related industries [1].

Once a radiation accident is reported, for the effective treatment of patients (i.e., exposed individuals) with acute radiation syndrome (ARS), medical triage should be performed accurately and quickly, whereby those patients who will develop symptoms are separately identified from those who do not require medical intervention. For this, it is necessary not only to carefully document clinical signs and symptoms, but also to accurately and rapidly estimate radiations doses to exposed individual.

Industrial radiation doses can be estimated by using various dosimetric techniques based on biological, physical, and computational approaches. However, all the existing dosimetry techniques have their own limitations, and thus none of them can be used as a stand-alone tool in a satisfactory manner for most of radiation accident scenarios [2]. Therefore, an integrated approach using multiple dosimetry techniques is considered as the best strategy [2].

In the present study, a comprehensive set of dose coefficients (DCs) for industrial radiography sources were produced by performing Monte Carlo dose calculations, which can be used as one of the dose estimators, particularly as an 'initial, rapid estimator.' For this, the adult mesh-type reference computational phantoms (MRCPs), recently developed by the International Commission on Radiological Protection (ICRP) [3], and the adult mesh-type non-reference phantoms, deformed from the MRCPs, representing the 10^{th} and 90^{th} percentiles of the Caucasian population [4], were implemented into the Geant4 Monte Carlo code [5]. In addition, the most commonly used industrial radiography sources (i.e., ^{192}Ir and ^{60}Co) placed in various locations were simulated.

2. Material and Methods

2.1. Mesh-type computational phantoms

In the present study, the adult MRCPs and 10^{th} and 90^{th} percentile phantoms were used in the DC calculations. The adult MRCPs are the counterparts of the adult voxel-type reference computational phantoms of the ICRP Publication 110 [6], which addressed limitations due to the limited voxel resolutions and the nature of voxel geometry. The 10^{th} and 90^{th} percentile phantoms were constructed by Lee et al. [4], by decreasing and increasing the body sizes of MRCPs. The 10^{th} percentile phantoms, which represent small people, have 10^{th} percentile standing height and 10^{th} percentile body mass (male: 1.67 m and 56 kg and female: 1.55 m and 44 kg). The 90^{th} percentile phantoms, which represent large people, have 90^{th} percentile standing height and the 90^{th} percentile body mass (male: 1.86 m and 108 kg and female: 1.72 m and 94 kg).

2.2. Calculation of dose coefficients for industrial radiography sources

The MRCPs and 10^{th} and 90^{th} percentile phantoms were implemented into the Geant4 Monte Carlo code to calculate DCs by simulating two industrial radiography sources, i.e., ^{192}Ir and ^{60}Co, as point sources placed near the phantoms. ^{192}Ir emits gamma rays with energies up to 0.820 MeV and a mean energy of 0.377 MeV, and ^{60}Co emits 1.33 and 1.17 MeV gamma rays. The point sources were assumed to be located at three different distances (0.005, 0.1, and 0.3 m) in four directions (anterior, posterior, right lateral, and left lateral) at five levels (ground, middle thigh and lower, middle, and upper torso). In addition, three longer distances (1, 1.5, and 3 m) were modelled in the four directions at the lower torso level.

To consider the doses of those organs/tissues that might manifest acute radiation syndrome, the doses for red bone marrow (RBM), brain, lungs, and small and large intestines were calculated as organ/tissue-averaged absorbed dose per source disintegration (Gy s^{-1} Bq^{-1}). Note that the RBM DCs were calculated by using the fluence-to-absorbed dose response functions

(DRFs) reported in Annex D of ICRP Publication 116 [7]. In addition, the DCs of effective dose (= effective dose per source disintegration) were calculated and could be used for the dosimetry of individuals exposed at low doses related to stochastic effects. The statistical errors of the calculated values were less than 5% for all cases.

Note that the DCs calculated in this study, assuming point sources, do not consider the source geometry. For users to consider the self-shielding effect by source geometry, the source self-shielding factors were additionally calculated for different thicknesses of radioactive material and capsule wall. For this, combinations of four different thicknesses of radioactive material (i.e., 1, 2, 3, and 4 mm) with two different thicknesses of capsule wall (i.e., 1 and 2 mm) were considered, which mostly cover the geometries of the radiography sources. The compositions of the capsule material were assumed as those of 316L stainless steel.

3. Results and Discussion

In the present study, the DCs for RBM, brain, lungs, and small and large intestines of the MRCPs and 10th and 90th percentile phantoms, as well as effective doses, were produced for the three types of industrial radiography sources (^{192}Ir and ^{60}Co) depending on 72 different locations near the phantoms. In addition, the source self-shielding factors for different thicknesses of radioactive material (1, 2, 3, and 4 mm) and capsule wall (1 and 2 mm) were produced as shown in Table 1.

The calculated DCs generally show that the body-size effect tends to be larger when the source is closer to the body. For example, the DC of the 90th percentile phantom is smaller than that of the MRCP by as large as ~8 times (i.e., for the female brain for the ^{192}Ir source located at 0.3 m from the phantom surface in the right direction at the ground level). If the source distance is greater than 1 m, the DC differences due to the body size are negligible, i.e., less than 20–30% for all the genders, organs, source directions, and sources energies considered in the present study. This indicates that the DCs are influenced mostly by distances of organs/tissues from sources (i.e., the inverse-square-law attenuation), rather than different thicknesses of surrounding tissues, mostly adipose tissue, (i.e., the exponential-law attenuation). Note that the differences in distances between organs/tissues and sources among the different size phantoms become more significant when the source position is closer to the phantom surface.

In addition, the 90th percentile phantom tends to show larger DC differences from the MRCP than the 10th percentile phantom. This tendency is partly because the MRCP does not exactly corresponds to the 50th percentile in mass; the adult male and female MRCP corresponds to ~30th and ~40th percentile in mass, respectively, which is closer to the 10th percentile than the 90th percentile.

It can be also seen that the body-size influence on the DCs generally tends to be less significant for the sources in the posterior direction rather than those in the anterior, left lateral, and right lateral directions. This is mainly due to the fact that the variation of the residual soft tissue (i.e., adipose tissue) among the phantoms in the back side is smaller than that in the other sides, especially in the abdominal region.

4. Conclusion

In the present study, a comprehensive data set of the DCs for industrial radiography sources (^{192}Ir and ^{60}Co) as well as source self-shielding factors were produced by performing Monte Carlo simulations with the MRCPs and the 10th and 90th percentile phantoms. In addition, the DCs among the different size phantoms were compared, and it was found that the body size indeed influences the DCs especially when the sources are closer to the human body. The DCs for the different size phantoms are expected to be used as an initial tool for rapid dose estimation of individuals who are accidently exposed by industrial radiography sources in the future. Acknowledging the significance of the results of this study, the ICRP is planning to include the DCs for industrial radiography sources in an ICRP report which is being prepared by the Task Group 103.

Table 1 Source self-shielding factors

Radioactive material thickness (diameter/height)	Capsule-wall thickness			
	1 mm		2 mm	
	^{192}Ir	^{60}Co	^{192}Ir	^{60}Co
1 mm	0.840	0.972	0.803	0.953
2 mm	0.717	0.965	0.694	0.947
3 mm	0.627	0.958	0.606	0.938
4 mm	0.556	0.949	0.536	0.929

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