Original article

Specific Absorbed Fractions of Internal Photon and Electron Emitters in a Human Voxel-based Phantom: A Monte Carlo Study

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Abstract

The specific absorbed fraction (SAF) of energy is an essential element of internal dose assessment. Here reported a set of SAFs calculated for selected organs of a human voxel-based phantom. The Monte Carlo transport code GATE version 6.1 was used to simulate monoenergetic photons and electrons with energies ranging from 10 keV to 2 MeV. The particles were emitted from three source organs: kidneys, liver, and spleen. SAFs were calculated for three target regions in the body (kidneys, liver, and spleen) and compared with the results obtained using the MCNP4B and GATE/GEANT4 Monte Carlo codes. For most photon energies, the self-irradiation is higher, and the cross-irradiation is lower in the GATE results compared to the MCNP4B. The results show generally good agreement for photons and high-energy electrons with discrepancies within – 2% ±3%. Nevertheless, significant differences were found for cross-irradiation of photons of lower energy and electrons of higher energy due to statistical uncertainties larger than 10%. The comparisons of the SAF values for the human voxel phantom do not show significant differences, and the results also demonstrated the usefulness and applicability of GATE Monte Carlo package for voxel level dose calculations in nonuniform media. The present SAFs calculation for the Zubal voxel phantom is validated by the intercomparison of the results obtained by other Monte Carlo codes.

Keywords: GATE calculation, internal dosimetry, phantom, specific absorbed fraction value

Introduction

The specific absorbed fraction (SAF) is the fraction of emitted energy from the source organ that is absorbed by the target organ per unit mass of target organ. The SAF of energy is an essential element of internal dose assessment. Several organs become a source of radiation after administered radiopharmaceutical to a patient during either diagnostic or therapeutic procedures in nuclear medicine. The accurate and realistic determine of the absorbed dose to the internal organs of the patient is important for radiation protection purposes. The SAF is usually useful quantity to evaluate the stochastic and deterministic effects.

In principal, a full Monte Carlo simulation together with a developed geometrical model of humans is the

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most accurate approach for calculation of absorbed dose fraction of energy and other dosimetric quantities. Thus, the development of more realistic anatomical models was desirable to achieve a better dose assessment. To do so, voxel phantoms were derived from computed tomography (CT) or magnetic resonance image (MRI) data of real persons and provide detailed information about the human anatomy. The Zubal[1] phantom is one of the earlier them that obtained from CT (thorax) and MRI (brain). Each organ in the Zubal phantom has a unique id number that identifies its voxels. The aim of this work is to the estimation of monoenergetic photon and electron SAFs for selected organs of a human voxelized phantom using GATE Monte Carlo package for application to internal dosimetry.

Materials and Methods

Voxelized phantom

The adult male computational phantom, shown in Figure 1, was used.[2] This voxelized phantom was developed at Yale University by Zubal *et al*.[1] on the basis of CT data of actual person. The phantom is consisted of a 128 × 128 × 243 array of 4 mm × 4 mm × 4 mm voxels. The Zubal phantom contained 56 segmented organs that a unique ID number (or tissue index) was given to each organ in the organ libraries. Table 1 shows the number of voxels, volumes, and the masses of several organs in the Zubal phantom. The mass of each organ was determined as the organ volume multiplied by the organ density obtained from the International Commission on Radiation Units and Measurements 44.[3]

Figure 1: Coronal slice through the Zubal voxel-based anthropomorphic phantom with inserted lesions (red points)

GATE Monte Carlo technique

All of the dosimetry simulations in this work were performed by GATE Monte Carlo package (version 6.1), which was built on Geant4.9.3p01. However, the uses of the GATE and GEANT4 have been evaluated for dosimetry applications at previous publications.[4-6]

The physics lists for photon and electron interactions used in the GATE simulations displays in Table 2. The cut-off energy (i.e., the limit at which the energy is regarded to be locally absorbed) and the cut-off range were set to 1 keV and 0.1 mm for the photons and the electrons, respectively, in all simulations. This range for electron was regarded as sufficiently small compared with the size of a voxel (4 mm). We used a computer with a 3.5 GHz Intel(R) Core (TM) i7-4770K processor and 8.0 GB RAM running Linux Fedora 13 for Monte Carlo simulation. The numbers of histories for photon and electron source organs were 100 million and 50 million, respectively.

Calculation of the photons and electrons specific absorbed fractions

Three combinations of the source and target organs have been considered with initial photon and electron energies ranging between 10 keV and 2 MeV. The activity was assumed to be uniformly distributed in the source organ and the absorbed doses transferred to the target

Table 1: The number of voxels, volumes and the masses of some selected organs in Zubal voxelized phantom

Organ/tissue	Number of voxels	Volume (cm^3)	Mass (g)
Adrenals	62	4.00	4.20
Bladder	3147	201.41	211.48
Kidneys	7618	487.55	511.93
Liver	29,277	1873.73	1986.15
Lungs	62,374	3991.94	1037.90
Heart	9354	598.66	628.59
Pancreas	792	50.69	52.72
Spleen	5568	356.35	377.73
Stomach	5133	328.51	338.37
Thyroid	105	6.72	7.39

organs of the phantom were determined. The procedure was performed considering the activity in the kidneys, liver and the spleen of the phantom independently. With GATE, the dose actor was used to score the energy absorbed by target organs. The SAF values were then calculated for each source and target organ based on the MIRD formalism,[7,8] using below equation:

$$\mathrm{SAF}(r_T \leftarrow r_S) = \frac{E_T / E_S}{m} \quad (1)$$

where r_S is a source organ, r_T is a target organ, E_T is the energy absorbed in r_T, E_S is the energy emitted from r_S, and m is the mass of r_T. The same SAF values calculated using the MCNP4B Monte Carlo code,[9,10] and the results were compared for quality assurance purpose. The relative percentage difference (RD %) between two corresponding photon and electron SAF values were calculated as:

$$\mathrm{RD}\% = \left[\frac{(\mathrm{SAF}_{\mathrm{GATE}} - \mathrm{SAF}_{\mathrm{MCNP4B}})}{\mathrm{SAF}_{\mathrm{MCNP4B}}}\right] \times 100 \quad (2)$$

In this work, the results obtained with MCNP4B were arbitrarily considered as the reference.

Results

The SAF values for monoenergetic photons and electrons in some organs of the Zubal voxelized phantom were calculated by GATE Monte Carlo package and compared to those reported by other Monte Carlo codes. The selected organ geometry was exactly the same as the organ geometry described by Yoriyaz *et al*.[9] and Parach *et al*.[10] in the simulation.

Photon specific absorbed fractions

The SAF values calculated for the monoenergetic photons of 10, 20, 50, 100, 200, 500, 1000, and 2000 keV using GATE Monte Carlo package are presented in Table 3 for three source and target combinations. The SAF values derived using MCNP4B Monte Carlo code[9] and the maximum relative percentage difference (RD %) between the GATE and MCNP4B data for each corresponding pair of organs (target ← source) were also included in the table. The photon SAF values derived with GATE and MCNP4B were divided into two groups, self-irradiation, and cross-irradiation. On average, photon SAFs calculated by GATE Monte Carlo was slightly higher values (+0.7%) for self-irradiation and lower values (−4.4%) for cross-irradiation compared to the MCNP4B results.

Table 2: Physics settings for photon and electron interactions in the GATE simulations[a]

Process	Model
Photoelectric absorption	Standard
Rayleigh scatter	Penelope
Compton scatter	Standard
Gamma conversion	Standard
Annihilation	Standard
Electron ionization	Standard
Bremsstrahlung	Standard
Multiple scatter	Distance to boundary
Particle decay	Radioactive decay

[a]GATE Users Guide V6.2

In Figure 2, the SAF values against the photon energy are presented for the self-irradiation data. The graphs visually reveal a good correlation between the two series of data. However, the minimum and maximum of absolute average difference in this photon energy range were 0.1% and 6.1%, respectively, for GATE compared to MCNP4B. The photon SAFs for self-irradiation decreases with increasing photon energy from 10 to 100 keV and begin to increase slightly and then begins to decrease again.

The photon SAF values against the energy range were 10–2000 keV for cross-irradiation when liver, kidneys, and spleen as source were displayed in Figure 3. The graphs show good correlation between the two series of data but smaller values for GATE compared to MCNP4B. The minimum and maximum of absolute average difference for cross-irradiation were 1.1% and 15.8%, respectively. In Figure 4, the average relative differences against photon energy are plotted. This figure reveals that the maximum and the minimum differences are with the photon energy of 50 keV and 2000 keV. However, the relative differences for self- and cross-irradiation decreasing in this range of photon energy.

Electron specific absorbed fractions

In Table 4, the SAF values for monoenergetic electrons of 10, 20, 50, 100, 200, 350, 500, 690, 935, 1200, and 2000 keV calculated with GATE Monte Carlo package are presented for three source and target combinations. The SAF values reported by Parach *et al*.[10] and the maximum relative percentage difference (RD %) for each corresponding pair

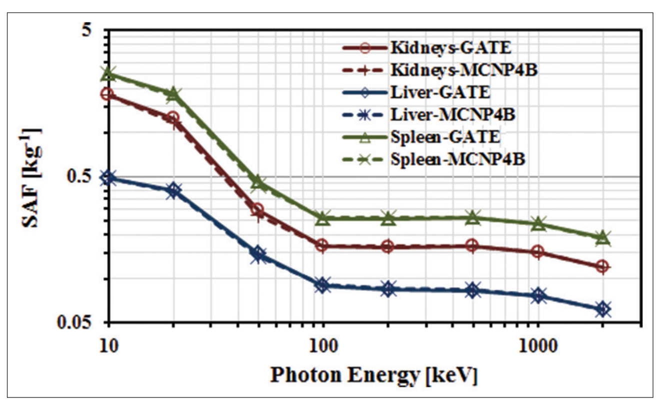

Figure 2: Photon specific absorbed fraction values derived with the GATE and MCNP4B against the photon energy for self-irradiation of kidneys, liver, and spleen

Table 3: Specific absorbed fraction values (kg^{-1}) for 10-2000 keV monoenergetic photons derived with GATE and reported data with MCNP4B using Zubal phantom

Organ	Energy (keV)							
Target ← source	10	20	50	100	200	500	1000	2000
Kidneys ← kidneys								
SAF_{GATE}	1.81E+00	1.23E+00	2.91E-01	1.66E-01	1.64E-01	1.67E-01	1.51E-01	1.20E-01
SAF_{MCNP4B}	1.81E+00	1.18E+00	2.71E-01	1.65E-01	1.67E-01	1.68E-01	1.51E-01	1.19E-01
RD (%)	0	4.58	7.53	0.42	−1.8	−0.36	0.2	0.5
Liver ← kidneys								
SAF_{GATE}	2.90E-03	1.86E-02	3.05E-02	2.26E-02	2.02E-02	1.89E-02	1.73E-02	1.48E-02
SAF_{MCNP4B}	3.30E-03	2.04E-02	3.00E-02	2.32E-02	2.10E-02	1.93E-02	1.74E-02	1.49E-02
RD (%)	−12.12	−8.82	1.67	−2.59	−3.81	−2.07	−0.57	−0.67
Spleen ← kidneys								
SAF_{GATE}	5.40E-03	4.21E-02	5.33E-02	3.54E-02	3.19E-02	3.06E-02	2.80E-02	2.38E-02
SAF_{MCNP4B}	6.28E-03	4.60E-02	5.18E-02	3.62E-02	3.31E-02	3.11E-02	2.80E-02	2.39E-02
RD (%)	−14.01	−8.48	2.9	−2.21	−3.63	−1.61	0	−0.42
Kidneys ← liver								
SAF_{GATE}	2.90E-03	1.84E-02	3.03E-02	2.25E-02	2.02E-02	1.90E-02	1.73E-02	1.48E-02
SAF_{MCNP4B}	3.25E-03	2.03E-02	3.00E-02	2.31E-02	2.10E-02	1.95E-02	1.76E-02	1.49E-02
RD (%)	−10.77	−9.36	1	−2.6	−3.81	−2.56	−1.7	−0.67
Liver ← liver								
SAF_{GATE}	4.85E-01	3.97E-01	1.48E-01	8.86E-02	8.38E-02	8.32E-02	7.56E-02	6.17E-02
SAF_{MCNP4B}	4.91E-01	3.91E-01	1.42E-01	9.01E-02	8.63E-02	8.41E-02	7.58E-02	6.19E-02
RD (%)	−1.28	1.56	4.3	−1.66	−2.9	−1.07	−0.26	−0.32
Spleen ← liver								
SAF_{GATE}	0.00E+00	4.13E-05	4.40E-03	5.40E-03	5.20E-03	5.00E-03	4.70E-03	4.30E-03
SAF_{MCNP4B}	0.00E+00	5.72E-05	4.38E-03	5.75E-03	5.47E-03	5.19E-03	4.82E-03	4.39E-03
RD (%)	0	−27.86	0.46	−6.09	−4.94	−3.66	−2.49	−2.05
Kidneys ← spleen								
SAF_{GATE}	5.30E-03	4.16E-02	5.30E-02	3.54E-02	3.21E-02	3.06E-02	2.80E-02	2.37E-02
SAF_{MCNP4B}	6.18E-03	4.60E-02	5.19E-02	3.65E-02	3.32E-02	3.10E-02	2.82E-02	2.40E-02
RD (%)	−14.24	−9.57	2.12	−3.01	−3.31	−1.29	−0.71	−1.25
Liver ← spleen								
SAF_{GATE}	0.00E+00	4.04E-05	4.50E-03	5.50E-03	5.30E-03	5.00E-03	4.70E-03	4.30E-03
SAF_{MCNP4B}	0.00E+00	5.81E-05	4.47E-03	5.73E-03	5.55E-03	5.15E-03	4.82E-03	4.36E-03
RD (%)	0	−30.41	0.67	−4.01	−4.5	−2.91	−2.49	−1.38
Spleen ← spleen								
SAF_{GATE}	2.51E+00	1.84E+00	4.58E-01	2.57E-01	2.55E-01	2.62E-01	2.38E-01	1.89E-01
SAF_{MCNP4B}	2.53E+00	1.77E+00	4.30E-01	2.59E-01	2.61E-01	2.63E-01	2.37E-01	1.88E-01
RD (%)	−0.91	3.99	6.58	−0.81	−2.18	−0.46	0.3	0.59

SAF: Specific absorbed fraction; RD: Relative difference

of organs were also included in the table. The comparison of electron SAFs was limited to five monoenergetic electrons since these energies were considered in the literature[10] to represent the average electron energy of ^{186}Re, ^{24}Na, ^{32}P, ^{90}Y, and ^{19}O radionuclides, respectively. On average, electron SAFs calculated by GATE Monte Carlo was also slightly higher values (+0.7%) for self-irradiation and lower values (−4.9%) for cross-irradiation than reported data from the literature.[10]

Figure 5 illustrates the SAF values against the electron energy for the self-absorption of liver, kidneys, and spleen of Zubal phantom. The graphs visually reveal a good correlation between the two series of data. However, the minimum and maximum of absolute average difference in this electron energy range for self-irradiation were 0% and 3%, respectively, for GATE compared to the corresponding reported data in the literature.[10] The electron SAFs for self-irradiation are constant with increasing electron energy since short electron ranges still in the large source organs. However, slight drop-off of the SAFs at high electron energies was observed.

Figure 6 shows the cross-absorption electron SAF values for the source in liver, kidneys, and spleen of the Zubal phantom. The graphs show good correlation between the two series of data. The minimum and maximum of absolute average difference for cross-irradiation were 3.3% and 5.7%, respectively. Figure 6 also shows the electron irradiation of adjacent organs cannot be always neglected, even though electrons are considered as weak penetrating radiation. The values for neighboring

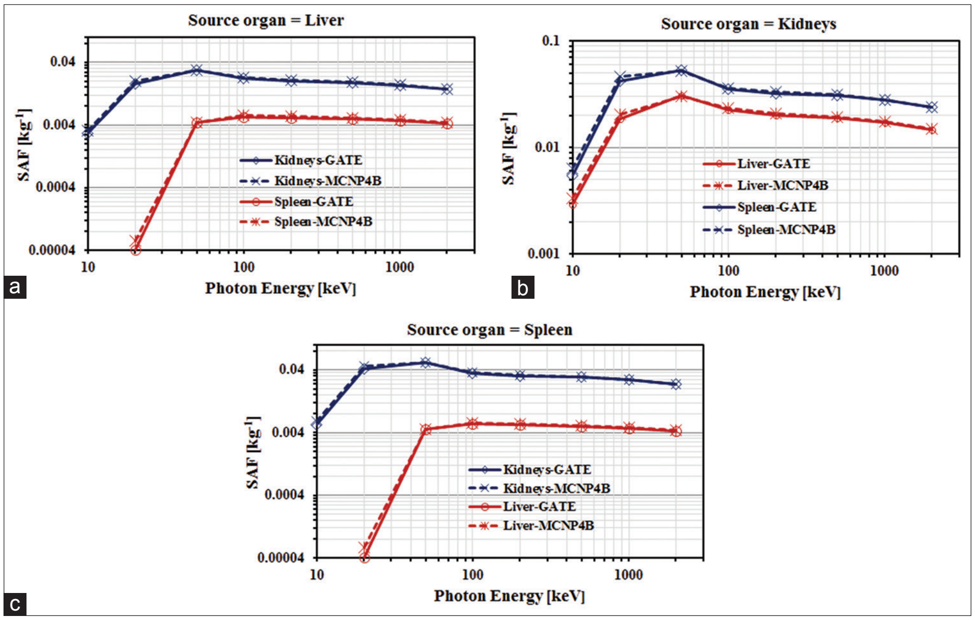

Figure 3: Photon specific absorbed fraction values derived with the GATE and MCNP4B against the photon energy for cross-irradiation from (a) liver, (b) kidneys, and (c) spleen to other selected organs

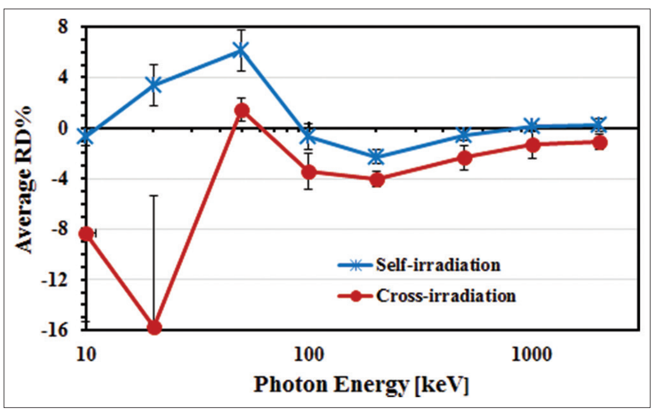

Figure 4: Average of relative percentage difference between the GATE and MCNP4B for self- and cross-irradiation against the photon energy

organs such as spleen and liver cannot be negligible for electron energy above 690 keV and 935 keV, respectively.

In Figure 7, the average relative percentage differences against electron energy are plotted. In contrast with photon energy, the average relative percentage differences are increasing with increasing electron energy for both self- and cross-irradiation. In other words, the maximum relative differences between the GATE and[10] results related to the electron energy 1200 keV for both self- and cross-irradiation.

Discussion

The estimation of monoenergetic photon and electron SAF values using GATE Monte Carlo package was performed in a humanoid voxel phantom and compared the data with the other well developed Monte Carlo codes. For better comparison, we divided the photon and electron SAF values into two groups, i.e., the self- and the cross-irradiation.

Specific absorbed fractions for photon energy

The comparison between the GATE and MCNP4B photon SAF values showed very good agreement. However, differences observed in some organs SAFs are related to difference Monte Carlo codes, which have been used for calculations. In other study, Pacilio *et al*.[11] reported differences within 10% between MCNP4C and GEANT4 for self-irradiation voxel S values for both photon and electrons. Relative uncertainties <10% are generally considered reliable and those between 10% and 20% are considered questionable.[12] By this standard, it was desired that all SAFs show uncertainties below 10%. All SAF values for selected source organs were considered reliable (≤5%). However, in this study, the absorbed dose to the organs was considered not to the voxels. Difference attenuation properties in GATE in our study compared to the MCNP4B would certainly result in higher absorption in source organs and, therefore, lower cross-irradiation to target organs. The bias between results that shown in Figure 4 are almost independent of the photon energy and do not follow a physically explainable trend. However, the relative differences would reduce by increasing of the photon energy for both self- and cross-irradiation due to the difference in the material composition attributed to the tissues in two Monte Carlo codes.[9] The tissue compositions were provided in GATE Monte Carlo

Table 4: Specific absorbed fraction values (kg^{-1}) for 10-2000 keV monoenergetic electrons derived with GATE and reported data using Zubal phantom

Organ	Energy (keV)										
Target ← source	10	20	50	100	200	350	500	690	935	1200	2000
Kidneys ← kidneys											
SAF_{GATE}	1.95E+02	1.95E+02	1.95E+02	1.95E+02	1.93E+02	1.91E+02	1.88E+02	1.84E+02	1.80E+02	1.76E+02	1.65E+02
$SAF_{GATE6.0}$	-	-	-	-	-	1.91E+02	1.88E+02	1.85E+02	1.80E+02	1.76E+02	-
RD (%)	-	-	-	-	-	−0.14	−0.01	−0.01	0.06	0.04	-
Liver ← kidneys											
SAF_{GATE}	1.63E−04	6.10E−04	3.39E−03	1.16E−02	3.87E−02	8.67E−02	1.40E−01	2.10E−01	2.90E−01	3.70E−01	6.20E−01
$SAF_{GATE6.0}$	-	-	-	-	-	8.91E−02	1.44E−01	2.14E−01	3.03E−01	3.92E−01	-
RD (%)	-	-	-	-	-	−2.68	−2.91	−1.87	−4.2	−5.61	-
Spleen ← kidneys											
SAF_{GATE}	3.29E−04	1.17E−03	6.30E−03	2.08E−02	6.84E−02	1.50E−01	2.50E−01	3.70E−01	5.20E−01	6.80E−01	1.18E+00
$SAF_{GATE6.0}$	-	-	-	-	-	1.55E−01	2.51E−01	3.77E−01	5.36E−01	7.06E−01	-
RD (%)	-	-	-	-	-	−3.47	−0.22	−1.78	−2.97	−3.68	-
Kidneys ← liver											
SAF_{GATE}	1.81E−04	6.38E−04	3.60E−03	1.17E−02	3.88E−02	8.66E−02	1.40E−01	2.00E−01	2.90E−01	3.70E−01	6.20E−01
$SAF_{GATE6.0}$	-	-	-	-	-	8.91E−02	1.43E−01	2.14E−01	3.04E−01	3.91E−01	-
RD (%)	-	-	-	-	-	−2.8	−2.1	−6.54	−4.32	−5.37	-
Liver ← liver											
SAF_{GATE}	5.04E+01	5.04E+01	5.04E+01	5.03E+01	5.01E+01	4.98E+01	4.94E+01	4.89E+01	4.84E+01	4.78E+01	4.61E+01
$SAF_{GATE6.0}$	-	-	-	-	-	4.98E+01	4.94E+01	4.89E+01	4.83E+01	4.77E+01	-
RD (%)	-	-	-	-	-	−0.1	0	0.04	0.12	0.17	-
Spleen ← liver											
SAF_{GATE}	0.00E+00	0.00E+00	1.12E−05	1.28E−04	3.42E−04	7.10E−04	9.93E−04	1.34E−03	1.77E−03	2.36E−03	4.22E−03
$SAF_{GATE6.0}$	-	-	-	-	-	7.42E−04	1.15E−03	1.50E−03	1.98E−03	2.57E−03	-
RD (%)	-	-	-	-	-	−4.4	−13.7	−10.63	−10.46	−8.21	-
Spleen ← spleen											
SAF_{GATE}	2.65E+01	2.65E+01	2.65E+01	2.64E+01	2.63E+01	2.60E+01	2.58E+01	2.54E+01	2.50E+01	2.46E+01	2.34E+01
$SAF_{GATE6.0}$	-	-	-	-	-	2.63E+01	2.62E+01	2.54E+01	2.41E+01	2.26E+01	-
RD (%)	-	-	-	-	-	−1.1	−1.5	0.0	3.7	8.8	-

SAF: Specific absorbed fraction; RD: Relative difference

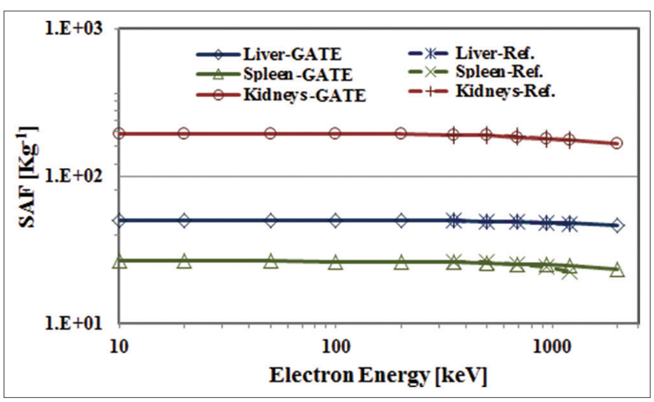

Figure 5: Electron specific absorbed fraction values derived with the GATE and reported data against the electron energy for self-irradiation of kidneys, liver, and spleen. As can be seen, the comparison limited to five electron energies

package in the present study. It can be also concluded from Figure 2 that organs with small mass obtain larger photon self SAFs than large mass organs (e.g., in here, spleen).

Visually assessment of SAF curves for photon self-irradiation in Figure 2 was revealed, the source organ is also the target organ for the photon energy ranges from 10 keV to 2000 keV. Nevertheless, photon self SAF values decrease with increasing photon energy not monotonically due to the highest escape probability of the scattered photons when the energy increases.[13]

The assessment of plotted curves in Figure 3 also confirmed that the organs geometry (such as size and shape), density and the interorgan distance have the significant influence on the photon cross-irradiation SAF values.[14,15]

Specific absorbed fractions for electron energy

The data in Table 4 show low relative differences (up to ± 13.7%) between two series data for monoenergetic electrons of 350, 500, 690, 935, and 1200 keV. However, the SAF values for the cross-irradiation of electrons were small in magnitude and therefore, the differences were most likely due to high statistical uncertainties in data. The average differences between data for all electron energies were low (−2.1% ±3.9%).

For electron SAFs self-irradiation [Figure 5], the trend versus energy is approximately constant due to the

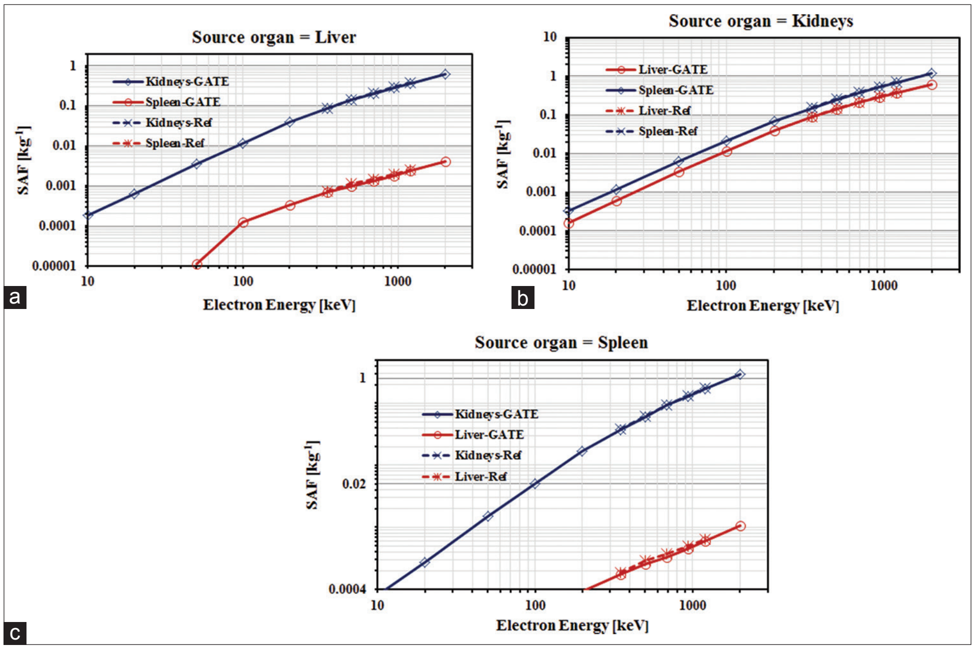

Figure 6: Electron specific absorbed fraction values derived with the GATE and reported data against the electron energy for cross-irradiation from (a) liver, (b) kidneys and (c) spleen to other selected organs. As can be seen, the comparison limited to five electron energies

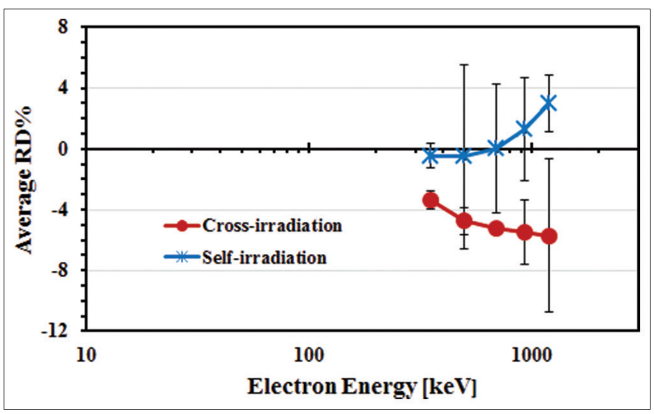

Figure 7: Average of relative percentage difference between the GATE and reported data for self- and cross-irradiation against the electron energy

electron stopping power trend versus energy. But for electron energies higher than about 500 keV, the SAFs slightly decrease with energy.

The cross-irradiation SAF values for electrons increase with energy at high energies, as already reported in the literature.[11] A close look at Figure 6b reveals that the SAF values for liver and spleen from kidneys as source organ are similar, but Figure 6a and c show the cross-absorption electron SAF values for the source in liver and spleen, respectively. In other words, Figure 6 shows the electron irradiation of adjacent organs cannot be always neglected, even though electrons are considered as weak penetrating radiation. For example, according to the Figure 6a and c, the SAF values for neighboring organs such as spleen and liver cannot be negligible for electron energies above 50 keV and 350 keV, respectively. From this comparison and GATE Monte Carlo calculations of electron cross-irradiation SAF values, the assumption of MIRD[16] and ICRP publication No. 30[17] (i.e., the electrons are fully absorbed in the source organ itself) not always correct and led to underestimate the absorption of the neighboring organs around the source organs.

As already reported in the literature,[5] the statistical uncertainties associated with the voxel S values depend on the voxel size, distance between the source and target voxel, energy, and type (electrons or photons) of starting particles.

Conclusion

There was a very good agreement between the two series of data for both photon and electron SAF values. The average relative differences decrease against the photon energy and increase against the electron energy for both self- and cross-irradiation. From results of this work, it can be concluded that the estimation of SAF values and other useful internal dosimetric quantities could be feasibly calculated for various organs of anthropomorphic voxel-based phantom using GATE Monte Carlo package with reasonably statistical uncertainty (≤5%). This comparison also has been confirmed that the SAFs for self-irradiation depended on the energy and the mass of the target and source organs, the SAFs for cross-irradiation depended on the relative position of source and target organs. The SAF values obtained using the GATE Monte Carlo package for real phantom and connected to the individual biokinetic data could make the patient 3D internal dose calculation possible with reliable uncertainty in nuclear medicine.

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Conflicts of interest

There are no conflicts of interest.

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