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EVALUATION OF S VALUES FOR BETA-RAY EMITTERS IN VOXEL PHANTOMS

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Abstract

The mean absorbed dose to the target region per unit cumulated activity in the source region (S value) has been evaluated for several beta-ray emitters in the brain and urinary bladder contents using the Monte Carlo simulation. The S values were evaluated on the Medical Internal Radiation Dose (MIRD) Committee of the Society of Nuclear Medicine Pamphlet No.5 type phantom (MIRD 5 type phantom) and the adult voxel phantoms developed at the Japan Atomic Energy Research Institute (JAERI). It was found that the self-dose S values largely depend on the beta-ray energy and the mass of each target region.

1. Introduction

Evaluation of the mean absorbed dose per unit cumulated activity (S value) to the target organ from uniformly distributed radioactivity within the source organ is of importance. S value has been used for dose estimates in diagnostic procedures. In particular, self-dose S values for positron emitters in the brain are necessary for an accurate quantification of the doses to patients administered a radiophaemaceutical for neuroimaging. S values for the urinary bladder wall is also very convenient for designing patient protocol strategies intended to minimize the dose for a specific radiopharmaceutical.

In general, self-dose S values for positron emitters in the brain follow the inverse first power of the mass, especially if the absorbed fraction remains at unity (no energy escape from the brain). S values for beta–ray emitters within the urinary bladder are derived from the simple assumption that the dose at the surface of the contents is approximately half that within their volume [1-3]. Previous researches on radionuclide S values for brain imaging [4,5] and for the walls of hollow organs [6] have demonstrated the usefulness of the Monte Carlo simulation. However, in their works, a comprehensive understanding of S values for real human bodies is still lacking since the S values were evaluated using the MIRD 5 type phantoms. Hence, S values evaluations for sophisticated models are necessary to estimate internal doses more accurately.

For the purpose, the present study was performed to evaluate self-dose S values to the brain for positron emitters such as ^{11}C, ^{15}O and ^{18}F and S values to the urinary bladder wall for several beta-ray emitters such as ^{14}C, ^{24}Na, ^{32}P, ^{60}Co, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{91}Y, ^{137}Cs, ^{147}Pm and ^{204}Tl on the adult voxel phantoms developed at the Japan Atomic Energy Research Institute (JAERI) and a MIRD 5 type phantom using the Monte Carlo simulation.

2. Materials and Methods

2.1 Phantoms

Three phantoms were used: the JAERI adult male "Otoko", the JAERI adult female "Onago" voxel phantoms [7,8] and the MIRD 5 type hermaphrodite adult phantom [2,9]. The Otoko and Onago phantoms constructed from CT data of real human bodies. The masses of the brain, urinary bladder wall and bladder contents for the phantoms are shown in Table 1. There are discrepancies between the masses of the Otoko, Onago and MIRD 5 type phantoms.

2.2 Monte Carlo simulations

S values for beta-ray emitters including positron emitters were evaluated using the Monte Carlo code, EGS4 [10], in conjunction with an EGS4 user code, UCSAF [11]. In the EGS4-UCSAF code, the radiation transport of electrons, positrons and photons in phantoms can be simulated, and correlations between primary and secondary particles are included. Beta-ray spectra for each radionuclide are taken as the relative number of beta-rays per MeV, $N(W)$, from the equation [12]

$$N(W) = p \cdot W \cdot (W_0 - W)^2 \cdot \mathrm{F}(Z,W) \cdot \mathrm{a_n}(Z,W)$$

where W is the total energy of the electron (kinetic energy + $m_e c^2$) in units of $m_e c^2$,
m_e is the electron mass and c is the velocity of light,
W_0 is the corresponding value at the maximum electron energy,
$p = (W^2-1)^{1/2}$ is the electron momentum in units of $m_e c$,
Z is the atomic number of the daughter nucleus,
$\mathrm{F}(Z,W)$ is the Fermi factor and
$\mathrm{a_n}(Z,W)$ is a shape factor for a transition of order of forbiddenness n.

The Parameter Reduced Electron–Step Transport Algorithm (PRESTA) [13] to improve the electron and positron transport in the low–energy region is used. The cross–section data for electrons and positrons are taken from ICRU report 37 [14,15] and the data for photons are taken from PHOTX [16,17].

2.3 S value evaluations

Self-dose S values for the brain were evaluated on the Otoko, Onago and MIRD 5 type phantoms. The brain was source/target organ. The beta-ray emitter -positron emitter such as ^{11}C, ^{15}O and ^{18}F- was uniformly distributed in the brain. To evaluate the S values, the total energies deposited in the brain per source particles were calculated using the EGS4-UCSAF code. Positron annihilation processes were taken into account in the calculations. The results were converted into S values, through consideration of the masses of the brains and the decay modes of the radionuclides. In addition, S values to the urinary bladder walls from uniformly distributed beta–ray emitters within the bladder contents were evaluated. The energy contribution of beta ray to the mucus in the bladder wall was taken to be unity. The beta-ray emitters were ^{14}C, ^{24}Na, ^{32}P, ^{60}Co, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{91}Y, ^{137}Cs, ^{147}Pm and ^{204}Tl. Furthermore, the S values calculated using the EGS4-UCSAF code were compared with those derived from the simple assumption that the dose to the bladder wall caused by activity in the contents is calculated as 50 % of the average dose to the contents [1-3]. Table 2 shows the main transitions, the maximum and mean energies of beta-ray emitters. The decay mode for each radionuclide was assumed to consist of a main branching since a few percentages branching for the decay mode would be insignificant for the S values evaluations.

The number of particle histories was determined to be a million in order to reduce statistical uncertainties below 5 %. No variance reduction technique was used.

3. Results and Discussion

3.1 S value evaluations for the brain

Figure 1 shows the self-dose S value ratios between the Otoko/Onago phantom to the MIRD 5 type phantom. The ratios for the Onago phantom are almost 1.3 times those for the Otoko phantom. This is considered to be due to the different masses of the brains. In Fig. 2, the self-dose S values for ^{11}C, ^{15}O and ^{18}F, respectively, are shown for the brains in the phantoms; the contributions from positrons and the two annihilation photons are presented separately. The S values increase with an increase in mean energy of beta ray. For nuclides with the large positron energies, positron interactions are large contributor to the self-dose S values.

3.2 S value evaluations for the urinary bladder

The S values for the urinary bladder walls are shown in Fig. 3. The S values increase with increasing beta-ray energy. Figure 4 shows the ratios of the S values derived from the simple assumption to those by the EGS4-UCSAF code for the Otoko, Onago and MIRD 5 type phantoms. The differences of the S values between the simple assumption and the code increase with a decrease in beta-ray energy. For ^{14}C, the S values from the simple assumption are 83-91 times those calculated using the code. It can be stated that the use of the simple assumption to evaluate S values to the urinary bladder walls from uniformly distributed beta–ray emitters within the bladder contents is conservative.

The S value ratios between the Otoko/Onago phantom to the MIRD 5 type phantom are shown in Fig. 5. The ratios between the Otoko/Onago phantom and the MIRD 5 type phantom do not vary much. The ratios for the Otoko phantom are almost twice those for the Onago phantom. This is considered to be due to the different masses of the bladder walls. Hence, the S value largely depends on the mass of the bladder wall.

4. Conclusions

The S values for beta-ray emitters in the voxel phantoms have been evaluated using the Monte Carlo simulations. The main results obtained are shown below.

1. The S values for the brain and bladder wall are largely dependent upon the beta-ray energy and the mass of each organ.
2. For nuclides with the large positron energies, the self-dose S value for the brain is largely contributed by the positron interactions.
3. The S values for the urinary bladder walls from the simple assumption are conservative.

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Table 1 Comparison of tissue masses for the MIRD 5 type, Otoko and Onago phantoms

Phantoms	Total brain (kg)	Bladder wall (kg)	Bladder contents (kg)
MIRD	1.4	4.7×10^{-2}	2.1×10^{-1}
Otoko	1.5	1.2×10^{-2}	4.4×10^{-2}
Onago	1.1	2.4×10^{-2}	8.2×10^{-2}

Table 2 Main transitions, maximum $E_{max.}$ and mean E_{mean} energies of beta-ray emitters

Nuclides	Transitions	$E_{max.}$ (MeV)	E_{mean} (MeV)
^{11}C	allowed	0.960	0.386
^{15}O	allowed	1.732	0.735
^{18}F	allowed	0.634	0.250
^{14}C	allowed	0.156	0.049
^{24}Na	allowed	1.390	0.554
^{32}P	allowed	1.710	0.695
^{60}Co	allowed	0.318	0.096
^{89}Sr	forbidden	1.492	0.583
^{90}Sr	forbidden	0.546	0.196
^{90}Y	forbidden	2.281	0.934
^{91}Y	forbidden	1.546	0.603
^{137}Cs	forbidden	1.175	0.188
^{147}Pm	forbidden	0.225	0.062
^{204}Tl	forbidden	0.763	0.244

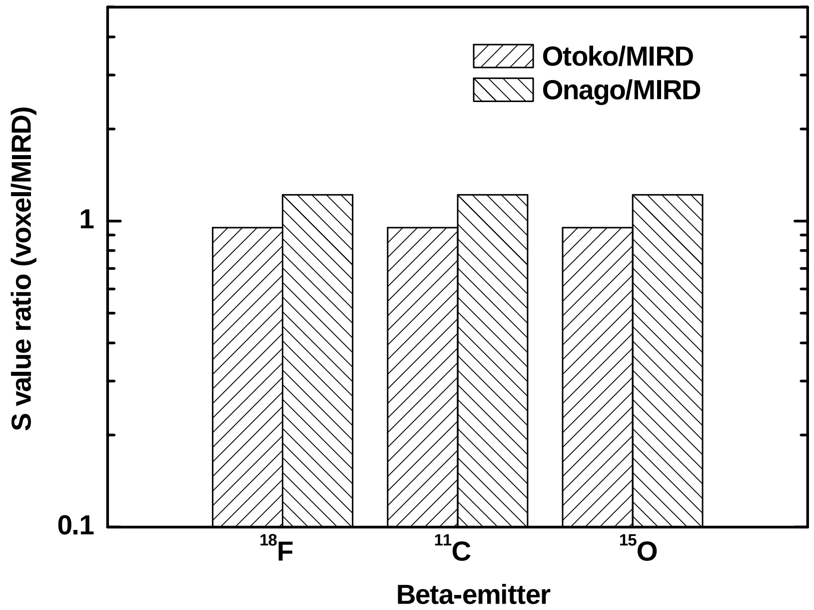

Figure 1 Comparison of S values for the brains between the voxel phantoms and the MIRD 5 type phantom.

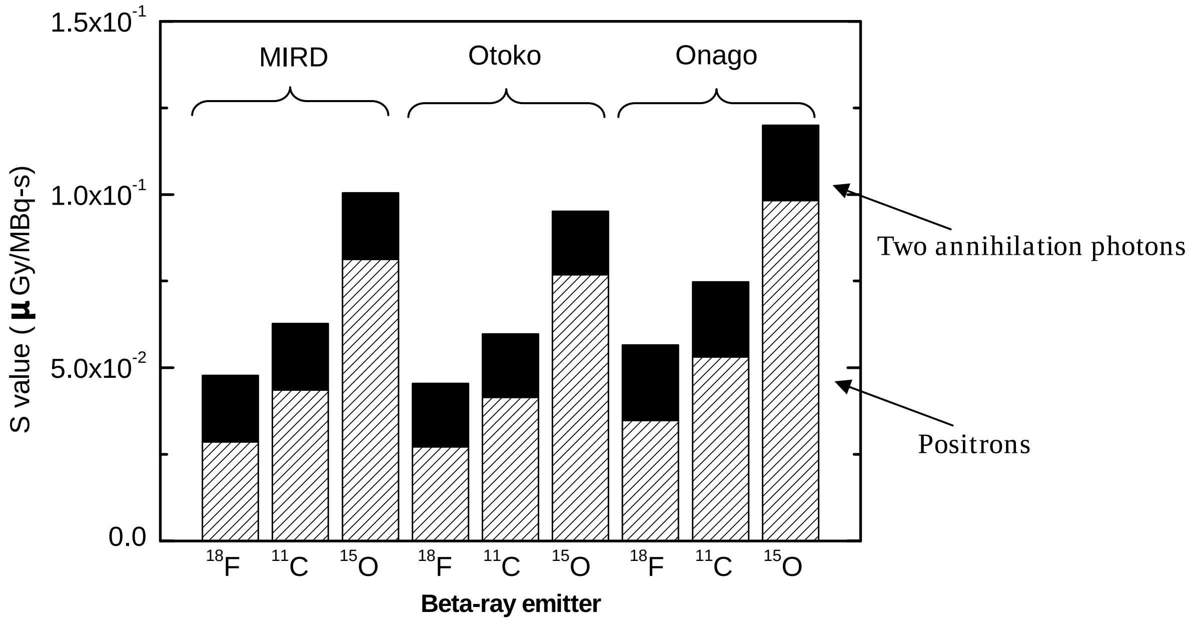

Figure 2 S values for beta-ray emitters distributed in the brains. Contributions from positrons and from two annihilation photons are illustrated for each S value.

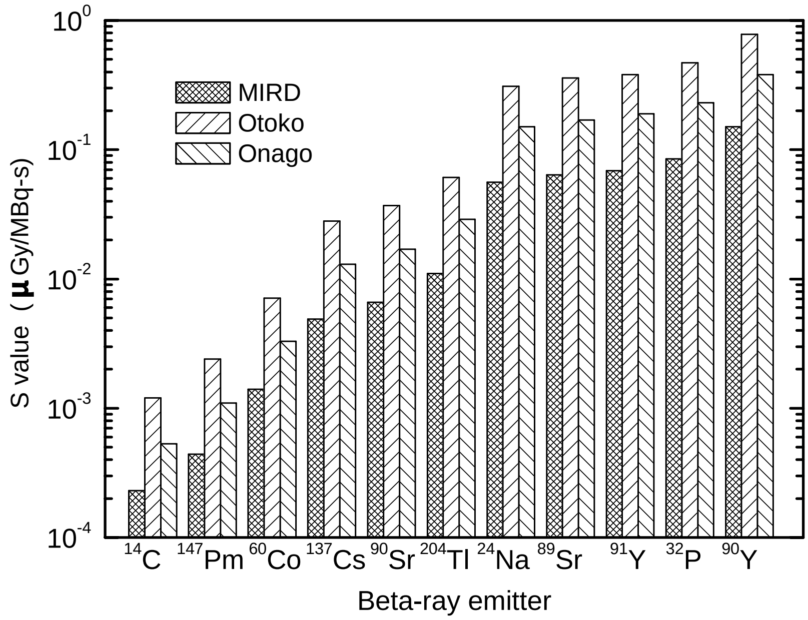

Figure 3 S values for the bladder walls in the MIRD 5 type, Otoko and Onago phantoms.

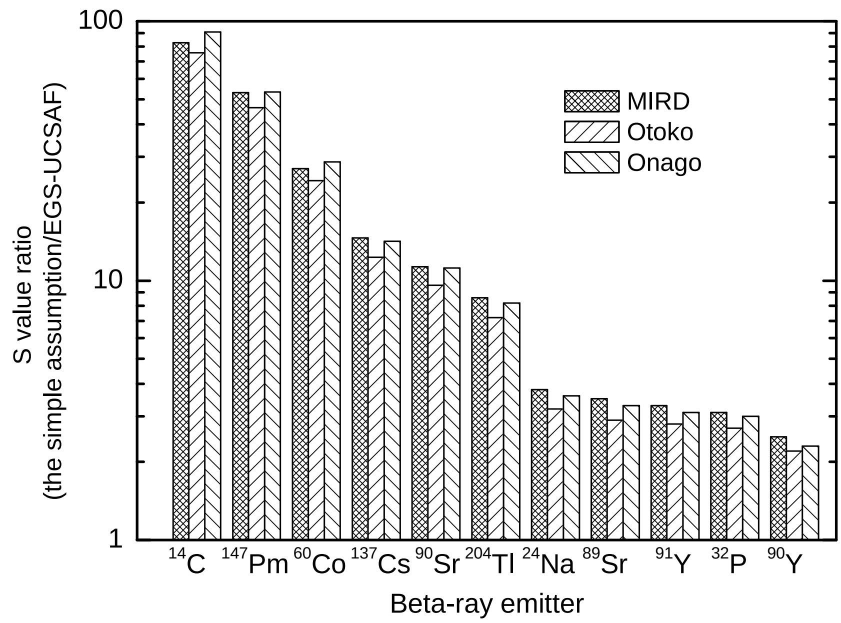

Figure 4 Comparison of S values between the simple assumption and EGS4-UCSAF code for the bladder walls in the MIRD 5 type, Otoko and Onago phantoms.

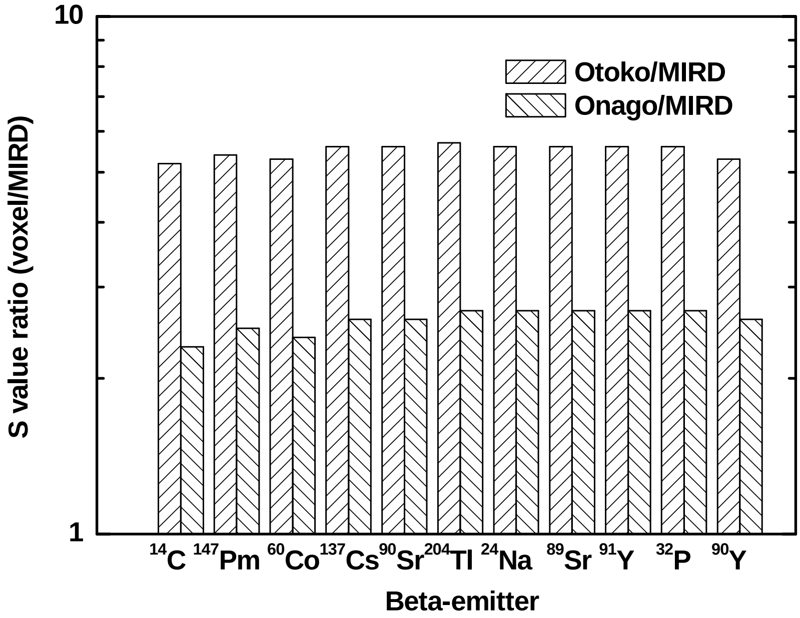

Figure 5　Comparison of S values for the bladder walls between the voxel phantoms and the MIRD 5 type phantom.