SPECIFIC ABSORBED FRACTIONS FOR INTERNAL ELECTRON EMITTERS DERIVED FOR A SET OF ANATOMICALLY REALISTIC REFERENCE PREGNANT FEMALE MODELS

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Received June 16 2009, revised August 3 2009, accepted August 25 2009

The specific absorbed fraction (Φ), defined by the Medical Internal Radiation Dose Committee, is generally applied to evaluate the average absorbed dose in a target organ as a result of radioactive materials deposited in a source organ. This paper reports a new set of Φ values for internal electron emitters ranging from 10 keV to 4 MeV from various internal organs of the mother to the fetus based on three newly developed pregnant female tomographic models, called RPI-P3, RPI-P6 and RPI-P9. The results show a linear log relationship between Φ values and electron energy. The linear log coefficients have been derived and reported. The relationship between Φ values and mean distances between source organs and the fetus were also determined to allow for individual dosimetry. Since the RPI-P models have finer details of human anatomy and more realistic organ volumes and geometries, which follow the latest ICRP reference values, the newly derived Φ values could be used as reference values in determination of the dose to the fetus from internal electron emitters.

INTRODUCTION

Radiation exposure to pregnant women has more than doubled in the past 10 y. (Presentation by Elizabeth Lazarus at Radiological Society of North America (RSNA) annual meeting, Chicago, IL, 27 November 2007; http://www.rsna.org/media/pressreleases/pr_target.cfm?ID=336.) This has raised wide concerns about the assessment of dose to pregnant women and especially the fetus in diagnostic, therapeutic and occupational procedures from both the external and internal radiation^(1–7). In nuclear medicine procedures, dose to the fetus mainly comes from internal sources. To assess the average dose to a fetus, a conversion factor, the specific absorbed fraction (Φ), defined by the Medical Internal Radiation Dose (MIRD) Schema⁽⁸⁾, is commonly used. Equation (1) shows the definition of Φ as follows:

$$\Phi(\text{target} \leftarrow \text{source}) = \frac{\phi(\text{target} \leftarrow \text{source})}{m}, \quad (1)$$

where $\phi(\text{target} \leftarrow \text{source})$ is the energy absorbed fraction from a source organ to a target organ, and m is the mass of the target organ. Appropriate specific absorbed fraction values, combined with information about radioactive decay and biokinetics for radiopharmaceuticals^(9,10), are essential in the

estimation of dose to an organ/structure for a nuclear medicine procedure.

In determination of the Φ value from a source organ to a target organ, the definition of organ shapes, masses, compositions and especially the distances between the source and target organs is necessary, but also quite complicated⁽¹¹⁾. For internal electron emitters, due to the weak penetrating ability of electrons, the accuracy of definition of organ shapes and distances becomes even more important than photon emitters. To best estimate the specific absorbed fraction values in real human anatomy for various populations, a common approach is to apply Monte Carlo radiation transportation methods (All the Monte Carlo method/simulation in this paper refers to ‘Monte Carlo radiation transport’) in a set of computational anthropomorphic models, which represent ‘average human’ anatomy of different genders, ages, sizes, etc.⁽¹²⁾

The development of pregnant woman models evolved from early stylised models with simplified geometries to more complicated mathematical models and voxel-based tomographic phantoms, then to hybrid models that combine the voxelised phantoms and mathematical surfaces⁽¹³⁾. The earliest complete set of pregnant woman models was reported in 1995 by Stabin *et al.*⁽¹⁴⁾. These stylised models were developed by inserting a fetus into a modified female model originally defined by Cristy and Stabin^(15,16). The S values calculated with this model were integrated into a computer program

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called MIRDose⁽¹⁶⁾ designed for internal dosimetry by Stabin *et al.* More complex and realistic stylised models were reported in the 2000s. Chen⁽¹⁷⁾ updated the fetus/embryo structure in Stabin's model, defined four pregnancy periods (8 weeks, 3, 6 and 9 months) according to the reference data by ICRP 89 report⁽¹⁸⁾, and published dose conversion factors for external photon, electron and neutron beams^(17,19–21). Kainz *et al.*^(22,23) developed a semi-heterogeneous pregnant woman model and extended the model into each month of pregnancy. One of the earliest voxelised pregnant woman/fetus models was developed by Shi and Xu,⁽²⁴⁾ based on a set of partial body CT images of a large sized patient who was 7.5-month pregnant when admitted into the emergency room. The CT images were segmented to identify 34 major internal organs and tissues considered sensitive to radiation, of which three (fetal skeleton, fetal brain and fetal soft tissue) belonged to the fetus and others belonged to the mother. Specific absorbed fraction values for internal electrons and photons were derived based on this model^(25,26). The photon Φ values, compared with those derived from Stabin's model, showed significant difference at low energies⁽²⁷⁾.

The model developed by Shi and Xu was more realistic in anatomy compared with previous analytical models. However, since it was converted solely from the image of a heavy individual, the volume and distances of the organs are inconsistent with the ICRP reference data, which made this phantom inapplicable as an 'average' pregnant woman model in radiation protection studies. In addition, the shapes and volumes of organs need to be altered to represent different gestational periods. Compared with analytical models, changing organ shapes/positions are more difficult in a voxelised phantom. To solve these problems, in 2007, Xu *et al.*⁽²⁶⁾ developed a new set of hybrid pregnant-female models, called RPI-P3, RPI-P6 and RPI-P9 phantoms, which represent an average pregnant female at 3, 6 and 9 months of gestation with organ masses and volumes carefully adjusted to the latest ICRP reference values⁽¹⁸⁾. This set of models

applied an innovative surface geometry-based modelling tool to allow the adjustment of organ volume/shapes while preserving the complexity of the structures. The models can be voxelised into 1 mm³ resolution to perform Monte Carlo simulations. Based on the new models, dose conversion factors for external photon and neutron beams and internal photons were calculated^(28–30). New Φ values for internal photons calculated by Shi and Xu were compared with the results derived from the 7.5-month anthropomorphic model by Shi and Xu⁽²⁴⁾ and the Stabin stylised model.⁽³⁰⁾ Considerable difference of Φ values between these models was found at low energies.

While the conversion factors for external beams and internal photons based on various models have been published^(15–30), reliable Φ values for internal electrons are still lacking. This is partially due to the belief that internal electrons deposit their energy locally and the doses to organs other than the source organ are minimal. However, studies have showed that for 'neighbouring' or 'nearby' organs, the doses could be too large to neglect⁽³¹⁾.

In this study, a complete set of Φ values for internal electron emitters based on the newly developed RPI-P series of pregnant female phantoms were calculated by Monte Carlo simulations. The relationship of Φ versus electron energy and organ distance was determined to allow for interpolation of data for individual dosimetry.

MATERIALS AND METHODS

Development of RPI-P serial pregnant-female models

The development of this new set of three pregnant female phantoms, RPI-P3, RPI-P6 and RPI-P9 (as shown in Figure 1) relied on a mixture of different image data sets as follows:⁽²⁷⁾

- (1) Segmented CT images of a 7.5-month pregnant female by Shi and Xu⁽²⁴⁾. This set of CT images covered the portion of the body between the lower breasts to upper thighs in 70 slices, each 7 mm thick. The image resolution was 512 ×

Figure 1. The RPI-P series pregnant-female models: (a) RPI-P3, (b) RPI-P6 and (c) RPI-P9.

- 512 pixels in a $48 \times 48 \text{ cm}^2$ field. The images were segmented to identify 34 organs and tissues.
- (2) Segmented images of VIP-Man⁽³²⁾ of various resolutions. This model was based on anatomical colour images of the Visible Man from the Visible Human Project (http://www.nlm.nih.gov/research/visible/visible_human.html). The original image resolution of the Visible Man was $0.33 \times 0.33 \text{ mm}^2$ and the slice thickness was 1 mm, which allowed for small and radiosensitive structures to be identified and modelled, including skin, eye lenses and red bone marrow.
 - (3) 3D anatomical models from Web 3D Service website (<http://www.web3dservice.com>) and INRIA website (<http://www-c.inria.fr/gamma/>) where polygonal meshes of organs are used in the 3D graphics industry.

The general workflow for construction of these new models from the reference data is shown in Figure 2. Starting from reference model, a new organ model was created in three dimensions, by extracting the voxel information into the so-called Boundary REpresentation (BREP) that consists of polygonal meshes or non-uniform rational B-spline^(32,33). Individual organs of the mother and the fetuses were integrated into a whole-body framework by carefully adjusting the organ shape and location to avoid

overlap. For each organ, the volume and mass were specified manually according to reference values recommended by ICRP 89 report⁽¹⁸⁾. Once all the organs and total body weights had been adjusted, the surface models were voxelised and the voxelised models were used in the Monte Carlo simulation. A careful examination of the organ volumes and masses before and after the voxelisation verified that organ volume and masses were consistent with the reference value after voxelisation. Standard tissue composition and densities were used for Monte Carlo simulations. For this paper, some minor changes have been made to the position of the upper larger intestine and the shape of the bladder of the mother to better represent these organs, which are important to internal dosimetry for a pregnant patient. The latest RPI-P models are shown in Figure 1a–c.

Specific absorbed fraction simulation using EGS4-VLSI

The pregnant woman models, RPI-P3, RPI-P6 and RPI-P9, were incorporated into a previously developed Monte Carlo user code for radiation transportation calculation, EGS4-VLSI³¹. Specific absorbed fractions from 35 source organ and 29 target organs are listed in Table 1 for internal electron energies of 10, 15, 20, 30, 50, 100, 200, 500, 1000, 1500, 2000

Figure 2. Flowchart of the steps in reconstructing the RPI-P series models and using them in Monte Carlo simulations.

Table 1. Source and target organs used to calculate specific absorbed fraction values for internal electron emitters.

Organ	Source	Target	Organ	Source	Target
Adrenals	Yes	Yes	Pancreas	Yes	Yes
Brain	Yes	Yes	Placenta	Yes	Yes
Oesophageal contents	Yes	No	Remainder (all other tissues)	Yes	Yes
Oesophageal wall	Yes	Yes	Skeleton	Yes	Yes
Eyeballs	Yes	Yes	Skin	Yes	Yes
Fetal brain	Yes	Yes	Small intestine (wall and contents)	Yes	Yes
Fetal skeleton	Yes	Yes	Spleen	Yes	Yes
Fetal soft tissue	Yes	Yes	Stomach contents	Yes	No
Fetus body total	No	Yes	Stomach wall	Yes	Yes
Gall bladder contents	Yes	No	Thymus	Yes	Yes
Gall bladder wall	Yes	Yes	Thyroid	Yes	Yes
Heart contents	Yes	No	Trachea	Yes	Yes
Heart wall	Yes	Yes	Upper large intestine contents	Yes	No
Kidneys	Yes	Yes	Upper large intestine wall	Yes	Yes
Lens	Yes	Yes	Urinary bladder contents	Yes	No
Liver	Yes	Yes	Urinary bladder wall	Yes	Yes
Lungs	Yes	Yes	Uterine contents	Yes	No
Ovaries	Yes	Yes	Uterine wall	Yes	Yes

and 4000 keV. The radiation source was assumed to be homogeneously distributed in each source organ. In each Monte Carlo run, a total of approximately 10 million histories were used to keep the statistical uncertainty under 10 % for most of the target organs except some target organs too small or too far from the source organ. In such cases, uncertainties on the order of 20 % or larger could be observed. The results were discarded if the relative uncertainty was higher than 40 %. The cutoff energies for both electron and photon calculations in the EGS4 user code were set to be 10 keV. No variance reduction method was used. A total of 420 simulations were performed and the total run time for the whole Φ value calculation was about 10 d. The calculations were performed on a cluster of 24 computers, each consisting of a CPU with a speed of 3.2 GHz and memory of 512 Mb. From the Monte Carlo calculations, the Φ values derived using equation (1) were tabulated with their associated uncertainties.

RESULTS AND DISCUSSIONS

Specific absorbed fraction for internal electron emitters

Table 2 lists the Φ values from selected source organs to the fetus for electron energies of 100, 1000 and 4000 keV, calculated in the RPI-P9 phantom. A complete set of Φ values for the source and target organs listed in Table 1 has been attached as an appendix file to this paper.

Since electrons in the MeV range are weakly penetrating particles compared to photons in the same

energy range, in Chao's study of internal electron emitters⁽³¹⁾, for the same source organ, target organs can be classified as 'highest targets', 'neighbouring targets', 'nearby targets' and 'irrelevant targets' according to their Φ values. 'Highest target' is the organ receiving the highest Φ from the source organ, which is usually the source organ itself. Organs having Φ values larger than 1 % of the maximum Φ value are 'neighbouring targets'; organs having Φ values lower than 0.1 % of the maximum Φ are 'irrelevant' organs; and those with Φ values in between 0.1 % and 1 % of the maximum Φ are defined as 'nearby targets'.

This concept can be extended so that when considering the Φ values to the same target organ, source organs can be classified as 'Highest sources', 'neighbouring sources', 'nearby sources' and 'irrelevant sources'. For the fetus as the target organ, the 'highest source' is the fetus itself in the energy range studied. Besides the fetus, uterine contents give the highest Φ to the fetus due to its proximity. A 'nearby source' can be described for electron emitters as having energy >100 keV and a 'neighbouring source' as having energy >1 MeV. The uterine wall is the second closest organ to the fetus. Depending on the energy of electrons and the model used, it can be an 'irrelevant source', 'nearby source' or 'neighbouring source'. Some of the other tissues in the abdominal cavity including the placenta, ovaries, small intestines, bladder and bladder contents also contribute considerable dose to the fetus at high energies. For energies greater than 2 MeV, they are considered to be 'nearby sources'. Distal structures including brain, eyeballs, thyroid and trachea give very small amounts of doses to the fetus that are

Table 2. Specific absorbed fraction values (1 per kg) from selected source organs of the mother to the fetus for the RPI-P9 model and electron energies of 100, 1000 and 4000 keV.

Source organs	100 keV	1000 keV	4000 keV
Fetus	2.85×10^{-1}	2.76×10^{-1}	2.45×10^{-1}
Adrenals	1.05×10^{-7}	7.78×10^{-6}	3.45×10^{-5}
Bladder contents	3.84×10^{-6}	7.19×10^{-5}	2.80×10^{-4}
Bladder	4.34×10^{-6}	7.11×10^{-5}	5.48×10^{-4}
Brain	N/A	1.49×10^{-7}	1.19×10^{-6}
Oesophagus	N/A	1.12×10^{-6}	6.21×10^{-6}
Eyeballs	N/A	5.17×10^{-7}	2.66×10^{-6}
Gall bladder contents	5.53×10^{-7}	2.00×10^{-5}	7.50×10^{-5}
Gall bladder	7.50×10^{-7}	2.00×10^{-5}	7.55×10^{-5}
Heart contents	N/A	2.39×10^{-6}	1.28×10^{-5}
Heart	N/A	1.97×10^{-6}	1.06×10^{-5}
Kidneys	6.24×10^{-7}	1.81×10^{-5}	7.05×10^{-5}
Low intestine contents	1.35×10^{-6}	3.60×10^{-5}	1.37×10^{-4}
Liver	2.03×10^{-7}	8.81×10^{-6}	3.77×10^{-5}
Low intestine	2.07×10^{-6}	4.31×10^{-5}	2.96×10^{-4}
Lungs	N/A	2.01×10^{-6}	1.06×10^{-5}
Ovaries	6.03×10^{-6}	9.28×10^{-5}	2.99×10^{-3}
Pancreas	1.03×10^{-6}	2.90×10^{-5}	1.05×10^{-4}
Placenta	2.35×10^{-6}	4.99×10^{-5}	3.34×10^{-4}
Remainder	5.42×10^{-7}	1.28×10^{-5}	2.05×10^{-4}
Small intestine	2.90×10^{-6}	6.38×10^{-5}	1.25×10^{-3}
Skeleton	4.17×10^{-7}	1.75×10^{-5}	1.18×10^{-4}
Skin	3.17×10^{-7}	7.96×10^{-6}	3.89×10^{-5}
Spleen	2.32×10^{-7}	1.01×10^{-5}	4.29×10^{-5}
Stomach contents	2.79×10^{-7}	1.06×10^{-5}	4.32×10^{-5}
Stomach	2.74×10^{-7}	1.09×10^{-5}	4.46×10^{-5}
Thymus	N/A	1.14×10^{-6}	7.36×10^{-6}
Thyroid	N/A	3.46×10^{-7}	2.40×10^{-6}
Trachea	N/A	5.46×10^{-7}	3.39×10^{-6}
Uterine content	4.06×10^{-4}	7.88×10^{-3}	2.73×10^{-2}
Uterus	1.36×10^{-5}	7.43×10^{-4}	8.61×10^{-3}

almost negligible; they are classified as ‘irrelevant sources’ for all the three models using the energy range that was studied. Table 3 lists the classification of organs based on their Φ values to the fetus.

In a nuclear medicine study, the typical dose to an organ is a few tens of sievert (Sv) while the monthly dose limit for the fetus is only 0.5 mSv. So the dose from an organ in the abdominal cavity, especially one which could be classified as a ‘neighbouring sources’ or ‘nearby sources’, is significant in radiation protection of the fetus.

Specific absorbed fraction–electron energy relationship

Figure 3 plots the Φ (fetus $\leftarrow$ fetus) values versus electron energies for RPI-P series phantoms. The self-absorption of the fetus is approximately constant for low-energy electrons and drops quickly with energies approaching 1 MeV. Figure 4 plots Φ (fetus $\leftarrow$ another source organ) values versus electron energies for a close source organ (uterine content), a source organ at intermediate distance (bladder

content) and a distal source organ (thyroid) for the RPI-P3, RPI-P6 and RPI-P9 phantoms. As energy increases, the Φ values from a source organ to the fetus increase, whether the source organ is close or far away from the fetus.

The electron Φ values to the fetus from the fetus itself or another source organ (whether it is close or far away) follow a linear-log relationship with the energy, as determined by equation (2),

$$\text{Log}\Phi(\text{fetus} \leftarrow \text{source}) = A \cdot \log(E) + B, \quad (2)$$

where E is the electron energy, A and B are coefficients dependent on the source/target organ and the model used.

A and B values were calculated for Φ of RPI-series phantoms, from different source organs to the fetus as the target. These values are listed in Table 4. The R^2 correlation coefficients of the determination were also shown.

The R^2 correlation coefficients are very close to 1 for all the source organs in the three models studied. Therefore, the linear-log relationship between the

Table 3. Classification of source organs based on their specific absorbed fraction values to the fetus.

Energy	<100 keV	100 keV to 1 MeV	1 MeV to 2 MeV	>2 MeV
RPI-P3				
Neighbouring sources			Uterine contents	Uterine contents Uterine wall
Nearby sources		Uterine contents	Uterine wall	Placenta Bladder
Irrelevant sources	All organs	All other organs	All other organs	All other organs
RPI-P6				
Neighbouring sources			Uterine contents	Uterine contents Uterine wall
Nearby sources		Uterine contents	Uterine wall	
Irrelevant sources	All organs	All other organs	All other organs	All other organs
RPI-P9				
Neighbouring sources			Uterine contents	Uterine contents Uterine wall Ovaries
Nearby sources		Uterine contents	Uterine wall	Bladder Bladder contents Small intestine Low intestine placenta
Irrelevant sources	All organs	All other organs	All other organs	All other organs

Figure 3. Φ (fetus — fetus) versus electron energy relationship. Closed triangles represent P3, asterisks P6 and closed circles P9.

source-to-fetus Φ values and the energy of electrons is justified, for the energy range (10 keV to 4 MeV) that was studied. For electron emitters with energy inside this range, equation (2) and the A and B values in Table 4 allow interpolation of Φ values at 3, 6 and 9 months of pregnancy.

Specific absorbed fraction—organ distance relationship

Dose assessment for individuals who have anatomy that differs from standard models requires interpolation of data among various geometries. Unlike the Φ -electron energy relationship, the Φ -organ geometry relationship is rather complicated. The Φ

values are functions of the source and target organ volumes, shapes and especially their distances. Figure 5 plots the Φ values (for electron energies of 100 keV, 1 MeV and 4 MeV) as a function of the mean distances between source organs and the fetus for all three phantoms that were studied. The overall trend in Figure 5 is that the Φ value will decrease with increasing distance from the source organs of the mother. However, the Φ value may increase for larger (such as liver) and distributed (such as muscle) source organs. Power functions were used to fit the values. For most organs, the Φ values and the mean distances between the source organs of the mother to the fetus follow an approximately power relationship with power index around -4 . However, for organs that are very close to the fetus (such as uterus and uterine contents) and organs whose distances to the fetus are ‘wide spread’ (such as skin, skeleton and muscles), the power fit will underestimate the Φ value to a large extent. Therefore, when the organ distances are either too close or too wide spread, the Φ value needs to be evaluated individually.

CONCLUSIONS

A full set of specific absorbed fraction values from organs in a pregnant woman to her fetus for different electron energies have been derived by Monte Carlo calculations based on newly developed RPI-P series of pregnant-female models representing 3-, 6- and 9-month pregnancy. These models were developed by Xu *et al.*⁽²⁹⁾ from multiple image sets that include a partial CT scan of a woman at 7.5 months

Figure 4. Φ (fetus $\leftarrow$ selected source organs) plot for electron energies based on RPI-P series models.Table 4. Coefficients and R^2 of linear-log fitting for the relationship between the specific absorbed fraction values (from a source organ of the mother to the fetus based on three RPI-P models) and the electron energies.

Source organs	RPI-P3			RPI-P6			RPI-P9		
	A	B	R^2	A	B	R^2	A	B	R^2
Fetus	1.2×10^{-3}	11.75	1	6×10^{-5}	1.00	1	1×10^{-5}	0.29	1
Adrenals	1.11	-19.58	1.00	1.34	-21.10	0.99	1.47	-22.09	0.98
Bladder contents	1.34	-17.01	0.97	1.32	-18.46	0.96	1.46	-19.72	0.98
Bladder wall	1.46	-17.42	0.90	1.33	-18.46	0.98	1.56	-20.07	0.96
Brain	-1.84	0.00	1.00	2.00	-30.52	0.98	1.57	-26.61	1.00
Breast	1.32	-22.89	0.99	1.41	-22.78	0.99	1.36	-22.31	0.99
Oesophagus	1.49	-24.46	0.93	1.21	-22.15	0.99	1.70	-25.72	0.96
Eye balls	-1.68	0.00	1.00	1.71	-27.05	0.96	1.34	-23.96	0.99
Gall bladder contents	1.34	-20.81	0.97	1.29	-19.99	0.99	1.26	-19.70	0.99
Gall bladder wall	1.17	-19.50	0.99	1.41	-20.92	0.96	1.29	-19.84	0.98
Heart contents	1.35	-22.89	0.99	1.40	-22.85	0.99	1.41	-22.80	0.99
Heart wall	1.21	-22.03	0.98	1.52	-23.95	0.98	1.40	-22.91	0.99
Kidneys	1.19	-19.14	0.99	1.35	-20.23	0.98	1.36	-20.50	0.97
Lower intestine contents	1.10	-17.23	0.98	1.22	-18.43	0.98	1.36	-19.61	0.98
Liver	1.32	-21.41	0.97	1.28	-20.70	0.99	1.41	-21.55	0.98
Lower intestine wall	1.13	-17.21	0.99	1.19	-18.19	0.99	1.41	-19.72	0.98
Lungs	1.43	-23.50	0.99	1.42	-23.03	0.99	1.31	-22.18	1.00
Ovaries	1.10	-16.36	0.99	1.27	-17.99	0.97	1.63	-20.22	0.96
Pancreas	1.11	-18.41	1.00	1.26	-19.26	0.98	1.27	-19.40	0.98
Placenta	2.01	-21.28	0.98	1.21	-18.32	1.00	1.42	-19.74	0.98
Other body tissues	1.23	-19.14	0.99	1.31	-20.17	0.99	1.54	-21.69	0.99
Small intestine	1.08	-16.60	0.99	1.32	-18.82	0.98	1.63	-20.69	0.98
Skeleton	1.13	-18.58	0.99	1.32	-20.19	0.98	1.43	-20.86	0.99
Skin	1.05	-19.00	0.99	1.36	-21.06	0.99	1.27	-20.64	0.99
Spleen	1.16	-19.87	0.99	1.31	-20.74	0.99	1.34	-20.92	0.99
Stomach contents	1.09	-19.46	0.99	1.35	-20.99	0.98	1.35	-21.00	0.98
Stomach wall	1.28	-20.77	0.99	1.37	-21.15	0.99	1.34	-20.90	0.98
Thymus	1.65	-26.01	1.00	1.37	-23.22	1.00	1.46	-23.82	0.99
Thyroid	1.47	-25.55	1.00	1.46	-25.27	0.99	1.41	-24.63	1.00
Trachea	1.91	-28.43	0.91	1.40	-24.24	0.99	1.48	-24.76	1.00
Uterine contents	1.38	-11.80	0.98	1.41	-14.20	0.99	1.40	-14.66	0.98
Uterine wall	1.53	-18.06	0.91	1.82	-20.36	0.98	1.78	-19.46	1.00

Figure 5. The relationship of Φ values versus organ distance.

of pregnancy, and have anatomically realistic organ geometries and volumes matching the latest ICRP reference values for an ‘average woman’ at different gestational stages. Linear-log relationships were established between specific absorbed fraction values and the energies of the electrons for different source/target organs and different stage of pregnancy. The coefficients for calculation of the specific absorbed fraction for different organs in the three phantoms were listed. The effect of the distance between the source organ and the target organ on the specific absorbed fraction value was discussed. This set of specific absorbed fraction values could be used as reference values in the determination of the dose to the fetus from internal electron emitters.

SUPPLEMENTARY MATERIAL

Supplementary material is available at *Radiation Protection Dosimetry* online.

FUNDING

This project was funded in part by grants from National Cancer Institute: R01CA116743 and R42CA115122 (awarded to RADAR).

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