SAF values for internal photon emitters calculated for the RPI-P pregnant-female models using Monte Carlo methods

C. Y. Shi

Department of Radiation Oncology, University of Texas Health Science Center, San Antonio, Texas 78229

X. George Xu^{a)}

Nuclear Engineering and Engineering Physics Program, Rensselaer Polytechnic Institute, Room 1-11, NES Building, Tibbits Avenue, Troy, New York 12180

Michael G. Stabin

Department of Radiology and Radiological Sciences, Vanderbilt University, Nashville, Tennessee 37232-2675

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Estimates of radiation absorbed doses from radionuclides internally deposited in a pregnant woman and her fetus are very important due to elevated fetal radiosensitivity. This paper reports a set of specific absorbed fractions (SAFs) for use with the dosimetry schema developed by the Society of Nuclear Medicine's Medical Internal Radiation Dose (MIRD) Committee. The calculations were based on three newly constructed pregnant female anatomic models, called RPI-P3, RPI-P6, and RPI-P9, that represent adult females at 3-, 6-, and 9-month gestational periods, respectively. Advanced Boundary REPresentation (BREP) surface-geometry modeling methods were used to create anatomically realistic geometries and organ volumes that were carefully adjusted to agree with the latest ICRP reference values. A Monte Carlo user code, EGS4-VLSI, was used to simulate internal photon emitters ranging from 10 keV to 4 MeV. SAF values were calculated and compared with previous data derived from stylized models of simplified geometries and with a model of a 7.5-month pregnant female developed previously from partial-body CT images. The results show considerable differences between these models for low energy photons, but generally good agreement at higher energies. These differences are caused mainly by different organ shapes and positions. Other factors, such as the organ mass, the source-to-target-organ centroid distance, and the Monte Carlo code used in each study, played lesser roles in the observed differences in these. Since the SAF values reported in this study are based on models that are anatomically more realistic than previous models, these data are recommended for future applications as standard reference values in internal dosimetry involving pregnant females. © 2008 American Association of Physicists in Medicine. [DOI: [10.1118/1.2936414](https://doi.org/10.1118/1.2936414)]

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I. INTRODUCTION

A pregnant female and her embryo/fetus may be exposed to internal and external radiation sources through nuclear medicine studies,¹⁻³ diagnostic imaging,⁴ radiation therapy,⁵ occupational exposures,⁶ and nuclear accidents. The elevated fetal radiosensitivity makes the dosimetry for the embryo/fetus particularly important. In the case of radionuclides internally deposited in the expecting mother, the dosimetry is quite challenging partially due to the complex source-to-target geometries. One practical dosimetry method involves the use of Monte Carlo techniques to simulate radiation interactions inside an anatomical model that represents a pregnant female and her fetus at various stages of pregnancy.⁷ In recent years, techniques used in human modeling have advanced significantly and this study focuses on the application of one of the latest sets of pregnant female models.

To date, a number of models have been developed and used to derive various internal and external dosimetry parameters for pregnant patients or workers. The earliest com-

plete set of pregnant adult female models was reported in 1995 by Stabin *et al.*,⁸ who added fetuses into a modified adult female model that was originally defined in 1987 by Cristy and Eckerman using the so-called "stylized" surface equations.⁹ Stabin and his co-authors modified some of the abdominal organs in the adult female model to accommodate the anatomical changes caused by the fetal development. In 2004, Chen extended the modeling approach used by Stabin *et al.* and reported models representing four pregnancy periods (8 weeks and 3, 6, and 9 months).¹⁰ Kainz *et al.* developed a semi-heterogeneous pregnant woman model based on laser scanned data and mathematical equations in 2003.¹¹ Kainz *et al.* also extended the pregnant woman model into each month in 2005.¹² Dimbylow combined the fetuses defined by Chen with a voxel-based adult female model called NAOMI in 2006.¹³ Kawai *et al.* published an abdomen model of a pregnant female and in 2006 applied the model to estimate the specific absorption rate (SAR) 2006.¹⁴ The set of clinical computed tomography images was used by Shi and co-workers in 2004 to develop a tomographic model for

a large-sized patient who was 7.5-months pregnant when admitted into the emergency room.¹⁵ The partial-body model was used to study internal photon and electron emitters in internal dosimetry.^{16,17} Later on, Cech *et al.* modified the image sets from Shi *et al.* and designed a pregnant woman model called SILVY in 2007.¹⁸ To overcome intractable problems in the previous methods, Xu and co-workers developed a new modeling approach using innovative surface-geometry-based modeling tools for a set of pregnant female models, called RPI-P3, RPI-P6, and RPI-P9.¹⁹ This set of deformable models is anatomically realistic in comparison with those stylized models developed previously. The surface geometry representation (such as meshes) allowed the organs to be easily adjusted to match with the ICRP reference organ masses recommended for an average pregnant female and her fetuses.²⁰

In internal dosimetry, the specific absorbed fraction (SAF), Φ , is defined by the Society of Nuclear Medicine's Medical Internal Radiation Dose (MIRD) schema²¹ as shown in Eq. (1),

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

where $\phi(\text{target} \leftarrow \text{source})$ is the average fraction of particle emitted from the source tissue that is deposited in the target tissue and m_{target} is the mass of the target organ. Since SAF values are dependent on the organ shape, relative distance from the source to the target, organ mass, and other factors, accurate modeling of the human body is important in developing anatomical models. The ICRP updated its recommended anatomical reference data in Publication 89.²⁰ Consequently, it is necessary to derive and to evaluate the SAF values for pregnant female models that are compatible with current ICRP recommendations. The SAF, when combined with radionuclide decay data²² and biokinetic data for individual radiopharmaceuticals,²³ permit the estimation of absorbed doses to the embryo/fetus. The OLINDA/EXM personal computer code²⁴ facilitates this kind of calculation and currently contains the pregnant woman phantom series by Stabin *et al.*⁸ The code is currently being updated to contain a complete set of realistic, NCAT-based,²⁵ models of adults and children, and will use the RPI-P pregnant female phantom series as an update.

In this paper, we report the use of newly developed RPI-P models representing pregnant females at 3-, 6-, and 9-month gestational periods to derive the SAFs for internal photon emitters. The Monte Carlo code EGS4 was used to define the anatomical models and to simulate radiation transport. The SAF values are presented and compared with those previously reported for the stylized model⁸ and a 7.5-month tomographic model,¹⁵ respectively.

II. MATERIALS AND METHODS

II.A. Development of RPI-P3, RPI-P6, and RPI-P9

Detailed methods to develop three pregnant female models, named RPI-P3, RPI-P6, and RPI-P9, representing 3-, 6-,

FIG. 1. Flowchart of the workflow undertaken for voxel model construction.

and 9-month pregnancy periods, respectively, have been described by Xu and co-workers.¹⁹ The models were based on a mixture of several image data sets:

- (1) Segmented CT images of a 7.5-month pregnant female.¹⁵ This set of CT images covered the portion of the body between the lower breast and the upper thigh in 70 slices, each 7 mm thick. The image resolution was 512×512 pixels in a 48×48 cm² field. The images were segmented to identify 34 organs and tissues.
- (2) Segmented images of VIP-Man²⁶ of various resolutions. This model was based on anatomical color 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 is 0.33×0.33 mm² and the slice thickness is 1 mm, which allowed for small and radiosensitive structures to be identified and modeled, including skin, eye lenses, and red bone marrow (RBM).
- (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 3D graphics industry.

The general workflow for construction of these new models from the reference data is shown in Fig. 1. Starting from reference data or model, a new organ model in 3D is created from extracting the voxel information into the so-called “boundary representation (BREP)” that consists of polygonal meshes or nonuniform rational B-spline (NURB).²⁷ Individual organs and the fetuses are 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 the ICRP 89.²⁰ Once all the organs and total bodyweights have been adjusted, the surface models are voxelized and the organ volumes and masses are examined again before the voxelized models are defined in the Monte Carlo code. Standard tissue composition and densities are used for Monte Carlo simulations.²⁰ For this paper, we have

FIG. 2. Rendering of 3D organ and body surfaces for RPI-P models used in this study and the 7.5-month pregnant female models (Ref. 15): Top: from left to right are RPI-P3 and RPI-P9; bottom: from left to right are RPI-P6 and the 7.5-month model.

made some minor changes to the position of the upper larger intestine and the shape of the bladder to better represent these organs that are important to internal dosimetry for a pregnant patient. The latest RPI-P models are shown in Fig. 2 along with the previously developed 7.5-month pregnant woman model.¹⁵

II.B. SAF simulation using EGS4-VLSI

A user Monte Carlo code, EGS4-VLSI, was used for the Monte Carlo simulations involving voxelized human model.²⁸ This user code was developed from the EGSnrc

(unix version 3.2) kernel with PRESTA, where the ESTEPE was set to be 0.02. The pregnant woman models, RPI-P3, RPI-P6, and RPI-P9, were voxelized and then implemented into EGS4-VLSI. In this study, internal photon emitters were considered for the following energies: 10, 15, 20, 30, 50, 100, 200, 500, 1000, 1500, 2000, and 4000 keV. SAF values were calculated for each of these energies for each of the 35 source organs and 29 target organs listed in Table I. The radiation source was assumed to be homogeneously distributed in each organ. The Monte Carlo run employed approximately 1×10^7 histories to keep the statistical uncertainty to

TABLE I. Source and target organs used to calculate SAF values for internal photon emitters.

Organ	Source	Target	Organ	Source	Target
Adrenals	Yes	Yes	Pancreas	Yes	Yes
Brain	Yes	Yes	Placenta	Yes	Yes
Esophagus contents	Yes	No	Remainder (all other tissues)	Yes	Yes
Esophagus 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

less than 10% for most of the target organs, except for photon energies below 30 keV and for some target organs that were too small or too far from the source organ. In the latter cases, uncertainties of 10% or more were observed. The results were discarded if the relative uncertainty was higher than 40% so we could include as many data points as possible. The cutoff energy for both electron and photon calculations in the EGS4-VLSI user code were set to be 10 keV. A total of 420 separate simulations were performed, taking about 50 days of CPU time. The calculations were performed on six personal computers, each consisting of a CPU with a minimum speed of 1.0 GHz and memory of 1.0 GB. The computer operating systems were Fedora 2.6.15 and Red Hat Enterprise WS 4. The Monte Carlo simulation time was relatively long since some organs (such as the lens and esophagus wall) were very small and the sampling efficiency was low. No variance reduction was used. From the Monte Carlo calculations, the SAF values were later derived using Eq. (1) discussed earlier and were tabulated according for different source organs. The final results are tabulated with associated uncertainties. Interested readers can contract the authors for the tabulated data.

III. RESULTS AND DISCUSSIONS

III.A. SAF comparison between the RPI-P9 model and the 7.5-month pregnant female model by Shi *et al.*^{15,16} for fetus as the target and six source organs

In this section, the newly calculated SAF results are compared with those reported previously for a 7.5-month pregnant female model by Shi and co-workers in 2004.^{15,16} The fetal mass for RPI-P9 model is 3.50 kg, which is heavier than the 1.72 kg for the 7.5-month pregnant female model. The fetal mass differences were due to the fact that the CT images were for a pregnant patient who has a different fetus size from the reference pregnant female. The SAF data are

normalized to the RPI-P9 model whose mass, as stated earlier, is consistent with the reference values recommended by the ICRP.²⁰ The following 15 source organs were selected for calculation because these organs are explicitly defined in both models as source organs: adrenals, gall bladder contents, heart contents, kidneys, liver, lungs, ovaries, pancreas, placenta, small intestine contents, spleen, stomach contents, upper large intestine contents, urinary bladder contents, and uterus. For the comparison, we consider the whole body of the fetus as the target organ. The statistical uncertainties are less than 1% for photon energy higher than 30 keV. Figure 3 plots the SAFs for the fetus for six selected source organs: adrenals, placenta, uterus, kidneys, liver, and ovaries.

Figure 3 shows that the normalized SAF results for these two models generally follow a very similar trend throughout the photon energy region, i.e., having dramatically smaller values in low photon energies and then increasing to nearly constant values for photons of energies greater than 0.1 MeV. However, for the same source-to-fetus irradiations, the SAFs for the model by Shi *et al.* differ by a few tens of percent from those for the RPI-P9 for photon energies less than 0.08 MeV, where strong photoelectric effects occur and slight differences in anatomy would be expected to cause noticeable differences in the energy deposition. As can be seen from Fig. 3, the differences in SAFs between the two models decrease as the photon energy increases to beyond 0.1 keV but are still observed for energies up to 4 MeV. These differences are to be expected from anatomically different models. Generally, the SAF values are influenced by several factors including the size and shape of the source/target organ, the distance between the source and target organs, attenuation by intervening organs between the source and target organs, and the photon energy. In certain cases, all these factors need to be considered together in order to fully understand the differences in data derived from two different models. For all

FIG. 3. Comparisons of fetal SAFs between the 7.5-month pregnant female model by Shi *et al.* and RPI-P9 model in this study for six source organs: adrenals, placenta, and uterus (top figure); kidneys, liver, and ovaries (bottom figure). The statistical uncertainties are less than 1% for photon energies greater than 30 keV. In this figure, “-Shi” denotes the data from Shi *et al.* that are normalized to RPI-P9 model; “-RPI” denotes the results obtained from this study for the RPI-P9 model.

15 common source organs, the SAF results suggest that the 7.5-month pregnant woman model yielded lower SAFs than the RPI-P9 model. These can be explained by the anatomical differences of the two models that were illustrated in Fig. 2: the RPI-P9 model has a larger fetus, so the fraction of energy absorbed will be greater than the 7.5-month model. Since the two models have been normalized to the same mass for the target, using Eq. (1), the higher energy absorption fraction will result in higher SAF values. However, there are exceptions for the source organs such as the uterus, placenta, and adrenals. The uterus envelops the target organ, the placenta is so close to the target organ, and the adrenals are small. As a result, SAF values for those source organs seem to primarily depend on the stage of the pregnancy.

SAF results based on the RPI-P9 and the 7.5-month model were simulated using the same Monte Carlo techniques. The 7.5-month model is created from a real patient CT image data set and the RPI-P9 is based on surface geometries that are adjusted according to the ICRP reference anatomical data. The comparison between RPI-P9 and 7.5-month models suggests that we may have tens of percentages uncertainties in lower energy photon calculations if we were to apply the SAF results to an individual person (i.e., the

7.5-month pregnant patient) who is so different from the “standard” adult female (i.e., the RPI-P model). This finding underscores the challenge in internal dosimetry where a library of whole-body models with different anatomies should be ultimately used to reduce the uncertainty.

III.B. Comparison of SAFs between the RPI-P models and the stylized models by Stabin *et al.*, for fetus as the target and ten source organs

Figure 4 presents SAF values for RPI-P3, -P6, and -P9 models, in comparison with those reported by Stabin *et al.*⁸ for stylized models representing the same gestational periods. The figure has ten panels to cover ten different source organs. A similar trend is observed for both types of models: The SAFs decrease as the photon energy increases for source organs that are located near the fetus (such as the placenta, uterus, bladder contents, and ovaries). However, for source organs located further away from the fetus (such as the lungs, heart contents, thyroid, etc.), SAFs increase as the photon energy increases. This is expected since the penetration ability of the photons increases with the increasing energy and the high-energy photons will deposit more energy to organs located further from the fetus. Overall, agreement of SAFs between the stylized and realistic models is quite reasonable. Clearly the SAFs from the more realistic models are to be preferred, but profound changes in calculated doses using the two models for given internal emitters would not be expected.

However, for the same source-to-fetus irradiations, the SAF results obtained for the RPI-P series differ by tens of percent from those reported by Stabin *et al.*⁸ for the stylized models, for the following 20 source organs compared: adrenals, brain, breasts, gall bladder contents, LLI (lower large intestine) contents, SI (small intestine) contents, stomach contents, heart contents, heart wall, kidneys, liver, lungs, ovaries, pancreas, placenta, spleen, thymus, thyroid, urinary bladder contents, and uterus. As expected, for low-energy photons, the differences are greater because of the greater proximity of organs in the realistic models and the attenuation caused by the dominant photoelectric effects in such low energies in various tissues. The differences can be explained by examining the anatomical details in these two types of models. Table II shows the comparison of mass differences between RPI-P series and the stylized models. Furthermore, Table III compares the centroid distances between the shared source organs to the fetus. Also, Fig. 5 shows the probability density functions (PDFs) for chord lengths from the liver, pancreas, thyroid, and adrenals to the fetus for the RPI-P3 model. The PDFs were calculated using the distance from a randomly sampled point in the source organ to a point in the target organ. Five hundred thousand point pairs were sampled to generate each PDF. The PDFs show more information about the relative source-to-target distance. For instance, a small source organ (such as the adrenals) has a narrow PDF distribution and vice versa. These two tables suggest that, for many source organs—such as adrenals, brain, gall bladder contents, heart wall, kidneys, liver, ova-

Fig. 4. SAFs for target=the fetus for photon emitters in ten different source organs: (a) placenta, (b) uterus, (c) bladder contents, (d) ovaries, (e) kidneys, (f) liver, (g) adrenals, (h) lungs, (i) heart contents, and (j) thyroid, where m3, m6, and m9 represent results of different gestational periods from Stabin *et al.* (Ref. 8) and RPI-P3, RPI-P6, and RPI-P9 represent results from this study. For the source organ close to the target, the SAF values will decrease with increasing photon energy and the difference between models will become smaller; for the source organ far from the target, the SAF values will increase with increasing photon energy and the difference between models will become smaller.

ries, stomach contents, thymus, and thyroid—the mass and centroid distance are similar between RPI-P series and stylized models. Therefore, we believe that the differences in the SAFs are caused by the real differences in anatomical shapes between two types of models. The realistic phantoms do a better job of modeling the true relationship of internal organs and their overlap. In our experience, the differences in the Monte Carlo codes only contribute to a small portion of the observed differences in the SAFs. Figure 6 shows SAF uncertainty distribution for selected source organs of the

RPI-P9 model. If the uncertainty is lower than 40%, we accepted the SAF values. Here the cutoff of 40% was chosen to balance the simulation time and usable results. Larger uncertainties exist for lower photon energies (less than 30 keV) due to the weak penetrating ability and fewer particles reaching the fetus. The uncertainties may be further reduced if the Monte Carlo simulation runs more histories or uses an effective variance reduction technique. However, these low energy data have very small impact on the overall dose estimates.

g)

h)

i)

j)

Fig. 4. (Continued).

TABLE II. Mass differences for shared source organs between RPI-P series and the stylized models by Stabin *et al.* (Ref. 8).

Source organ	RPI-P (g)			Stabin <i>et al.</i> (g) ^a		
	3 months	6 months	9 months	3 months	6 months	9 months
Adrenals	13	13	13	14	14	14
Brain	1299	1299	1299	1200	1200	1200
Breasts	570	797	906	360	360	360
Fetus	85	1115	3495	485	1640	2960
Gall bladder contents	48	48	48	50	50	50
Heart contents	370	370	370	410	410	410
Heart wall	250	250	250	240	240	240
Kidneys	275	275	275	275	275	275
Liver	1400	1400	1400	1400	1400	1400
LLI contents	320	320	320	135	135	135
Lungs	950	950	950	651	651	651
Ovaries	11	11	11	11	11	11
Pancreas	120	120	120	85	85	85
Placenta	48	319	650	0	310	466
SI contents	880	880	880	375	375	375
Spleen	130	130	130	150	150	150
Stomach contents	231	231	231	230	230	230
Thymus	20	20	20	20	20	20
Thyroid	17	17	17	17	17	17
Urinary bladder contents	129	139	129	128	107	42.3
Uterus	270	550	1047	374	834	1095

^aData is based on Stabin *et al.* (Ref. 8, Table 3.7, p. 41).

TABLE III. Comparison of centroid distance differences from shared source organs to the fetus between RPI-P series and the stylized models.

Source organ	RPI-P (cm)			Stabin <i>et al.</i> (cm) ^a		
	3 months	6 months	9 months	3 months	6 months	9 months
Adrenals (left)	24.8	24.0	25.1	25.0	22.6	22.3
Adrenals (right)	23.3	22.8	24.0	25.0	22.6	22.3
Brain	70.9	67.7	67.8	66.8	66.8	65.7
Breasts (left)	35.8	31.6	32.1	36.4	31.8	30.4
Breasts (right)	35.7	31.5	31.7	36.4	31.8	29.0
Fetus	0.0	0.0	0.0	0.0	0.0	0.0
Gall bladder contents	21.8	18.8	19.3	16.3	15.4	15.0
Heart contents	35.4	32.7	33.1	32.6	29.5	28.4
Heart wall	37.4	34.7	35.1	31.6	28.4	27.3
Kidney (left)	19.3	19.1	20.4	19.9	18.6	18.7
Kidney (right)	17.9	18.3	19.8	19.9	18.6	18.7
Liver	25.6	22.9	23.4	22.6	20.1	19.5
LLI contents	9.8	9.0	12.7	7.1	8.5	11.2
Lung (left)	37.2	35.4	36.0	36.2	33.6	32.7
Lung (right)	37.6	35.6	36.3	35.6	32.9	32.0
Ovary (left)	8.9	14.7	16.9	6.0	11.1	11.6
Ovary (right)	8.3	13.5	15.7	6.0	11.1	11.6
Pancreas	17.5	15.6	16.6	21.9	18.7	18.1
Placenta	9.4	13.6	15.7	—	7.9	9.8
SI contents	8.7	12.6	13.4	7.7	7.3	13.4
Spleen	25.0	22.7	23.2	23.8	21.4	21.1
Stomach contents	25.2	23.0	23.6	20.4	17.6	16.7
Thymus	40.8	37.6	37.9	39.9	36.4	35.1
Thyroid	51.9	49.0	49.2	52.7	48.4	47.3
Urinary bladder contents	6.4	13.6	17.1	6.7	10.7	11.3
Uterus	5.7	5.6	7.7	1.5	0.0	1.2

^aData is based on Stabin *et al.* (Ref. 8 Table 3.8, p. 42).

As noted above, these new SAFs will be incorporated into the next release of the OLINDA/EXM software package for internal dosimetry.²⁴ As with the realistic pediatric and adult models based on the NCAT phantoms,²⁵ some differences are to be expected when dose estimates for particular radiophar-

maceuticals are calculated. These differences are expected to be minor, as most of the total dose for a given organ is contributed by moderate energy photons and particulate radiations; the differences noted in SAFs for low energy photons in some cases are interesting but not significant in the

FIG. 5. Possibility density function of chord length from selected source organ to the fetus of RPI-P3 model.

FIG. 6. Uncertainty distribution for some selected source organs of RPI-P9 model where 40% has been selected as acceptance for calculated SAF values.

overall calculation of dose for most radionuclides. This is a positive benefit of the use of the newer, more realistic phantom types—the newer SAFs are based on more realistic modeling of interorgan spacing and overlap. However, dose estimates based on any reference model give only an estimation of dose, ostensibly for the 50th percentile individual, and the actual doses received by individual subjects may vary considerably, by perhaps a factor of 2–3 or more.²⁹

IV. CONCLUSIONS

SAFs for internal radiation dosimetry have been calculated for a set of newly developed pregnant female models that were designed from advanced BREP surface-geometry modeling methods. The organ volumes and masses of this set of models were carefully adjusted in accordance with the latest ICRP reference values. The re-voxelized models at 1 mm resolution were implemented in an EGS4-VLSI user code to calculate radiation transport of photon emitters from various source organs. The SAFs for the fetus as a target were presented and compared with previously reported data that were based on less-sophisticated models: those for a 7.5-month pregnant model from a partial-body CT image set by Shi *et al.*^{15,16} and those for stylized models by Stabin *et al.*,⁸ respectively. The results show that one or two orders of difference may occur for low energy photons, but that differences for more energetic photons are much smaller. The differences were believed to be caused mainly by the anatomical shapes of the organs that are involved. Other factors, such as the organ mass, the centroid distance from source to target organ and model, and the Monte Carlo codes, played a less important role in the observed differences in the SAFs. Since the newly calculated SAF values are based on anatomically realistic pregnant female models whose organs have been adjusted to match with the ICRP reference values, the data reported here are recommended as a de facto standard in internal dosimetry for average pregnant workers and patients according to the ICRP recommendations. Furthermore, the new set of RPI-P models can be adjusted to represent different body sizes. Therefore, it is possible to study

dose uncertainty in individuals of different anatomies and even to address the need for patient-specific dosimetry in the future.

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- ^{a)} Author to whom correspondence should be addressed. Telephone: 518-276-4014; Fax: 518-276-4832; Electronic mail: xug2@rpi.edu
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