

EFFECTIVE DOSE RATIOS FOR TOMOGRAPHIC AND STYLIZED MODELS FROM INTERNAL EXPOSURE TO ELECTRONS

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ABSTRACT

The development of new, sophisticated Monte Carlo codes, and of tomographic or voxel-based human phantoms motivated the International Commission on Radiological Protection (ICRP) to call for a revision of traditional exposure models, which have been used in the past to calculate organ and tissue as well as effective dose coefficients for stylized MIRD5-type phantoms. This paper reports about calculations made with the recently developed tomographic MAX (Male Adult voXel) and FAX (Female Adult voXel) phantoms, as well as with the gender-specific MIRD-type phantoms ADAM and EVA, coupled to the EGS4 Monte Carlo code, for internal exposures to electrons with energies between 100 keV and 4 MeV for various source organs. Effective doses for the tomographic and for the stylized exposure models will be compared separately as function of the replacement of the Monte Carlo code, of human tissue compositions, and of the stylized by the tomographic anatomy. The results indicate that for internal exposures to electrons the introduction of voxel-based exposure models causes changes of the effective dose between +20% and – 40% depending on the energies and source organs considered compared to corresponding data of the MIRD5-type phantoms.

Key Words: voxel phantoms, Monte Carlo, radiation protection, effective dose

1 INTRODUCTION

Conversion coefficients (CCs) between effective dose and physical quantities characterizing the radiation source have been published by the International Commission on Radiological Protection (ICRP) internal exposures in order to facilitate the interpretation of accumulated activity in a source organ in terms of the primary protection quantity.

This primary protection quantity, the effective dose, “is the sum of the weighted equivalent doses in all tissues and organs of the body. It is given by the expression

$$E = \sum w_T H_T$$

where H_T is the equivalent dose in tissue or organ T and w_T is the weighting factor for tissue T [1].

According to Table 1, the ICRP recommends tissue weighting factors for 13 selected tissues and organs, plus one single tissue weighting factor for a so-called “remainder”, which is composed of another 10 organs and tissues. The quantity H_T represents the equivalent dose averaged over the volume of tissue T , which reflects the assumption of a linear dose-risk relationship.

Table 1. Tissue weighting factors from ICRP60 [1]

Tissue/Organ	w_T
Testes, Ovaries	0.20
RBM, Colon, Lungs, Stomach	0.12
Bladder, Breast, Liver, Oesopagus, Thyroid	0.05
Skin, Bone surface	0.01
Remainder	0.05

Remainder: adrenals, brain, trachea, small intestine, muscle, pancreas, kidneys, spleen, thymus, uterus

Effective dose CCs have been calculated by applying Monte Carlo radiation transport methods to virtual representations of the human body, so-called mathematical or stylized phantoms. In mathematical human phantoms size and form of the body and its organs are described by mathematical expressions representing combinations and intersections of planes, circular and elliptical cylinders, spheres, cones, tori, etc.

Fisher and Snyder [2, 3] introduced this type of phantom for an adult male which also contains ovaries and a uterus. During the compilation of the Report of the Task Group on Reference Man, Publication No.23 [4] the phantom has been further developed by Snyder et al [5, 6]. Since then it is known as “MIRD5 phantom” (Medical Internal Radiation Dose Committee (MIRD) Pamphlet No.5).

The MIRD5 phantom has been the basis for various derivations representing infants and children of various ages [7], gender-specific adult phantoms, called ADAM and EVA [8], and a pregnant female adult phantom [9]. Body height and weight as well as the organ masses of these MIRD5-type phantoms are in accordance with the Reference Man data from 1975 [4].

For beta emitters homogeneously distributed in various organs of the human body, this paper presents ratios between effective doses calculated on the one hand with MIRD5-type phantoms ADAM and EVA, and on the other hand with the voxel-based MAX and FAX phantoms in order to show the dosimetric consequences when stylized exposure models will be replaced by tomographic models. For want of adequate published Monte Carlo data a comparison was made with analytically calculated CCs found in MIRD pamphlet No.11 [10].

2 MATERIALS AND METHODS

2.1 The MAX and the FAX phantoms

The MAX and FAX have been developed based on CT images from patients [11, 12]. After segmentation the volumes of the radiosensitive organs and tissues have been adjusted in order to match the reference masses defined by ICRP89 [13]. The phantoms have heterogeneously structured skeletons with voxel-specific skeletal tissue compositions based on masses, percentage distributions, and cellularity factors from ICRP70 [14]. This was achieved by use of the so-called CT number method [15] as adopted by Kramer et al [11], which takes advantage of the CT numbers (= grey values) contained in the bone pixels of the CT images. Thereby it was possible to improve the calculation of the equivalent dose to the red bone marrow (RBM). Dosimetrical separation instead of geometrical segmentation allows for the calculation of skin equivalent dose in the 1.5mm surface layer of the MAX phantom, and in the 1.2mm surface layer of the FAX phantom, in spite of 3.6mm voxel thickness. Detailed descriptions of both voxel phantoms are given in Kramer et al [11, 12]. Figures 1 and 2 show frontal and lateral views of the MAX and the FAX phantoms, respectively.

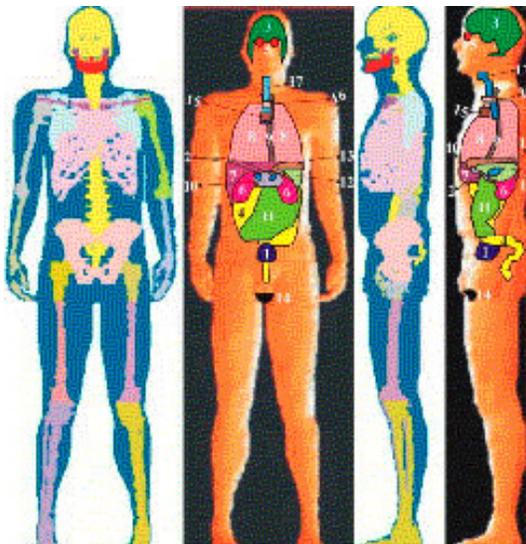


Figure 1: The MAX phantom

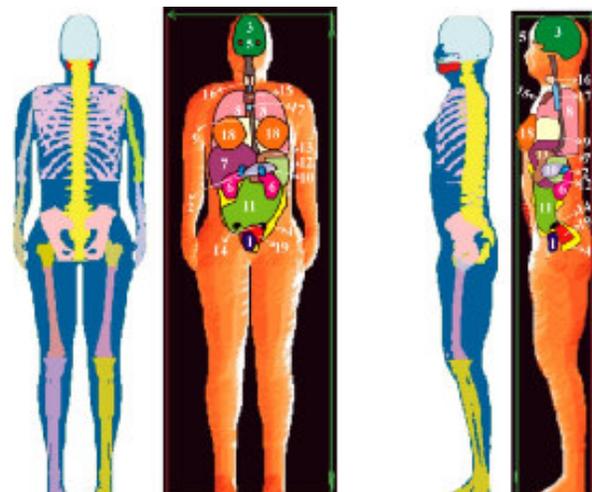


Figure 2: The FAX phantom

2.2 The ADAM and EVA phantoms

The gender-specific adult MIRD5-type phantoms ADAM and EVA have been taken from Kramer et al [8]. Their organ and tissue masses correspond to the anatomical specifications given by the ICRP in its first Reference Man Report, Publication No.23 [4]. Figure 3 shows frontal views of the ADAM and the EVA phantom.

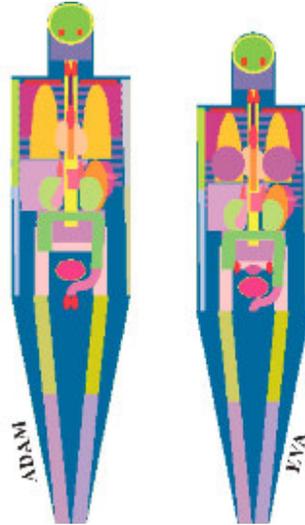


Figure 3: The ADAM and EVA phantoms

2.3 The EGS4 Monte Carlo code

The EGS4 Monte Carlo code [16] simulates coupled electron-photon transport through arbitrary media. The default version of EGS4 applies an analog Monte Carlo method, which was used for the calculations of this investigation, which also included the use of the PRESTA algorithm [17].

2.4 Exposure models

For any given exposure condition the effective dose CC is primarily a function of the phantom anatomy, of the tissue composition, and of the the Monte Carlo code. In order to study the dosimetric effects of these three components separately, the following exposure models have been studied:

- a) The EGS4 Monte Carlo code connected to the ADAM and EVA phantoms with the original ORNL tissue composition [8].
- b) The EGS4 Monte Carlo code connected to the ADAM and EVA phantoms with ICRU44-based tissue compositions [18].
- c) The EGS4 and MCNP4C Monte Carlo code connected to the MAX and FAX phantoms with ICRU44-based tissue compositions, and ICRP70-based skeletal tissue distribution [14].

3 RESULTS

The effective dose ratios presented in the following sections have been calculated for homogeneously distributed beta emitters in the kidneys, the skeleton, and the spleen with electron energies ranging from 100 keV to 4 MeV. Equivalent doses have been averaged over the volume of the organs and tissues of interest. The effective dose was determined as recommended by the ICRP68 [19]. The remainder equivalent dose has been calculated according to ICRP60 [1], which recommends the mass-weighted average of the contributing organ and tissue equivalent doses, also taking into account footnote 3 of Table 2 from ICRP60, i.e. that if the equivalent dose of one of the remainder organs or tissues is greater than the maximum equivalent dose of the main organs or tissues, then half of the remainder weighting factor should be applied to the equivalent dose of that remainder organ or tissue, while the other half should be used for the arithmetic average of the equivalent dose of the remaining organs or tissues. In this study if the coefficient of variance (CV) of an organ or tissue mentioned in Table 1 was greater than 30%, then its equivalent dose was disregarded.

3.1 Comparison with MIRD-11

For the time being no Monte Carlo reference data have been found which would allow for direct comparative calculations of effective dose per cumulated activity from exposure to internal beta emitters. Therefore a “comparison” has been made with data found in MIRD pamphlet No.11 [10], which had been calculated analytically for the MIRD5 phantom based on the assumption that the emitted energy is totally absorbed in the source organ. In the ADAM/EGS4 calculation this case has been simulated by setting the electron cut-off energy equal to the initial electron energy. Table 2 presents equivalent dose to the spleen per unit cumulated activity from Sr-90, P-32, and Y-90 homogeneously distributed in the spleen of the MIRD5 and of the ADAM phantom, respectively. Considering the quite different calculational methods applied, the agreement between the two sets of equivalent doses to the spleen is satisfactory.

Table 2: Equivalent dose to the spleen per cumulated activity for beta emitters in the spleen

Radionuclide	E _{av} [MeV]	MIRD-11 mGy / Bq s	ADAM/EGS4 mGy / Bq s	Perc. Diff. [%]
Sr-90	0.196	1.730E-10	1.808E-10	+4.5
P-32	0.695	6.150E-10	6.410E-10	+4.2
Y-90	0.935	8.250E-10	8.623E+00	+4.5

Source organ: Spleen, Target organ: Spleen

3.2 The replacement of the tissue compositions

The study of the replacement of the tissue compositions and of the human anatomy was performed with the ADAM and the EVA phantoms. The initial tissue compositions [8] are shown in the “ADEV” columns 2 – 5 of Table 3, except for some small fractions for heavier elements. In the ADAM and EVA phantoms the soft-tissue composition was not only used for organs, like the liver, the stomach, the pancreas, etc., but also for the unspecified regions surrounding the organs, the lungs, and the skeleton, which in real humans are mostly filled with adipose and muscle. The new tissue compositions shown in the “ADEV44” columns 6 – 11 of Table 3 are based on data provided by ICRU44 [18], and additionally the skeletal ADEV44 mixture was designed to contain 11.3% of calcium as recommended by ICRP70 [14]. As the ADAM and EVA phantoms have no separately segmented regions for adipose and muscle, homogeneous mixtures ADIMUSM and ADIMUSF of the two tissues were defined based on their mass ratios in the MAX and FAX phantom, respectively. The ICRP23-based RBM masses, RBM mass fractions, and the calculational RBM model of the ADEV phantoms [8] have not been changed at this stage.

Table 3. Tissue compositions for the ADEV and the ADEV44 phantoms

ELEMENT	SOFT	SKIN	LUNGS	SKEL	SOFT	SKIN	LUNGS	SKEL	ADIMUSM	ADIMUSF
	ADEV	ADEV	ADEV	ADEV	ADEV44	ADEV44	ADEV44	ADEV44	ADAM44	EVA44
	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
H	10	10.2	10	7	10.5	10	10.3	7.2	10.6	10.8
C	23	26.9	10	23	12.5	20.4	10.5	31.3	30.8	37.1
N	2.3	4.3	2.8	3.9	2.6	4.2	3.1	3.2	2.4	2.1
O	63	58	76	49	73.5	64.5	74.9	41.1	55.4	49.4
Na	0.13	0.01	0.2	0.32	0.2	0.2	0.2	0.1	0.1	0.1
Mg	0.015	0.005	0.007	0.11				0.1		
P	0.24	0.3	0.08	6.9	0.2	0.1	0.2	5.3	0.128	0.1
S	0.22	0.15	0.23	0.17	0.18	0.2	0.3	0.25	0.227	0.2
Cl	0.14	0.25	0.27	0.14	0.22	0.3	0.3	0.1	0.1	0.1
K	0.21	0.1	0.2	0.15	0.21	0.1	0.2	0.05	0.245	0.2
Ca		0.14	0.007	9.9	0.01			11.3		
Fe	0.006	0.002	0.04	0.008	0.01					
ρ [gcm ⁻³]	0.98	1.105	0.296	1.486	1.05	1.09	0.26	1.469	1.012	1.00

SOFT = SOFT TISSUE, SKEL = SKELETON, ADIMUSM (F) = 36.2% (50.7%) ADIPOSE + 63.8% (49.3%) MUSCLE

Figure 4 shows ratios between effective doses calculated with the ADEV and the ADEV44 phantoms for monoenergetic beta emitters homogeneously distributed in the kidneys, the skeleton, and the spleen as a function of the electron energy. Introduction of the ICRU44-based tissue compositions led to a decrease of the effective dose by ca. 6 % when the kidneys and the spleen were the source organs, while almost no change can be observed when the skeleton is the source organ.

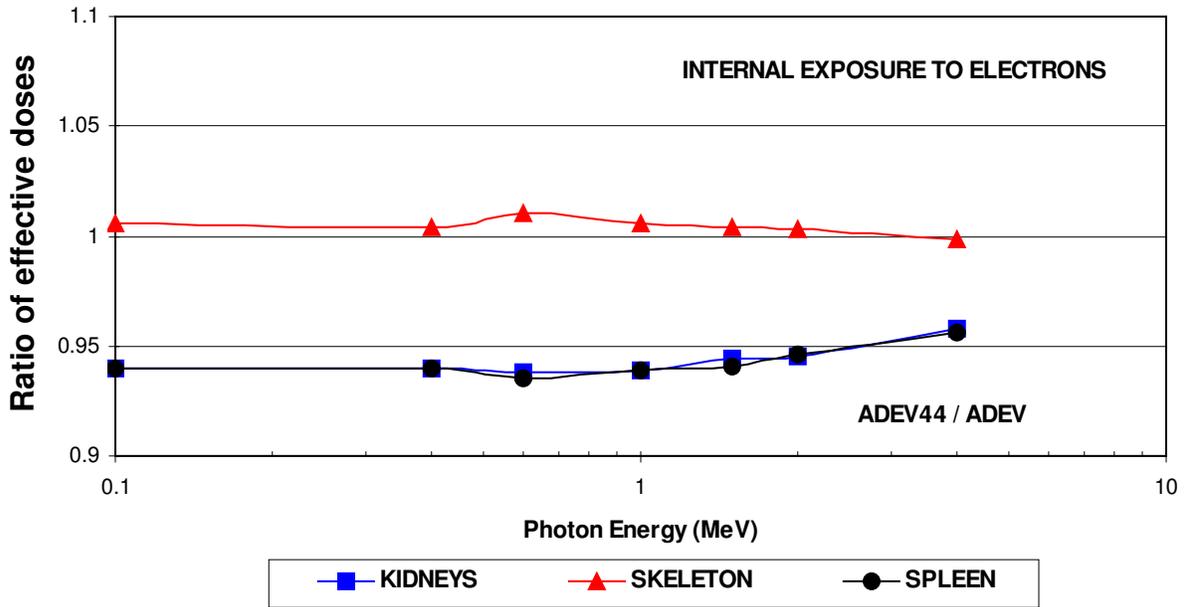


Figure 4: Replacement of the tissue composition

3.3 Replacement of the anatomy

The replacement of the stylized MIRD5 bodies by real human bodies was done in two steps:

First homogenized versions of the MAX and the FAX phantoms, called MAXHOM and FAXHOM, have been designed, each of which contains a homogeneous skeleton, and

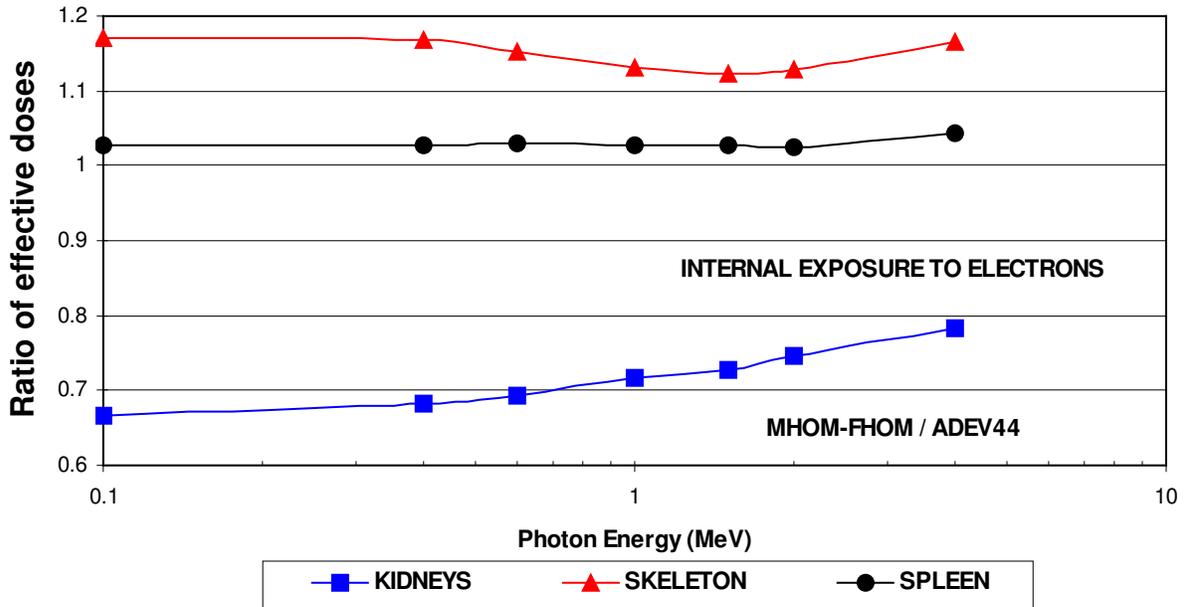


Figure 5: Replacement of the anatomy

homogeneous mixtures of adipose and muscle, with tissue compositions shown in columns 6 - 11 of Table 3, and still with the ICRP23-based RBM model. In terms of the elemental compositions of tissues and their distribution throughout the body, the ADAM44 and the MAXHOM, and the EVA44 and the FAXHOM phantoms are equivalent, and consequently all differences of equivalent doses between the two pairs of phantoms are expected to be caused by their different “geometrical anatomies” only, i.e. differences with regard to the volume, the form, and the location of organs and tissues.

Figure 5 presents ratios between effective doses for the two pair of tissue-equivalent phantoms with beta emitters homogeneously distributed in the kidneys, the skeleton, and the spleen, for electron energies between 100 keV and 4 MeV, and with ICRU44-based tissue compositions and ICRP23-based RBM models applied to all of them. “ADEV44” represents the ADAM44 and the EVA44 phantoms, while “MHOM-FHOM” stands for the MAXHOM and the FAXHOM phantoms. Introduction of a real human anatomy generally leads to an increase of the effective dose, an observation also made for internal photon emitters [20]. The reasons are the shorter distances between organs in a real human body compared to the inter-organ distances in the MIRD5-type phantoms. Figure 5 shows increases by up to 17% for the skeleton effective dose, and by up to 3.5% for the spleen effective dose. However, the increases of the effective dose in case of internal electron emitters are usually smaller because of the smaller range of the electrons compared to photons for a given energy. The decrease of the effective dose for the kidneys in Figure 5 is due to the presence of voxels of urine in the kidneys of the MAXHOM-FAXHOM phantoms. A part of the energy emitted from the radionuclides in the cortex of the MAXHOM-FAXHOM kidneys is absorbed in the urine voxels, i.e. that this energy does not appear in the equivalent dose for the kidneys. As the “cortex kidneys” of the voxel phantoms have almost the same mass as the kidneys of the ADEV phantoms, the effective doses per cumulated activity for the MAXHOM-FAXHOM phantoms become smaller which is reflected in Figure 5 by the ratio for the kidneys.

The second step of the transition from the MIRD5-type ADAM and EVA to the voxel-based MAX and FAX anatomies represents the introduction

- of ICRP70-based masses, mass fractions, and cellularity factors for the RBM,
- of the revised correction factors for photo-electrons,
- of heterogeneously distributed skeletal tissues among the bone voxels, and
- of separately segmented regions of adipose and muscle.

The first three items affect the equivalent dose to the bone surface (= skeleton), and to the RBM. Figure 6 shows almost no change of the effective dose for the source organs kidneys and spleen after the introduction of the heterogeneously distributed skeletal tissues or adipose and muscle. Most of the electrons are absorbed in the soft-tissue source organs, and those high-energy particles which reach a neighbouring bone cannot alter the equivalent dose to the bone surface or the RBM for the whole body significantly. When the skeleton is the source organ the effective dose decreases between 1% and 4% due to the different models of skeletal dosimetry involved.

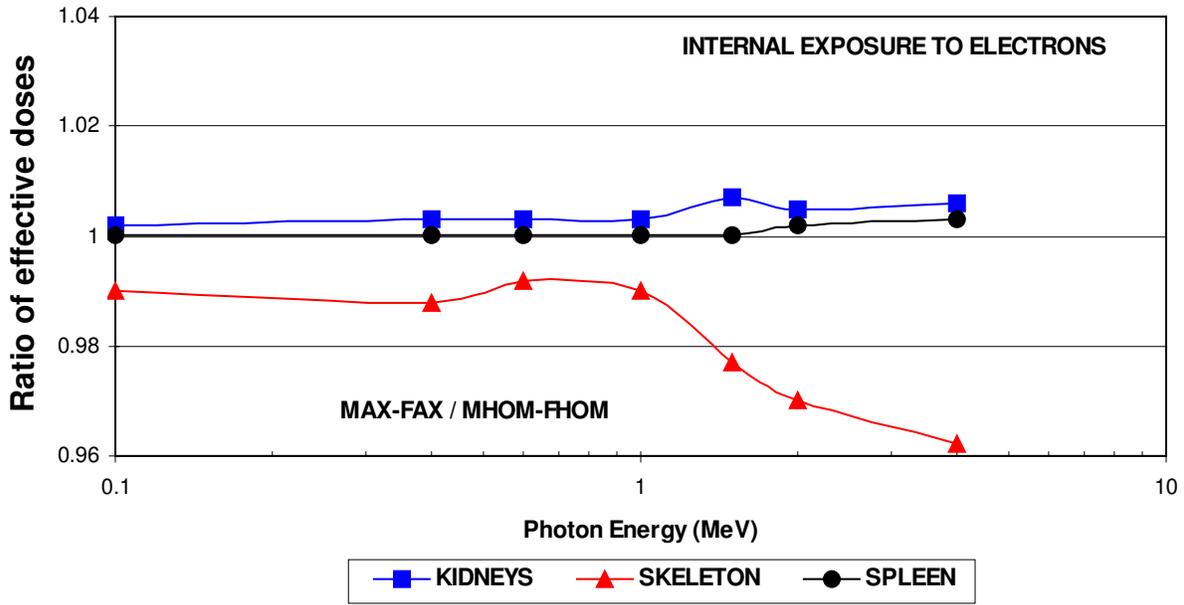


Figure 6: Introduction of heterogeneously distributed skeletal tissues, adipose and muscle

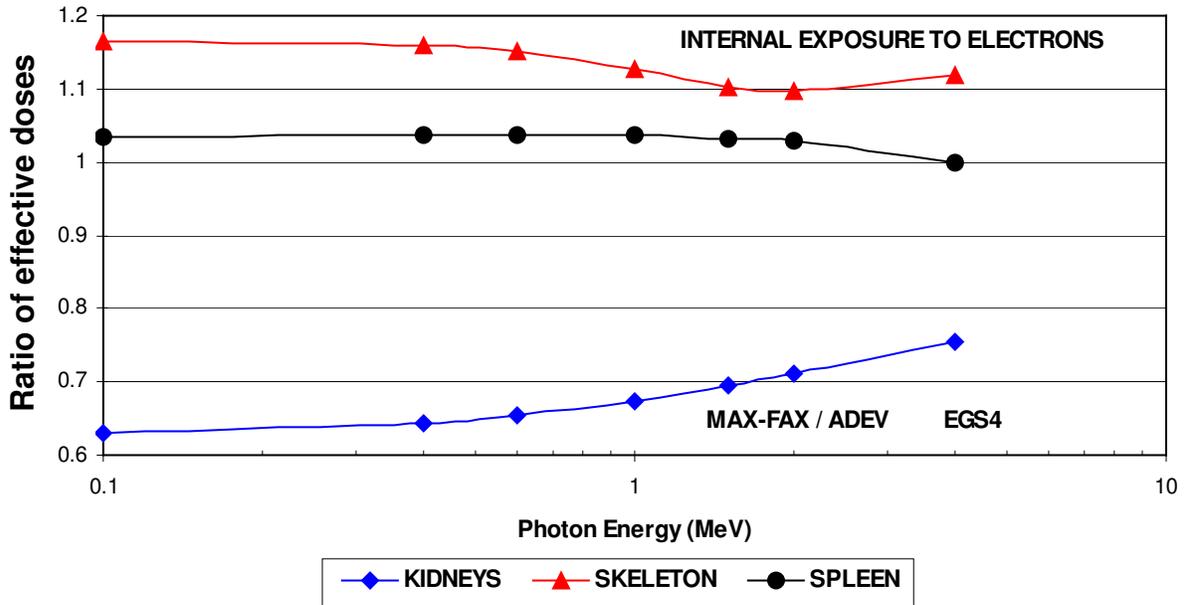


Figure 7: Replacement of the ADAM-EVA by the MAX-FAX exposure model

Figure 7 summarizes the replacements of the tissue compositions, and of the anatomy, but also the introduction of heterogeneously distributed skeletal tissues, adipose, and muscle, and of the RBM model. For the source organs considered here the results show an increase of the effective dose by ca. 17% when the skeleton is the source organ, a decrease of the effective dose by ca.

35% when the cortex of the kidneys is the source organ, and a slight increase of 3.5% of the effective dose when the spleen is the source organ.

4 CONCLUSIONS

The purpose of this paper was to investigate for internal irradiation with electrons the dosimetric consequences for the effective dose, when the MIRD5-type exposure model ADAM-EVA is replaced by voxel-based exposure model MAX-FAX. The analysis was done separately for the replacement of the Monte Carlo code, of the tissue composition, and of the anatomy. The data have been presented as ratios between effective doses as function of the electron energy, for three different source organs. For electron energies between 100 keV and 4 MeV the results have shown that repeating the MIRD-11 calculations with the ADAM/EGS4 Monte Carlo code caused differences of ca. 5% for the equivalent dose to the source organ. Introduction of ICRU44-based tissue compositions led to a decrease of the effective dose by up to 6%, while the replacement of the MIRD5 by the voxel anatomy can increase the effective dose by up to 17%, or decrease the effective dose by 35%, depending on the source organ considered. If the replacement of the Monte Carlo code is also taken into account, the transition from the MIRD5-type to the voxel-based exposure models can cause variations of the effective dose between ca. +20% and -40% at least for the source organs considered in this investigation.

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