The Monte Carlo Method: Versatility Unbounded In A Dynamic Computing World
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EFFECTIVE DOSE RATIOS FOR TOMOGRAPHIC AND STYLIZED MODELS FROM INTERNAL EXPOSURE TO PHOTONS

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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, and have been released in Publication No. 68, and 72, for example, for internal exposures to photons. 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 photons with energies between 10 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 photons the introduction of voxel-based exposure models causes an increase of the effective dose of up to 70% for some of the source organs considered in this study.

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) for internal exposures in order to facilitate the interpretation of cumulated 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

$$E = \sum_T w_T H_T$$

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

Mathematical MIRD5 phantoms representing various ages [2] have been used for the calculations of effective dose CCs for internal exposures to photons published by the ICRP [3, 4]. For the Reference Female and Male Adult this paper presents ratios between effective doses calculated on the one hand with the stylized 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.

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 [5, 6]. After segmentation the volumes of the radiosensitive organs and tissues have been adjusted in order to match the reference masses defined by ICRP89 [7]. The phantoms have heterogeneously structured skeletons with voxel-specific skeletal tissue compositions based on masses, percentage distributions, and cellullarity factors from ICRP70 [8]. 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 [5,6]. Figures 1 and 2 show frontal and lateral views of the MAX and of the FAX phantoms, respectively.

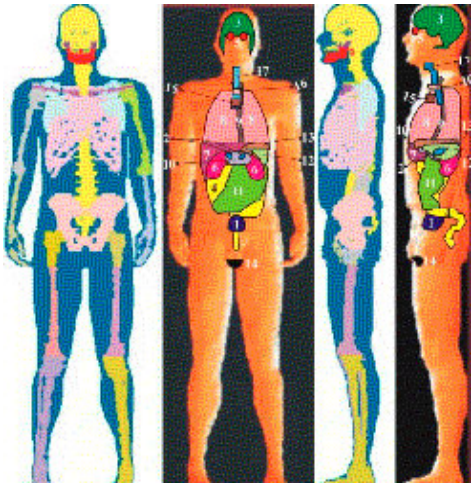

Figure 1: The MAX phantom

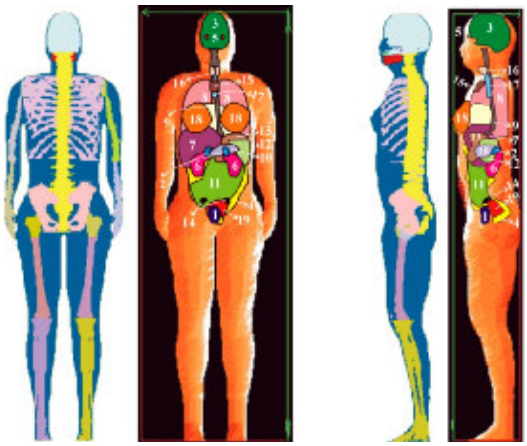

Figure 2: The FAX phantom

2.2 The MIRD5-type ADAM and EVA phantoms

For the purpose of the calculations to be presented here the gender-specific adult MIRD5-type phantoms ADAM and EVA have been taken from Kramer et al [9]. Their organ and tissue masses correspond to the anatomical specifications given by the ICRP in its first Reference Man Report, Publication No.23 [10]. Figure 3 shows frontal views of the ADAM and the EVA phantoms.

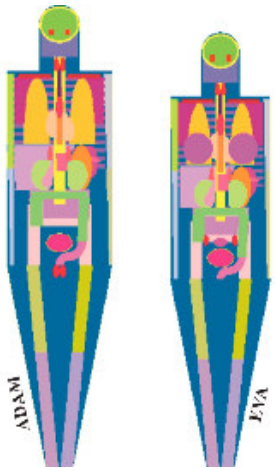

Figure 3: The ADAM and EVA phantoms

2.3 The EGS4 Monte Carlo code

The EGS4 Monte Carlo code [11] simulates coupled electron-photon transport through arbitrary media. The default version of EGS4 applies an analogue Monte Carlo method, which was used for the calculations of this investigation. Rayleigh scattering has been taken into account in the calculations, however secondary electrons have not been transported.

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 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 [9].

b) The EGS4 Monte Carlo code connected to the ADAM and EVA phantoms with ICRU44-based tissue compositions [12].

c) The EGS4 Monte Carlo code connected to the MAX and FAX phantoms with ICRU44-based tissue compositions [12], and ICRP70-based skeletal tissue distribution [8].

3 RESULTS

The effective dose ratios presented in the following sections have been calculated for homogeneously distributed photon emitters in the liver, the lungs, the skeleton, and the thyroid with energies ranging from 10 keV to 4 MeV. Secondary electrons have not been transported, i.e. equivalent doses have been calculated as kerma averaged over the volumes of the organs and tissues of interest. The effective dose was determined as recommended by ICRP68 [3]. 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 equiavlent 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 Replacement of the Monte Carlo code

The effective dose CCs for internal photon sources published by the ICRP are based on specific absorbed fractions (SAFs) of energy calculated by Cristy and Eckerman [13] with the ALGAMP Monte Carlo code [14] for MIRD5-type phantoms at various ages. The SAFs for male and female adults have been determined with an “Adult male”, which represents the adult male MIRD5 phantom including female organs, like breasts, ovaries, and a uterus.

Apart from Monte Carlo techniques also other computational methods, like the point-source kernel method, or the reciprocal dose principle have been used by Cristy and Eckerman in order

to get reliable results, especially when the coefficient of variance (CV) of the direct Monte Carlo estimate was greater than 50%.

Using the ORNL tissue composition [13], SAFs have been calculated with the ADAM-EGS4 exposure model for photon sources uniformly distributed in the liver and in the kidneys. In contrast to the MIRD5-"Adult male" the ADAM phantom has no female organs, but this does not impair the comparison of data presented here.

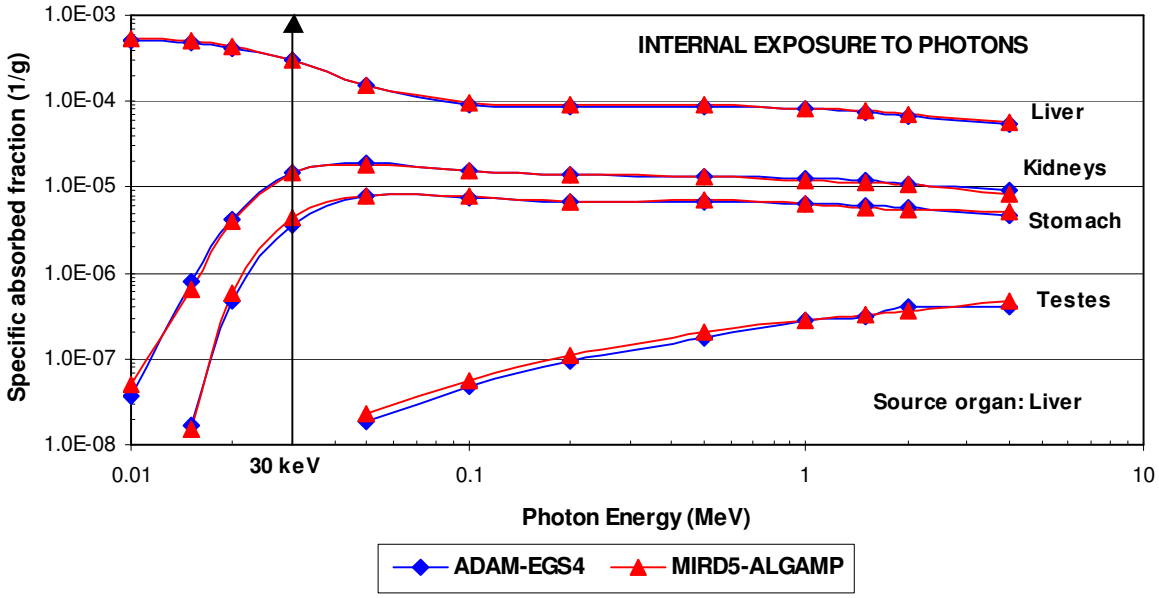

Figure 4: Replacement of the Monte Carlo code

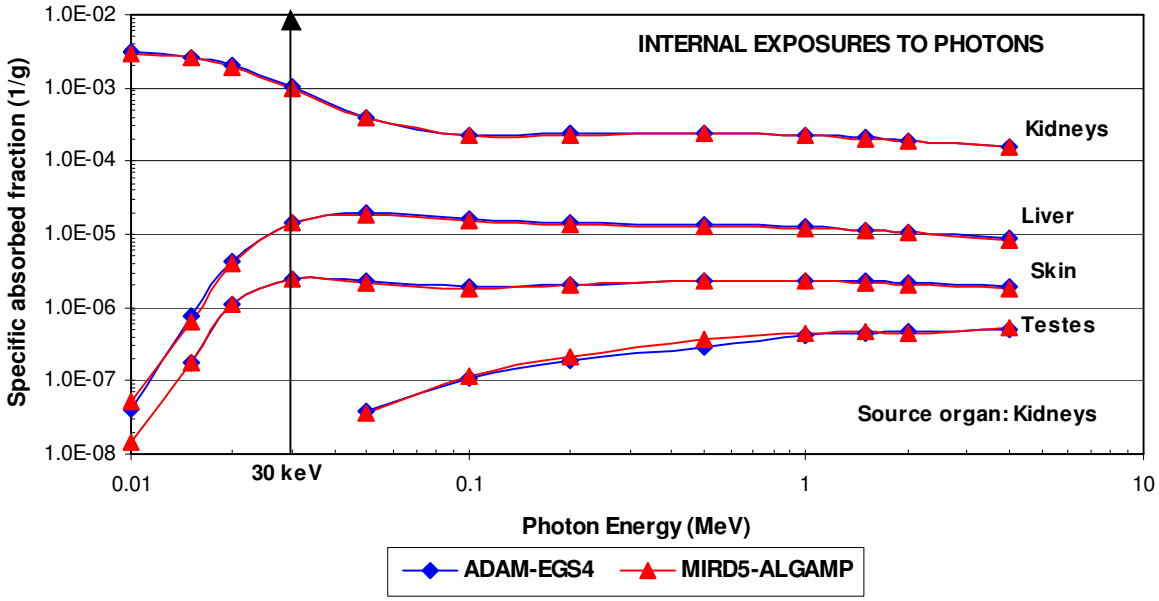

Figure 5: Replacement of the Monte Carlo code

Figures 4 and 5 show SAFs for various organs resulting from photons emitted in the liver and in the kidneys, respectively, for the ADAM-EGS4 and for the "Adult male"-ALGAMP exposure models. When the source organ is also the target organ the SAFs of both exposure models agree quite well for all energies within a margin of 3% on average. For other target organs differences between 5% and 8% can be observed for energies above 30 keV, while for smaller energies the differences are 15% on average.

3.2 The replacement of the tissue compositions

For the study of the replacement of the tissue compositions and of the human antomy, instead of using an "Adult male" with female organs, it was decided to start with the MIRD5-type ADAM and the EVA phantoms, because this approach corresponds better to the concept of effective dose. The initial tissue composition was taken from Kramer et al [9], in order to be consistent with the method applied to the same investigation for external exposures [15].

The initial tissue compositions are shown in the "ADEV" columns 2 – 5 of Table 2, 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 2 are based on data provided by ICRU44 [12], and additionally the skeletal ADEV44 mixture was designed to contain 11.3% of calcium as recommended by ICRP70 [8]. 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 MAXand FAX phantom, respectively. The ICRP23-based RBM masses, RBM mass fractions, and the calculational RBM model of the ADEV phantoms [9] have not been changed a 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

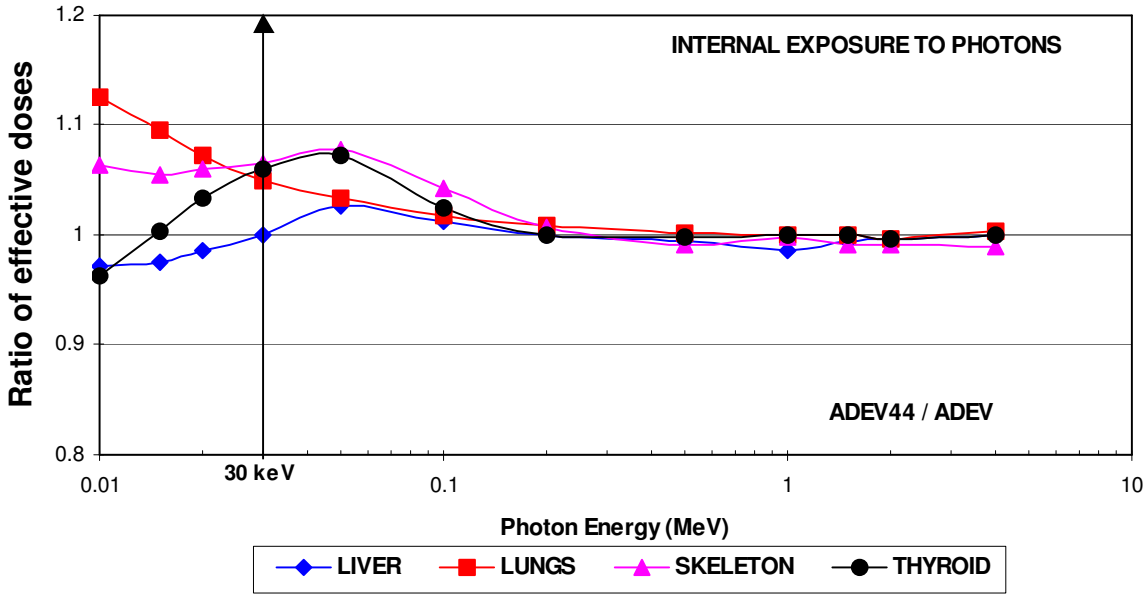

Figure 6: Replacement of the tissue composition

Figure 6 presents ratios between effective doses calculated with the tissue compositions from Table 2 for photon emitters homogeneously distributed in the liver, the lungs, the skeleton, and the thyroid of the ADEV and ADEV44 phantoms as function of the photon energy. For energies up to 20-30 keV, depending on organ size, basically most of the emitted energy will be absorbed in the source organ itself. If at the same time the source organ belongs to the group of organs and tissues mentioned in the main list of Table 1, then the effective dose is more or less equal to the equivalent dose to the source organ multiplied with its tissue weighting factor. This observation applies to the curves for the liver, the lungs, and the thyroid in Figure 6. However if the skeleton is the source organ the main contributors to the effective dose are the RBM, the bone surface, the lungs, and the liver in this range of low energies. According to Figure 6 for the source organs considered here, the effective dose can increase up to 7.5% for energies above 30 keV as a result of the replacement of the tissue compositions. For energies below 30 keV soft-tissue source organs, like the thyroid or the liver, show decreases of the effective dose by up to 5%, while an increase by more then 10% can be observed for the lungs. When the skeleton is the source organ the effective dose for the ADEV44 phantoms is ca 5% higher than the effective dose for the ADEV phantoms from 10 to 30 keV. Although below 30 keV the ratios certainly reflect dosimetric properties of the tissues involved, one should interprete these data with caution because of the large CVs for small organs like the testes, ovaries, or thyroid, and because of rounding error effects for small values of effective dose [15].

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, which contain a homogeneous skeleton, and homogeneous mixtures of adipose and muscle, with the tissue compositions shown in columns 6 – 11 of Table 2, 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 the two pair 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.

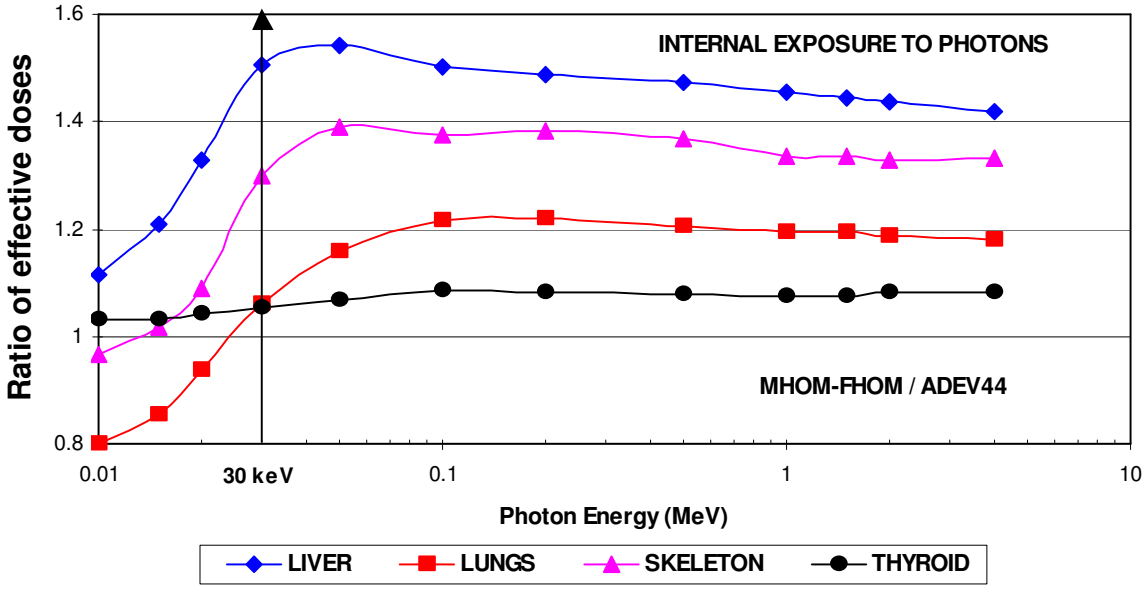

Figure 7: Replacement of the anatomy

Figure 7 presents ratios between effective doses for the two tissue-equivalent pair of phantoms MAXHOM-FAXHOM and ADAM-EVA with photon emitters homogeneously distributed in the liver, the lungs, the skeleton, and the thyroid, for photon energies ranging from 10 keV to 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. In contrast to the findings for external exposures [15], for internal exposures to photons, at least for the source organs considered here, the introduction of a real human anatomy increases the effective dose for energies above 30 keV by more than 50%. The main reason are shorter distances between organs in a real human body compared to the inter-organ distances in the MIRD5-type phantoms.

These observations have also been made by others. Jones [16], for example, compared SAFs calculated for the NORMAN voxel phantom [17] with corresponding data for the MIRD5 phantoms [13]. The results showed sometimes significant differences between the SAFs of the two exposure models. Jones' calculations demonstrated that a change of the tissue composition

had only little effect on the results, and he concluded that especially different inter-organ distances in the two phantoms were the main cause of the large discrepancies between the SAF values. Differences in organ and tissues masses could not have been the reason, because both phantoms had organ and tissue masses, which agreed fairly well with the reference masses of ICRP23 [10].

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 cellullarity 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.

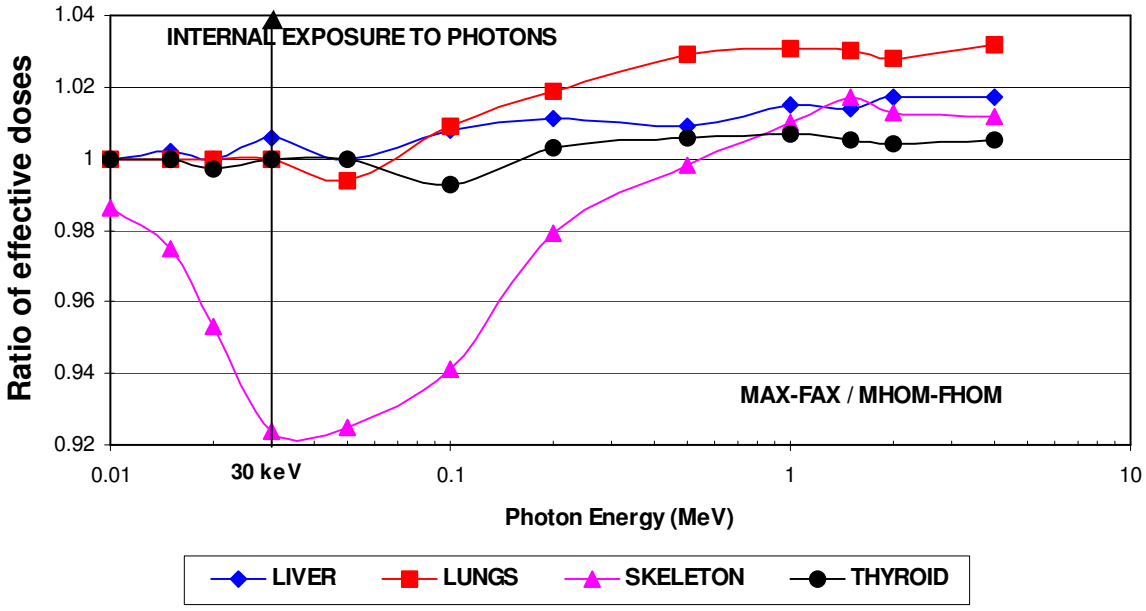

Figure 8: Introduction of heterogeneously distributed skeletal tissues, adipose and muscle

The first three items affect the equivalent dose to the bone surface (= skeleton) and to the RBM. When the liver, the lungs, or the thyroid are source organs, the effective dose increases with increasing energy, because primarily the equivalent dose to the skeleton and to the RBM have been found to be always greater in the MAX-FAX phantoms than in the MHOM-FHOM phantoms. This translates into a small increase of up to 3% for the effective dose shown in Figure 8. Decrease of the equivalent dose to the bone surface by up to 3.1% around 40 keV, and of the equiavlent dose to the RBM by up to 25.5% around 40 keV have been observed from the comparison of the data calculated for the MAX-FAX and the MHOM-FHOM phantoms when the skeleton is the source organ. Consequently the effective dose ratio decreases by up to 8% in

this range of energies, particularily reflecting the fact that for this source organ the weighted equivalent dose to the RBM represents ca. 30% of the effective dose.

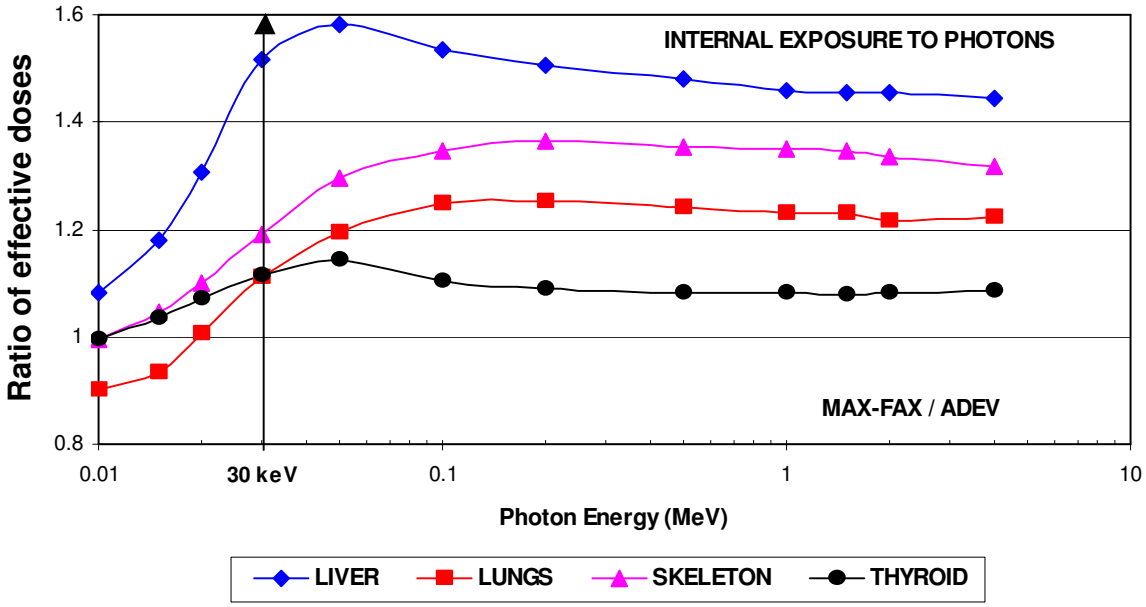

Figure 9: Replacement of the ADAM-EVA by the MAX-FAX exposure model

Figure 9 summarizes the replacements of the tissue compositions, of the anatomy, of heterogenously distributed skeletal tissues, adipose, and muscle, and of the RBM model. For the source organs considered here, the various replacements caused mostly an increase of the effective dose, except for the introduction of the skeletal tissue distribution and the RBM model when the skeleton is the source. The net increase of the effective dose can reach 60%, at least for the source organs shown in Figure 9. For the replacement of the Monte Carlo code, one should take into account another 10% of variation of the effective dose.

4 CONCLUSIONS

The purpose of this paper was to investigate for internal irradiation with photons the dosimetric consequences for the effective dose, when the MIRD5-type exposure model ADAM-EVA is replaced by the 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 photon energy for four different source organs. For incident photon energies between 30 keV and 4 MeV the results have shown that replacing the ALGAMP Monte Carlo code by the EGS4 Monte Carlo code normally causes differences of less than 10% for the effective dose. Introduction of ICRU44-based tissue compositions caused an increase of the effective dose by up

to 7.5%, while the replacement of the MIRD5 by the voxel anatomy can increase the effective dose by up to 50% depending on the source organ. For the source organs considered in this investigation the net effect of the transition from the MIRD5-type to the voxel-based exposure models is a possible 50-70% increase of the effective dose.

5 ACKNOWLEDGEMENT

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