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EFFECTIVE DOSE RATIOS FOR TOMOGRAPHIC AND STYLIZED MODELS FROM EXTERNAL 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. 74 for external 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 MIRD5-type phantoms ADAM and EVA, coupled to the EGS4 and to the MCNP4C Monte Carlo code, for external whole-body irradiation with photons for anterior-posterior, posterior-anterior, and rotational incidence for energies between 10 keV and 10 MeV. 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 external exposures to photons the introduction of voxel-based exposure models is expected to cause a reduction of the effective dose by about 10% for the energies and geometries 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 field have been published by the International Commission on Radiological Protection (ICRP) for external exposures in order to facilitate the interpretation of data measured in routine radiation protection 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

$$E = \sum_T w_T H_T \text{ ,}$$

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

Mainly the MIRD5-type ADAM and EVA phantoms [2] have been used for the calculations of the CCs for external exposures to photons recommended by the ICRP in its Publication No. 74 [3]. Therefore this investigation presents ratios between CCs calculated on the one hand with the mathematical ADAM and EVA phantoms, and on the other hand with the voxel-based MAX and FAX phantoms in order to show the dosimetric consequences when the 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 phantoms have been developed based on CT images from patients [4,5]. After segmentation the volumes of the radiosensitive organs and tissues have been adjusted in order to match the reference masses defined by ICRP89 [6]. The phantoms have heterogeneously structured skeletons with voxel-specific skeletal tissue compositions based on masses, percentage distributions, and cellullarity factors from ICRP70 [7]. 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 [4,5]. Figures 1 and 2 show frontal and lateral views of the MAX and the FAX phantoms, respectively.

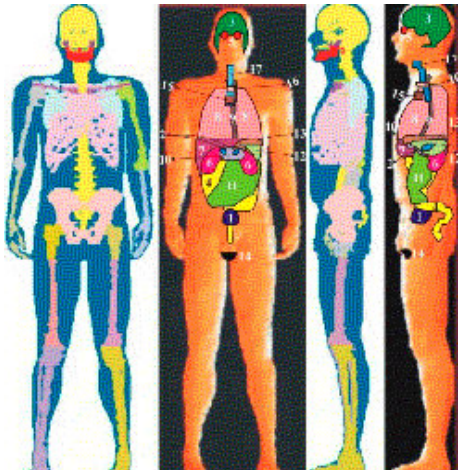

Figure 1: The MAX phantom

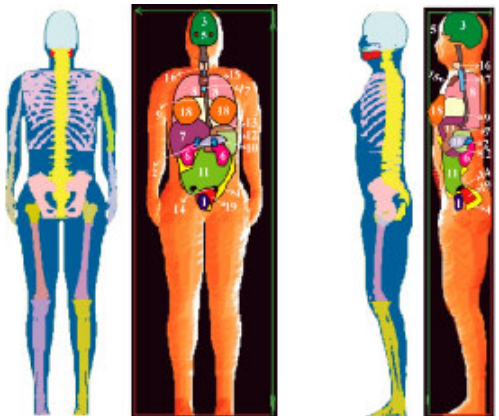

Figure 2: The FAX phantom

2.2 The ADAM and EVA phantoms

The gender-specific adult MIRD5-type phantoms ADAM and EVA have been taken from Kramer et al [2]. Their organ and tissue masses correspond to the anatomical specifications given by the ICRP in its first Reference Man Report, Publication No. 23 [8]. Figure 3 shows frontal views of the ADAM and the EVA phantoms.

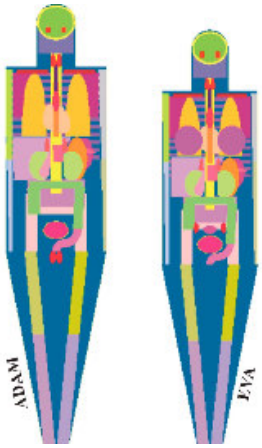

Figure 3: The ADAM and EVA phantoms

2.3 The EGS4 and MCNP4 Monte Carlo codes

The EGS4 Monte Carlo code [9] 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, and secondary electrons have been transported, except for the MIRD5-type phantoms when comparisons with data already published by the ICRP were made.

The MCNP-4C [10] code is a general purpose Monte Carlo code which simulates neutron, photon and electron transport. Any arbitrary three-dimensional geometry configuration can be defined using first and second-degree surfaces and fourth-degree elliptical tori. The *Repeated Structure* option permits to model segmented geometries with great flexibility. For photons MCNP-4C takes into account incoherent and coherent scattering, fluorescent emission and pair production.

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 and the MCNP4C Monte Carlo code connected to the ADAM and EVA phantoms with the original tissue composition [2].

b) The EGS4 Monte Carlo code connected to the ADAM and EVA phantoms with ICRU44-based tissue compositions [11].

c) The EGS4 and the MCNP4C Monte Carlo code connected to the MAX and FAX phantoms with ICRU44-based tissue compositions [11], and ICRP70-based skeletal tissue distribution [7].

3 RESULTS

ICRP Publication 74 [3] presents CCs between equivalent dose to radiosensitive body organs and tissues, as well as effective dose, and air kerma free-in-air calculated with the GSF Monte Carlo code [12] connected to the ADAM and EVA phantoms for external exposures to photons as function of the radiation energy, and for different directions of incidence.

In this study the same CCs have been calculated with the EGS4 and the MCNP4C Monte Carlo codes with broad parallel beams covering the whole body for anterior-posterior (AP), and for posterior-anterior (PA) incidence, as well as for a broad parallel beam rotating 360° around the phantom's vertical axis (ROT) for the ADAM-EVA and for the MAX-FAX phantoms. Secondary electrons have been persued only for the MAX-FAX/EGS4 exposure model, i.e. generally 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 the ICRP [3]. The remainder equivalent dose was calculated as the arithmetic average of the individual remainder organ contributions. 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

For the ADEV (*AD*AM and *EV*A) phantoms Figure 4 presents ratios between effective doses calculated with the EGS4 and the GSF Monte Carlo code, and calculated with the MCNP4 and the GSF code, respectively, as a function of the photon energy for AP- and PA-incidence. The CVs of the effective doses were 2-3% for the ICRP74 data, smaller than 1% for the EGS4, as well as for the MCNP4 code for photon energies above 30 keV. Figure 4 shows that in this range of energies the average difference between the ICRP74-CCs and the EGS4-CCs is ca. 1% for both directions of incidence, and about 5.3% and 3.8% between the ICRP74-CCs and the MCNP4-CCs for AP- and PA-incidence, respectively. For incident energies between 10 and 30 keV the average difference increases to about 10% for the EGS4/ICRP74 ratios, and to about 20-38% for the MCNP4/GSF ratios, which is caused by fluctuations of equivalent dose due to low numbers of interactions, especially in small organs, like the testes, the ovaries, and by rounding error effects (see also the next section).

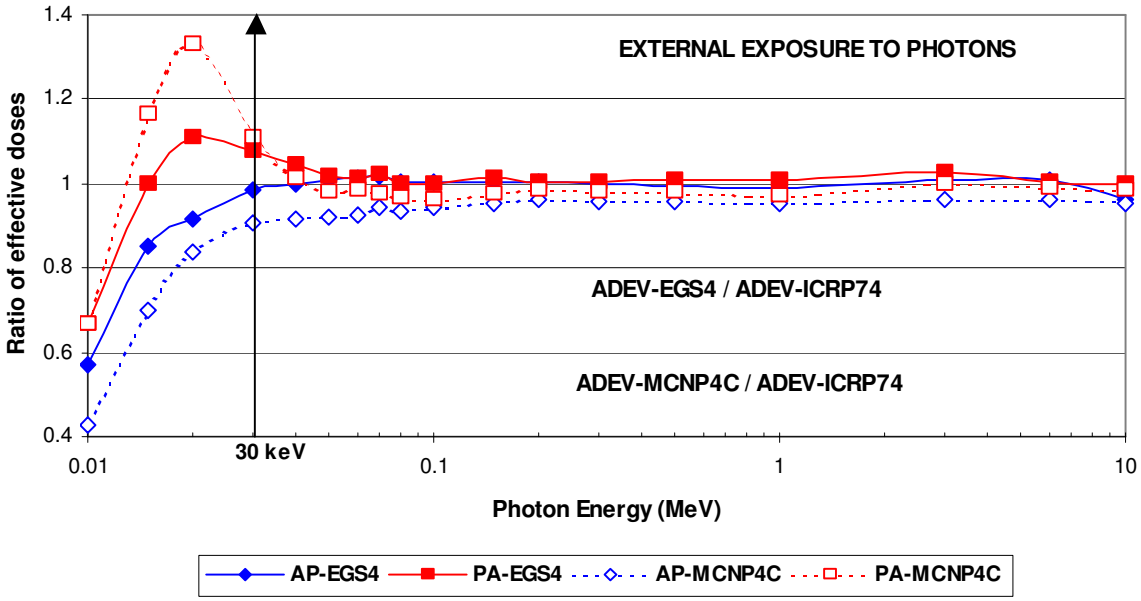

Figure 4: Replacement of the Monte Carlo code

3.2 The replacement of the tissue compositions

Tissue compositions used for the ICRP74 CCs 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 [11], and additionally the skeletal mixture was designed to contain 11.3% of calcium as recommended by ICRP70 [7]. 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 have not been changed a this stage.

Ratios between the ADEV44 and the ADEV effective doses are presented in Figure 5, which show an increase of the effective dose caused by the replacement of the tissue compositions of up to 9% for all directions of incidence, and for energies above 30 keV. Below 30 keV the data are sometimes not very accurate, because especially small organs with great tissue weighting factors, like the testes and the ovaries, have large CVs, and also rounding error effects effects can impair the accuracy of the effective doses. According to Figure 5 for PA-incidence and a photon energy of 15 keV, for example, the ratio between the ADEV44 and the ADEV effective dose shows a value of 1.17 calculated by the algorithm attached to the Monte Carlo code. As the absolute values of

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

the effective doses are small for this energy, typically ca. 0.015 Sv/Gy, rounding error effects can lead to false ratios, because a re-calculation by hand without rounding the organ and tissue equivalent doses to 3 digits gave a ratio of 1.098, and consequently the PA-ratio of the effective doses would rather follow the curve “PAcorr” shown in Figure 5. Therefore with regard to data interpretation for external exposures to photons one has to bare in mind that for incident particle energies below 30 keV the CCs can show significant variations because of statistical fluctuations of equivalent dose to small organs, and because of rounding errors effects even for equivalent doses with small CVs.

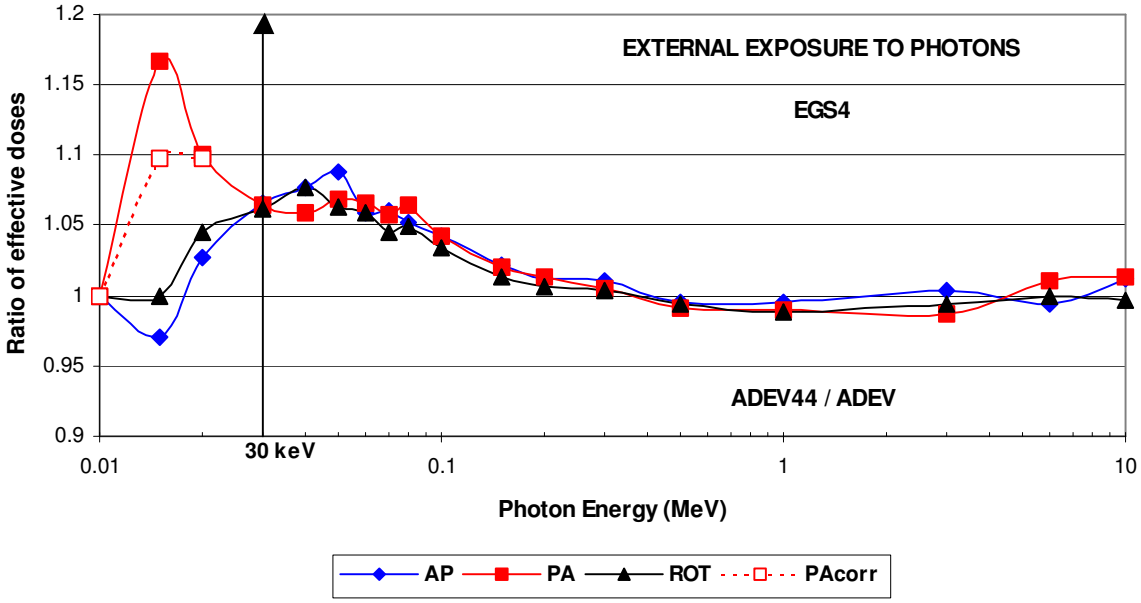

Figure 5: Replacement of the tissue compositions

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 homogeneous mixtures of adipose and muscle, with 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, of their distribution throughout the body, and of the RBM model 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 6 presents ratios between effective doses for the two tissue-equivalent pair of phantoms for AP-, PA-, and ROT-incidence,and as a function of the incident photon energy between 10 keV and 10 MeV, 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. The curves show that the introduction of real human anatomies leads to a decrease of the effective dose of more than 30% for photon energies above 30 keV. The data for energies between 10 and 30 keV should be considered with caution, taking into account the considerations presented at the end of the previous section about CVs and rounding error effects.

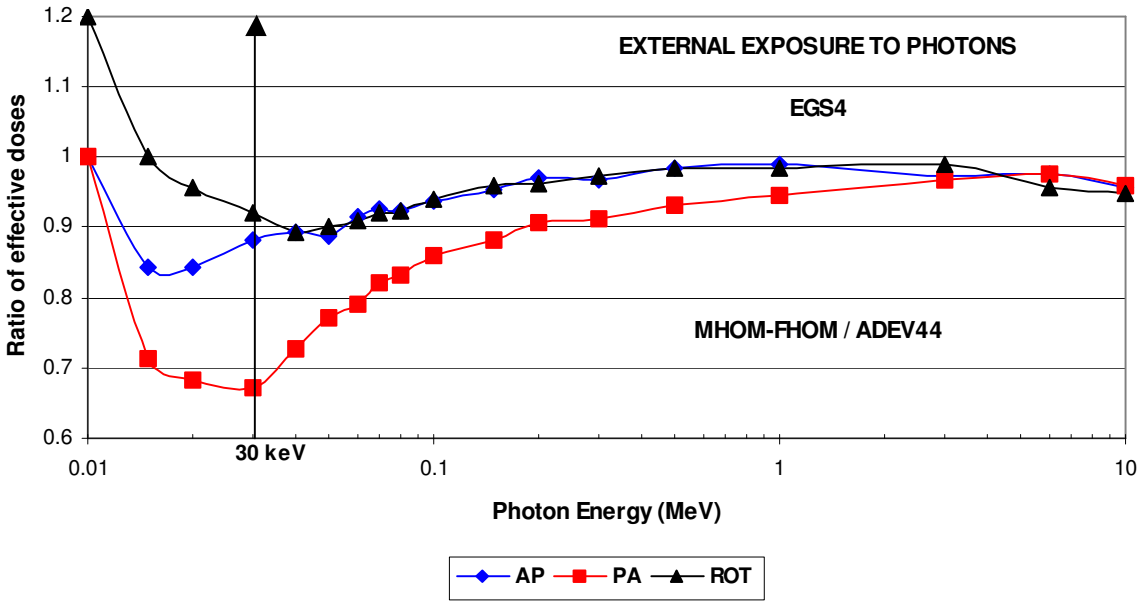

Figure 6: Replacement of the anatomy

The effective dose is the sum of weighted equivalent doses to 23 organs and tissues, whose size, form, and location relative to each other determine a complex distribution of their equivalent doses as a function of the radiation energy and direction of incidence. In order to understand the effective dose decreases shown in Figure 6 as consequence of the transition from the stylized MIRD5 to the real voxel anatomy, one should observe some general anatomical differences between the two types of phantoms from a comparison of Figures 1 and 2 with Figure 3:

The trunks of the ADEV44 phantoms are elliptical cylinders with integrated arms and constant thicknesses of 20cm (18.8cm)* sagittal, and 40cm (37.6cm) lateral, while the MAXHOM-FAXHOM phantoms' body thicknesses vary between 20-24cm (19.5-22cm) sagittal, 50-52cm (43-45cm) lateral in the regions of the upper arms, and 30-33cm (29-31cm) in the abdominal regions, where the lower arms and hands are separated from the trunk. (* numbers in brackets for EVA44 and FAXHOM, respectively)

Compared to the mathematical skeleton of the ADEV44 phantoms, MAXHOM and FAXHOM have naturally structured skeletons with sterni, quite differently shaped pelvises, and the natural structure of their ribcages seems to provide more shielding to internal organs.

Often the skeletons and internal organs of the MAXHOM and FAXHOM phantoms are surrounded by thicker layers of adipose and muscle compared to the ADEV44 phantoms.

Last but not least one has to analyze the anatomical reasons for the change of the effective dose organ by organ. This, however, is beyond the scope of this paper, but this kind of information can be found elsewhere [13].

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,
- of separately segmented regions of adipose and muscle, and
- of the transport of secondary electrons.

Figure 7 shows ratios between the effective doses for the MAX-FAX and the MAXHOM-FAXHOM phantoms for incident photon energies ranging from 10 keV to 10 MeV for AP-, PA-, and ROT-incidence, respectively. For energies above 30 keV the differences between the two effective doses are in the range of +2% to – 4% depending on the energy considered. Although the ICRP70-based RBM distribution can cause greater effective doses for AP- and ROT-incidence, the values of the ratios for these directions of incidence for energies below 30 keV have to be considered with caution for reasons already explained earlier. For the MAX-FAX phantoms secondary electrons have been followed down to a cut-off energy of 200 keV. Their effect becomes observable especially for superficial organs, like the testes, the skin, the thyroid, etc. for incident photon energies above 3 MeV, but not for the effective dose.

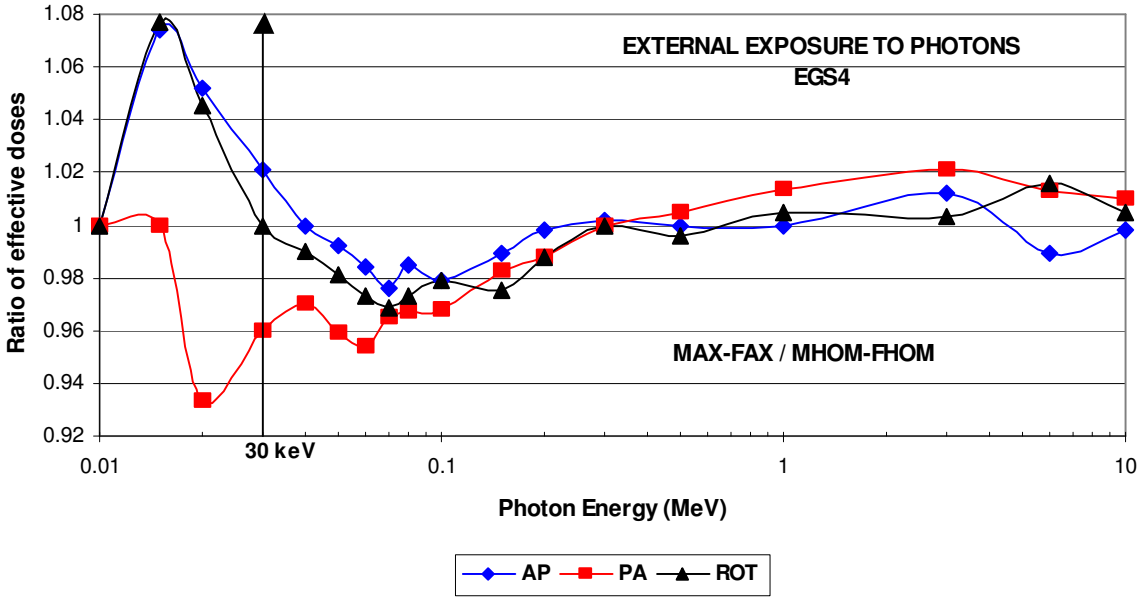

Figure 7: Introduction of heterogeneously distributed skeletal tissues, adipose and muscle

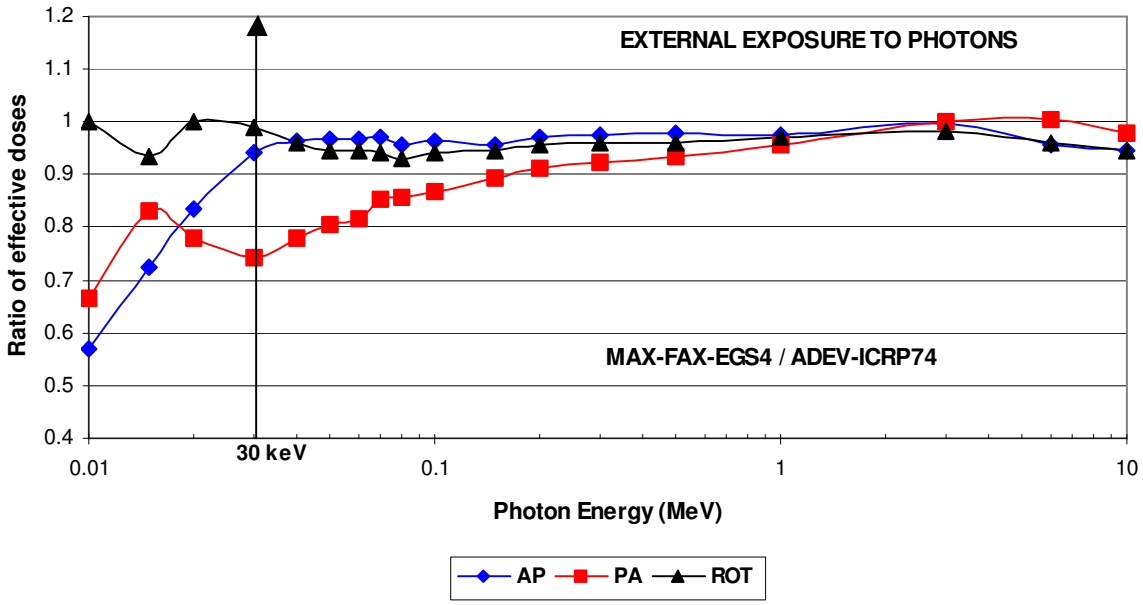

Figure 8: Replacement of the ADAM-EVA by the MAX-FAX exposure model

The consequences of all replacements together are shown in Figure 8 for external photon radiation as a function of the incident energy between 10 keV and 10 MeV for AP-, PA-, and ROT-incidence. For the EGS4-calculated data due to the differences between the ADEV/GSF and MAX-FAX/EGS4 exposure models discussed in the previous sections, the effective dose

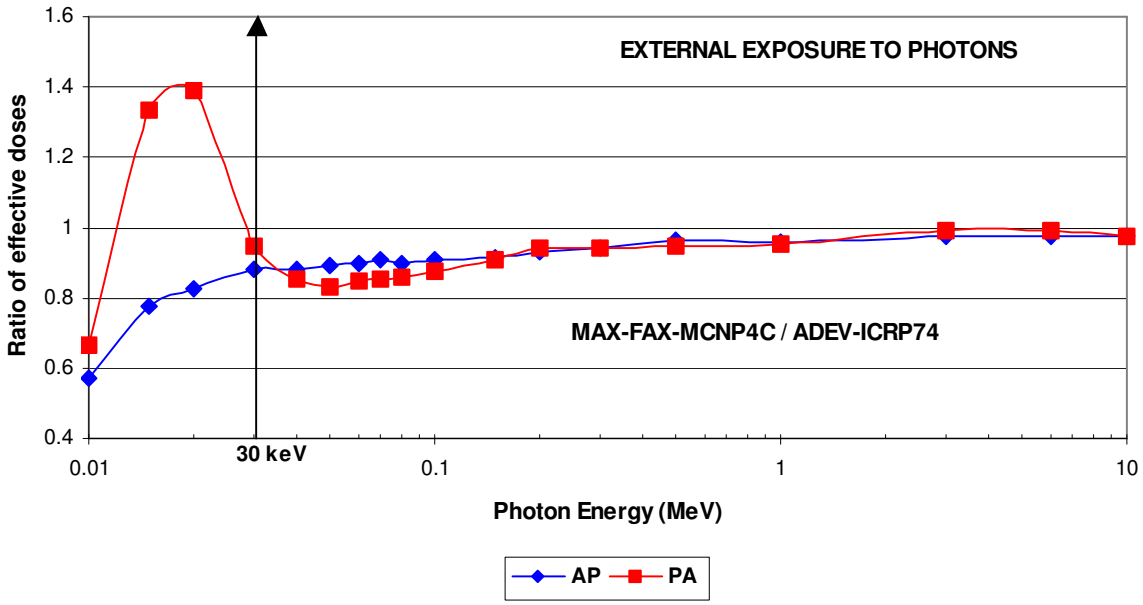

Figure 9: Replacement of the ADAM-EVA by the MAX-FAX exposure model

decreased, which above 30 keV incident photon energy did not exceed 10% for AP-, and ROT-incidence, and 25% for PA-incidence. Below 30 keV a decrease of the effective dose by ca. 43% seems possible according to Figure 8, however the discussion on statistical fluctuations and rounding errors effects in the previous sections has shown that the data in this range of energies should be used with caution. On the other hand it has to remembered that below 30 keV the values of the effective dose are usually small compared, lets say to the reading of an air kerma instrument. Moreover, in practical situations of radiation protection rotational or semi-rotational incidence is more likely than AP-, or PA-incidence, and energy distributions of radiation fields are mostly in a range above 30 keV, which leads to the final conclusion that in pracical situations for external exposures to photons the reduction of the effective dose due to the introduction of voxel-based models is ca. 10%.

Figure 9 shows MAX-FAX/ADEV effective dose ratios calculated with the MCNP4C Monte Carlo code for AP- and PA-incidence. For photon energies above 30 keV the data confirm the results of the EGS4 calculations presented in Figure 8.

4 CONCLUSIONS

The purpose of this paper was to investigate for external irradiation with photons the dosimetric consequences for the effective dose, when the MIRD5-type exposure models ADAM-EVA are replaced by voxel-based exposure models 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 a function of the photon energy, and of the direction of incidence. For incident photon energies between 30 keV and 10 MeV the results have shown that replacing the ICRP74 Monte Carlo code by the EGS4 Monte Carlo code caused differences of ca.1% for the effective dose which is significantly smaller than the range of the combined CVs, and replacing the ICRP74 Monte Carlo code by the MCNP4 Monte Carlo code led to a decrease of the effective dose of about 5% on the avergage for AP- and PA-incidence. Introduction of ICRU44-based tissue compositions caused an increase of the effective dose by up to 9%, while introducing real human anatomy led to a decrease by up to 30% of the effective dose. Finally the combined effect from all replacements suggests that the effective dose for the voxel-based model MAX-FAX would decrease by ca. 10% for incident energies between 30 keV and 10 MeV, and for most directions of incidence compared to the ADAM-EVA effective dose.

5 ACKNOWLEDGEMENT

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