

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

R. Kramer and H. J. Khoury

Departamento de Energia Nuclear
Universidade Federal de Pernambuco
Av. Prof. Luiz Freire, 1000, Cidade Universitária, CEP 50740-540, Recife, PE, Brazil
rkramer@uol.com.br; hjkhoury@globocom.com

J. W. Vieira

Centro Federal de Educação Tecnológica de Pernambuco, CEFET-PE
Av. Prof. Luiz Freire, 500, Cidade Universitária, CEP 50740-540, Recife, PE, Brazil
jwvieira@br.inter.net

H. Yoriyaz

Instituto de Pesquisas Energéticas e Nucleares, IPEN-CNEN/SP
Av. Prof. Lineu Prestes, 2242, Cidade Universitária, CEP 05508-000, São Paulo, SP, Brazil
hyoriyaz@ipen.br

E. C. M. Loureiro

Escola Politécnica da Universidade de Pernambuco, POLI/UPE
Rua Benfica, 455, Madalena, CEP 50751-460, Recife, PE, Brazil
eduloureiro@uol.com.br

F. R. A. Lima

Centro Regional de Ciências Nucleares
Comissão Nacional de Energia Nuclear
R. Cônego Barata 999, CEP 52110-120, Recife, PE, Brazil
falima@cnen.gov.br

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 MIRD5-type phantoms ADAM and EVA, coupled to the EGS4 and to the MCNP4C Monte Carlo code, for external whole-body irradiation with electrons. 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 electrons the introduction of voxel-based exposure models causes changes of the effective dose between +40% and – 60% depending on the energies and geometries 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 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

$$E = \sum_T w_T H_T \quad (1)$$

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].

The gender-specific ADAM and EVA phantoms have been used for the calculations of the CCs for external exposures to electrons published by the ICRP [10]. Therefore this paper presents effective dose ratios calculated on the one hand with the stylized 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 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 [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.

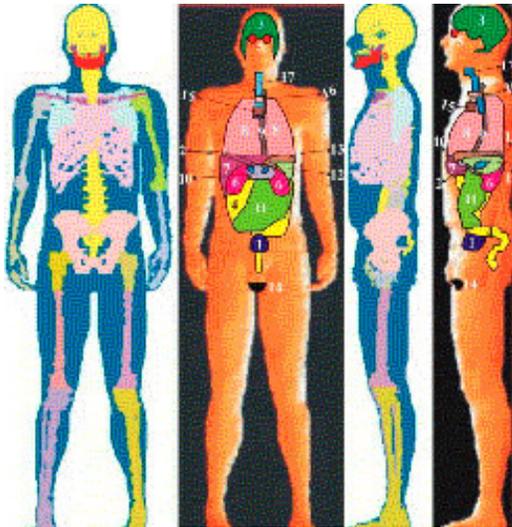


Figure 1: The MAX phantom

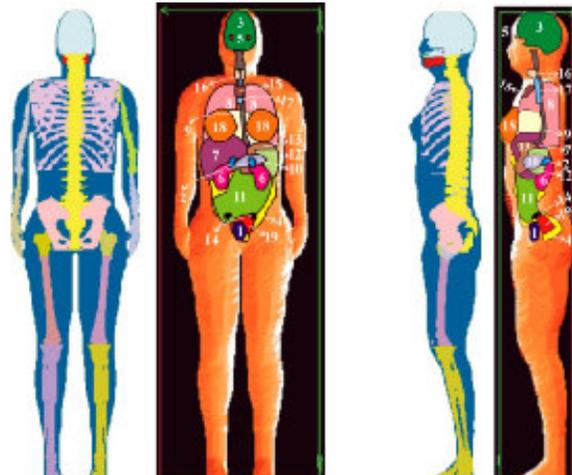


Figure 2: The FAX phantom

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]. The skin thickness is 2mm. Figure 3 shows frontal views of the ADAM and the EVA phantom.

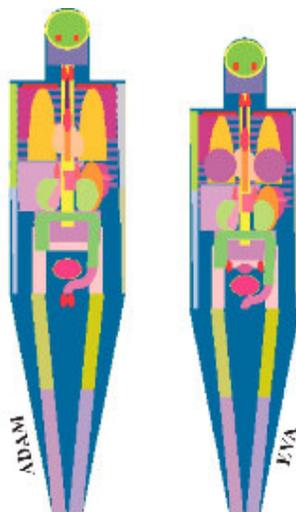


Figure 3: The ADAM and EVA phantoms

2.3 The EGS4 and MCNP4 Monte Carlo Codes

The EGS4 Monte Carlo code [16] 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, together with PRESTA [17] for the transport of the electrons.

The MCNP-4C [18] code is a general purpose Monte Carlo code which simulates neutron, photon and electron transport. Any arbitrary three-dimensional geometry configuration can be treated 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 account of incoherent and coherent scattering, fluorescent emission and pair production. For electron transport a continuous slowing-down model is used that includes positrons, x-rays, and bremsstrahlung.

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:

The EGS4 and the MCNP4C Monte Carlo code connected to the ADAM and EVA phantoms with the original tissue composition [8].

The EGS4 Monte Carlo code connected to the ADAM and EVA phantoms with ICRU44-based tissue compositions [19].

The EGS4 and the MCNP4C Monte Carlo code connected to the MAX and FAX phantoms with ICRU44-based tissue compositions [19], and ICRP70-based skeletal tissue distribution [14].

3 RESULTS

Table 2 presents absorbed doses to some of the organs and tissues mentioned in Table 1, as well as effective doses for an external electron beam covering the whole body of the ADAM and the EVA phantoms. The incidence was anterior-posterior (AP), and the electron energies ranged between 0.1 and 10.0 MeV.

Table 2: Organ absorbed dose per unit fluence (pGy cm2) from ICRP74 [10]**

Energy (MeV)	0.1	0.4	0.6	1.0	1.5	2.0	4.0	10.0
Skin	8	98	171*	164**	158	153	150	165
Testes			0	1	14	37	214	345
Bone marrow			0	1	5	11	28	52
Stomach						0	3	184
Breast			0	14	43	75	200	325
Liver							0	97
Thyroid						0	121	297
Effective dose	0.1	1	1.5	2.7	5.9	11	44	131

* Correct value: 147 ** Correct value: 171

These data have been taken from ICRP74 [10], but according to the authors of these CCs, the tabulated numbers of the skin absorbed doses for 0.6 and 1.0 MeV have to be replaced by 147 and 171, respectively [20]. The data have been calculated with the MCNP4A Monte Carlo code with ca. 600000 particles per energy point [21,22]. The effective doses of Table 2 have been determined with a breast weighting factor of 0.1 [22] instead of 0.05.

3.1 Replacement of the Monte Carlo Code

Figure 4 shows a comparison between the ICRP74 effective doses from Table 2 and corresponding data calculated with the ADEV-EGS4 (ADEV = ADAM and EVA) and the ADEV-MCNP4C exposure models for AP-incidence as a function of the electron energy. These new calculations applied 10 Million electrons per energy point, and used also a breast weighting factor of 0.1. The electron cut-off energies were 8 keV for incident energies up to 1.0 MeV, 200 keV above 1.0 MeV, and the CVs for the effective doses were 1.5% on average. Many organ and tissue equivalent doses presented in Table 2 have zero values or no values at all, which is probably due to the poor CVs of the calculations [21]. With 10 Million incident electrons per energy point the ADEV-EGS4 exposure model calculates statistically reliable equivalent doses also for low energies, but for the sake of comparison zero values have also been assigned to these organ and tissue equivalent doses in the new calculations. This is indicated in the legend of Figure 4 by “ADEV(74)-EGS4” and ADEV(74)-MCNP4C, respectively.

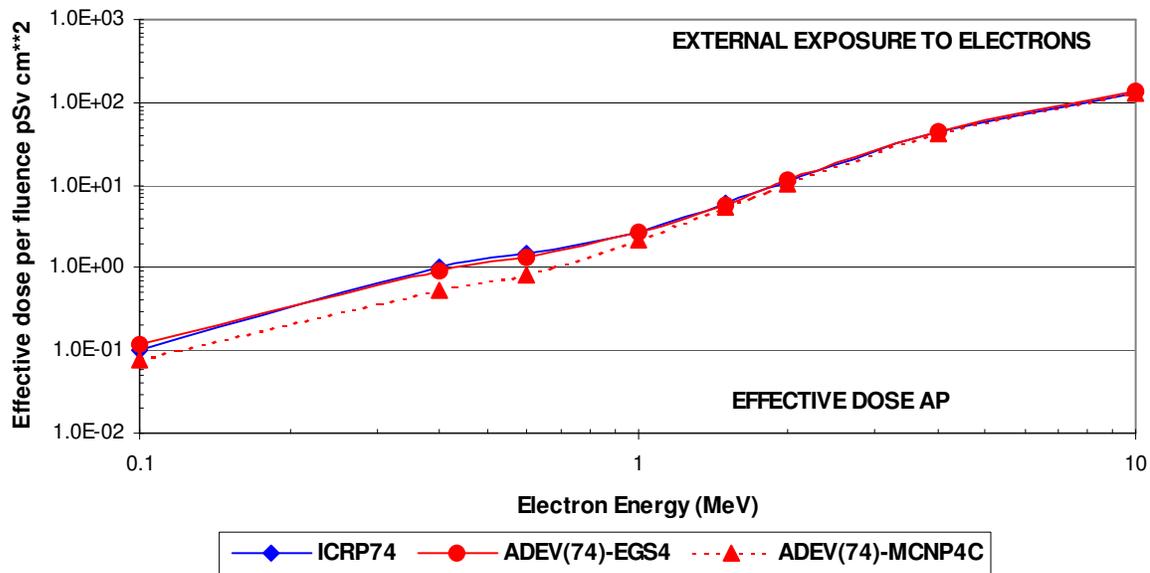


Figure 4: Replacement of the Monte Carlo code

The ADEV(74)-EGS4 effective dose per unit fluence agrees well with the data from ICRP74 within a margin $\pm 2\%$ on average for the whole range of energies in Figure 4. For energies between 0.1 and 1.0 MeV the ADEV(74)-MCNP4C effective dose is on average 33% smaller than the ICRP74 effective dose. This difference decreases to 6.2% on average for electron energies between 1.0 MeV and 4.0 MeV.

The MCNP4 CC differs from the EGS4 CC for low energies where the skin equivalent dose represents the predominant contributor to the effective dose. The EGS4 exposure model uses dosimetrical separation of the skin thickness within the first voxel layer [11], while the MCNP4C exposure model applies a sub-segmentation of the skin thickness in the first voxel layer. Although not quite understandable what causes this difference, it has to be pointed out that the ADEV(74)-EGS4 data shows excellent agreement with the ICRP74 effective doses.

3.2 The Replacement of the Tissue Compositions

For the investigation of the replacements of the tissue compositions and the anatomy the effective dose was determined as recommended by ICRP74 [10], i.e. based on the relationship suggested by Kramer and Drexler [23], and particularly with a breast weighting factor of 0.05. The remainder equivalent dose was calculated as the arithmetic average of the individual remainder organ contributions. 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. External beams of electrons covering the whole body were incident on the phantoms anterior-posterior (AP), posterior-anterior (PA), and rotating by 360 degrees around the vertical axis of the body (ROT) for energies between 0.1 and 10 MeV. The tissue compositions used for the ICRP74 CCs 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

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

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 [19], and additionally the skeletal mixture was designed to contain 11.3% of calcium as recommended by ICRP70 [14].

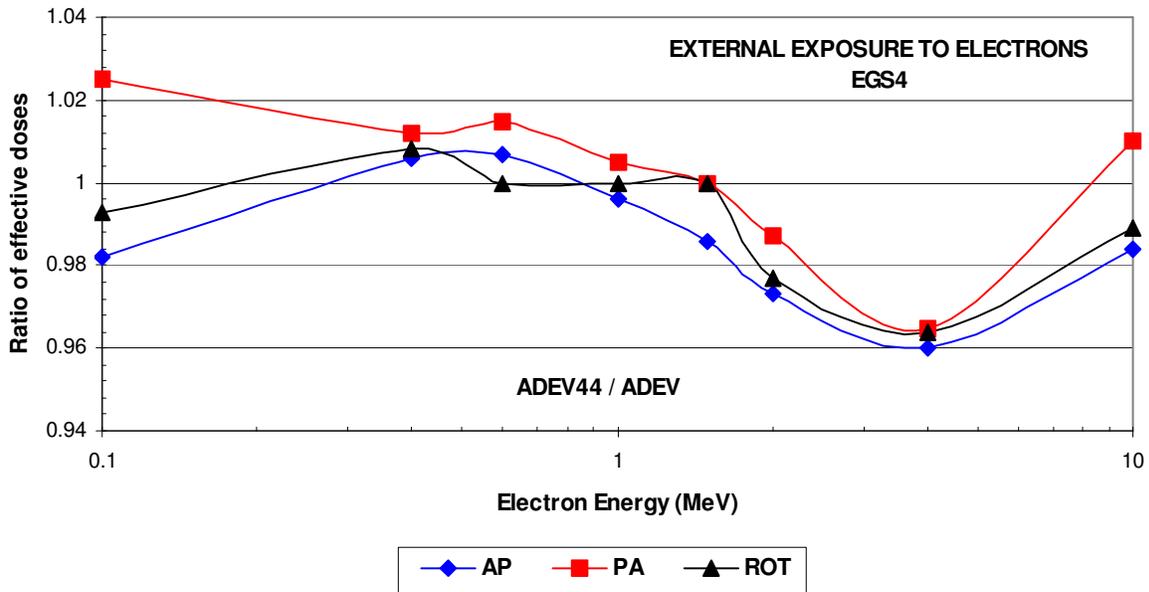


Figure 5: Replacement of the tissue composition

Figure 5 shows ratios between effective doses calculated with the ADEV and with the ADEV44 phantoms as function of the incident electron energy for AP-, PA-, and ROT-incidence. After replacing the tissue compositions an analysis of the data for low energies revealed an increase of the skin equivalent dose for all directions of incidence, while the breast equivalent dose decreased for AP-, and ROT-incidence. As these two organs contribute the major part to the effective dose for low energies, the ratios shown in Figure 5 reflect these findings. For higher energies the skin equivalent dose remains constant, the breast equivalent dose is still decreasing, and internal organs and tissues show increase as well as decrease of equivalent dose. The ratios presented in Figure 5 show variations of the effective dose between +2% and -6%.

3.3 Replacement of the anatomy

The replacement of the stylized MIRD5 body by the realistic human body 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 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 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.

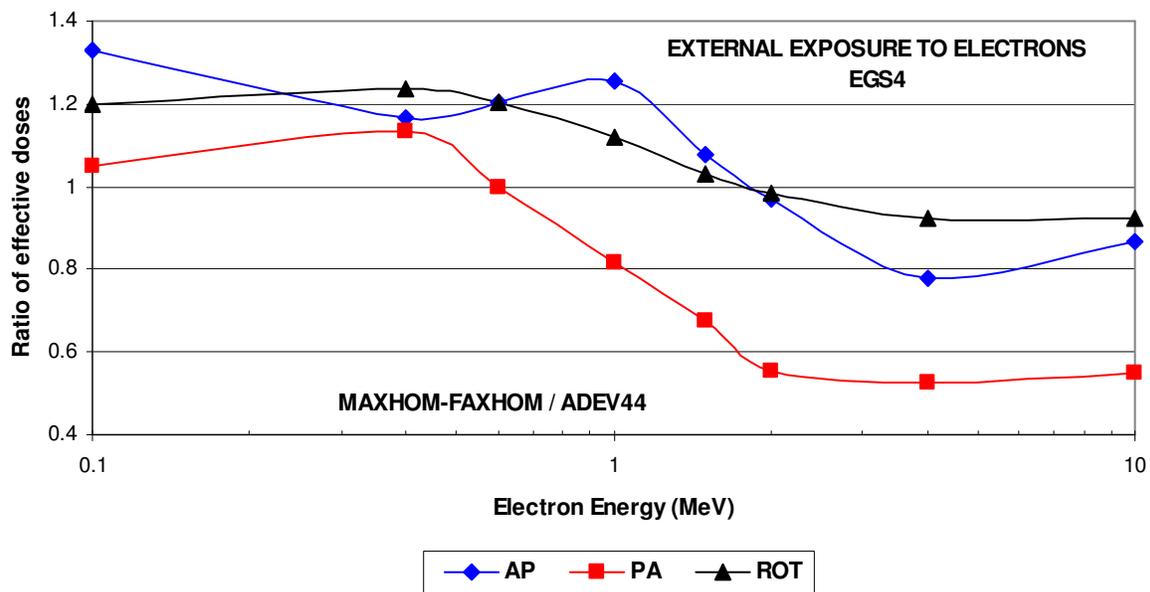


Figure 6: Replacement of the anatomy

Figure 6 presents ratios between effective doses for the two tissue-equivalent pair of phantoms for AP-, PA-, and ROT-incidence as a function of the incident electron energy between 100 keV and 10 MeV, with ICRU44-based tissue compositions and ICRP23-based RBM models applied to all models. “ADEV44” represents the ADAM44 and the EVA44 phantoms, while “MHOM-FHOM” stands for the MAXHOM and the FAXHOM phantoms. For AP-, and ROT-incidence Figure 6 shows that the introduction of a real human anatomy leads to an increase of the effective dose by ca. 30% for electron energies up to 1.6 MeV. Greater equivalent doses to superficial organs, like the testes, the thyroid, the breasts, and especially the thinner skin of the MAXHOM-FAXHOM phantoms are responsible for this increase. For higher energies equivalent doses to many internal organs of the ADEV44 phantoms are greater, because in the MAXHOM-FAXHOM phantoms these organs are more shielded by the real human skeleton or thicker layers of adipose or muscle, leading to a decrease of the effective dose by up to 20%. For PA-incidence the curve has the same shape, but the increase is smaller (ca. 17%) and limited up to ca. 500 keV because the breasts, the testes, and the thyroid do not contribute to the effective dose. At the same time the decrease for higher energies is greater (ca. 50%) because of increased shielding by the pelvis and the spine.

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 heterogeneously distributed skeletal tissues among the bone voxels, and
- of separately segmented regions of adipose and muscle.

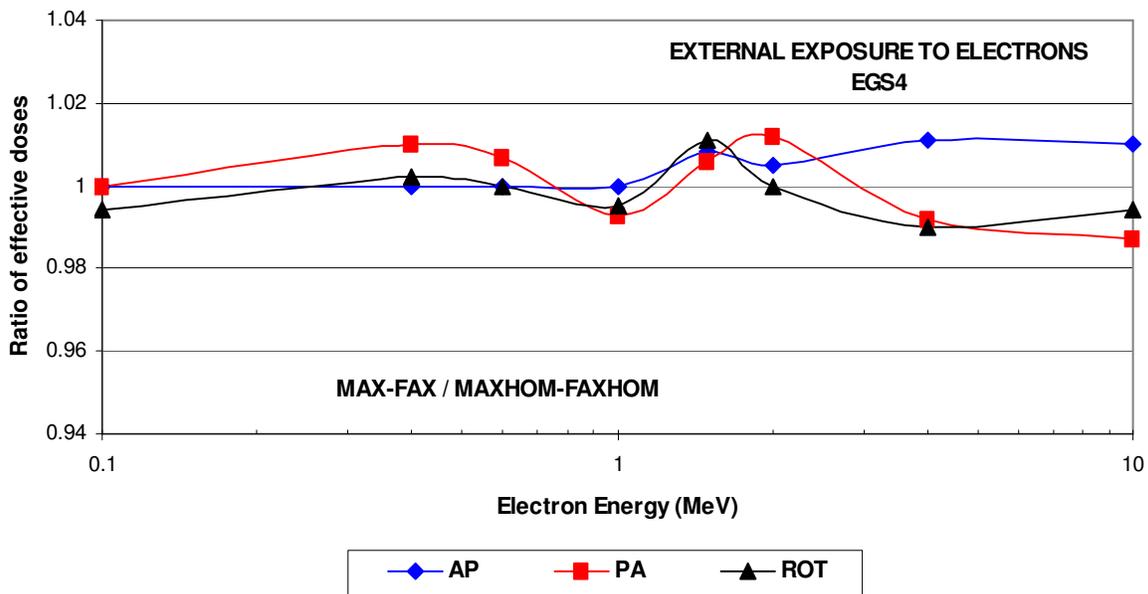


Figure 7: Introduction of heterogeneously distributed skeletal tissues, adipose and muscle

For the introduction of heterogeneous distributions of skeletal tissues, adipose and muscle Figure 7 shows ratios between the effective doses for the MAX-FAX and the MAXHOM-FAXHOM phantoms for incident electron energies between 100 keV and 10 MeV for AP-, PA-, and ROT-incidence, respectively. The differences are between +1% and -2%, i.e. they are small compared to the combined range of the CVs of the four phantoms.

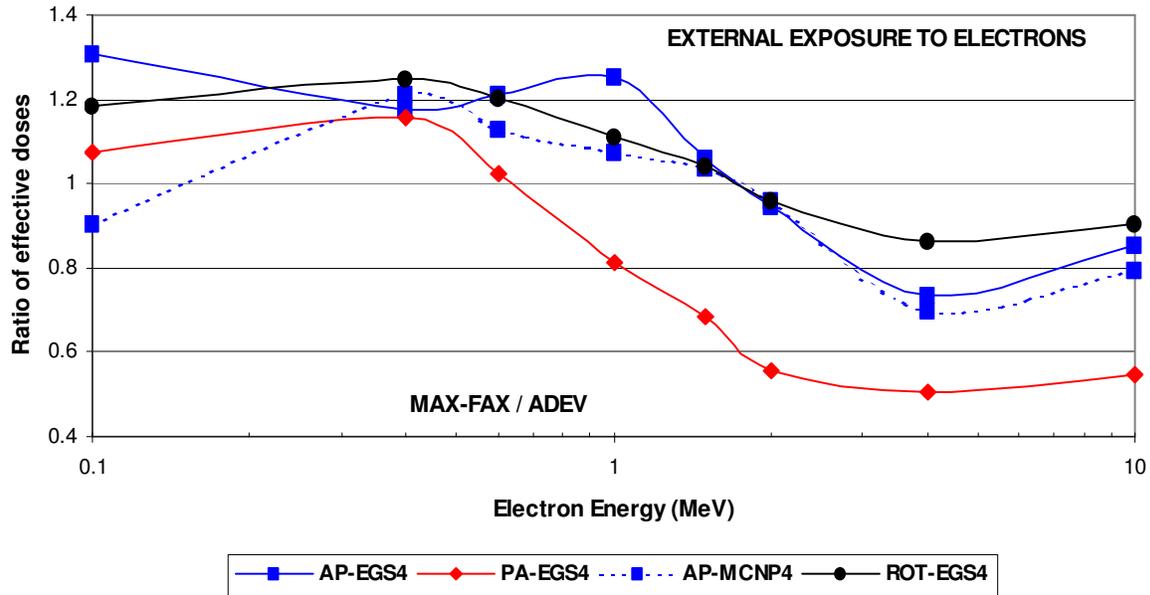


Figure 8: Replacement of the ADAM-EVA by the MAX-FAX exposure model

The consequences of all replacements are shown in Figure 8 for external electron radiation as a function of the incident energy between 100 keV and 10 MeV for AP-, PA-, and ROT-incidence representing calculations with the EGS4 and the MCNP4 Monte Carlo code. Understandably the EGS4 ratios are quite similar to those shown in Figure 6, because Figures 5 and 7 have demonstrated that the replacement of the tissue compositions, and the introduction of a new model for skeletal dosimetry had only little influence on the effective dose. Depending on the electron energy and the direction of incidence the effective dose can increase up to 30%, or decrease by 50% when MIRD5-type phantoms are replaced by voxel-based models with ICRU44-based tissue composition. For the replacement of the Monte Carlo code one should take another +/- 10% into account.

4 CONCLUSIONS

The purpose of this paper was to investigate for external 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 compositions, and of the anatomy. The data have been presented as ratios between effective doses as function of the electron energy, and of the direction of incidence. The results have shown that replacing the Monte Carlo code could cause differences of ca. +/- 10% for the effective dose. Introduction of ICRU44-based tissue

compositions caused variations of the effective dose between +2% and -6%, while introducing real human anatomy led to an increase of 30% for low energies, but to a decrease of almost 50% for high energies of the effective dose. Finally the net effect from all replacements suggests that the effective dose for the voxel-based model MAX-FAX would differ from the ADAM-EVA effective dose between +40% and -60% depending on the electron energies and geometries of the radiation field considered.

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