# EFFECTIVE DOSE RATIOS FOR THE TOMOGRAPHIC MAX AND FAX PHANTOMS

### R. Kramer

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

#### ABSTRACT

For the last two decades organ and tissue equivalent dose as well as effective dose coefficients recommended by the International Commission on Radiological Protection (ICRP) have been determined with exposure models based on stylized MIRD5-type phantoms representing the human body with its radiosensitive organs and tissues according to the ICRP Reference Man released in Publication No.23, Monte Carlo codes simulating rather simplified radiation physics, tissue compositions from different sources, and in part falsely applied, and the list of organs and tissues with their corresponding tissue weighting factors considered at risk by ICRP Publication No.60. Meanwhile the International Commission on Radiation Units and Measurements (ICRU) has published reference data for human tissue compositions in Publication No.44, and the ICRP has released a new report on anatomical reference data in Publication No.89. In addition a draft report of the upcoming 2005 recommendations (http://www.icrp.org/) previews significant changes with respect to the list of radiosensitive organs and tissues as well as to their corresponding tissue weighting factors to be included in the determination of effective dose. As a consequence practically all components of traditional stylized exposure models have to be replaced: Monte Carlo codes, human phantoms, tissue compositions, and the selection of organs and tissues at risk with their tissue weighting factors to determine the effective dose. This paper presents results of comprehensive investigations on the dosimetric consequences to be expected from the changes of the traditional stylized exposure models. Calculations have been performed with the EGS4 and MCNCP4C Monte Carlo codes for external and internal exposures to photons and electrons with the stylized, gender-specific MIRD5-type phantoms ADAM and EVA, as well as with the recently developed tomographic phantoms MAX and FAX for different tissue compositions and distributions. Ratios between effective doses for the stylized and the voxelbased exposure models will be presented for external and internal exposures to photons and electrons. These data indicate that for the exposure conditions considered in these investigations the effective dose may change at least between +60% and -50% after the replacement of the traditional exposure models.

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 or field have been published by the International Commission on Radiological Protection (ICRP) for external and internal 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

$$E = \sum_{T} w_T H_T$$

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.

Tissue/Organ	WT
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

 Table 1: Tissue weighting factors from ICRP60 [1]

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" (*M*edical *I*nternal *R*adiation *D*ose 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].

Mainly the gender-specific ADAM and EVA phantoms have been used for the calculations of the CCs for external exposures to photons, electrons recommended by the ICRP in its Publication 74 [10]. CCs for internal exposures to photons and electrons have been calculated with a hermaphrodite MIRD5 phantom, and have been published in ICRP reports [11,12] or

MIRD5 pamphlets [13]. This paper presents ratios between CCs 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 phantoms have been developed based on CT images from patients [14, 15]. After segmentation the volumes of the radiosensitive organs and tissues have been adjusted in order to match the reference masses defined by ICRP89 [16]. The phantoms have heterogeneously structured skeletons with voxel-specific skeletal tissue compositions based on masses, percentage distributions, and cellularity factors from ICRP70 [17]. This was achieved by use of the so-called CT number method [18] as adopted by Kramer et al [14], 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 1.5 mm surface layer of the MAX phantom, and in the 1.2mm surface layer of the FAX phantom, in spite of 3.6 mm voxel thickness. Detailed descriptions of both voxel phantoms are given in Kramer et al [14, 15]. 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 phantoms.



Figure 3: The ADAM and EVA phantoms

## 2.3 The EGS4 and MCNP4C Monte Carlo code

The EGS4 Monte Carlo code [19] 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 generally been transported, except for the MIRD5-type phantoms when comparisons with data already published by the ICRP were made.

The MCNP-4C [20] 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 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 CCs are 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 in four separate investigations [21, 22, 23, 24]:

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

b) The EGS4 Monte Carlo code connected to the ADAM and EVA phantoms with ICRU44based tissue compositions [25]. c) The EGS4 and the MCNP4C Monte Carlo code connected to the MAX and FAX phantoms with ICRU44-based tissue compositions [25], and ICRP70-based skeletal tissue distribution [17].

### **3 RESULTS**

#### **3.1** External exposures

The CCs between effective dose and kerma in air free-in-air or unit fluence for external exposures have been calculated 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). The effective dose was determined as recommended by the ICRP [10], i.e., based on the relationship suggested by Kramer and Drexler [26]. 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 for the calculations.

#### 3.1.1 Photons

Figure 4 shows ratios between effective doses for the MAX-FAX and for the ADEV (= ADAM and EVA) phantoms for external photon radiation as a function of the incident energy between 10 keV and 10 MeV, for AP-, PA-, and ROT-incidence, and for the EGS4 and the MCNP4C Monte Carlo codes. One can observe a decrease of the effective dose, which above 30 keV incident photon energy does not exceed 12% for AP-, and ROT-incidence, and 25% for PA-incidence. Stronger shielding of internal organs by the real human skeleton and by thicker layers of adipose and muscle in the MAX-FAX phantoms are some of the reasons for the reduction of the effective dose [21].



Figure 4: Replacement of the ADAM-EVA by the MAX-FAX exposure model

Below 30 keV an effective dose decrease by ca. 43% and an increase by 40% seem possible according to Figure 4, however statistical fluctuations and rounding error effects, especially for small organs, like the testes or ovaries, impair the accuracy of the data and therefore they should be considered with caution in this range of energies [21]. On the other hand it has to be remembered that below 30 keV the values of the effective dose are usually only around 0.1 Sv/Gy. 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 practical situations for external exposures to photons the reduction of the effective dose due to the introduction of voxel-based models is ca. 10%.

### 3.1.2 Electrons

Figure 5 shows ratios between effective doses for the MAX-FAX and for the ADEV phantoms for external electron radiation as a function of the incident energy between 100 keV and 10 MeV, for AP-, PA-, and ROT-incidence, for the EGS4 and the MCNP4C Monte Carlo codes [22].



Figure 5: Replacement of the ADAM-EVA by the MAX-FAX exposure model

For AP-, and ROT-incidence Figure 5 shows that the introduction of a real human anatomy leads to an increase of the effective dose by up to 30% for electron energies below 1.6 MeV. Greater equivalent doses to superficial organs, like the testes, the thyroid, the breasts, and especially the thinner skin of the MAX-FAX phantoms are mainly responsible for this increase. For higher energies equivalent doses to many internal organs of the ADEV phantoms are greater, because in the MAX-FAX phantoms these organs are more shielded by the real human skeleton

or thicker layers of adipose or muscle, and the effective dose decreases by up to 30%. For PAincidence 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 significantly 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.

#### **3.2 Internal exposures**

Effective dose ratios have been calculated for photon and beta emitters homogeneously distributed in various organs. The effective dose was determined as recommended by ICRP68 [11]. 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. 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 in the calculations.

### 3.2.1 Photons

Figure 6 shows ratios between effective doses for the MAX-FAX and for the ADEV phantoms for internal photon emitters homogeneously distributed in the liver, the lungs, the skeleton, and the thyroid as a function of the energy between 10 keV and 4 MeV, for the EGS4 Monte Carlo code [23].



Figure 6: Replacement of the ADAM-EVA by the MAX-FAX exposure model

In contrast to the findings for external exposures in Figure 4, for internal exposures to photons the introduction of a real human anatomy leads to an increase of effective dose by up to 60% at least for the source organs considered here. 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 [27], for example, compared SAFs calculated for the NORMAN voxel phantom [28] with corresponding data for the MIRD5 phantoms [29]. 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 in 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 [4].

#### 3.2.2 Electrons

Figure 7 shows ratios between effective doses for the MAX-FAX and for the ADEV phantoms for internal beta emitters homogeneously distributed in the kidneys, the skeleton, and the spleen as a function of the energy between 100 keV and 4 MeV, for the EGS4 Monte Carlo codes [24].



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

Introduction of a real human anatomy generally leads to an increase of the effective dose, an observation also made in Figure 6 for internal photon emitters. 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 7 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 7 is due to the presence of voxels of urine in the kidneys of the MAX-FAX phantoms. A part of the energy emitted from the radionuclides in the cortex of the MAX-FAX 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 MAX-FAX phantoms become smaller which is reflected in Figure 7 by the ratio for the kidneys.

#### 4 CONCLUSIONS

The previous sections presented ratios between effective doses of the MAX-FAX and of the ADAM-EVA exposure models for internal and external exposure to photons and electrons as a function of the radiation energy and field conditions. The data illustrate the dosimetric consequences for the effective dose when the stylized MIRD5-type exposure models would be replaced by voxel-based exposure models. Regardless of exposure conditions beyond those considered in this study, an attempt was made in Figures 8 and 9 to summarize effective dose ratios for the exposure conditions studied in this investigation as a function of the particle energy. One can observe that the effective dose would change between +60% and -50% because of the replacement of the ADAM-EVA exposure model by the MAX-FAX exposure model. This margin does not include additional changes from replacing a Monte Carlo code.

According to the revised definition of the effective dose in the upcoming recommendations of the ICRP, new organs and tissues are currently being segmented in the MAX and the FAX phantom. Later both phantoms will be released to be used by the scientific community.



Figure 8: Effective dose ratios for internal and external photon and electron radiation

**Legends in Figures 8 and 9:** PH\_EX: External photons, EL\_EX: External electrons, PH\_IN: Internal photons, EL\_IN: Internal electrons



Figure 9: Effective dose ratios for internal and external photon and electron radiation

## **5** ACKNOWLEDGEMENT

The authors would like to thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq and the Fundação de Amparo à Ciência do Estado de Pernambuco -FACEPE for the financial support.

### **6 REFERENCES**

- 1. ICRP 60, "Recommendations of the International Commission on Radiological Protection", *International Commission on Radiological Protection Publication*, Pergamon Press, Oxford, (1990).
- 2. FISHER H. L and SNYDER W. S., "Distribution of dose in the body from a source of gamma rays distributed uniformly in an organ", Report n°. ORNL-4168, Oak Ridge National Laboratory, Oak Ridge, Tenn, USA, (1967).
- 3. FISHER H. L. and SNYDER W. S., "Distribution of dose in the body from a source of gamma rays distributed uniformly in an organ", *Proceedings of the First International Congress on Radiation Protection*, Pergamon Press, Oxford, pp 1473-1486 (1968).
- 4. ICRP 23, "Report of the task group on reference man", *International Commission on Radiological Protection Publication*, Pergamon Press, Oxford, (1975).
- 5. SNYDER W. S., FORD M. R., WARNER G. G. and WATSON S. B., "Revision of MIRD pamphlet no. 5 entitled: estimates of absorbed fractions for monoenergetic photon sources

uniformly distributed in various organs of a heterogeneous phantom". *Report no. ORNL-* 4979, Oak Ridge National Laboratory, Oak Ridge, Tenn, (1974).

- 6. SNYDER W. S., FORD M. R. and WARNER G. G., "Estimates of absorbed fractions for monoenergetic photon sources uniformly distributed in various organs of a heterogeneous phantom", *MIRD pamphlet no.5*, revised, Society of Nuclear Medicine, New York, (1978).
- 7. CRISTY M., "Mathematical phantoms representing children at various ages for use in estimates of internal dose", *Report ORNL/NUREG/TM-367*, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA, (1980).
- 8. KRAMER R., ZANKL M., WILLIAMS G. and DREXLER G., "The calculation of dose from external photon exposures using reference human phantoms and Monte Carlo methods. Part I: the male (ADAM) and female (EVA) adult mathematical phantoms", *GSF-report s-885*, reprint July 1999, Institut für Strahlenschutz, GSF-Forschungszentrum für Umwelt und Gesundheit, Neuherberg-Muenchen, (1982).
- STABIN M., WATSON E., CRISTY M., RYMAN J., ECKERMAN K., DAVIS J., MARSHALL D. and GEHLEN K., "Mathematical models and specific absorbed fractions of photon energy in the nonpregnant adult female and at the end of each trimester of pregnancy", *Report no. ORNL/TM-12907*, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA, (1995).
- 10. ICRP 74, "Conversion Coefficients for use in Radiological Protection against External Radiation", ICRP Publication 74. International Commission on Radiological Protection, Pergamon Press, Oxford, (1996).
- ICRP 68, "Dose Coefficients for Intakes of Radionuclides by Workers". ICRP Publication No. 68, International Commission on Radiological Protection, Pergamon Press, Oxford, (1995).
- 12. ICRP 72, "Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 5 Compilation of Ingestion and Inhalation Coefficients". ICRP Publication No. 72, International Commission on Radiological Protection, Pergamon Press, Oxford, (1996).
- 13. SNYDER W. S., FORD M. R., WARNER G. G. and WATSON S. B., "Absorbed Dose per Unit Cumulated Activity for Selected Radionuclides and Organs", MIRD pamphlet No.11, The Society of Nuclear Medicine (1975).
- 14. KRAMER R., VIEIRA J. W., KHOURY H. J., LIMA F. R. A. and FUELLE D., "All About MAX: a *M*ale Adult voXel Phantom for Monte Carlo Calculations in Radiation Protection Dosimetry", *Phys. Med. Biol.*, **48**, no. 10, 1239-1262, (2003).
- KRAMER R., VIEIRA J. W., KHOURY H. J., LIMA F. R. A., LOUREIRO E. C. M., LIMA V. J. M. and HOFF G., "All about FAX: a *Female Adult voXel Phantom for Monte* Carlo Calculation in Radiation Protection Dosimetry", *Phys. Med. Biol.* 49, 5203-5216, (2004).
- 16. ICRP 89, "Basic Anatomical and Physiological Data for Use in Radiological Protection: Reference Values". ICRP Publication 89, International Commission on Radiological Protection, Pergamon Press, Oxford, (2003).

- 17. ICRP 70, "Basic Anatomical and Physiological Data for Use in Radiological Protection: The Skeleton". ICRP Publication 70. International Commission on Radiological Protection, Pergamon Press, Oxford, (1995).
- 18. ZANKL M. and WITTMANN A., "The adult male voxel model GOLEM segmented from whole-body ct patient data", *Radiat Environ Biophys*, **40**: 153-162, (2001).
- NELSON W. R., HIRAYAMA H. and ROGERS D. W. O., "The EGS4 Code System". SLAC-265 Stanford Linear Accelerator Center, Stanford University, Stanford, California, (1985).
- 20. BRIESMEISTER J. F. *et al*, "MCNP: A General Monte Carlo N-Particle Transport Code", Version 4C. Edited by J F Briesmeister, Report No. LA-13709-M, Los Alamos Scientific Laboratory, Los Alamos, NM, (2000).
- 21. KRAMER R., KHOURY H. J., VIEIRA J. W., YORIYAZ H. and LIMA F. R. A., "Effective Dose Ratios for Tomographic and Stylized Models from External Exposure to Photons". Paper submitted to the MC2005 conference, (2005).
- 22. LIMA F. R. A., KRAMER R., KHOURY H. J., VIEIRA J. W., "Effective Dose Ratios for Tomographic and Stylized Models from Internal Exposure to Photons". Paper submitted to the MC2005 conference, (2005).
- 23. KRAMER R., KHOURY H. J., VIEIRA J. W., YORIYAZ H. and LIMA F. R. A., "Effective Dose Ratios for Tomographic and Stylized Models from External Exposure to Electrons". Paper submitted to the MC2005 conference, (2005).
- 24. KRAMER R., KHOURY H. J., VIEIRA J. W., YORIYAZ H. and LIMA F. R. A., "Effective Dose Ratios for Tomographic and Stylized Models from Internal Exposure to Electrons". Paper submitted to the MC2005 conference, (2005).
- 25. ICRU 44, "Tissue Substitutes in Radiation Dosimetry and Measurement". ICRU Report 44. International Commission On Radiation Units And Measurements, Bethesda, MD, (1989).
- 26. KRAMER R. and DREXLER G., "On the Calculation of the Effective Dose Equivalent, *Rad. Prot. Dos.*, **3**, 13-24, (1982).
- 27. JONES D. G., "A realistic Anthropomorphic Phantom for Calculating Specific Absorbed Fractions of Energy from Internal Gamma Emitters", *Rad. Prot. Dos.*, **79**, Nos.1-4, pp. 411-414, (1998).
- 28. DIMBYLOW P. J., "The Development of Realistic Voxel Phantoms For Electromagnetic Field Dosimetry", In: Proceedings of an International Workshop on Voxel Phantom Development held at the National Radiological Protection Board, Chilton, UK, 6-7 July, (1995).
- 29. CRISTY M and ECKERMAN K F, "Specific Absorbed Fractions of Energy at Various Ages from Internal Photon Sources". Report ORNL/TM-8381/ V1-7, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA, (1987).