The Monte Carlo Method: Versatility Unbounded In A Dynamic Computing World
Chattanooga, Tennessee, April 17–21, 2005, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2005)

FAX, A FEMALE ADULT VOXEL PHANTOM FOR RADIATION PROTECTION DOSIMETRY

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@globo.com

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

E. C. M. Loureiro
Escola Politécnica
Universidade de Pernambuco
Rua Benfica, 455, Madalena, CEP 50751-460, Recife, PE, Brazil
eduloureiro@uol.com.br

V. J. M. Lima
Departamento de Anatomia
Universidade Federal de Pernambuco
Av. Prof. Luiz Freire, 1000, Cidade Universitária, CEP 50740-540, Recife, PE, Brazil
vjr@npd.ufpe.br

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

G. Hoff
Faculdade de Física
Pontifícia Universidade Católica do Rio Grande do Sul
Faculdade de Física
Av. Ipiranga, 6681/P10-207, Porto Alegre, RS, Brazil
ghoff@pucrs.br

ABSTRACT

The International Commission on Radiological Protection (ICRP) has created a task group on dose calculations, which, among other objectives, should replace the currently used stylized MIRD-type phantoms by tomographic or voxel(-based) phantoms. Voxel phantoms are based on digital images recorded from scanning of real persons by computed tomography (CT) or magnetic resonance imaging (MRI). Compared to the mathematical MIRD phantoms, voxel phantoms are true to nature representations of a human body. Connected to a radiation transport code, voxel phantoms serve as virtual humans for which organ equivalent doses from exposure to ionizing radiation can be calculated. The principal data base for the construction of the FAX (Female Adult voXel) phantom consisted of 151 CT images recorded from scanning of the trunk and parts of the head of a female patient, whose body weight and height were close to the corresponding data recommended by the ICRP in Publication 89. All 23 organs and tissues at risk, except for the red bone marrow and the osteogenic cells on the endosteal surface of bone ('bone surface'), have been segmented manually with a technique recently developed at the Departamento de Energia Nuclear of the UFPE in Recife, Brazil. After segmentation the volumes of the organs and tissues have been adjusted to reach agreement with the organ and tissue masses recommended by the ICRP for the Female Reference Adult in Publication 89. Comparisons with the organ and tissue masses of the stylized, gender-specific EVA phantom, as well as with corresponding data for other female voxel phantoms are presented. Additionally bone and red bone marrow mass fractions have been adjusted also according to data given by the ICRP.

***Key Words*:** Voxel phantoms, Monte Carlo, Radiation Protection, Effective Dose

1. INTRODUCTION

The development of mathematical heterogeneous human phantoms was essential to calculate equivalent dose to the radiosensitive organs and tissues included in the definition of effective dose [1]. 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 "MIRD-5 phantom" (*M*edical *I*nternal *R*adiation *D*ose Committee (MIRD) Pamphlet No.5).

The MIRD-5 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 MIRD-type phantoms are in accordance with the Reference Man data from 1975 [4].

Although facilitating significantly the task of equivalent dose determination, the mathematical MIRD5-type phantoms are still rather stylized models of the human body and its organs. This problem has been resolved by the development of tomographic or voxel (based) phantoms. Voxel phantoms are based on digital images recorded from scanning of real persons by computed tomography (CT) or magnetic resonance imaging (MRI). Each image consists of a matrix of pixels (picture elements), whose number depends on the resolution chosen during scanning. A consecutive set of such images can be considered as a three-dimensional matrix made of voxels (volume pixels), where each voxel belongs to a specific organ or tissue. Compared to the mathematical phantoms, voxel phantoms are true to nature representations of human bodies.

Based on data published by Zubal [10] on a website of the YALE University, Kramer et al [11] developed the MAX (*M*ale *A*dult vo*X*el) phantom which corresponds anatomically to the specifications of the revised Male Reference Adult, published by the ICRP in Report No.89 [12].

This paper presents the development of the FAX (*F*emale *A*dult vo*X*el) phantom based on CT images of female patients. Similar to the development of the MAX phantom, the organ and tissue masses of the FAX phantom have been adjusted in order to correspond to the anatomical specifications defined by the ICRP for the Female Reference Adult [12].

2. MATERIALS AND METHODS

2.1 Data base

The main set of data used for the construction of the FAX phantom consisted of 151 consecutive CT images of a 37 year old female patient. The patient's height was 165cm, and her weight was 63.4kg. The images covered the trunk, the neck and the lower part of the head including the mandible with the lower teeth. The pixel size was 0.073cm x 0.073cm, and the distance between two consecutive images was 0.5cm. The images had been provided by CT Screening International, Irvine, CA92612, USA in October 2002.

A second set of data consisted of 206 consecutive CT images of the legs and feet of a 62 year old woman. The pixel size was 0.07cm x 0.07cm, and the distance between two consecutive images was 0.25cm. The images had been provided by the university hospital of the city of Porto Alegre, Brazil in September of 2003.

2.2 Segmentation

The CT images of the patients have been obtained in the format DICOM (Digital Imaging and Communications in Medicine), and have been visualized by means of the software OSIRIS [13], which is available on the internet. OSIRIS has several types of filters which allow to improve the visualization of boundaries between organs. After editing the images have been saved as BitMap files with the software PAINT, which is included in the Microsoft WINDOWS accessories.

Segmentation was done in each of the 357 images with PAINT by manually painting every organ and tissue of interest with a different color [14]. Thereby the grey values of the pixels which belong to a specific organ were replaced by a specific color, which corresponds to a specific number. At the end of the procedure the pile of images represents a three-dimensional voxel matrix, in which all voxels of a specific organ or tissue have the same identification number. According to the definition of the effective dose [1] the following organs and tissues have been segmented: Adrenals, bladder wall, skeleton, brain, breasts, colon, kidneys, liver, lungs, muscle, oesophagus, ovaries, pancreas, small intestine, skin, spleen, stomach, thymus, thyroid, trachea, and uterus. Although not included in the effective dose, the heart and adipose tissue have also been segmented.

2.3 Addition of head and arms

The head of the MAX phantom was attached to the neck of the FAX phantom, after scaling down the MAX phantom's head according to the anatomical differences between the Male and the Female Reference Adult as defined by ICRP89 [12]. The same procedure was applied to the addition of the arms, which also have been taken from the MAX phantom.

2.4 Anatomical corrections

During screening the patient was asked to raise the arms behind her head. Therefore the shoulders and the upper part of the arms have been re-designed according to data from anatomical text books. The images of the trunk, the head, the arms and the legs originated from three different patients. Therefore, with respect to the representation of the skeleton some adjustments had to be made again based on anatomical textbooks, but at the same time also taking into account as much as possible the reference distribution of bone mass fractions given by ICRP89 [12]. The form of the breasts has also been modified in order to represent an upright standing adult female. Finally all segmented images have been resampled to achieve the same voxel size of 0.36cm x 0.36cm x 0.36cm = 0.046656cm^3 as in the case of the MAX phantom, and the total number of slices has been adjusted to 453, which corresponds to a body height of 163cm.

2.5 Adjustment of organ and tissue masses

The organ and tissue masses of the Female Reference Adult are defined by ICRP89 [12]. Applying the ICRU44 tissue densities [15] shown in Table 1, the corresponding organ volumes have been determined. The composition and density of soft tissue has been averaged from the data for brain, breasts, colon, heart, kidneys, liver, pancreas, spleen, ovaries and thyroid.

Table 1. Tissue compositions and densities based on ICRU 44

Atomic No.	1	6	7	8	11	12	15	16	17	19	20	26	53	Density
Symbol	H	C	N	O	Na	Mg	P	S	Cl	K	Ca	Fe	I	
	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[g/cm^3]
SOFT TISS	10.5	12.5	2.6	73.5	0.2		0.2	0.18	0.22	0.21	0.01	0.01	0.01	1.05
ADIPOSE	11.4	59.8	0.7	27.8	0.1			0.1	0.1					0.95
LUNG	10.3	10.5	3.1	74.9	0.2		0.2	0.3	0.3	0.2				0.26
MUSCLE	10.2	14.3	3.4	71	0.1		0.2	0.3	0.1	0.4				1.05
SKIN	10	20.4	4.2	64.5	0.2		0.1	0.2	0.3	0.1				1.09
CARTILAGE	9.6	9.9	2.2	74.4	0.5		2.2	0.9	0.3					1.1
BONE	3.4	15.5	4.2	43.5	0.1	0.2	10.3	0.3			22.5			1.92
RED BM*	10.5	41.4	3.4	43.9			0.1	0.2	0.2	0.2		0.1		1.03
YELL BM*	11.5	64.4	0.7	23.1	0.1			0.1	0.1					0.98

*BM: Bone Marrow

Division of these volumes by 0.046656 cm^3 yields the number of voxels contained in each organ and tissue. Accordingly the actual voxel numbers of the organs have been increased or decreased until the desired voxel number was realized. As practically all organs are surrounded by adipose and/or muscle tissue, the procedure of adjustment actually consisted of exchanging

ID numbers between voxels of a specific organ with those of surrounding adipose or muscle tissue.

2.6 Dosimetry for the skin

Based on data given by ICRP89 [12] an average thickness of 1.2mm for the female skin was calculated. Similar to the procedure applied to the MAX phantom [11], instead of sub-segmenting the 3.6mm surface voxel layer, equivalent dose to the first 1.2mm skin depth will be calculated by 'dosimetric separation' within the 3.6mm voxel thickness. Depending on the location of the radiation interaction in the first voxel layer, the energy lost by the particle will be deposited either within the 1.2mm superficial skin layer, or within the underlying 2.4mm of adipose tissue.

2.7 Skeletal tissue distribution

Segmentation of the red bone marrow (RBM) within trabecular bone requires CT images with pixel sizes in the micrometer range. For selected bone samples progress has been made in the area of RBM segmentation [16], but for the time being such pixel resolutions for a complete human skeleton are still not available. Therefore whole-body RBM dosimetry still has to be based on the calculation of the radiation energy deposited in a homogeneous mixture of bone, marrow and cartilage to which then certain correction factors are applied.

While in the mathematical phantoms [8] only one specific homogeneous skeletal mixture was used for the whole skeleton, in voxel phantoms it is possible to create a heterogeneous skeletal tissue distribution throughout the bones by assigning specific mixtures to each skeletal voxel. This is done with the CT number method [17] as adopted by Kramer et al [11], which uses the grey values of bone pixels in the original CT images of the scanned patient to establish voxel-specific tissue distributions of bone, marrow and cartilage.

Table 2. Female skeletal tissue distribution based on ICRP89

TISSUE	MASS	DENSITY	VOLUME	VOLUME
	g	g/cm^3	cm^3	FRACTION
BONE	4000	1.92	2083.3	0.361
RED BM	900	1.03	873.8	0.151
YELL BM	1800	0.98	1836.7	0.318
CARTILAGE	900	1.10	818.2	0.142
MISC*	200	1.20	166.7	0.029
TOTAL	7800		5778.7	1.000

***MISC. = teeth, periosteum, and blood vessels**

Column 2 of table 2 shows the ICRP89 reference masses [12] for bone, RBM, yellow bone marrow, cartilage and miscellaneous tissues. With the densities from table 1 it is possible to calculate the corresponding volumes to be seen in column 4, and finally to determine the volume fractions for each skeletal tissue shown in the last column. The density for the miscellaneous tissues has been assessed based on data given by ICRP70 [18].

The volume of a skeleton with a tissue distribution based on ICRP89 contains ca. 17% of cartilage plus miscellaneous tissues. During the segmentation of CT images cartilage is usually segmented sometimes as part of bone and sometimes as part of skeletal muscle in order to achieve smooth surfaces between the skeleton and the surrounding muscle tissue. This also happens with the periosteum and the connected blood vessels, which are mostly located on the surface of bone. It was therefore decided to include only half of that volume, or 8.5%, in the skeletal tissue distribution of the FAX skeleton. The teeth, representing only 0.3% of the total skeletal volume, are already part of the segmented bone volume, and have therefore been neglected for further explicit considerations.

After segmentation and adjustment of the bone masses, the skeleton of the FAX phantom turned out to consist of 119938 voxels, which correspond to a volume of 119938 x 0.04666cm^3 = 5596 cm^3. The mass of the RBM becomes therefore 5596cm^3 x 0.151 x 1.03gcm^{-3} = 870g, which have to be distributed among the various bones of the skeleton. However, this distribution has to take into account additional information provided by ICRP70: Table 3 shows the cellularity factors, which indicate the percentage of bone marrow volume occupied by the haematopoietic cells of the RBM, and the mass of RBM in a specific bone (group) as a percentage of the total RBM mass.

Table 3. Cellularity factors and percentage mass fraction of RBM from ICRP70

Specific Bone	Cellularity Factor	RBM mass [%]
Lower Arms	0	0
Upper Arms	0.25	2.3
Ribcage*	0.60	22.8
Spine/Sacr.	0.70	42.2
Skull/Mand.	0.38	8.4
Pelvis	0.48	17.5
Upper Legs	0.25	6.7
Lower Legs	0	0

*** Ribs, sternum, clavicles, scapulae**

Following the CT number method, grey values in the range between 0 and 255 contained in the bone pixels of the original CT images have been used to establish a heterogeneous tissue distribution throughout the skeleton, taking into account the calculated RBM mass of 870g, the RBM mass fractions and the cellularity factors from table 3, and also the adjustments applied to the skeleton.

3. RESULTS

3.1 Organ and tissue masses

Table 4 summarizes the 22 radiosensitive female organs and tissues which are included in the definition of the effective dose plus adipose for the Female Reference Adult [12], for the

Table 4. Organ and tissue masses for the Female Reference Adult and various phantoms

		Math. Phant.	Female Adult Voxel Phantoms				
	ICRP89	GSF	GSF	GSF	GSF	UFPE	Perc. Diff.
ORGAN/TISSUE	Female Ref.	EVA	DONNA	HELGA	IRENE	FAX	FAX/Fem.Ref.
	[g]	[g]	[g]	[g]	[g]	[g]	[%]
Adipose (Fat)	18000		34820	39800	11630	18175	+1.0
Adrenals	13	12.9	21.7	6.6	12.4	13	0
Bladder wall	40	45	61	60.8	39	40	0
Skeleton	7800	8360	7484	6503	8201	8084	+3.6
Brain	1300	1120	1208	1279	1255	1300	0
Breasts	500	532	43.9*	134*	57*	500	0
Colon	680	600	322	426	271	680	0
Kidneys	275	236	281	390	212	275	0
Liver	1400	1471	1585	1757	1225	1400	0
Lung	950	830	631	463	685	950	0
Muscle, skeletal	17500		25420	21340	21100	17500	0
Oesophagus	35	39.7	27.7	28	24.3	35	0
Ovaries	11	10.9	12.1	11.9	11.9	11	0
Pancreas	120	79.6	41.2	43.3	61.9	120	0
Red BM	900	1246	1012	1043	916	870	-3.3
Small Intestine	880	894	435	443	396	880	0
Skin	2300	2803	4351	1653	3620	2302	+0.1
Spleen	130	144	306	298	203	130	0
Stomach	370	125.3	500	73.1	368	370	0
Thymus	20	20	19	7.7	25.3	20	0
Thyroid	17	16.4	18.7	31.5	20	17	0
Trachea	8					8	0
Uterus	80	80	71.7	79.8	25	80	0
Total Body	60000	59193	79000	81000	51000	59762	-0.4
Height	163 cm	160cm	176cm	170cm	163cm	163cm	0

Colon, Small Intestine and Stomach include contents, *=only glandular tissue; GSF = Research Center for Environment and Health, Munich, Germany; UFPE=Universidade Federal de Pernambuco, Recife, Brazil.

GSF mathematical EVA phantom [8], for the adult female GSF voxel phantoms DONNA, HELGA, IRENE [19], and for the FAX phantom. The last column shows the percentage difference between the masses for the FAX phantom and the Female Reference Adult.

Most organ and tissue masses of the FAX phantom have values recommended by ICRP89. However, the RBM mass is 3.3% smaller than the reference mass, because with $5596cm^3$ the volume of the FAX skeleton is ca. 3.3% smaller than the reference volume shown in table 3.

Nevertheless the mass of the FAX skeleton is by about the same margin greater than the reference mass, which is due to the average density of $1.445gcm^{-3}$ of the FAX skeleton calculated by the CT number method, while on the other hand table 3 would suggest an average skeletal density of only $7800g / 5778.7cm^3 = 1.35gcm^{-3}$. As already pointed out elsewhere [11] average skeletal densities published by the ICRP [4, 18, 12] vary between 1.3 – $1.4g\ cm^{-3}$, while for voxel phantoms the reported values are usually greater than $1.4gcm^{-3}$ [20, 21, 11].

3.2 Bone mass adjustment and RBM distribution

Table 5 shows the mass fractions of bone for the Female Reference Adult and for the FAX phantom. The average deviation from the reference values is less than 6%.

Columnn 3 of table 6 shows the percentage mass fractions of RBM achieved for the FAX phantom after distributing 870 g of RBM throughout the skeleton by the CT

Table 5. Fractions of total fresh skeletal mass contributed by various bones, including bone marrow for the Female Reference Adult and the FAX phantom

Specific Bone	ICRP89 mass fraction	FAX mass fraction
Lower Arms	0.056	0.056
Upper Arms	0.047	0.054
Ribcage*	0.104	0.106
Spine/Sacr.	0.204	0.197
Skull/Mand.	0.131	0.147
Pelvis	0.106	0.109
Upper Legs	0.159	0.148
Lower Legs	0.193	0.183

*** Ribs, sternum, clavicles, scapulae**

number method, after taking into account the cellularity factors of table 4, and after “tuning” the skeletal tissue distribution to approximate the ICRP RBM mass fraction shown in tables 3 and 6. Like for the MAX phantom [11] the average deviation from the reference data is ca. 1%. The last column of table 6 presents for comparison the RBM mass fractions of the mathematical ADAM and EVA phantom [8], which are based on the data from the first Reference Man Report published in ICRP 23 [4].

Table 6. Percentage mass fractions of RBM for the Female Reference Adult and various phantoms

Bone	ICRP89 [%]	FAX [%]	MAX [%]	ADAM/EVA [%]
Lower Arms	0	0	0	0
Upper Arms	2.3	3.0	3.6	1.9
Ribcage*	22.8	21.7	23.0	16.6
Spine/Sacr.	42.2	43.6	42.7	28.4
Skull/Mand.	8.4	8.4	7.7	13.1
Pelvis	17.5	16.6	16.3	36.2
Upper Legs	6.7	6.7	6.7	3.8
Lower Legs	0	0	0	0
Total	99.9	100.0	100.0	100.0

*** Ribs, sternum, clavicles, scapulae**

3.3 Images of the FAX phantom

Figure 1 shows a frontal and a lateral view of the FAX phantom. Apart from the skeleton, most of the segmented organs can be seen. 3D views of the FAX phanotm's surface are shown in Figure 2.

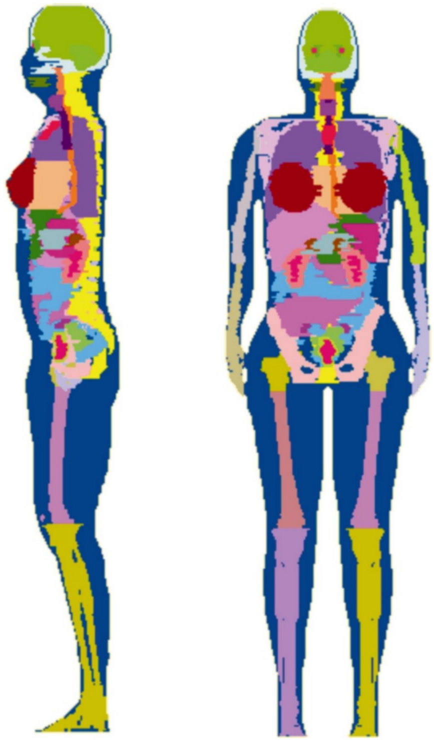

Figure 1. The FAX phantom: Frontal and lateral view with skeleton and internal organs

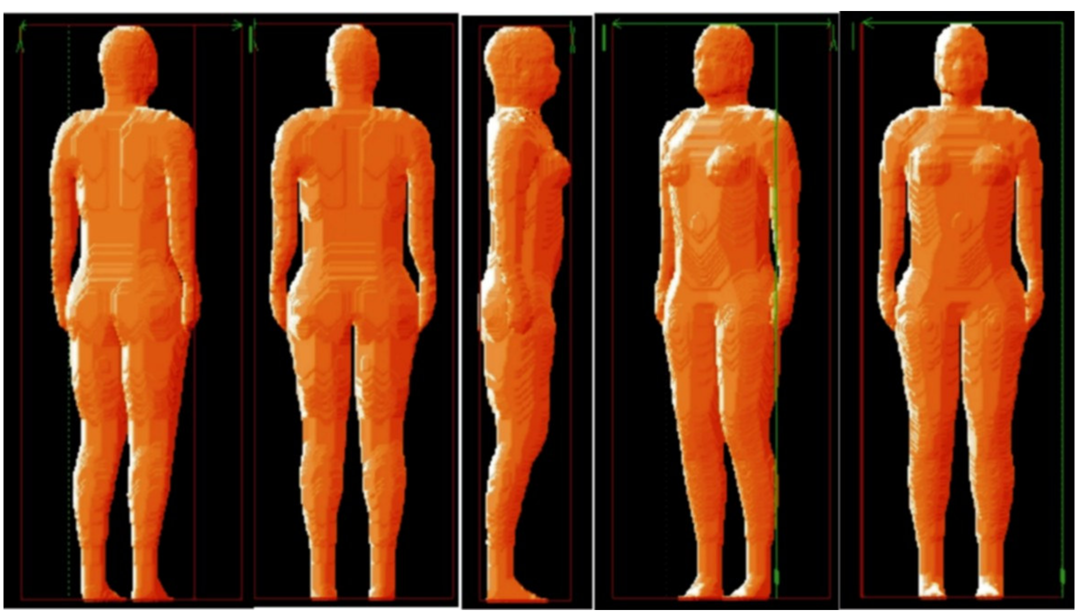

Figure 2. The FAX phantom: 3D views for different projections

4. CONCLUSIONS

CT images from female patients have been segmented with respect to the organs and tissues of the human body considered relevant by ICRP for the calculation of the effective dose. The segmented images have been assembled to form a three-dimensional voxel matrix, called FAX phantom.

The masses of all relevant organs and tissues have been adjusted to match the reference values given by ICRP89 for the Female Reference Adult. Using skeletal tissue data from ICRP70 and ICRP89 it was possible to determine the RBM mass which corresponds to the segmented volume of the FAX skeleton. Application of the CT number method and consideration of the cellularity factors made it possible to realize a RBM distribution in a heterogeneous skeleton close to the RBM mass fractions given by ICRP89.

Together with the earlier developed MAX phantom it is now possible to calculate the effective dose for female and male voxel phantoms, which correspond in their anatomical specifications to the reference data given by ICRP89. Future projects include the calculation and publication of conversion coefficients between effective dose and operational quantities for occupational, environmental, and medical radiation protection, the development of a user friendly software to calculate MAX/FAX conversion coefficients to be used in the daily routine work, and the MAX and the FAX phantoms will be released for research projects performed by members of the international scientific community. Additional information on the FAX phantom can be found elsewhere [22].

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*, Publication 60, Pergamon Press, Oxford, (1990).
2. FISHER H L; SNYDER W S, "Distribution of dose in the body from a source of gamma rays distributed uniformly in an organ", *Report no. ORNL-4168*, Oak Ridge National Laboratory, Oak Ridge, Tenn, USA, (1967)
3. FISHER H L; 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, Publication 23, Pergamon Press, Oxford, (1975).

5. SNYDER W S; FORD M R; WARNER G G; WATSON G G, "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; 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; 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).
9. STABIN M; WATSON E; CRISTY M; RYMAN J; ECKERMAN K; DAVIS J; MARSHALL D; 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. ZUBAL I G, "The Zubal phantom data, voxel-based anthropomorphic phantoms", http://noodle.med.yale.edu/phantom, (2001).
11. KRAMER R; VIEIRA J W; KHOURY H J; LIMA F R A, FUELLE D, "All about MAX: a *m*ale *a*dult vo*x*el phantom for monte carlo calculations in radiation protection dosimetry", *Phys. Med. Biol.*, 48, no.10, 1239-1262, (2003).
12. ICRP 89, "Basic anatomical and physiological data for use in radiological protection: reference values", *International Commission on Radiological Protection Publication*, Publication 89, Pergamon Press, Oxford, (2003).
13. LIGIER Y; RATIB O; LOGEAN M; GIRARD C, "OSIRIS: a medical image manipulation system", *M. D. Comput. J.*, 11(4): 212-218, (1994).
14. LOUREIRO E C M; LIMA F R A; STABIN M, "A voxel-based head-and-neck phantom built from tomographic colored images", *Cell Mol Biol*, 48(5):46104-464, (2002).
15. ICRU 44, "Tissue substitutes in radiation dosimetry and measurement", *International Commission on Radiation Units and Measurements Report*, ICRU Report 44, Bethesda, MD, USA, (1989).
16. BOLCH W E; PATTON P W; RAJON D A; SHAH A P; JOKISCH D W; INGLIS B A, "Consideration of marrow cellularity in 3-dimensional dosimetric models of the trabecular skeleton", *J Nucl Med*, 43:97-108, (2002).
17. ZANKL M; WITTMANN A, "The adult male voxel model GOLEM segmented from whole-body ct patient data", *Radiat Environ Biophys,* 40: 153-162, (2001).

18. ICRP 70, “Basic anatomical and physiological data for use in radiological protection: the skeleton” *International Commission on Radiological Protection Publication*, Publication 70, Pergamon Press, Oxford, (1995).

19. ZANKL M; FILL U; PETOUSSI-HENSS N; REGULLA D, “Organ dose conversion coefficients for external photon irradiation of male and female voxel models”, *Phys Med Biol*, 47, no.14, 2367-2386, (2002).

20. CHAO T C; BOZKURT A; XU X G, “Conversion coefficients based on the VIP-MAN anatomical model and EGS4-VLSI code for external monoenergetic photons from 10 kev to 10 MeV”, *Health Physics*, 81(2):163-183, (2001).

21. ZANKL M, Private Communication, E-mail from January 18, (2002).

22. KRAMER R; KHOURY H J; VIEIRA J W, LOUREIRO E C M; LIMA V J M; LIMA F R A; 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).