MAX06 and FAX06: Update of two adult human phantoms for radiation protection dosimetry

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ABSTRACT

The International Commission on Radiological Protection (ICRP) is currently preparing new recommendations which will replace those released in Publication 60 in 1991. The draft report previews a change for the effective dose with respect to the number of organs and tissues to be included in its calculation. In the future additionally adipose tissue, connective tissue, the extrathorarcic airways, the gall bladder, the heart wall, the lymphatic nodes, the prostate and the salivary glands have to be taken into account for the determination of the effective dose. This study reports about a second segmentation of the recently introduced MAX and FAX phantoms with regard to the new organs and tissues, but also presents a revised representation of the skeletons, which had not been adjusted to ICRP-based volumes in the first release of the two phantoms.

1. Introduction

According to the recommendations of the International Commission on Radiological Protection (ICRP) released in Publication 60 (ICRP 1991), the determination of the effective dose, the most important dose quantity in radiological protection, requires the calculation of the equivalent dose to radiosensitive organs and tissues shown in column 1 and 2 of table 1.

Table 1. Radiosensitive organs and tissues to be included in the calculation of the effective dose according to ICRP60/66 (ICRP 1991/94), and new organs and tissues to be included in the future

Organs and tissues from ICRP60 (1991)		New organs and tissues
Adrenals	Oesophagus	Adipose tissue
Bladder	Pancreas	Connective tissue
Bone surface	Red bone marrow	Extrathorarcic airways
Brain	Skin	Gallbladder
Breast	Small intestine	Heart wall
Colon	Spleen	Lymphatic nodes
Gonads	Stomach	Prostate
Kidneys	Thymus	Salivary glands
Liver	Thyroid	
Lungs	Trachea	
Muscle	Uterus	

The trachea replaced the upper large intestine (ICRP 1994), which was part of the original list of tissues (ICRP 1991), but actually is already included in the colon.

Meanwhile the ICRP has posted a draft report of its new recommendations for consultation on its website (ICRP 2004), which contains an extension of the number of radiosensitive organs and tissues to be taken into account for the determination of the effective dose in the future, because recently reported evidence about stochastic radiation effects in these organs and tissue suggests to do so. These organs and tissues are shown in the third column of table 1.

The recently introduced MAX (*M*ale *A*dult vo*X*el) and FAX (*F*emale *A*dult vo*X*el) phantoms (Kramer et al 2003, 2004) have organ and tissue masses which have been adjusted to the reference masses given in ICRP Publication 89 (ICRP 2003), but the segmented organs and tissues comprise basically those mentioned in table 1, which is, of course, sufficient for the determination of the effective dose according to ICRP60 (ICRP 1991). However, the masses of the skeletal tissues of the MAX and the FAX phantoms have not been adjusted to the data recommended by ICRP89 at the time of their first release in 2003 and 2004, because the CT number method used to calculate the equivalent dose to the red bone marrow requests the application of the skeletal grey values contained in the original CT images of the patient. As these skeletal grey values have to match the segmented bone pixels exactly, it was not possible to change the segmented bone structure at that time.

In order to be prepared for future effective dose calculations it was decided to segment and/or adjust the organs and tissues shown in column 3 of table 1 in the MAX and the FAX phantoms, and in addition to use this opportunity to segment also the walls and the contents of the stomach, the colon and the small intestine, as well as cortical bone, medular yellow bone marrow, spongiosa and cartilage in the skeletons, segmentations which had not been done during the original design of the MAX and the FAX phantoms.
For the time being the new recommendations of the ICRP exist only as a draft, however, it is not very probable that more organs and tissues would be included in the finally adopted recommendations, because table 1 contains already all organs and tissues relevant for the purposes of radiological protection. The updated phantoms will be named MAX06 and FAX06.

One would expect that all major human voxel phantoms in use today are currently undergoing update procedures, and as for the NORMAN voxel phantom (Dimbylow 1995) the results for this update have already been published by Ferrari and Gualdrini (2005).
For the sake of keeping a reasonable volume, this paper refrains from reviewing the literature of phantom development, and also does not present dosimetric data. As for the review the reader is recommended to look at the references quoted in Kramer et al (2003, 2004). Dosimetric data for the MAX06 and the FAX06 phantoms will be published shortly in separate publications.

2. Materials and methods

The MAX phantom has been developed (Kramer et al 2003) based on segmented images from a male patient (Zubal et al 1994), while the FAX phantom has been segmented based on CT images of a female patient (Kramer et al 2004). The MAX phantom consists of 3.6mm cubic voxels. The voxels of the FAX phantom have been adjusted to the same size because thereby it became possible to use the same algorithm for the coupling with a Monte Carlo radiation transport code. After segmentation the volumes of relevant radiosensitive organs and tissues have been adjusted in order to match the reference masses defined by ICRP89 (ICRP 2003). The MAX and the FAX phantoms have heterogeneously structured skeletons made of cortical bone, spongiosa (= “trabecular bone plus its supported soft tissue” (ICRP 1995)), marrow, and cartilage with voxel-specific skeletal tissue compositions based on masses, percentage distributions, and cellularity factors derived from ICRP70 (ICRP 1995). This was achieved by use of the so-called CT number method (Zankl and Wittmann 2001) as adopted by Kramer et al (2003), which takes advantage of the CT numbers (= grey values) contained in the bone pixels of the CT images. However, this heterogeneity did not represent a permanently segmented part of the MAX and the FAX skeletons, because it was created by an algorithm only during the execution of a radiation transport calculation. Now this heterogeneity should be made an integral part of the skeletons in the MAX06 and the FAX06 phantoms.

Table 2. Elemental tissue composition used in the MAX06 and the FAX06 phantoms based on ICRU44 (ICRU 1989)

ATOM	SOFT TISSUE [%]	ADIPOSE TISSUE [%]	SKIN TISSUE [%]	LUNGS TISSUE [%]	SKELETON CARTILAGE [%]	SKELETON CORTICAL [%]	SKELETON SPONGIOSA [%]	SKELETON YBM [%]
H	10.5	11.4	10.0	10.3	9.6	3.4	8.5	11.5
C	12.5	59.8	20.4	10.5	9.9	15.5	40.4	64.4
N	2.6	0.7	4.2	3.1	2.2	4.2	2.8	0.7
O	73.4	27.8	64.5	74.9	74.4	43.5	36.7	23.1
Na	0.2	0.1	0.2	0.2	0.5	0.1	0.1	0.1
Mg						0.2	0.1	
P	0.2		0.1	0.2	2.2	10.3	3.4	
S	0.18	0.1	0.2	0.3	0.9	0.3	0.2	0.1
Cl	0.2	0.1	0.3	0.3	0.3		0.2	0.1
K	0.2		0.1	0.2			0.1	
Ca	0.01					22.5	7.4	
Fe	0.01						0.1	
ρ [gcm^{-3}]	1.05	0.95	1.09	0.26	1.1	1.92	1.18	0.98

The segmentation of the new organs and tissues was based on the original CT images, on anatomical textbooks (Netter 1998, Sobotta 1995), ICRP70 (ICRP 1995) and on ICRP89 (ICRP 2003), and if not stated otherwise, the following description refers to both phantoms. The images of the two phantoms have been edited with the SCION software (SCION 2001), and ajustments were made to the volumes by changing the organ and tissue identification numbers literally pixel by pixel. Tissue compositions and densities from ICRU44 (ICRU 1989) shown in table 2 have been used to control the match with the ICRP reference masses.

Adipose tissue

Adipose tissue had already been segmented in the original versions of the two phantoms. Only minor adjustments of the masses had to be made.

Connective tissue

Separable connective tissue includes primarily periarticular tissue, tendons and fascia. Periarticular tissue has been segmented at the shoulders, the knees, the hips, the ellbows, between the vertebrae, between vertebrae and ribs, and between the sacrum and the ilium, and also at the sinfisis pubis for the FAX06 phantom. The fascia has been introduced between the deepest layer of the subcutaneous tissue and the muscle tissue distributed over the whole body, while the tendons have been segmented mainly at the joints.

Extrathorarcic airways

From ICRP89 (ICRP 2003) and from the ICRP draft document (ICRP 2004) it is understood that the extrathorarcic airways consist of the anterior and posterior nasal passages, the mouth cavity, the farynx and the larynx. Reference masses for the larynx are given in ICRP89. The volumes for the farynx have been determined with data from anatomical textbooks, while estimates for the volumes of the nasal passages and the mouth cavity have been made based on data provided by ICRP89 (ICRP 2003) on page 92 and also based on anatomical textbooks (Netter 1998, Sobotta 1995).

Gall bladder

The gall bladder was segmented below the liver, separately for wall and contents.

Heart wall

The heart walls had already been segmented in both phantoms, but now the volumes have been adjusted to match the masses recommended by ICRP89 (ICRP 2003).

Lymphatic nodes

Lymphatic nodes have been segmented at the armpit, at the groins, behind the knees, in front of the ellbows, at the neck, and around abdominal soft-tissue organs. ICRP89 states: "Except for the lymphocytes, which are present in most tissues, the lymphatic tissue is contained in the red bone marrow and in the lymphatic organs: lymph nodes, spleen, thymus, mucous membranes, tonsils, adenoids, Peyer's patches, and the vermiform appendix" (ICRP 2003). Therefore the segmented volume of the lymphatic nodes was confined to 50% of the volume recommended by ICRP89.

Prostate

The prostate had already been segmented in the MAX phantom, but now the volume has been adjusted in order to match the mass recommended by ICRP89 (ICRP 2003).

Salivary glands

The salivary glands have been segmented around the mandible as parotid, submaxillary, and sublingual parts, observing the mass ratios 10:5:2 between them according to ICRP89 (ICRP 2003).

Stomach, colon and small intestine

Walls and contents of the stomach and the colon have been segmented by introducing a wall thickness of one voxel layer, i.e. of 3.6 mm. Because of the many twists and turns of the small intestine it is almost impossible to segment a continuous and steady wall based on voxels. Therefore the total volume of the small intestine was divided between wall and contents by distributing the wall voxels homogeneously throughout the volume of the organ.

Skeleton

The skeletons of the MAX and the FAX phantoms had been segmented with respect to the surrounding muscle tissue, but no attempt was made until now to segment tissues within the skeletal structures, like cortical bone, spongiosa, medular yellow bone marrow in the shafts of the long bones and cartilage. The images of the VOX_TISS8 phantom (Zubal 2001), which had been the basis for the development of the MAX phantom, show areas of segmented bone marrow, however, it was demonstrated (Kramer et al 2003) that this bone marrow segmentation was faulty.

In order to prepare the phantoms for advanced skeletal dosimetry in the future, it was decided to segment cortical bone, spongiosa, medular yellow bone marrow in the shafts of the long bones, and cartilage in the skeletons of the MAX and the FAX phantoms, based on the original CT images, as well as by using anatomical textbooks (Netter 1998, Sobotta 1995), and the color photographs of the Visible Human (Spitzer and Woodlock 1998). However, similar to the procedure applied to the segmented soft tissue organs, the new skeletons should also be based on recommendations published by the ICRP as far as anatomically possible. Therefore the segmentation of the skeletal tissues took into account the following data provided by ICRP89 (ICRP 2003) and ICRP70 (ICRP 1995):

Table 3. Skeletal tissue masses, volumes and densities based on ICRP89 (ICRP 2003) and ICRU44 (ICRU 1989)

Skeletal tissues	Density ρ [g cm^{-3}]	Reference Male m [g]	v [cm^3]	Reference Female m [g]	v [cm^3]
BONE	1.92*	5500	2864.6	4000	2083.3
Red BM	1.03*	1170	1135.9	900	873.8
Yellow BM	0.98*	2480	2530.6	1800	1836.7
CARTILAGE	1.10*	550	500.0	450	409.1
MISC	1.20**	250	208.3	200	166.7
TOTAL	1.37**	9950	7239.4	7350	5369.5

BM: Bone marrow, MISC: Teeth, periostenum and blood vessels
* ICRU densities, ** calculated densities

a) Reference masses for bone, red bone marrow (RBM), yellow bone marrow (YBM), cartilage, and miscellaneous tissues (teeth, periostenum, and blood vessels) are shown in table 3 for the reference adult male and female (ICRP 2003). For the cartilage masses only half of the recommended mass was taken into account because a part of the cartilage included by ICRP89 into the mass of the skeleton actually is located "off-bone", like in the ear, in the nose, etc., and also because in order to achieve smooth surfaces between bone and skeletal muscle the cartilage is sometimes segmented as bone or sometimes as muscle. The density for the miscellaneous tissues has been calculated based on data from ICRP23 (ICRP 1975) as 1.20 g cm^{-3}. With the ICRU44 densities and the calculated densities shown in column 2, the corresponding skeletal tissue volumes have been determined and are presented in columns 4 and 6 of table 3. The average density of 1.37 g cm^{-3} calculated from the total skeletal mass and volume is, of course, greater than the 1.3 g cm^{-3} recommended byICRP89 because of the smaller cartilage mass.

Table 4. Skeletal tissues data based on ICRP70 (ICRP 1995) and ICRP89 (ICRP 2003)

ICRP 70/89 Skeletal region	Male bone mass fract.	Female bone mass fract.	Mass ratio of bone cortical / trabecular	RBM mass fract.	Cellularity factor
Lower arm bone	0.059	0.056	87/13	0	0
Upper arm bone	0.053	0.047	80/20	0.023	0.25
Ribcage	0.126	0.104	94/6	0.228	0.60
Spine	0.190	0.204	30/70	0.422	0.70
Skull	0.118	0.119	95/5	0.076	0.38
Mandible	0.012	0.012	90/10	0.008	0.38
Pelvis	0.106	0.105	90/10	0.176	0.48
Upper leg bone	0.153	0.159	70/30	0.067	0.25
Lower leg bone	0.183	0.193	80/20	0	0

Ribcage: Ribs, sternum, clavicles and scapulae

b) For 9 important bones or bone groups table 4 presents gender-specific mass fractions, mass ratios between cortical and trabecular bone, RBM mass fractions, taken or derived from data recommended in ICRP89 (ICRP 2003), and cellularity factors, which indicate the fraction of marrow volume occupied by RBM, taken from ICRP70 (ICRP 1995).

Table 5. Theoretical volume distribution of skeletal tissues for the adult male

Adult male Skeletal region	Cortical bone cm^3	Spongiosa cm^3	med YBM cm^3	Cart/misc cm^3	Total cm^3
Lower arm bone	164.9	144.4	59.0	42.6	410.9
Upper arm bone	85.8	215.8	89.9	37.4	428.9
Ribcage	351.0	454.1		89.7	894.8
Spine	163.2	1065.2		134.8	1363.2
Skull	422.5	249.3		83.1	754.9
Mandible	40.2	28.5		8.5	77.2
Pelvis	258.8	445.5		74.7	779.0
Upper leg bone	201.9	669.3	277.4	108.8	1257.4
Lower leg bone	470.5	489.2	184.8	128.8	1273.3
Total volume	2158.8	3761.3	611.1	708.4	7239.6

Cart/misc: Cartilage + miscellaneous tissues
Ribcage: Ribs, sternum, clavicles and scapulae
med YBM: medular yellow bone marrow in the shafts of the longbones

Tables 5 and 6 show theoretical distributions of skeletal tissue volumes for the reference adult male and female, respectively, which have been calculated with the data from tables 3 and 4. The volumes of the miscellaneous tissues have been added to the volumes for cartilage.

Table 6. Theoretical volume distribution of skeletal tissues for the adult female

ICRP-based adult female Skeletal region	Cortical bone cm^3	Spongiosa cm^3	med YBM cm^3	Cart/misc cm^3	Total cm^3
Lower arm bone	118.8	94.6	38.4	32.4	284.2
Upper arm bone	50.9	150.7	57.6	27.2	286.4
Ribcage	177.0	343.3		59.8	580.1
Spine	130.0	829.9		117.6	1077.5
Skull	307.9	190.9		68.9	567.7
Mandible	29.3	21.6		6.9	57.8
Pelvis	181.7	340.6		61.4	583.7
Upper leg bone	162.1	502.2	198.3	91.2	953.8
Lower leg bone	377.1	358.8	132.2	110.4	978.5
Total volume	1534.8	2832.6	426.5	575.8	5369.7

Cart/misc: Cartilage + miscellaneous tissues
Ribcage: Ribs, sternum, clavicles and scapulae
med YBM: medular yellow bone marrow in the shafts of the longbones

As an example, the calculational procedure which created the distribution of skeletal tissue volumes in tables 5 and 6 will be demonstrated for the spine of the adult male:

Application of the RBM mass fraction

From tables 3 and 4 one can calculate the amount of RBM mass in the spine as 1170 g x 0.422 = 493.7 g, or the RBM volume in the spine as 493.7 g / 1.03 g cm^{-3} = 479.3 cm^3.

Application of the cellularity factor

According to the cellularity factor from table 4 the RBM volume of 479.3 cm^3 represents 70% of the total marrow volume in the spine. Therefore the YBM volume in the spine is 479.3 cm^3 x 3/7 = 205.4 cm^3 , or the YBM mass in the spine is 205.4 cm^3 x 0.98 g cm^{-3} = 201.3 g.

Application of the male bone mass fraction

From tables 3 and 4 one can calculate the total mass of the spine as 9950 g x 0.190 = 1890.5 g. From table 3 one can calculate the mass for Cart/misc as (550 g + 250 g) / 9950 g x 1890.5 g = 152 g, or the volume for Cart/misc as 152 g / 1.128 g cm^{-3} = 134.8 cm^3.

Application of the mass ratio between cortical and trabecular bone

With the ratios between cortical and trabecular bone from table 4 one can calculate the masses and volumes for cortical and trabecular bone in the spine as
cortical mass = (1890.5 g - 493.7 g – 201.3 g – 152 g) x 0.3 = 313.1 g, and the cortical volume as 313.1 g / 1.92 g cm^{-3} = 163.2 cm^3, and the
trabecular mass = (1890.5 g - 493.7 g – 201.3 g – 152 g) x 0.7 = 730.5 g, and the trabecular volume as 730.5 g / 1.92 g cm^{-3} = 380.5 cm^3.

The spongiosa volume is: 479.3 cm^3 + 205.4 cm^3 + 380.5 cm^3 = 1065.2 cm^3

Application of this method to all 9 bones yielded 1036 g of YBM in all RBM containing bones. Taking into account the total YBM mass from table 3 one finds 2480 g – 1036 g = 1444 g of YBM which is located in the shafts of the long bones, in the spongiosa of the lower part of the upper long bones and in the lower long bones. These regions of spongiosa do not contain RBM. Finally, using the bone mass fraction of the longbones, and anatomical data from the CT images and the textbooks it was possible to determine the volume of the YBM in the shafts of the long bones, also called medular YBM, shown in column 4 of tables 5 and 6. The idea was, that the segmentation of the skeleton into cortical bone, spongiosa, medular YBM and cartilage should take the volumes shown in tables 5 and 6 into account as far as skeletal anatomy would permit to do so.

In the bones of the human skeleton spongiosa is usually surrounded by regions of cortical bone. Measurements on cortical bone thickness in various bones in the CT images used for the design of the MAX and the FAX phantom have shown that for both gender ca. 1.2 mm can be considered as a minimum thickness for cortical bone covering the spongiosa. This value has been confirmed independently by similar measurements performed by Brindle and Bolch (2005). However, a cortical bone thickness of 1.2 mm cannot be represented by a 3.6 mm cubic voxel. Therefore the voxel matrizes of both phantoms were re-sampled in order to achieve a 1.2 mm cubic voxel matrix. The re-sampling procedure divided each dimension of a 3.6mm cubic voxel of the MAX and the FAX phantoms by 3, which gave 3 x 3 x 3 = 27 1.2

mm cubic voxels for every 3.6mm cubic voxel. With this finer voxel resolution it became possible to realize anatomically meaningful distributions between cortical bone voxels and spongiosa voxels, as well as between skin voxels and adipose voxels. For example, in the MAX and the FAX phantoms the absorbed dose to the skin was calculated with a special algorithm in the first 1.5 mm and 1.2 mm depths of the surface voxels, respectively, because the voxel depth of 3.6 mm is not representative for the depth of the skin. In the new MAX06 and FAX06 phantoms the skin absorbed dose is now calculated as the absorbed dose to the 1.2 mm cubic surface voxel layer, i.e. averaged over a depth of 1.2 mm for both phantoms.

3. Results

The MAX06 phantom

For the most part, the skeleton of the MAX phantom is the skeleton of the VOX_TISS8 phantom (Zubal 2001). Table 7 shows the total volumes of bones and bone groups for the MAX phantom together with the ICRP-based data from table 5.

Table 7. Comparison of bone volumes between the MAX phantom and the ICRP reference adult male

Adult male Skeletal region	MAX cm**3	ICRP-based cm**3	Difference in %
Lower arm bone	308.0	410.9	-25
Upper arm bone	600.2	428.9	+40
Ribcage	1537.2	894.8	+72
Spine	1131.1	1362.2	-17
Skull	497.0	754.9	-34
Mandible	102.4	77.2	+33
Pelvis	1020.0	779.0	+31
Upper leg bone	1132.0	1257.4	-10
Lower leg bone	1597.7	1273.3	+25
Total	7925.6	7239.6	+9

Ribcage: Ribs, sternum, clavicles and scapulae

The percentage deviations in the last column are significant, especially for RBM containing bones, like the ribcage, the skull, the mandible and the pelvis. At the first release of the MAX phantom (Kramer et al 2003) the skeleton basically was not changed, because of the requirements of the CT number method as explained above, and also because the overall volume of the MAX skeleton deviated only 9% from the ICRP-based total skeletal volume. But now it was felt that a segmentation of skeletal tissues should be based on anatomically reasonable volumes for the main bones and bone groups.

The attempt to repair the falsely segmented MAX skeleton turned out to be extremely complicated, and showed that this process would probably take many months to achieve the objective. Therefore it was decided to “borrow” the FAX skeleton (Kramer et al 2004), and to increase the dimensions of this female skeleton to arrive at the dimensions of the male skeleton, at the same time observing the gender-specific mass ratios from table 4.

Table 8 shows the skeletal tissue volumes which have been segmented in the MAX06 skeleton. For some bones it was possible to realize the ICRP-based volumes from table 5 without compromising the skeletal anatomy. The total cortical bone volume of the MAX06 skeleton is 8.6% greater, and the total spongiosa volume is 4.9% smaller than the ICRP-based value from table 5, however for the total skeleton the volume equals the theoretical value.

Table 8. Volume distribution of the segmented MAX06 skeletal tissues

MAX06 phantom Skeletal region	Cortical bone cm^3	Spongiosa cm^3	YBM med cm^3	Cart/misc cm^3	Total cm^3
Lower arm bone	172.1	137.1	59.9	41.6	410.7
Upper arm bone	100.5	201.1	89.9	37.4	428.9
Ribcage	376.3	429.7		88.8	894.8
Spine	293.8	934.6		133.8	1362.2
Skull	422.5	249.0		73.0	744.5
Mandible	40.2	28.5		18.6	87.3
Pelvis	258.8	445.5		74.7	779.0
Upper leg bone	210.2	661.1	277.0	109.4	1257.7
Lower leg bone	470.5	489.1	183.7	130.9	1274.2
Total volume	2344.9	3575.7	610.5	708.2	7239.3

Cart/misc: Cartilage + miscellaneous tissues Ribcage: Ribs, sternum, clavicles and scapulae
YBM med: Medular yellow bone marrow in the shafts of the long bones

After completion of the segmentation of the skeletal tissues, the soft-tissue organs of the MAX phantom plus the newly segmented soft-tissue organs were assembled together with the MAX06 skeleton to form the new MAX06 phantom, which consists of 1461 transversal images, each of which has 474 pixel x 222 pixel, i.e. the phantom matrix has 153738108 voxel, 41461410 of which are filled with human tissues.

Figures 1 to 4 present images of the MAX06 phantom, which show especially some of the additionally segmented organs and tissues.

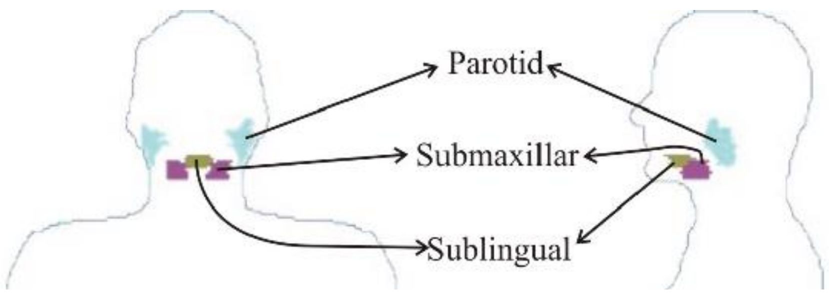


Figure 1. MAX06 phantom: Salivary glands

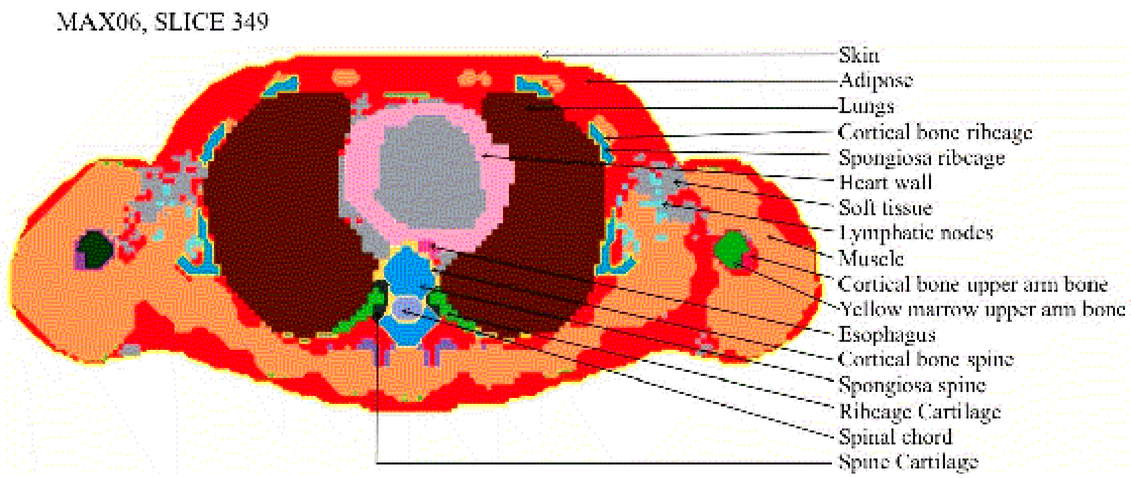


Figure 2. MAX06 phantom: Transversal image in the heart region

Table 9. Comparison of organ and tissue masses between the MAX06 phantom and the ICRP reference adult male

ORG/TISS ADULT MALE	ICRP89 [g]	MAX06 [g]	DIFF [g]
Adrenals	14.0	14.0	
Salivary Glands	85.0	85.0	
Oesoph.	40.0	40.0	
Stomach wall	150.0	150.0	
Sm Intest. wall	650.0	650.0	
Colon wall	370.0	370.0	
Liver	1800.0	1800.0	
Gallblader wall	10.0	10.0	
Pancreas	140.0	140.0	
Brain	1450.0	1450.0	
Heart wall	330.0	330.0	
Adipose	14500.0	14544.1	+ 44.1g = +0.3%
Skin	3300.0	3383.9	+ 83.9g = +2.5%
Muscle	29000.0	29000.0	
Lungs	1200.0	1200.0	
Skeleton	10500.0	9950.4	- 549.6g = -5.2%
Spleen	150.0	150.0	
Thymus	25.0	25.0	
Thyroid	20.0	20.0	
Kidneys	310.0	310.0	
Bladder wall	50.0	50.0	
Testes	35.0	35.0	
Prostate	17.0	17.0	
	64146.0	63724.4	- 421.6g = -0.7%
Breasts	25.0		
Tongue	73.0		
Larynx	28.0		
Extra thor.airw.		133.4	
GI content	900.0	900.0	
Gall.blad.cont	58.0	58.0	
Trachea	10.0	10.3	
Tonsils	3.0		
Ureter/Urethra	26.0		
Epididymes	4.0		
Pituary Gland	0.6		
Eyes	15.0	15.1	+0.1g = +0.7%
Optic nerve		1.6	
Blood	4900*		
Hard palate		33.6	
Feces		39.2	
Spinal chord		183.8	
	70188.6	65099.4	- 5089.2g = -7.3%
Connective Tiss.	2600.0	2600.0	
Lymphatic Nodes	730.0	365.0	-365g = -50%
	73518.6	68064.4	- 5454.2g = -7.4%
Soft tissue		4426.3**	
	73518.6	72490.7	- 1027.9g = -1.4%

* without lungs

** includes blood

Table 9 presents a comparison of the organ and tissue masses of the MAX06 phantom with those recommended in table 2.8 of the ICRP89 report. The main differences between the organ and tissue masses of the two data sets occur for the skeleton (cartilage) and the lymphatic nodes for reasons which have been explained above, and for some tissues, like extrathorarcic airways, spinal chord, etc., which are not listed in the table of ICRP89. As these differences partly compensate, the total weight of the MAX06 phantom turns out to be about half a kilogramm less than the reference weight of 73 kg, which corresponds to a difference of 0.7%, while at the same time the total sum of the ICRP recommended organ and tissue masses exceeds the reference weight by about half a kilogramm.

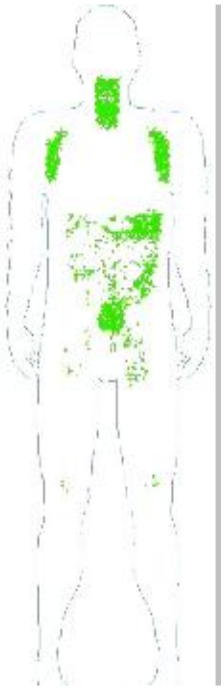


Figure 3. MAX06 phantom: Lymphatic nodes

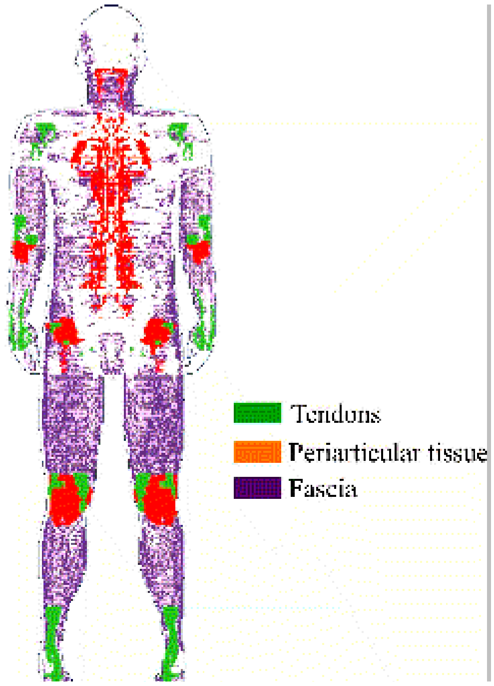


Figure 4. MAX06 phantom: Connective Tissues

The FAX06 phantom

Table 10. Volume distribution of the segmented FAX06 skeletal tissues

FAX06 phantom Skeletal region	Cortical bone cm^3	Spongiosa cm^3	YBM med cm^3	Cart/misc cm^3	Total cm^3
Lower arm bone	130.1	83.2	38.4	32.4	284.1
Upper arm bone	93.2	108.4	57.6	27.2	286.4
Ribcage	280.5	239.6		59.8	579.9
Spine	273.0	686.9		117.6	1077.5
Skull	278.1	220.0		59.7	557.8
Mandible	29.1	21.6		16.8	67.5
Pelvis	174.2	348.5		60.9	583.6
Upper leg bone	162.2	502.2	198.3	91.0	953.7
Lower leg bone	377.2	358.8	132.2	110.4	978.6
Total volume	1797.6	2569.2	426.5	575.8	5369.1

Cart/misc: Cartilage + miscellaneous tissues
Ribcage: Ribs, sternum, clavicles and scapulae
YBM med: Medular yellow bone marrow in the shafts of the long bones

Table 10 shows the skeletal tissue volumes segmented for the FAX06 phantom, and again for some bones the spongiosa and the cortical bone volume match the ICRP-based value exactly.The total cortical bone volume is 17.1% greater, the total spongiosa volume 9.3% smaller than the corresponding value from table 6. These numbers differ from those found for the MAX06 skeleton above, because both genders have different bone mass fractions as table 4 shows. Again the total skeletal volume equals the theoretical value from table 6.

Figures 5 and 6 present images of the FAX06 phantom, which show especially some of the the additionally segmented organs and tissues.

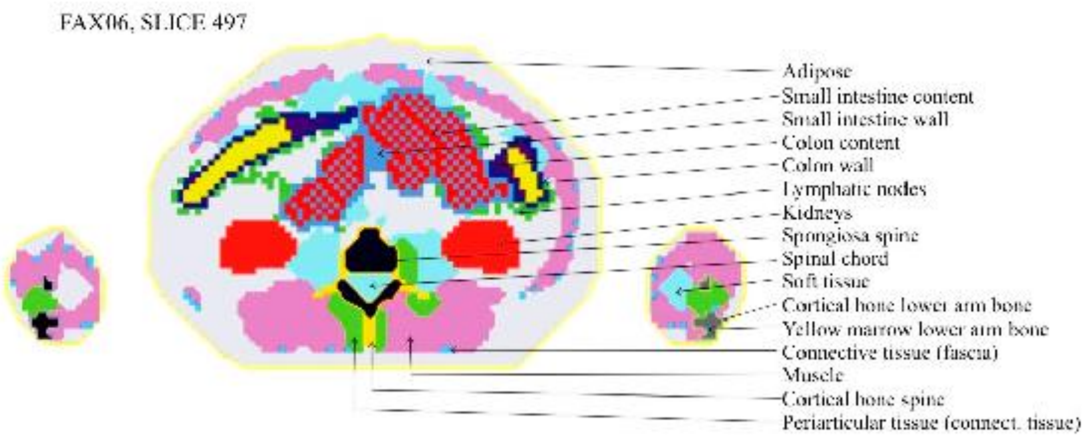
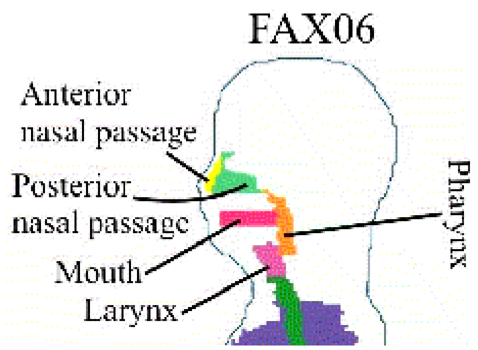


Figure 5. The FAX 06 phantom: Transversal image in the abdominal region



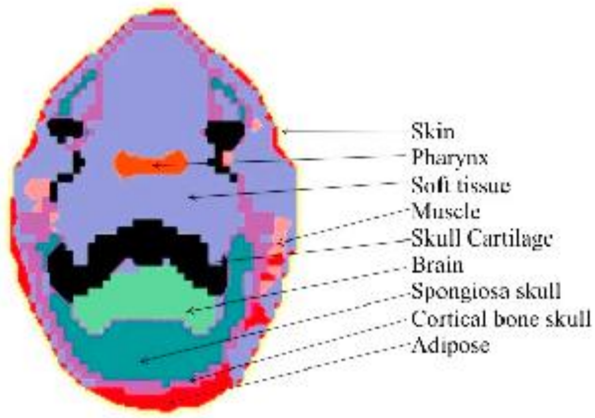


Figure 6a. The FAX06 phantom: Extrathorarcic airways

Figure 6b. The FAX06 phantom: Transversal image between mouth and nasal passage

The comparison of the organ and tissue masses between the ICRP reference adult female and the FAX06 phantom is presented in table 11. Here the sum of the ICRP masses from table 2.8 of Publication 89 (ICRP 2003) exceeds the reference weight of 60 kg by 193 g. Apart from the differences between the masses of the skeleton (cartilage) and the lymphatic nodes, the FAX 06 phantom has one kilogramm of fat less than the reference adult female. The FAX06 phantom consists of 1359 transversal images each of which has 474 pixel x 222 pixel, i.e. the phantom matrix has 143004852 voxel, 34208854 of which are filled with human tissues.

Table 11. Comparison of organ and tissue masses between the MAX06 phantom and the ICRP reference adult female

ORG/TISS ADULT FEMALE	ICRP89 [g]	FAX06 [g]	DIFF [g]
Adrenals	13.0	13.0	
Salivary Glands	70.0	70.0	
Oesoph.	35.0	35.0	
Stomach wall	140.0	140.0	
SMIntest. wall	600.0	600.0	
Colon wall	360.0	360.0	
Liver	1400.0	1400.0	
Gallblader wall	8.0	8.0	
Pancreas	120.0	120.0	
Brain	1300.0	1300.0	
Breasts	500.0	500.0	
Heart wall	250.0	250.0	
Adipose	19000.0	18000.0	-1000g = -5.3%
Skin	2300.0	2300.0	
Muscle	17500.0	17497.9	- 2.1g < - 0.1%
Lungs	950.0	950.0	
Skeleton	7800.0	7355.5	- 444.5g = - 5.7%
Spleen	130.0	130.0	
Thymus	20.0	20.0	
Thyroid	17.0	17.0	
Kidneys	275.0	275.0	
Bladder wall	40.0	40.0	
Ovaries	11.0	11.0	
Uterus	80.0	80.0	
	52919.0	51472.4	- 1446.6g = - 2.7%
Tongue	60.0		
Larynx	19.0		
Extra thor.airw.		112.6	
GI content	830.0	830.0	
Gall.blad.cont	48.0	48.0	
Trachea	8.0	8.1	+0.1g = +1.3%
Tonsils	3.0		
Ureter/Urethra	18.0		
Fallopian Tub.	2.1		
Pituary Gland	0.6		
Eyes	15.0	15.0	
Optic nerve		1.3	
Blood	3570*		
Hard palate		30.0	
Feces		33.6	
Spinal chord		72.2	
	57492.7	52623.3	- 4869.5g = -8.5%
Connect. Tiss.	2100.0	2100.0	
Lymph. Nodes	600.0	300.0	- 300g = -50%
	60192.7	55023.2	- 5169.5g = -8.6%
Soft tissue		3979.8**	
	60192.7	59003.0	-1189.7g = -2.0%

* without lungs

** includes blood

Figures 7 and 8 show three-dimensional representation of the skeltons and the body surface of the MAX06 and the FAX06 phantom, respectively.

Figure 7. Lateral and frontal three-dimensional view of the skeletons of the FAX06 phantom (on the left) and the MAX06 phantom (on the right)

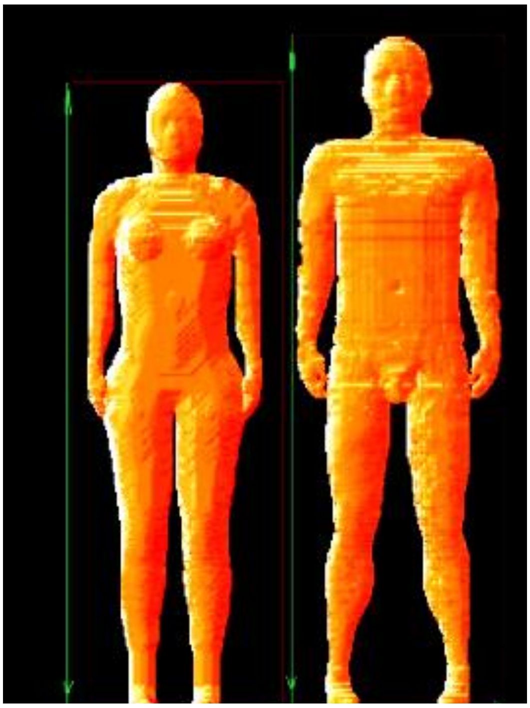


Figure 8. Three-dimensional frontal view of the surface of the FAX06 phantom and the MAX06 phantom

4. Conclusions

To our knowledge the MAX06 and the FAX06 phantoms are the first human models with skeletons which have been segmented into spongiosa, cortical bone, medular YBM in the shafts of the long bones, and cartilage+miscellaneous tissues. The two main skeletal tissues at risk, the RBM and the cells at the surface of the bone endosteum (also called " bone surface"), are located in the cavities of trabecular bone, i.e. that the segmentation of spongiosa is an important prerequisit for the developement of advanced methods of skeletal dosimetry, which could imply further segmentation of spongiosa into trabecular bone, marrow and bone surface in the future.
Actually, what was done here with respect to the distribution of skeletal tissues volumes is basically the same method already applied to the soft-tissue organs in the first release of the MAX and the FAX phantoms, namely adjustment of organ and tissue masses with regard to the ICRP-recommended values as closely as possible. In this sense the segmented skeletons of the MAX06 and the FAX06 phantoms are ICRP-based, i.e. that at least the total skeletal masses and volumes correspond to the reference values recommended by ICRP, and this is also the case for the skeletal tissues volumes of some of the bones or bone groups.

In order to achieve this segmentation in an anatomically correct manner it was necessary to re-sample the MAX and the FAX phantom, i.e. that each 3.6mm voxel of the old phantoms had to be replaced by 27 1.2mm voxels in the new MAX06 and FAX06 phantoms, which enabled the segmentation of spongiosa and cortical bone to be done according to skeletal anatomy, and at the same time observing the ICRP-based skeletal tissue volumes as much as possible. Finally, with the replacement of the the old MAX skeleton by a FAX-based skeleton, the updated MAX06 phantom has no segmented tissue or organ whatsoever anymore in common with the VOX_TISS8 phantom from Zubal (2001).
Apart from the skeletons, additionally adipose tissue, connective tissue, the extrathorarcic airways, the gall bladder, the heart wall, the lymphatic nodes, the prostate and the salivary glands have been segmented or adjusted in order to enable the calculation of the effective dose according to the revised definition in the upcoming recommendations of the ICRP.

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