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)

GSF MALE AND FEMALE ADULT VOXEL MODELS REPRESENTING ICRP REFERENCE MAN – THE PRESENT STATUS

Zankl M, Becker J, Fill U and Petoussi-Henss N
GSF – National Research Center for Environment and Health, Institute of Radiation Protection
Ingolstaedter Landstr. 1, 85764 Neuherberg, Germany
zankl@gsf.de; janine.becker@gsf.de; fill@gsf.de; petoussi@gsf.de

Eckerman KF
Oak Ridge National Laboratory, Life Science Division
1060 Commerce Park, Oak Ridge, TN 37831-6480, USA
eckermankf@ornl.gov

ABSTRACT

Studies performed by various research groups have shown that the more realistic organ topology of voxel models constructed from medical image data of real persons has an impact on calculated doses for external as well as internal exposures. As a consequence of these findings, the ICRP decided to use voxel models for the forthcoming update of organ dose conversion coefficients. These voxel models should be representative of an average population, i.e. they should resemble the ICRP Reference Man with respect to their external dimensions, their organ topology, and their organ masses. The first step towards a whole family of voxel models covering various age groups was to establish adult male and female voxel models representing the working population. To meet the ICRP requirements, workers at GSF constructed voxel models of a male and female adult, based on the voxel models of two individuals whose body height and weight resembled those of Reference Man. The organ masses of both models were adjusted to the ICRP data on Reference Man, without spoiling their realistic anatomy. The paper describes the method used for this process and the current status of the resulting voxel models.

Key Words: Voxel models, ICRP Reference Man, organ mass, anatomical realism

1 INTRODUCTION

Computational models of the human body – together with radiation transport codes – have been used for the evaluation of organ dose conversion coefficients in occupational, medical and environmental radiation protection. During the last two decades, voxel models were introduced that are derived mostly from (whole body) medical image data of real persons instead of the older mathematical MIRD-type body models. Among other laboratories, the GSF developed 10 voxel models of individuals of different stature and ages: 2 paediatric ones, 4 male and 4 female adult models [1-3]. It was shown that the schematic organ shapes of the MIRD-type phantoms presented an over-simplification, having an influence on the resulting dose coefficients, which – for some cases – deviate systematically from those calculated for voxel models.

For external radiation, the parameters influencing the organ doses are mainly: depth of the organ below the body surface, exterior shape of the trunk, and trunk diameter relative to the incoming radiation beam. For internal dosimetry, the influencing parameters are the relative position of source and target organs (for organ cross-fire) and organ mass (for organ selfabsorption). Hence, the International Commission on Radiological Protection (ICRP) decided to use voxel models for the update of organ dose conversion coefficients, following the forthcoming revision of the ICRP Recommendations. According to the ICRP philosophy, these voxel models should be representative of Reference Man [4] with respect to their external dimensions, their organ topology, and their organ masses.

To meet these requirements, at GSF two voxel adult reference models of a male and a female have been developed, based on the voxel models of two individuals whose body height and weight resembled those of the Reference Man. Approximately 90 organs and tissues were segmented, including also objects that were not previously contained in the MIRD-type phantoms, such as the main blood vessels, cartilage, and muscles. The organ masses of both models were adjusted to the ICRP data on Reference Man, without spoiling their realistic anatomy. The method used for this process and the resulting voxel models are described in the following.

2 MATERIALS AND METHODS

2.1 ICRP's Demands on the "Reference Voxel Models"

When it became clear that ICRP wanted to adopt voxel models representing ICRP Reference Man, first a list of organs and tissues had to be agreed upon that should be segmented in the voxel models. This organ list is given in Table I.

Table I. List of organs and tissues segmented in the voxel models of male and female Reference Man

No.	Organ	No.	Organ
1	Adipose tissue, head	**46**	Stomach wall
2	Adipose tissue, trunk	**47**	Stomach contents
3	Adipose tissue, arms	**48**	Small intestine wall
4	Adipose tissue, legs	**49**	Small intestine contents
5	Adrenals	**50**	Ascending colon wall
6	ET1 (anterior nasal passage)	**51**	Ascending colon contents
7	ET2 (extrathoracic airways, part 2)	**52**	Transverse colon (right) wall
8	Trachea	**53**	Transverse colon (right) contents
9	Bronchi	**54**	Transverse colon (left) wall
10	Bladder wall	**55**	Transverse colon (left) contents
11	Bladder contents	**56**	Descending colon wall
12	Blood vessels, head	**57**	Descending colon contents
13	Blood vessels, trunk	**58**	Rectosigmoid colon wall

14	Blood vessels, arms	**59**	Rectosigmoid colon contents
15	Blood vessels, legs	**60**	Heart wall
16	Humeri, upper half	**61**	Heart contents (blood)
17	Humeri, lower half	**62**	Kidney, left
18	Lower arm bones	**63**	Kidney, right
19	Hand bones	**64**	Liver
20	Clavicles	**65**	Lung, left
21	Cranium	**66**	Lung, right
22	Femora, upper half	**67**	Muscle, head
23	Femora, lower half	**68**	Muscle, trunk
24	Lower leg bones (incl. patella)	**69**	Muscle, arms
25	Foot bones	**70**	Muscle, legs
26	Mandible	**71**	Oesophagus
27	Pelvis	**72**	Ovaries
28	Ribs	**73**	Pancreas
29	Scapulae	**74**	Pituitary gland
30	Cervical spine	**75**	Prostate
31	Thoracic spine	**76**	Salivary glands
32	Lumbar spine	**77**	Skin, head
33	Sacrum	**78**	Skin, trunk
34	Sternum	**79**	Skin, arms
35	Brain	**80**	Skin, legs
36	Breast, adipose tissue	**81**	Spinal cord
37	Breast, glandular tissue	**82**	Spleen
38	Cartilage, head	**83**	Teeth
39	Cartilage, trunk	**84**	Testes
40	Cartilage, arms	**85**	Thymus
41	Cartilage, legs	**86**	Thyroid
42	Eye lenses	**87**	Tongue
43	Eyes	**88**	Tonsils
44	Gall bladder wall	**89**	Ureters
45	Gall bladder contents	**90**	Uterus

Although the internal geometry of a person depends on his or her posture, and one might expect the reference persons to be in an upright position, ICRP agreed to accept the voxel model geometry as-is, i.e. in the supine position, since it is believed that the dosimetric impact of the person's position would be limited. This means that the lungs have a higher density, acknowledging their condition of being compressed.

Furthermore, it is clear that some of the listed objects cannot be segmented correctly from medical image data sets, partly due to the limited resolution (such as very fine structures, e.g. the thin tissue layers representing the bone surface and extrathoracic airways), partly because of limited visibility (such as the entire blood pool, of which only larger blood vessels can be identified on the images).

In order to construct the reference voxel male (respectively female) model, an appropriate voxel model was used as a starting point, i.e. a model with external dimensions close to those of the Reference Man [4] since then the required modifications remained moderate, and the danger of distorting the anatomical relations was small. The following steps were then followed: (1) adjustment of the body height and the skeleton mass of the segmented model to the reference data by voxel scaling, (2) adjustment of the single organ masses to the reference values by adding or subtracting a respective number of organ voxels, and (3) adjustment of the whole body mass to the reference values by adding or subtracting a respective number of adipose tissue voxels.

2.2 Male and Female Adult Voxel Models "Golem" and "Laura"

As a basis for the male reference model, the male adult voxel model "Golem" [5] was used that was constructed from whole-body CT images of a 38-year old single individual patient, had a height of 176 cm and a whole body mass of slightly below 70 kg (male Reference Man: 176 cm; 73 kg) and was, thus, an eligible candidate for this procedure. The data set consisted of 220 slices of 256 x 256 pixels. The original voxel size was 8 mm in height with an in-plane resolution of 2.08 mm, resulting in a voxel volume of 34.6 mm^3. 122 individual objects were segmented (67 of these being bones or bone groups), including many – but not all – of the organs and tissues later identified in the ICRP characterization of Reference Man [4].

One of the tissues that cannot be segmented from image data of the given resolution, is the bone marrow which is contained in small cavities in the trabecular bone that are much smaller than the voxel size (in the order of a few hundred micrometers) [6]. An attempt was, however, made to assess the amount of bone marrow in each skeletal voxel from the CT grey values which show a much larger variation in bones than in any other tissue of the body. The method chosen to distinguish the relative amount of hard bone, yellow (YBM) and red bone marrow (RBM), for each skeletal voxel individually, was a linear interpolation. Voxels with grey values below 800 were assumed to consist of bone marrow only, voxels with grey values of 2040 and above were considered to consist of mineral bone only, i.e. they were considered to belong to a cortical bone region. All voxels with intermediate grey values were assumed to be located in trabecular bone regions and to consist partly of mineral bone and partly of bone marrow. The relative amounts of marrow and bone were estimated by linearly interpolating between the above mentioned limiting grey values. The lower extremities, including the lower halves of humeri and femora, do not contain red bone marrow; in these bone regions, all marrow was, therefore, assigned to YBM. In all other bones, the estimated amount of bone marrow was divided into equal volumes of RBM and YBM, due to lacking knowledge of more detailed data. Multiplying the volumes of hard bone, RBM and YBM that have been estimated with this method with 1.92, 1.03 and 0.98 g/cm^3, the densities given for these tissues in ICRU Report 46 [7], resulted in a mass of Golem's entire skeleton of 10.450 kg. The relative amounts of the different skeletal constituents depend, of course, on the limits chosen for the interpolation. The actual values were chosen such that the total RBM mass amounted to 1.6% of the whole body mass, the reference value suggested in ICRP Publication 70 [6].

The volumes of all soft tissue organs were also multiplied with densities from ICRU Report 46 [7].This resulted in individual organ masses, 33% of which agreed within 15% with the ICRP reference values valid at that time [8], 44% agreed within 50% tolerance of the ICRP values, and discrepancies exceeding 50% were found for 22%. These findings are comparable with those for two other adult male voxel models, the Visible Human [9] and Voxelman [10].

Golem had been segmented at the end of the last decade, and contained nearly all organs that were then considered to be relevant for dose calculations in radiation protection, i.e. those organs that contributed to the evaluation of the effective dose [11], the quantity considered to be approximately characterizing the overall radiation risk from a certain radiation exposure. Recently, segmentation of further structures took place to meet the new requirements.

Due to the limited resolution of the image data (8 mm slice thickness) it was difficult to identify small structures, such as blood vessels much smaller than the large main vessels in the trunk. Therefore, only a rather small proportion of the blood pool could be segmented. Furthermore, since no cartilage had been considered in the original segmented model, and due to the limited dosimetric importance of this tissue, also the effort towards its supplementary segmentation was limited.

The female reference voxel model was constructed on the basis of the voxel model "Laura". The primary data were derived from a high resolution whole body CT scan of a 43-year old patient of 167 cm height and a weight of 59 kg (corresponding ICRP reference values: 163 cm and 60 kg). The data set consisted of 174 slices of 5 mm width (head and trunk) and 43 slices of 2 cm width (legs), each with 256 x 256 pixels. The 2-cm slice images were re-sampled to result also in slices of 5 mm width, using data interpolation rather than simply repeating identical slices. The resulting data set consisted of 346 slices; the voxel size was then 5 mm height with an in-plane resolution of 1.875 mm; this corresponds to a voxel volume of 17.6 mm^3.

The segmentation was performed with a commercial software package, called "AnalyzeAVW 3.0" (Biomedical Image Resource, Mayo Foundation, Rochester, MN). The segmentation tools used primarily were grey-value thresholding (for body contours, cartilage, bones and the distinction between muscle and adipose tissue), region growing (lung tissue, air passages, and several soft-tissue organs), and manual segmentation involving Bezier spline functions that could be inherited from slice to slice, with subsequently adjusting the spline function to the organ outlines as found in the respective slices by moving its control points. A total of 88 objects were segmented; and the number of different bone sites was 19.

As described above for Golem, the composition of the skeleton was assessed on voxel basis. The thresholds for the linear interpolation for hard bone and bone marrow (820 and 2235) were again chosen such that the total amount of red bone marrow amounted to the reference value suggested in Table 39 of ICRP Publication 70 [6], i.e. 1.5% of the whole body mass for an adult female. Additionally, the cellularity factors (Table 41 of ICRP Publication 70) for the various bone sites, i.e. the relative amount of marrow in each bone that is still active (red), were taken into account to evaluate the proportions of hard bone, red and yellow bone marrow in each bone voxel. Multiplying the volumes of the different bone constituents with their respective densities resulted in a total skeleton mass of 8.5 kg (or 9.1 kg when the segmented proportion of cartilage is included).

2.3 Modifications to the Segmented Voxel Models to Create Voxel Models of ICRP Reference Man

2.3.1 Adjustment of body height and skeleton mass

As already mentioned above, the mass of the skeleton was 10.45 kg for Golem, compared to a reference value of 10.5 kg. It was our wish not to manipulate the skeleton shape in order to avoid introducing distortions in the "frame" of the body. Therefore, it was decided to adjust the skeleton mass by scaling the voxel dimensions. Since Golem's body height was in accordance with that of the male Reference Man, no modification was made to the voxel height. The necessary volume increase had then to come from the in-plane resolution which was, therefore, increased from 2.08 mm to 2.085 mm.

Laura was 168.5 cm high that is too tall compared to the reference value of 163 cm. Therefore, the first step was to change the voxel height from 5 mm to 4.84 mm to correct for this deviation. The skeleton mass of 7.8 kg that was aimed at (compared to Laura's original 9.096 kg) requested moreover a modification of the pixel side length from 1.875 mm to 1.765 mm. This resulted in a whole body mass of 53.2 kg.

2.3.2 Individual organ adjustment

Following the preparations described above, individual adjustment of the single organs was performed. For this purpose, a software package called "VolumeChange" was designed. It uses the programming language IDL ("Interactive Data Language" that is similar to "pvwave") and represents each organs by its surface voxels, i.e. all voxels having at least one neighbour that does not belong to the same organ. The volumes are then modified by shifting surface voxels – inward for decreasing, outward for increasing the respective volume.

The software "VolumeChange" can be worked in two modes – 3-dimensional or 2-dimensional. The user surface of the 3-dimensional mode is shown in Fig. 1. The individual organ names are listed on a 4-page panel – the first page showing the solid soft-tissue organs, the second the bones (and eventual additional organs that are excluded from the possibility of being partly overwritten), the third the walled organs and their contents. On these panel pages, each organ has a checkbox next to its name. If checked, the organ is displayed on the screen. The organ that has been the last to be checked is the one that will be modified by the subsequent actions. The fourth panel page displays the volume and mass of the organ to be modified or – upon request – the volumes and masses of all checked organs. Additionally, an empty field is shown where the user can enter the desired mass of the organ to be modified. If the value entered is different from the actual value, the organ surface will be changed.

In case of decreasing the organ mass, the "superfluous" voxels are by default replaced with adipose tissue; upon request also another organ can be selected that should replace these voxels. In case the volume has to be increased, by default only those neighbouring voxels can be overwritten that are either adipose or muscle tissue. If the user wants to have the possibility to change also such voxels that already belong to specific organs, he may chose to do so. In this case, for each affected organ the number of voxels is displayed in a separate window that would potentially be overwritten by the volume increase, and the user can accept or reject this for each organ separately. The functionality of "VolumeChange" will be described in more detail elsewhere.

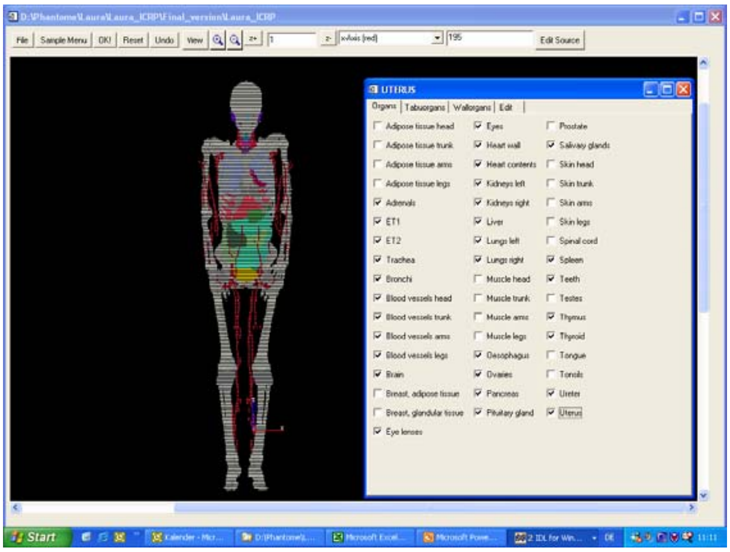

Figure 1: User surface of the 3-dimensional mode of "VolumeChange"

When adjustment of Golem's individual organs was started, it was noticed that the brain was too small compared to the reference value. Since it is tightly surrounded by the skull, it could not be increased by simply adding more voxels. However, other organs in the head turned out to be small as well, and Golem's head was remarkably narrow; therefore, it was decided to increase the size of the head as a whole. To accommodate the desired brain mass, the pixel side length in the head had to be increased to 2.269 mm. The head volume was then re-sampled to the same voxel size as the rest of the body; thus the voxel number in the head was increased, and a constant voxel size could be kept throughout the entire body. This resulted, of course, in an increased size of the cranium, and thus the total mass of the skeleton was increased to 10.585 kg, a value considered to be acceptable.

As for Golem, also for Laura it had to be noticed that the brain was too small compared to the reference value. In contrast to Golem, however, Laura's head had normal size. Therefore, it was decided – deviating from the general principle not to modify the skeleton shape – to increase the brain by replacing the innermost voxels of the cranium with brain voxels. To preserve more or less the original cranium volume, cranium voxels were then added by re-assigning previous soft-tissue voxels exterior to the original cranium. Thus, the original CT numbers of the cranium were, unfortunately but unavoidably, falsified, and the mean density of the cranium decreased. This was corrected by artificially increasing the CT number of each cranium voxel by a value of approximately 300, the difference of the average CT numbers of the original and modified cranium. This correction was necessary in order to preserve the correct relative content of the various bone tissues, especially red bone marrow, in the cranium.

Having overcome these initial difficulties, the individual organs were adjusted to the respective reference values one by one, beginning with those that were larger than reference size in order to make room for those that had to be enlarged. Some very fine structures could not be adjusted exactly to the reference values, due to limitations of voxel resolution and visibility. For most organs, however, a very close approximation of the reference values could be achieved. The only limitation then was due to the fact that each organ has to consist of an integer number of voxels. That means that the resulting volumes may deviate from the value aimed at by at most half a voxel volume, i.e. approximately 17.4 mm^3 for Golem and 7.8 mm^3 for Laura. The changes introduced to all the individual organs and tissue of Golem and Laura will also be described in more detail elsewhere.

2.3.3 Adjustment of whole body mass

After adjusting the individual organ and tissue masses as far as possible to the reference values, the final step was then adjusting the whole body masses to 73 and 60 kg for the male and female "reference" voxel models, respectively. In both cases, the whole body masses were lower than the value aimed at, so the body had to be "wrapped" with additional layers of adipose tissue. Towards the end of this procedure, small iterations had to be made, since each modification of the number of adipose tissue voxels resulted also in small changes to the skin mass, because the number of body surface voxels was modified. Finally, the whole body masses were adjusted to the reference values within 0.01 g.

3 RESULTS

The results of this work are voxel models that are close representations of the ICRP male and female adult Reference Man [4] and are therefore suitable to represent the average or standard Caucasian individual. The reference male model is 1.76 m tall and weights 73 kg, the reference female model 1.63 m and 60 kg, respectively. Except for few organs and tissues, the masses were adjusted individually to the data presented by ICRP with deviations below 0.02 g for Golem and 0.01 g for Laura, respectively. The reference male model contains 2,021,500 tissue voxels of 34.8 mm^3 size, whereas the reference female contains 3,914,647 voxels of 15.1 mm^3 size. Ninety separate organs and tissues are identified and the tissue types assigned to them are lung tissue, adipose tissue, soft tissue, skin, glandular tissue (breast), muscle tissue, red and yellow bone marrow, hard bone, cartilage and blood. Figure 2 shows 3-dimensional views of some organs of these models. To clearly distinguish these "reference" voxel models from the models from which they originate, new names were given to them: while they may still be subject to further modifications (see below), and names – that should be nice as well as meaningful – for the final models representing ICRP Reference Man are still being sought, these current versions are now called "Godwin" and "Klara", respectively.

Each of these "reference" voxel models was constructed on the basis of whole-body medical image data of one single individual that already had dimensions close to the ICRP Reference Man data, that means the original voxel models Golem and Laura had a self-consistent anatomy that had to be changed only moderately for Godwin and Klara, and thus distortion towards unrealistic external or internal proportions could be avoided.

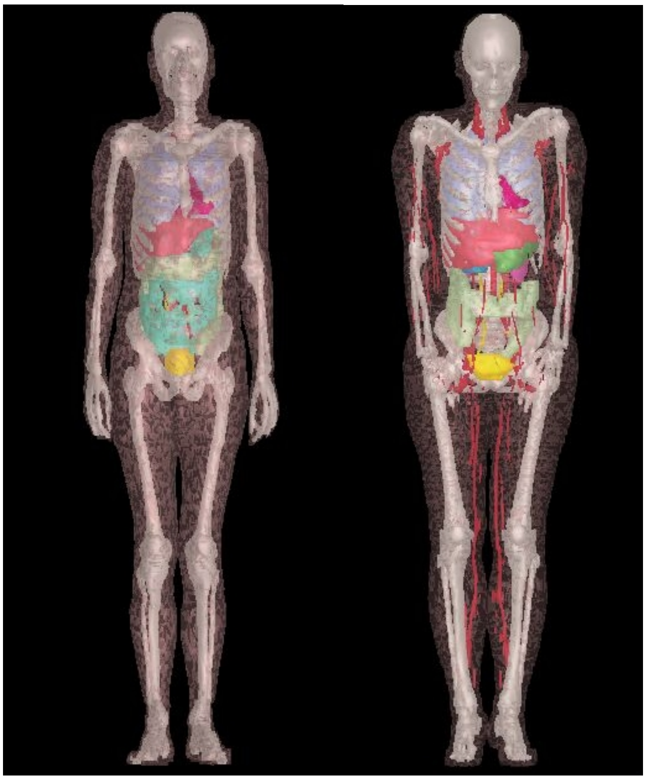

Figure 2: 3-dimensional view of Godwin (left) and Klara (right)

Since the patients' CT examinations usually are performed in supine position, the abdomen is flattened compared to when the person stands upright, the intestines are slightly shifted towards the thoracic region, and the lungs are, thus, compressed. Therefore, the lung volume is lower than it would be if the person were in an upright position. Correcting for these effects would mean the necessity for extensive modifications in organ positioning in the body. On the other hand, although this effect is qualitatively obvious, there is little or no quantitative information on the amount of positional changes of individual organs, since usually no comparable examinations of the patient in different positions are available. In view of these problems and believing that the dosimetric impact of the person's position would be limited, ICRP agreed to accept the voxel model geometry as-is, i.e. in the supine position. This means also that the adjustment of the lung mass to the reference value had not to be performed by modifying the volume, like for most other organs, but by increasing the lung density, acknowledging its condition of being compressed.

3.1 Organs that were Adjusted to Reference Values

The following is a list of all those organs that were exactly adjusted to the reference values, that means with deviations of less than 0.02 g for Godwin and 0.01 g for Laura: adrenals, bladder wall, bone (for Klara only, with a slight deviation of 85 g for Godwin), brain, breast (adipose as well as glandular tissue), eyes (including the reference value for the eye lenses), gall bladder (wall and contents together, as explained below), the walls of stomach, small intestine, ascending colon, transverse colon (right and left section), descending colon, and recto-sigmoid colon, the contents of the respective parts of the gastro-intestinal tract, heart (both wall and contents), kidneys, liver, lungs (adjusted by modifying the density, as mentioned above), muscle tissue, oesophagus, ovaries, pancreas, pituitary gland, prostate, salivary glands, spleen, teeth, testes, thymus, thyroid, tonsils, trachea, ureters, and uterus. These are approximately 88% of the segmented tissues.

3.2 Organs that could not be Adjusted to Reference Values

The following organs were not or could not be exactly adjusted to the reference values, due to various reasons:

Due to the large variability of the CT values in bones, it was difficult to clearly distinguish cartilage from "soft" bone voxels by grey value thresholding. Since this tissue is of limited importance, it was agreed that the effort towards its segmentation should be limited, and the reference mass values need not be achieved. The cartilage mass for Godwin is only 128 g, compared to the reference value of 1100 g; for Klara, an amount of 612 g of cartilage was segmented, compared to the reference value of 900 g.

There is a series of tissues that could not be properly adjusted to the reference masses due to the limited voxel resolution. In addition to the marrow cavities and the bone surface, which have not been represented in the mathematical MIRD-type phantoms either, these were:

(1) The extrathoracic airways which are very thin tissue layers with dimensions below voxel resolution. They were represented by one voxel layer around the respective airways and are, thus, at the correct locations. This is considered to be a clear improvement compared to the MIRD-type models where these tissues have been approximated by "surrogate" organs that are located elsewhere.

(2) The skin which is also represented by one layer of voxels covering the outer surface of the voxel models. The masses are 4404 g and 2708 g for Godwin and Klara, respectively, compared to 3300 g and 2300 g for the male and female Reference Man.

(3) The gall bladder wall which would not enwind the entire contents volume, if it were restricted to the reference mass value. Therefore, it was decided to adjust the entire gall bladder (wall + contents) to the reference value and define as many surface voxels as wall as are needed to fully envelope the contents.

Furthermore, only the larger blood vessels could be detected, since no contrast agent had been administered to the patients before the CT examination that would clearly improve the visibility of small blood vessels. For the female model with its higher voxel resolution slightly more blood vessels were visible than for the male model.

A different problem occurred for the adipose tissue: As described above, this tissue was used to "fill up" the difference between the sum of individual organ masses and the whole body mass that was aimed at. Since on the one hand – as described above – not all tissues could be properly adjusted to the reference values and on the other hand the organ and tissue masses given in ICRP Publication 89 do not exactly sum up to the reference whole body masses, the amount of adipose tissue that was needed to achieve the reference whole body mass deviates from the reference mass given for this tissue. Thus, Godwin has 20056 g of adipose tissue compared to a reference value of 18200 g, and Klara has 23720 g compared to 22500 g.

With the exception of skin and gall bladder wall, all tissues that could not be represented correctly have not been contained in the previous MIRD-type models either. It would, consequently, on no account be justified to consider their lacking agreement with the reference values as a disadvantage of the voxel type phantoms.

3.3 Present Status of Voxel Models Representing Male and Female Adult ICRP Reference Man

Figure 2 shows 3-dimensional views of selected organs of Godwin and Klara in their present appearance.

The voxel models Godwin and Klara have meanwhile been submitted to the DOCAL Task Group of ICRP Committee 2 for approval, and are now being subjected to an external review by several anatomists and other medical professionals. There may be further modifications necessary as a result of this process that cannot be predicted right now.

4 CONCLUSIONS

While in the past mathematical phantoms of the human body, the so-called MIRD-type phantoms having simplified shapes of the body and its internal organs, have been used for all types of organ dose calculations relevant to regulations concerning doses to a working population, a variety of voxel models became available in recent years that are based on medical image data of real persons. It was shown by a series of studies performed by different research groups that the voxel models do not only have the advantage of a much more realistic anatomy – which is quite obvious – but that this difference has also a clear impact on the calculated organ doses. These findings have persuaded the ICRP to employ this new type of computational body models for the next update of dose coefficients for external and internal exposures to ionizing radiation that is planned following the forthcoming revision of the ICRP Recommendations.

According to the ICRP philosophy, and moreover also due to the fact that the external and internal dimensions have been shown to influence the resulting dose calculations, it was clear that the voxel models to be adopted by ICRP should be representative of an average population; that means that they have to resemble the data on the adult Reference Man collected by ICRP with respect to their external dimensions, their organ topology, and their organ masses. The models Godwin and Klara described in this work present the current status of the effort undertaken at our working group upon request by ICRP's DOCAL Task Group to construct voxel models that fulfill this demand.

Independent of further modifications that may still be due, they have been successfully combined with EGSnrc and MCNPX [12, 13], which are among the most frequently used radiation transport codes in radiation protection and have quite different methods of geometry representation. Thus, these models have been proven to be applicable to various types of codes; it is, therefore, to be expected that they can be used by a large number of researchers without particular difficulties.

In summary, it can be concluded that the final versions of the male and female voxel models representing ICRP Reference Man data will fulfill all necessary requirements for computational models needed to perform the dose calculations planned by ICRP: (1) they represent average persons and are, thus, representative of large populations which is important for dose calculations on which future international regulations will be based; (2) they have a realistic anatomy which is a clear advantage compared to the MIRD-type phantoms that were previously employed for these calculations; and (3) they can be used together with a variety of radiation transport codes. Therefore, ICRP intends to adopt these models as the computational representations of Reference Man for the forthcoming updates of dose coefficients for workers and adult members of the public. Similar voxel models representing younger age groups of the public need to be constructed as well.

5 ACKNOWLEDGMENTS

This work was financially supported by the German Federal Office of Radiation Protection under contract no. StSch 4256. Furthermore, the authors would like to express their gratitude to Dr. D. Gosch, Dr. W. Witteck and Professor K. Friedrich, Zentrum für Radiologie, Universität Leipzig, as well as Dr. D. Hebbinghaus and Professor B. Kimmig, Klinik für Strahlentherapie, Universität Kiel, for providing the patient computed tomographic data.

6 REFERENCES

1. N. Petoussi-Henss, M. Zankl, U. Fill, D. Regulla, "The GSF family of voxel phantoms," *Physics in Medicine and Biology*, **47**, pp.89-106 (2002).
2. M. Zankl, U. Fill, N. Petoussi-Henss, D. Regulla, "Organ dose conversion coefficients for external photon irradiation of male and female voxel models," *Physics in Medicine and Biology*, **47**, pp.2367-2385 (2002).
3. U. Fill, M. Zankl, N. Petoussi-Henss, M. Siebert, D. Regulla, "Adult female voxel models of different stature and photon conversion coefficients for radiation protection," *Health Physics*, **86**, pp.253-272 (2004).
4. International Commission on Radiological Protection, *Basic anatomical and physiological data for use in radiological protection: reference values*, ICRP Publication 89, Pergamon Press, Oxford, UK (2002).
5. M. Zankl, A. Wittmann, "The adult male voxel model "Golem" segmented from whole body CT patient data," *Radiation and Environmental Biophysics*, **40**, pp.153-162 (2001).
6. International Commission on Radiological Protection, *Basic anatomical and physiological data for use in radiological protection: the skeleton*, ICRP Publication 70, Pergamon Press, Oxford, UK (1995).
7. International Commission on Radiation Units and Measurements, *Photon, Electron, Proton and Neutron Interaction Data for Body Tissues*, ICRU Report 46, International Commission on Radiation Units and Measurements, Bethesda, MD (1992).
8. International Commission on Radiological Protection, *Reference man: Anatomical, physiological and metabolic characteristics*, ICRP Publication 23, Pergamon Press, Oxford, UK (1975).
9. X. G. Xu, T. C. Chao, A. Bozkurt, "VIP-MAN: An image-based whole-body adult male model constructed from color photographs of the Visible Human Project for multi-particle Monte Carlo calculations," *Health Physics*, **78**, pp.476-486 (2000).

10. I. G. Zubal, C. R. Harrell, E. O. Smith, Z. Rattner, G. Gindi, P. B. Hoffer, "Computerized three-dimensional segmented human anatomy," *Medical Physics*, **21**, pp.299-302 (1994).

11. International Commission on Radiological Protection, *1990 Recommendations of the International Commission on Radiological Protection*, ICRP Publication 60, Pergamon Press, Oxford, UK (1991).

12. H. Schlattl, M. Zankl, "Dose distributions for cineangiographic examinations of coronary arteries," *Proceeding of The Monte Carlo Method: Versatility Unbounded in a Dynamic Computing World*, Chattanooga, TN, 17-21 April 2005, Vol. (2005).

13. V. Taranenko, M. Zankl, H. Schlattl, "Voxel phantom setup in MCNPX," *Proceeding of The Monte Carlo Method: Versatility Unbounded in a Dynamic Computing World,* Chattanooga, TN, 17-21 April 2005, Vol. (2005).