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The construction of computer tomographic phantoms and their application in radiology and radiation protection*

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Summary. In order to assess human organ doses for risk estimates under natural and man made radiation exposure conditions, human phantoms have to be used. As an improvement to the mathematical anthropomorphic phantoms, a new family of phantoms is proposed, constructed from computer tomographic (CT) data. A technique is developed which allows any physical phantom to be converted into computer files to be used for several applications. The new human phantoms present advantages towards the location and shape of the organs, in particular the hard bone and bone marrow. The CT phantoms were used to construct three dimensional images of high resolution; some examples are given and their potential is discussed. The use of CT phantoms is also demonstrated to assess accurately the proportion of bone marrow in the skeleton. Finally, the use of CT phantoms for Monte Carlo (MC) calculations of doses resulting from various photon exposures in radiology and radiation protection is discussed.

1. Introduction

It is of importance to determine the organ and tissue doses resulting from various exposures: diagnostic, therapeutic, occupational or environmental. The Monte Carlo method of calculating organ doses is very suitable for this purpose and has been extensively used. The construction of mathematically defined phantoms necessary for those calculations began over 10 years ago with the MIRD phantoms (1, 2) or other similar mathematical phantoms such as the ADAM and EVA of the GSF (3) for adults, and the Cristy phantoms for children (4).

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Using those phantoms and a Monte Carlo code, organ and tissue doses were calculated for diagnostic (5, 6, 7, 8) and therapeutic radiology (9, 10) and for various occupational exposures (11).

Although the body characteristics of these phantoms are in good agreement with those for the reference man, woman and children (12), they have some disadvantages related to the location and shape of organs and the form of the whole body.

In order to overcome these disadvantages and obtain more "realistic" phantoms, a technique based on computer tomographic data was developed.

This technique allows patient picture data to be converted into computer files which can be attached to a Monte Carlo code for the calculation of absorbed doses in organs and tissues, as well as three dimensional dose distributions. This improvement is of special importance with regard to the skeleton, because a better modelling of the bone surfaces and separation of hard bone and bone marrow can be achieved.

Additionally, three dimensional (3D) images from the CT data were constructed using the GSF Biomedical Image Processing code BIP (13) and the GSF version of the MOVIE BYU code (14); these images were prepared for use in radiology and also to demonstrate the anatomical accuracy of the mathematical CT phantoms.

Particular emphasis was given in the construction of phantoms for children due to the special features of the skeleton and of the distribution of bone marrow in the child's bones.

2. Construction of CT phantoms

So far, two CT phantoms were constructed for the research purposes of this work, one of an 8 week old baby and one of a 7 year old child. The baby was dead for 24 h and the child was a leukemia patient who was to receive a whole body radiation treatment before a bone marrow transplant. Compared to the required whole body irradiation with ^{60}Co, resulting in a dose of approximately 12 Gy, the irradiation from the whole body CT scan is negligible (it results in a dose of 0.03–0.05 Gy).

Table 1 gives some body characteristics of the baby and of the child. The whole body scans were performed at the children's hospital of the Ludwig-Maximilians-Universität in Munich, using a SIEMENS SOMATOM DR3 computer tomographic machine.

The baby was scanned with 142 slices of 4 mm thickness and the child with 144 slices of 8 mm thickness. The size of the volume elements (voxels) is then $0.85 \times 0.85 \times 4.00\ mm^3$ (ca. $2.9\ mm^3$) for the baby and $1.54 \times 1.54 \times 8.00\ mm^3$ (ca. $19\ mm^3$) for the child.

The scan picture data were first stored on floppy discs and then loaded into a VAX 11/750 computer where they were further processed using BIP (13) and MOVIE BYU (14) on the VAX computer with a VICOM subsystem.

Table 1. Body characteristics of the two patients whose CT data were used to construct the phantoms

Patients	Sex	Weight kg	Height cm	Width of the body cm	Front to back distance cm
8 week old baby	female	4.2	57	21.8	12.2
7 year old child	female	21.7	115	33.1	17.6

Each slice consisted of a matrix of 256×256 picture elements (pixels) with grey values between 0 and 4095. The grey values of the pixels represent different attenuation coefficients and respectively different densities of the corresponding volume elements.

To reduce the large mass of data and for storage reasons, each slice was renormalised to grey values between 0 and 255. Thus, one pixel requires only one byte storage instead of double the amount. In these pictures (in the following sections called "original" pictures) a grey value of 0 indicates air, while a value of 255 indicates hard bone.

In order to use these CT picture files for 3D imaging or in Monte Carlo calculations of organ doses, it is necessary not only to know the density of each voxel but also to determine to which organ or tissue every voxel belongs. For this purpose an identification number was given to each organ and tissue. For the mathematical models of the baby and child 54 and 64 different organs and collecting regions were considered respectively. New pictures of all slices were then constructed (now called "full" pictures) using the original pictures where most of the organ boundaries could be relatively well recognised from the differences in the tissue densities. In these new pictures every pixel was given a "grey value" according to the number of the organ to which the corresponding voxel belongs. These new "grey values" are not original grey values and do not give any information on the densities of the voxels. For most organs, this does not introduce a significant error because the voxels of a single organ do not greatly vary in their densities and one can assign a uniform density to each organ.

The only organ in which the voxels have greatly varying densities is the skeleton. Here different voxel densities represent different mixtures of hard bone ($\sim 1.8\ g/cm^3$) and bone marrow ($\sim 1.0\ g/cm^3$). As one is especially interested in the volume of and the dose to the bone marrow, it is necessary to calculate the percentage of hard bone and bone marrow in each voxel in the skeleton. The proportion of bone marrow in a voxel is determined using the original grey value of this voxel and by linearly interpolating between the grey value of bone marrow and the grey value of hard bone. As this is done in the MC program, one must retain for every CT slice the grey values of all bone sections in the original picture in addition to the "full" picture data of that slice.

It should be emphasised that seven different media are simulated according to their elemental composition: bone, bone marrow, soft tissue, skin, lung tissue, muscle tissue and air.

3. Three dimensional picture reconstruction

The CT data files produced by the BIP program were coupled to the MOVIE BYU (14) code, modified by the Image Analysis group of the GSF, to produce 3D images of bone structures and tissue and organ surfaces on a video display system.

In this case the organ boundary data have been applied to a three dimensional surface fitting "triangulation" procedure to obtain files for the skin, organ and skeleton surfaces in true 3D space, and not as basic CT slice "stepped" surfaces.

Figure 1 shows a reconstruction of the skin surface of the seven year old child and Fig. 2 shows the anterior view of the child's skeleton together with some organs.

It can be seen that these pictures have a very good resolution, i.e. 1.54 mm in width and depth respectively and 8 mm in height and can be used for diagnostic or other medical purposes such as reconstructive surgery. The organ in question can be viewed in 3D from every possible angle. Thus, once the CT is made, any projection desired can be reconstructed without subjecting the patient to further exposures.

4. Assessment of bone marrow distributions

One of the most important tissues for which the dose is needed and is difficult to calculate is the bone marrow. The reason for this is that the bone marrow distribution varies in the skeleton and that the bone marrow dose is increased by secondary electrons produced in the hard bone. These electrons pass into the bone marrow space and deposit energy in the bone marrow. The amount of energy deposited by the electrons depends on the incident photon spectrum, the size of the child, the thickness of bone and the degree of trabecular bone development in the child. The marrow space is different for and varies within each bone. That is, the relative volumes of the trabecular region occupied by hard bone and by marrow change with age and in a different manner for each region of trabeculation. Consequently, the degree of trabeculation influences strongly the level of bone marrow dose resulting from diagnostic examinations.

Fig. 1. Anterior three dimensional view of the skin surface of the seven year old child

Fig. 2. Anterior three dimensional view of the child's skeleton and main organs

Fig. 3. Single slice of the child CT phantom through thorax. Different colours indicate different organ identification numbers ("full" picture)

Fig. 4. Dose distribution for the CT slice shown in Fig. 3. The doses are calculated using the Monte Carlo technique and are normalised to maximum dose. The different colours represent different percentages of the maximum dose. The percentages are given in steps of 10% and the respective colours are assigned to them in ascending order as given in the scale, red representing the maximum dose

Fig. 1

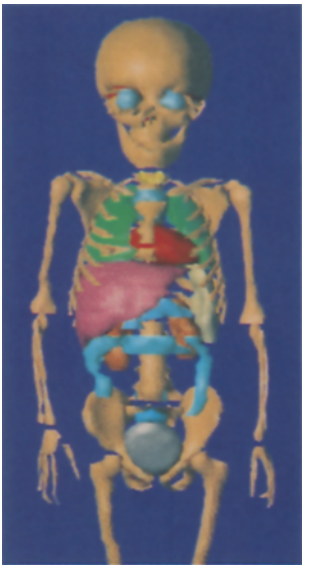

Fig. 2

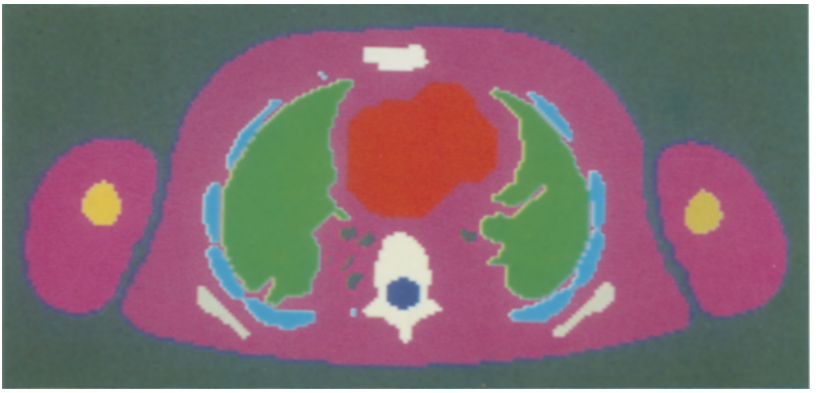

Fig. 3

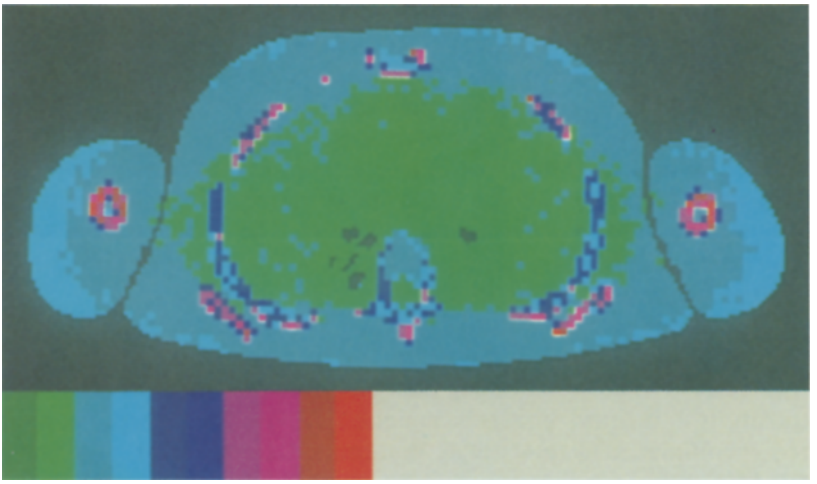

Fig. 4

Table 2. Active marrow in a given bone expressed as a percentage of whole body active marrow

Bone	8 week old (GSF)	Newborn (Cristy)	7 year old (GSF)	5 year old (Cristy)
Arm bones	9.4	10.7	9.4	7.5
Clavicles	1.0	0.8	0.7	0.9
Facial skeleton	3.0	2.5	1.3	1.6
Leg bones	15.8	23.7	32.6	24.6
Pelvis	5.2	9.3	10.3	18.6
Ribs	10.1	9.2	6.1	8.8
Scapulae	3.0	2.7	2.9	2.7
Skull	36.9	27.0	18.4	15.9
Spine	15.2	14.1	17.3	17.9
Sternum	0.4	0	0.9	1.7

Although it is not possible to model the complicated trabecular bone structure exactly, the percentage of hard bone and bone marrow in each voxel in the skeleton was accurately estimated from the CT pictures.

Table 2 shows the percentage of bone marrow for the baby and the child as estimated by this method. In the same table, the respective values as calculated by Cristy (15) are shown for a newborn and a 5 year old child.

5. Dose calculations using a Monte Carlo technique

5.1. Principles of the calculation

Each photon history starts at a certain point outside the body according to the source type that has been chosen for the irradiation (i.e. parallel source, point source, isotropic irradiation etc.). Further, an initial direction and an initial energy are assigned to each photon. For tracing the photon within the body a free path is selected before its first (next) interaction according to the energy of the photon and the media involved. The radiation interaction processes considered are photoelectric absorption, Compton scattering and pair production, each of them having a probability depending on the energy of the photon before the interaction.

The cross section data for the photon interactions are taken from ORNL (16). They have uncertainties which are approximately 2–4% and can be neglected when compared to other sources of error. The energy is deposited either at the point of photon interaction (KERMA approximation) or is transferred to secondary electrons which are pursued further.

Every point of energy deposition lies exactly within a voxel which specifies by its identification number the organ or tissue in which the energy is deposited. If this tissue is a bone, it is to be determined whether the energy deposition is in hard bone or in bone marrow. The proportion of bone marrow volume in that voxel is determined from its original grey value as already mentioned. According to that volume ratio each bone

voxel is divided geometrically into a hard bone and a bone marrow portion and, therefore, the energy deposition clearly takes place in bone or in marrow.

The tracking of secondary electrons in the MC calculation is modelled using the continuous slowing down approximation. That means, the energy loss at any point along the electron track is assumed to be equal to the stopping power.

The doses are finally obtained by dividing the total energy deposited in a tissue by the mass of this tissue.

At present the MC code, coupled to the CT phantoms, is running on the IBM 4381-2, Siemens 7561 and DEC VAX 11/750 computers. The amount of the total core space needed is about 4 Megabyte. The computer time used in such a study is 8000 to 80000 s for 5 million photons incident on the body depending on the photon energy and the way of simulation of energy deposition. Acceptable statistical standard deviations are then obtained for the dose equivalent to the smallest volume organs (less than 10%) and less than 1% for all main organs.

5.2 Organ doses for some common cases of pediatric radiology

5.2.1 Organ doses in X-ray diagnosis. Using the CT phantom of the baby, the organ and tissue doses were calculated for some typical diagnostic exposures in pediatric radiology. With respect to the irradiation of the baby, the high voltage, the field sizes and the projections were chosen to be representative for patients between the ages of four and ten weeks who had been X-rayed in the last ten years. The selection was reduced to five specific examinations, which were thorax anteroposterior (AP), abdomen AP, pelvis AP, skull AP and skull lateral (LAT). The high voltage spectrum used depended on the type of examination, being 65 or 70 kV (Filter: 1.5 mm inherent + 2.0 mm added Al) with a corresponding exposure area product which was in the range 0.8 to 8.0 $R \times cm^2$. The focus to film distance was taken as either 100 or 150 cm.

For the thorax and pelvis examinations no grid was used and the film was assumed to be in contact with the body, and for the other examinations with grids the film was set at 3.0 cm behind the body surface.

Table 3 summarises the irradiation parameters. The X-ray spectra which were used as an input for the Monte Carlo program were calculated using a theoretical method (17). In Table 4 the results of the calculations are shown.

Initial calculations using the CT mathematical models of the baby and child have already been performed to determine the doses due to CT examinations. The tissue dose distribution for a single CT slice is shown in Fig. 4 for the slice anatomy given in Fig. 3.

5.2.2. Organ doses in radiotherapy. Using the CT phantoms, it is also possible to perform calculations of doses resulting from radiotherapy. A whole body irradiation for leukemia treatment of the 7 year old child whose CT data were used to construct the child phantom was simulated.

Table 3. Exposure parameters used as input data for the dose calculation of the baby. AP = anteroposterior; LAT = lateral; FFD = focus to film distance

Type of Examination	Voltage kV	Height of Field cm	Width of Field cm	FFD cm	Exposure Area Product R × cm²	Entrance Exposure mR
Thorax AP	65	13.8	14.5	150	0.79	4.528
Abdomen AP	70	20.0	16.3	100	2.21	8.684
Pelvis AP	70	11.6	13.9	100	0.90	6.438
Skull AP	70	22.9	15.1	100	7.96	31.382
Skull LAT	65	19.8	20.1	100	5.86	20.462

Table 4. Doses in μSv to organs and tissues of an 8 week old baby for different X-ray procedures. The acronyms shown have the following meaning: AP = anteroposterior; LAT = lateral; BM = bone marrow

Body Organs and Tissues	Thorax AP μSv	Abdomen AP μSv	Pelvis AP μSv	Skull AP μSv	Skull LAT μSv
Bladder Wall	0.02	60.85	47.55	0.02	0.00
Brain	0.28	0.04	0.00	88.92	60.21
Eyelens	0.86	0.00	0.00	294.96	124.66
Heart	23.29	37.06	0.14	6.99	1.66
Lungs	18.59	23.78	0.11	16.64	2.68
Ovaries	0.02	52.14	42.09	0.03	0.00
Small intestine wall	0.13	68.98	25.78	0.26	0.07
Stomach wall	0.88	69.99	0.99	0.78	0.29
Testes	0.00	10.10	67.27	0.01	0.03
Thymus	27.37	4.38	0.06	51.66	6.04
Thyroid	34.15	1.12	0.02	211.63	90.33
Total Skeleton[a]	22.08	39.13	15.65	303.56	186.15
BM Pelvis	0.01	29.19	22.12	0.07	0.04
BM Ribs	7.53	13.26	0.10	11.67	1.46
BM Skull	1.43	0.07	0.00	86.92	52.06
Total Body BM	3.02	5.83	2.81	43.83	22.76

[a] Only hard bone

The procedure of the leukemia treatment before bone marrow transplantation is rather complicated due to the fact that, on the one hand, the patient should receive a rather uniform dose to the red bone marrow to kill all leukemia cells – the planned midline dose in the pelvis was 12 Gy – but, on the other hand, the lung dose should not exceed 9 Gy to prevent complications caused by pneumonia after the radiation treatment.

This is hoped to be achieved by five therapy sessions: three whole body irradiations on 3 successive days with a planned dose of 4 Gy each, where the patient is placed in the midplane of two ^{60}Co sources with a dose rate free in air of 5.88 R/min; two additional ^{60}Co treatments have to be

Table 5. Calculated doses in Sv to the red bone marrow, the lungs and the skeleton, resulting from the leukemia treatment of the seven year old child as described in the text

Organ	Dose (Sv)
Red Bone Marrow:	
Total	11.76
Arm bones	11.56
Clavicles	9.59
Facial Skeleton	11.81
Leg bones	13.48
Pelvis	11.76
Ribs	8.91
Sacrum	11.59
Scapulae	10.52
Skull	11.27
Spine	10.59
Sternum	10.14
Lungs	8.56
Skeleton	11.44
For the sake of comparison, the doses aimed to achieve were the following:	
Lungs	9 Sv
Midline pelvis	12 Sv

delivered to the trunk region AP (anteroposterior) and PA (posteroanterior) with a dose of 1 Gy each, where the lungs are protected by a blocking filter which is formed according to the shape of the lungs on the X-ray picture. Approximately 68% of the whole body irradiation is delivered laterally with 3 different shielding blocks of varying transmission for the head, trunk and lungs and 32% of the irradiation is delivered from AP and PA directions without any shielding.

To simulate this procedure with a Monte Carlo calculation, 14 different dose calculations had to be combined. For the dose calculation of the trunk region, the lung filter was simulated according to the shape of the lungs on the CT pictures.

The resulting doses are shown in Table 5 for the red bone marrow of the different bones, the lungs and the skeleton (compact bone). As it can be seen from the table, the lung dose is well below 9 Sv but the dose distribution in the red marrow is not uniform, varying from 8.91 Sv for the red marrow in the ribs to 13.48 Sv for the red marrow in the leg bones.

5.3 Environmental sources

Following radiation accidents, estimation of the organ and tissue doses due to contaminated ground sources might be needed. After the accident in Chernobyl, the doses due to a plane source contaminated with ^{137}Cs were calculated using the baby CT data. It should be noted that only gamma rays have been taken into account. The baby was chosen due to the increased

Table 6. Dose equivalent of organs and tissues of the baby phantom resulting from ground-contamination with ^{137}Cs, normalised to 1 Gy air Kerma at 1 m above ground. Only the gamma component is taken into account

Organ and tissue	DE (Sv)
Lungs	1.83
Ovaries	2.20
Red Bone Marrow	2.09
Skeleton	2.00
Testes	2.09
Thyroid	2.11
Trunk Skin	2.37
Whole Body	2.09

risk of babies from radiation and it was modelled to lie with its back on the ground. Table 6 shows the results of this investigation.

6. Conclusions

The computer tomographic phantoms are more realistic than any other type of phantoms available so far for dose calculations. They do not exactly represent all persons of a certain age and sex as the shape of the body and the shape and the location of the organs varies within people of the same age and sex, and even for different positions. However, as the shape and location of the organs is accurate for a particular person in a certain position, the phantoms constructed from these data give the best, so far, approach to reality. For organ dose calculations seven different media in the body are taken into account and the distribution of bone marrow in bone is calculated with acceptable precision.

The reconstructed three dimensional whole body images are of high quality and can be useful in diagnosis and, especially, to support preoperative decisions in reconstructive or cancer surgery.

The assessment of hard bone and bone marrow volumes in single bones using the computer tomographic data and suitable software give satisfactory results, when compared to other methods, for example Cristy's. The biggest discrepancy in the percentage of whole body active marrow in a given bone is with the skull of the 8 week old baby (i.e. 37% as estimated by the CT method and 27% as predicted by Cristy for a newborn baby). It was noticed, however, that the head of the baby was relatively large and this could explain the higher percentage of bone marrow in the skull.

It should be emphasised here that the main aim of our work is dose calculations. It is believed that with the present method the doses to the organs and particularly to the bone marrow are estimated with greater accuracy than with the MIRD type phantoms.

Some examples of dose calculations for typical X-ray examinations in pediatric radiology are given in Table 4. It is interesting to notice that for the skull X-ray examinations, the doses to the whole body bone marrow and the skeleton are high compared to other examinations, due to the high entrance exposure required.

Regarding the calculations of doses resulting from leukemia treatment (Table 5), it can be seen that the doses to the red bone marrow are varying. Although the dose to the whole body marrow is 11.8 Sv, the dose to the bone marrow of the ribs is only 8.9 Sv, which might not be sufficient to kill all red bone marrow cells.

In Table 6 some preliminary results are shown of doses to a baby due to ground contamination with ^{137}Cs (only the gamma component was taken into account). If we consider a typical air Kerma rate measured in Munich in June 1986, which was 0.35 μGy/h at 1 m above ground, it could be concluded that if the baby was lying on the ground for 60 h, it would get the same dose to the whole body marrow as if it had had a skull AP X-ray examination (Tables 4 and 6).

It should be noted that all the results of the dose calculations given in this paper are valid only for patients with physical characteristics closely correlated to those of the patients whose CT data were used to construct the phantoms. It is planned, however, using the same methods, to develop a whole family of three dimensional models of humans based on CT data. In this way, one can carry out realistic dose calculations of organ and tissue doses and risk estimates for every age group, in diagnostic and therapeutic radiology and generally for radiation protection purposes.

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