The Monte Carlo Method: Versatility Unbounded In A Dynamic Computing World
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REFERENCE KOREAN HUMAN MODELS: PAST, PRESENT AND FUTURE

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ABSTRACT

Tomographic models provide currently the most realistic representation of human anatomy for radiation dosimetry calculation since they are based on medical tomography data obtained from a real human subject. Since the dose distribution in a body is affected by the physical and anatomical characteristics of the body, it is worthwhile for each racial group to have its specific human model. The project on “Formulation of the Reference Korean for Radiation Protection Purpose” has been performed by the authors since 1999. The construction of the reference Korean tomographic model was an essential part of the project. Three male models (KORMAN, KTMAN-1 and KTMAN-2), and one female model (KORWOMAN) have been developed from tomography data of typical Korean healthy volunteers. The male and female subjects whose body dimension was close to average Korean values were recruited for this work. This article was intended to introduce several techniques and results accumulated at the moment. Acquisition and manipulation of medical tomographic images, CT (computed tomography) and MR (magnetic resonance), and semi-automated segmentation of organs and tissues from the images were explained. Mass of organs and tissues of the resulting Korean models were tabulated, and compared with those of Korean and Caucasian reference data. The selected results of organ dose conversion coefficients computed using Monte Carlo method were presented, and compared with those from reference Caucasian stylized model. Four Korean models are just “typical” Korean models, not “reference” models yet. In order to establish the reference Korean models, three requirements should be satisfied: body dimension and organ mass should be closer to Korean average values, voxel resolution should be so high as to represent small organs and tissues, and organ segmentation should be more sophisticated and automated. To address these requirements, 4th male tomographic model is being constructed from whole body sectional photographs with the vertical interval of 0.2 mm, which were obtained by medical doctors in Ajou University. The authors are convinced that faster computing machine, advanced whole body scanning modality, and automated segmentation techniques will accelerate a variety of applications.

Key Words: Korean, tomographic model, dosimetry, Monte Carlo

1 INTRODUCTION

Since the radiation dose distribution in human body cannot be directly measured, they have to be derived from measurable quantities with the help of dose conversion coefficients. The dose conversion coefficients have been calculated using the Monte Carlo simulation of the radiation transport in computational human model, which are the mathematical representation of the external body and internal organs and tissues.

The first heterogeneous human model, known as Medical Internal Radiation Dose (MIRD) phantom, was designed at Oak Ridge National Laboratory for the adult human male [1]. This model represented the shapes of human body and organs by the combinations of simplified mathematical equations describing planes, cylindrical, conical, elliptical, and spherical surfaces in three-dimensional space. Several modified and extended versions of the MIRD phantom have been developed thereafter, and utilized for dosimetry in diagnostic radiology examination, nuclear medicine, and radiation protection [2-5].

Although the stylized (also called MIRD-type) models have significantly contributed to computational radiation dosimetry, there are potential deviations in the model from accurate human anatomy. Particularly, in case of those organs or tissues having complicated geometries, it is difficult to realistically represent them by simplified geometrical equations used in the stylized models. As an approach to overcome the problem, there have been efforts to develop tomographic (also called voxel) model, which very precisely describes both the shape of the body and of the internal organs by using tomographic image data. They provide currently the most realistic representation of human anatomy for radiation dosimetry calculation. The tomographic models were first introduced by Gibbs et al. and several tomographic models have been constructed by different investigators during the last decade [6]. Information of the currently existing tomographic models is summarized in the review article of Caon [7]. More recently, male and female tomographic models, modified to conform to the dimensions and anatomical measurements of ICRP Reference Man have been developed and published by Kramer et al. [8-10].

Since the dose distribution in a body is significantly affected by the physical and anatomical characteristics of the body, it is worthwhile for each racial group to have its specific human model. The project on “Formulation of the Reference Korean for Radiation Protection Purpose” has been performed by the authors since 1999. The objective of this project was to establish the reference Korean data including body dimension, organ position and volume, and organ composition, and to develop dosimetry calculation procedure using the reference Korean data. The construction of reference Korean stylized and tomographic models has been an essential part of the project.

Three male models (KORMAN, KTMAN-1 and KTMAN-2), and one female model (KORWOMAN) have been developed from tomography data of typical Korean healthy volunteers. This article was intended to introduce techniques and results accumulated during the construction of Korean models. Acquisition and manipulation of medical tomographic images and semi-automated segmentation of organs and tissues from the images were presented. Major features including body dimension and mass of organs and tissues were tabulated, and compared with those of Korean and Caucasian reference data. The selected results of organ dose conversion coefficients computed using Monte Carlo method also were presented, and compared with those from reference Caucasian stylized models.

2 MATERIALS AND MATHODS

2.1 Acquisition of MR and CT data

To construct tomographic models close to Korean average adults, healthy volunteers whose height and weight were close to Korean average values were recruited. The Survey of National Physique Standard has been carried out to obtain Korean average body dimension by Korean Agency for Technology and Standards since 1979. In the recent 4^{th} survey, the body size data of 13,062 Koreans (6,578 males and 6,484 females) were obtained [11]. The average height and weight of Korean adult were 170.9±3.7 cm and 67.9±4.8 kg for male, and 160.0±4.0 cm and 54.1±4.8 kg for female. The body dimensions of the recruited male and female subjects were within the range of the average values. Age and body dimension of recruited volunteers, scanning modality, and covered area of scanning were tabulated in Table I.

Table I. Age, height, and weight of recruited volunteers, tomography modality used to obtain anatomic data, and covered area of scanning.

Name of model	Sex/Age	Height/Weight	Modality	Covered Area
KORMAN	Male/30	170/68	MRI	Mid thigh and up
KORWOMAN	Female/35	160/55	MRI	Mid thigh and up
KTMAN-1	Male/25	172/65	MRI	Whole body
KTMAN-2	Male/35	172/68	CT	Whole body

The 30-year-old male (KORMAN) and 35-year-old female (KORWOMAN), were scanned using Siemens MagneTom vision 1.5T. Since total time required for the arrangement and scanning was several hours, the subjects were so fatigue that unclear MR images were obtained especially for internal organs in torso region. In case of 25-year-old male (KTMAN-1), the same MR scanner was used and 537 slices of transversal and sagittal MR images covering whole body were obtained. At this time, total time required for the arrangement of subject and image acquisition was also approximately 9 hours. However, the image acquisition was divided into 3 times to reduce volunteer's fatigue. Clearer MR images of torso region than the previous two cases were obtained. The arms were stretched upward for this male subject since the bore of the MR scanner was too small for him to enter with arms. Therefore, the arm structure was absent in the resulting MR images.

CT images of the 35-year-old adult male (KTMAN-2) were acquired using fusion PET (Positron Emission Tomography) machine, Siemens Somatom Emotion Duo system. Fusion PET scanning service has been performed at Radiation Health Research Institute of Korea since 2003. The subject was recruited for cancer diagnosis. It was approved by radiologists that no cancer was found in the resulting fusion PET images. Total time required only for CT image acquisition was about 20 minutes. 1788 slices of transversal whole body CT images were obtained at 1 mm interval, and 68 slices of them were overlapped. 343 slices were selected at 5 mm interval for construction of whole body tomographic model.

2.2 Data segmentation methods

Segmentation and indexing of cross-sectional images required specialized anatomic knowledge. The authors referred several anatomical atlas to segment organs and tissues from source images. The results of segmentation were reviewed by an experienced radiologist. The image processing software, Photoshop7.0^{TM} (Adobe Systems, Inc., San Jose, CA) and screen digitizer PL-400^{TM} (WACOM Co., Ltd, Japan) were adopted for image segmentation. Photoshop7.0 is well known for image manipulation and provides several functions for importing and exporting images data, as well as sophisticated image processing tools with a graphical user interface. Tomographic images, MR and CT in Digital Communications in Medicine (DICOM) format were converted into Joint Photographic Coding Experts Group (JPEG)-formatted images files using preprocessing program, and then were imported to Photoshop7.0. Three different segmentation methods were applied depending on visibility of the organs and tissues as followings.

Manual drawing was applied to organs and tissues whose boundaries with surroundings could not be seen or whose contents provided too unclear gray contrast to apply region growing method. Most of organs and tissues in MR images were fully manually segmented. In case of CT images, thyroid, large (upper and lower) and small intestine, eyes, esophagus, stomach, spleen, pancreas, kidneys, adrenals and testes were segmented by manual drawing with the help of anatomical atlas.

Region growing method was applied to the organs and tissues clearly separated from the surrounding tissues or the contacted organs by their contrast. *Magic wand tool* of Photoshop7.0 was used for region growing process. This tool could select the area with the same contrast by manually selecting a starting seed point in the center of organs in consideration. Brain, fat, lungs, liver, heart, and bladder were semi-automatically segmented using this method.

Thresholding method was applied to skeletal tissues and muscle in CT images. *Color range tool* of Photoshop7.0 automatically segmented those tissues by setting minimum and maximum gray values. Bone tissues with white color were segmented from surrounding gray organs and tissues. Muscle and most of organs had similar gray color range. After muscle including organs was segmented, then organs were separated and indexed from muscle. In case of MR images, only muscle was segmented using this method since skeletal tissues on MR images were not clearly identified.

Example of segmentation for the CT image of lower trunk slices was shown in figure 1. As shown in the figure, bone structure was hard to recognize in MR image. Manual drawing was inevitable to segment bone from MR image whereas full automated segmentation was applied to CT image using thresholding method. Full segmentation of the MR images of KORMAN, KORWOMAN and KTMAN-1 took about 1 year, respectively, whereas 6 months for the CT images of KTMAN-2.

2.3 Monte Carlo simulation

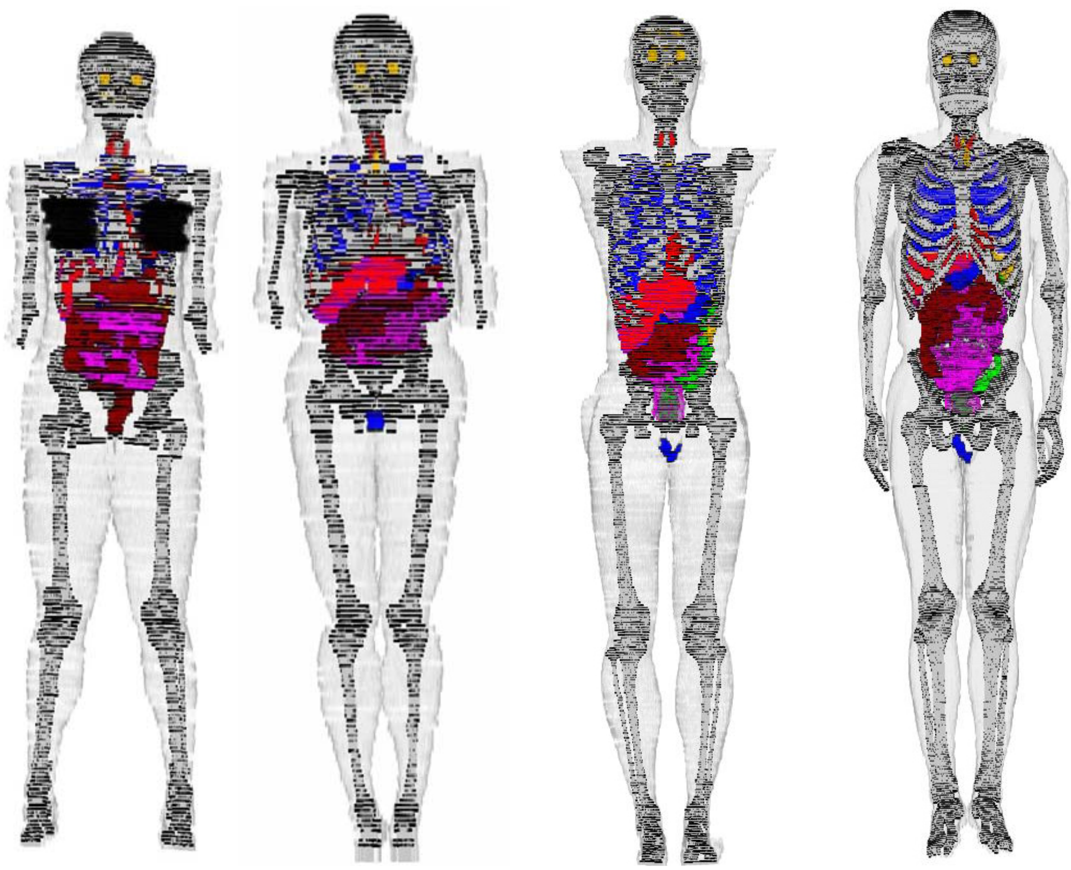
The segmented images in PSD format generated by Photoshop7.0 were converted into two-dimensional RAW-formatted binary arrays. Then, the final three-dimensional voxel matrix was constructed by stacking the two-dimensional pixel slices. The voxel matrix was ported to Monte Carlo particle transport code, MCNPX2.4 [12]. A preprocessing code, *Voxelmaker2.0* was written in IDL5.6 programming language to stacking two-dimensional slices, and to convert three-dimensional binary voxel data into the geometry input deck for the MCNPX2.4. The four different types of elemental tissue compositions were considered for the calculation: soft tissue (1.05 g cm-3), lung (0.26 g cm-3), skin (1.09 g cm-3), and bone (1.3 g cm-3). The average tissue compositions and densities recommended by International Commission on Radiation Unit and Measurement (ICRU) were used to describe the tissues [13]. Most organs were composed of soft tissue: adrenals, bladder, brain, colon, esophagus, heart, kidney, liver, ovaries, pancreas, skin, small bowel, spleen, stomach, testes, thymus, thyroid, and uterus. Since bone surface could not be described with the voxel resolution used in Korean models, the average dose to the bone was taken as a conservative estimate of the dose to bone surface.

Figure 1. Example of segmentation for the CT image of lower trunk slices

3 RESULTS AND DISCUSSIONS

3.1 Typical Korean tomographic models

Four typical Korean tomographic models were constructed by using MR and CT images of four different healthy volunteers (three males and one female). The three-dimensional frontal views of the Korean tomographic models including internal organs and skeletal tissues were depicted in figure 2. KORWOMAN was the first Korean tomographic model, of which legs were those of VHP (Visible Human Project) man since MR images of legs were not available. Since transversal MR images of legs for KORMAN were also not available in original images, those were reconstructed from sagittal images available. KTMAN-2, the first CT-based Korean tomographic model, shows the most detailed shape of skeletal tissues and internal organs thanks to high resolution CT images. The voxel size was $2\times2\times8$ mm^3 and $2\times2\times10$ mm^3 for KORWOMAN and KORMAN, respectively. Both KTMAN-1 and KTMAN-2 had the voxel size of $2\times2\times5$ mm^3. Table II tabulated the mass of organ and tissues in Korean models, and comparison with those of Caucasian and Korean reference data.



(a) KORWOMAN (b) KORMAN (c) KTMAN-1 (d) KTMAN-2

Figure 2. Three-dimensional frontal views of the Korean tomographic models.

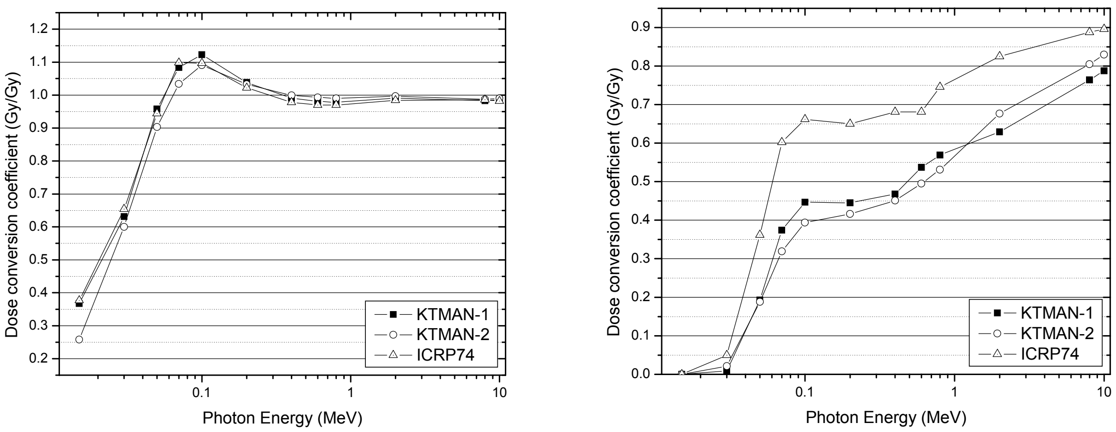
Table II. Mass of organs and tissues in Korean tomographic models, and comparison with reference values of Caucasian and Korean.

Organ/Tissue	KOR-WOMAN	KORMAN	KTMAN-1	KTMAN-2	Reference Korean		Reference Caucasian	
					M	F	M	F
Adrenal	11.0	13.7	8.9	12.1	10	10	14	13
Bladder[3)]	52.7	64.8	37.2	30.8	45	35	50	40
Brain	1353.5	1790.5	1303.0	1403.3	1370	1230	1450	1300
Breast	260.9	-	-	-	-	260	-	500
Colon	792.9	331.1	332.5	481.0	-	-	370	360
Esophagus	31.8	32.3	41.1	41.7	40	40	40	35
Eye ball	19.4	24.6	18.7	16.8	15	15	15	15
Heart	802.5	800.9	891.7	785.3	340[1)]	300[1)]	840	620
Kidney	296.4	316.0	295.2	279.2	260	230	310	275
Liver	1174.2	1579.9	1488.7	1199.6	1800	1400	1800	1400
Lung[2)]	661.9	986.2	1318.7	892.6	1000	920	1200	950
Ovaries	13.3	-	-	-	-	11	-	11
Pancreas	95.8	122.2	56.4	44.3	60	60	140	120
Skin	2351.8	2719.3	3031.4	3060.9	-	-	3300	2300
Small bowel[3)]	533.2	373.5	373.7	630.0	-	-	650	600
Spleen	159.6	103.2	240.8	160.0	200	160	150	130
Stomach[3)]	114.6	116.8	163.8	139.9	150	140	150	140
Testes	-	25.4	22.8	23.9	32	-	35	-
Thymus	-	25.2	-	1.2	-	-	25	20
Thyroid	19.8	17.5	14.3	10.3	20	17	20	17
Uterus	105.0	-	-	-	-	-	-	80

[1)] Mass of heart in reference Korean is tissue-only mass. Another data of heart mass are blood-included mass.
[2)] Mass of lungs in all models is tissue-only mass.
[3)] Contents free mass (wall only)

3.2 Organ dose calculation

Example calculation of dose conversion coefficients, organ absorbed dose per unit air kerma free-in-air (D_T/K_a) for some selected organs and tissues of KTMAN-1 and KTMAN-2 were presented in Figure 3. Dose conversion coefficients of ICRP74 which are mainly based on stylized human models were included for comparison [14]. Some organ dose data for KORMAN can be referred from published article [15]. Organ dose data for KTMAN-1 and KTMAN-2 has been submitted for publication. Complete data sets for all organs and models can be available on request. As expected, dose conversion coefficients of individual organs were significantly different from those of ICRP74 except for skin and skeletal tissues distributed through whole body. These differences revealed unrealistic representation of reference stylized models. Although difference of organ mass and position between Korean models and western reference ones caused insignificant discrepancies of organ doses for external dosimetry, typical Korean models will be more valuable for internal dosimetry where dosimetric quantities are sensitively affected by organ mass.



(a) Skin dose conversion coefficient (AP) **(b) Esophagus dose conversion coefficient (LLAT)**

Figure 2. Example of dose conversion coefficients for skin and esophagus using KTMAN-1 and KTMAN-2.

4 CONCLUSIONS

The project on "Formulation of the Reference Korean for Radiation Protection Purpose" has been performed by the authors since 1999. The construction of the reference Korean tomographic model was an essential part of the project. Three male models (KORMAN, KTMAN-1 and KTMAN-2), and one female model (KORWOMAN) have been developed from tomography data of typical Korean healthy volunteers. The male and female volunteers whose body dimension was close to average Korean values were recruited for this work. Several techniques and results accumulated during the project were presented in this article.

Four Korean models are just "typical" Korean models, not "reference" models yet. In order to establish the reference Korean models, the authors consider three requirements as follows should be satisfied. Firstly, organ mass as well as body dimension should be closer to Korean average values than the previous models. For this purpose, two approaches are possible. One is to adjust the organ shape of the existing models to agree with reference values. The other is to choose the best model among several models after constructing more Korean typical models. Secondly, voxel resolution should be so higher than that of the existing models as to represent tiny organs and tissues including additional radiosensitive organs and tissues which have been tentatively recommended by ICRP. Finally, organ segmentation should be so sophisticated and automated that subjectivity should be minimized. Morphological image technique also may be adopted to reduce human labor.

To address these requirements, the 4th male tomographic model is being constructed from whole body sectional photographs data. Whole body CT/MR/color photographs were obtained by the Visible Korean Human project of Ajou university school of medicine to build the most detailed digital image library of the reference Koran anatomy. A Korean male cadaver who was 33-years-old, and had body size close to Korean average values, the height of 171.8 cm and the weight of 55 kg, was donated. The cadaver was embedded, frozen, serially sectioned, and photographed by high resolution digital camera at 0.2 mm interval. Advanced automatic segmentation and morphological image manipulation techniques are being adopted. Several organs and tissues which were omitted in the previous models are being segmented in this model. Voxel resolution will be 0.2×0.2×0.2 mm^3.

Tomographic human models provide the most realistic and subject-specific representation at the moment. For radiation protection use, the advanced reference models including additional radiosensitive organs and tissues will be required for calculating reference dosimetric quantities. In case of medical use, however, patient-specific models which exactly represent a patient under consideration will be more required than reference model. The authors are convinced that faster computing machine, advanced whole body scanning modality, and automated segmentation techniques will accelerate a variety of applications.

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