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Development of Voxel Phantom Representing Reference Korean Female for Use in Radiation Protection Dosimetry

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This paper describes the procedures that have been used for the construction of the reference Korean female phantom, HDRK-Woman. The phantom was developed using the high-resolution color slice images obtained from an adult Korean female cadaver (160 cm, 52.35 kg). A total of 40 organs were segmented including the 27 organs specified in ICRP 103 for effective dose calculation. The voxel resolution of the unadjusted phantom was $2 \times 2 \times 2$ mm^3 (i.e., $261 \times 109 \times 825$ voxels). Then, the voxel resolution was changed to $2.0351 \times 2.0351 \times 2.0747$ mm^3 in order to adjust the height and total bone mass of the phantom to the Reference Korean data. Finally, the internal organs and tissue were adjusted with an in-house software program that had been developed for 3D volume adjustment of the organs and tissue. The developed phantom, HDRK-Woman, was then ported to MCNPX to calculate effective dose values for several irradiation geometries (AP, PA, and LLAT) of the broad parallel photon beam. The calculated effective dose values were finally compared with the results of the ICRP reference phantoms.

KEYWORDS: voxel phantom, reference Korean, Monte Carlo, segmentation

I. Introduction

Recently a reference Korean male phantom called 'High-definition Reference Korean-Man (HDRK-Man)' was developed in Korea[1] based on a set of high resolution serially-sectioned color images of Korean male cadaver. The phantom was adjusted to the Reference Korean data[2], including height, weight, and organ masses. However, it was impossible to calculate the effective dose values for the Korean workers owing to the absent of a reference Korea female phantom. Then, a female phantom was recently developed in Korea by a research project at Hanyang University in collaboration with Ajou University College of Medicine and Korean Institute of Nuclear Safety (KINS).

This paper describes the procedures that were used for the construction of the reference Korean female phantom, HDRK-Woman. The developed phantom was ported to the MCNPX Monte Carlo particle transport simulation code[3] to calculate effective dose values for several irradiation geometries (AP, PA, and LLAT) of the broad parallel photon beam. The calculated effective dose values were finally compared with the results of the ICRP reference phantoms.

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II. Methods
1. VKH anatomical images

For the development of the female phantom, a complete set of serially-sectioned color images was obtained from a 26-years-old Korean female cadaver (160 cm in height and 52.35 kg in weight, similar to 161 cm and 54 kg of the Reference Korean female data). The cadaver was serially sectioned at 0.2 mm intervals, except for the legs and feet for which the interval was 1 mm. A total of 5,901 photographic images of 0.1×0.1 mm^2 resolution were acquired from the cadaver. The high resolution color images provided very accurate anatomical information, when compared to CT and MRI images, for segmentation of the organs and tissue, especially for the small anatomical structures. CT images at 1-mm intervals were also acquired for use in bone segmentation.

2. Segmentation of organs

The segmentation work needs to be carefully performed and takes a huge amount of time. The color slice images selected for every 1-mm interval were used for organ segmentation. The majority of organs were manually segmented with a screen digitizer (CINTIQ 15X, WACOM Co., Ltd, Japan), whereas some organs distributed in the whole body and clearly distinguished, such as muscle and blood, were automatically segmented with Photoshop®CS4 (Abode Systems, Inc., San Jose, CA). The CT images were used for the segmentation of the skeleton system. Then, some highly complicated and erratically segmented structures caused by artifacts were corrected very carefully. Finally, a total of 40 organs were segmented including the 27 organs specified in ICRP 103[4] for effective dose calculation.

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Fig. 1 Comparison of unadjusted (left) and adjusted (right) alimentary system in 3D views.

Table 1 HDRK-Woman organs and tissue weight.

Organ	Mass(g)		
	HDRK-Woman	Reference Korean	Diff. (%)
Red bone Marrow	780	780	0.0 %
Large intestine	260	260	0.0 %
Lung	688	688	0.0 %
Stomach	122	122	0.0 %
Breast, adipose tissue	200	200	0.0 %
Breast, glandular tissue	300	300	0.0 %
Ovary	11	11	0.0 %
Bladder	30	30	0.0 %
Oesophagus	30	30	0.0 %
Liver	1212	1212	0.0 %
Thyriod	12	12	0.0 %
Bone	6408	6408	0.0 %
Brain	1403	1403	0.0 %
Salivary glands	62	62	0.0 %
Skin	4028	1800	123.8%
Adrenals	13	13	0.0%
Extrathoracic region	45	-	-
Gall bladder	17	17	0.0%
Heart	287	287	0.0%
Kidneys	290	290	0.0%
Lymphatic nodes	473	3800	-87.6%
Muscle	20000	20000	0.0%
Oral mucosa	31	-	-
Pancreas	58	58	0.0%
Uterus	70	70	0.0%
Small intestine	450	450	0.0%
Spleen	153	153	0.0%
Thymus	29	29	0.0%

3. Adjustment of height and skeletal mass

The voxel resolution of the unadjusted phantom was $2 \times 2 \times 2$ mm^3. The adjustment of the phantom for height and skeletal mass was carried out by changing the voxel resolution. The height of the unadjusted model (160 cm) was adjusted to the height of the reference Korean (161 cm) by increasing the size of the voxels from 2 mm to 2.0747 mm in the longitudinal direction.

There is no information available for the total skeletal mass in the Reference Korean data and, therefore, it was determined to use the equation given by Clays et al.[5] which relates total body weight with total skeletal mass. By using the equation, the total weight was calculated as 7.2 kg. The skeletal mass of the phantom was then adjusted to 7.2 kg (including RBM) by increasing the size of the voxels in the transverse directions, from 2×2 mm^2 to 2.0351×2.0351 mm^2. Consequently, the voxel resolution of the adjusted phantom was $2.0351 \times 2.0351 \times 2.0747$ mm^3.

4. Adjustment of organs and body weight

After the determination of the voxel resolution, the dimensions of the individual internal organs and tissue were adjusted to the Reference Korean data by using an in-house software program for 3D volume adjustment of organs and tissue. The use of 3D volume adjustment program not only saved a great deal of repetitive work, when compared to Inner Grow and Outer Grow functions of Photoshop7.0^{TM} which were used in the HDRK-Man development, but also made it possible to exactly match the masses of the organs and tissue to the Reference Korean data for the most organs,

i.e., except for some organs such as skin, blood vessel, respiration tract, and bronchi.

Basically, the volumes of the larger organs than those of the Reference Korean data were reduced by eliminating the voxels on the surface of the organs, and the eliminated regions were replaced by adipose tissue. In contrast, the smaller organs were enlarged by changing the adipose tissue on the boundary region of the organs to corresponding organs. Especially, the organs composed of wall were adjusted by moving the wall region toward inside for the larger organs and toward the outside for the smaller organs.

It was difficult to adjust very thin structures to the Reference Korean data due to the limited voxel resolution. For instance, even after the skin was defined as one voxel layer on the surface, the weight of the skin was greater than that of the Reference Korean data by 123.7%. The remaining volume in the phantom was filled with adipose tissue. The Reference Asia data[6] were used for some organs (oesophagus, bladder, blood vessel, breast, colon, small intestines, etc.), for which the Reference Korean data were not available. After the adjustment of height, skeletal mass, and organ and tissue volumes, the phantom was slightly heavier than the Reference Korean (54 kg), and therefore the weight was adjusted by eliminating some adipose tissue from the surface of the legs.

Consequently, the adjustment to reference Korean data was completed within nearly 0% of error except for some organs for which volume adjustment was impossible. **Figure 1** compares 3D views of alimentary system, before and after adjustment. The masses of the organs and tissue contributing to the calculation of effective dose values are compared, between HDRK-Woman and Reference Korean, in **Table 1**.

Fig. 2 HDRK-Woman.

5. Monte Carlo Simulation

The developed phantom, HDRK-Woman, and HDRK-Man were then ported to a Monte Carlo particle transport simulation code, MCNPX, to calculate the organ equivalent dose values and effective dose values. The three-dimensional voxel data were converted into a data format that is compatible with MCNPX. The considered irradiation geometries included broad parallel photon beams of anterior-posterior (AP), posterior-anterior (PA), and left lateral (LLAT) with photon energies from 0.015 to 10 MeV. The number of particles simulated was within the range of 10^6-10^8 depending on photon energies to keep the statistical errors less than 5%, except for 0.015 MeV.

Ⅲ. Results and Discussion

The Reference Korean female phantom, HDRK-Woman, was constructed based on the high-resolution photographic anatomical images of a Korean adult female cadaver. **Figure 2** shows coronal and sagittal views of HDRK-Woman. The height and weight of the phantom are 161 cm and 54 kg, respectively. The size of the voxels (voxel resolution) is $2.0351 \times 2.0351 \times 2.0747$ mm^3, and the voxel array size is $261 \times 109 \times 825$ (23,470,425 voxels) in the x, y, and z directions, which is equivalent to 531.1611, 221.8259, and 1711.6275 mm, respectively. The voxel phantom consists of a total of 40 organs and tissue including the 27 organs that are required for effective dose calculation.

In the present study, the organ equivalent dose conversion coefficients of HDRK phantoms were calculated and used for calculation of effective dose conversion coefficients. The calculated effective dose values were then compared with those of the ICRP Reference phantoms which were given in
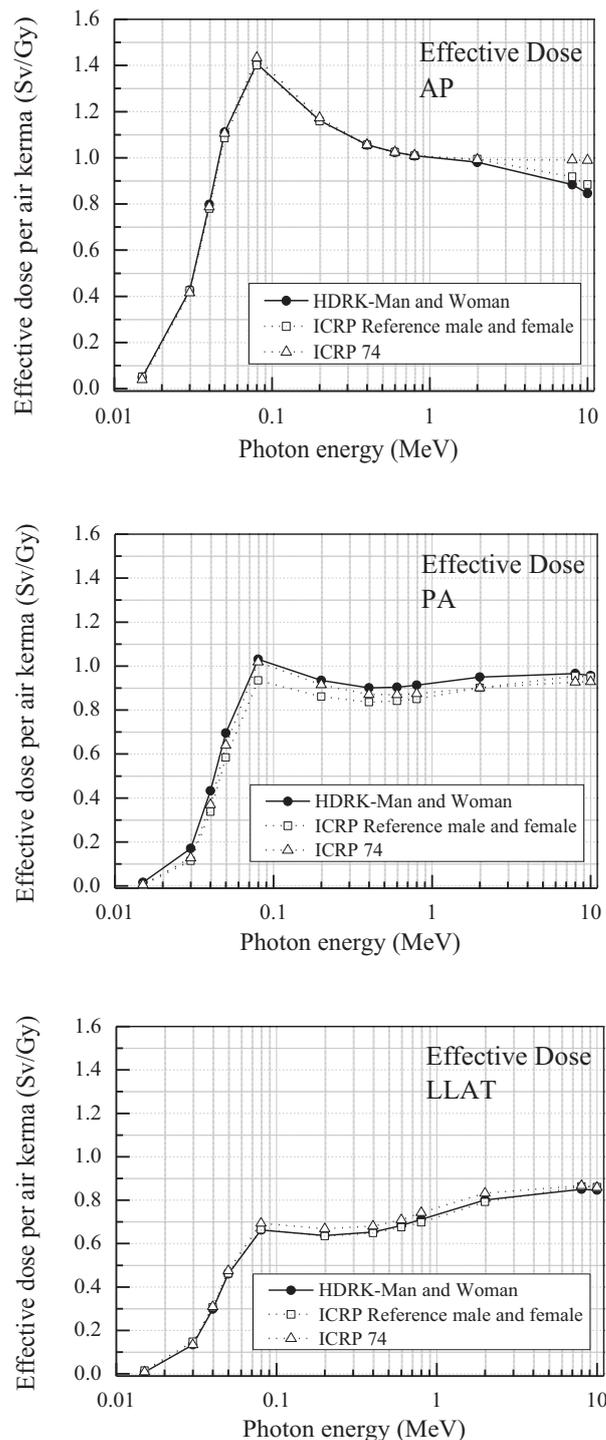

Fig. 3 Comparison of effective dose values of HDRK phantoms with ICRP Reference phantoms.

ICRP-74 and ICRP-110. The results show that the difference in effective dose values, for all of the photon energies considered in the present study (except for 0.015MeV), were less than 5% and 9% for anterior-posterior (AP) and left lateral (LLAT), respectively. For posterior- anterior (PA), the effective dose values of HDRK phantoms were generally higher than those of ICRP Reference phantoms, with 49% maximum difference at 0.03 MeV, which is mainly due to the difference in organ topologies between these two

phantoms. **Figure 3** illustrates the comparison of effective dose values.

Ⅳ. Conclusions

In the present study, a Reference Korean female adult voxel phantom, named HDRK-Woman, was constructed by using the high-resolution color photographic slice images of a Korean adult female cadaver. The height, weight, and organ masses of the phantom were adjusted to the Reference Korean data, and it is believed that HDRK-Woman, with the previously developed HDRK-Man, can represent the average workers in Korea for radiation protection purpose. The developed model was then ported to MCNPX to calculate effective dose conversion coefficients, which were then compared with those of the ICRP Reference phantoms. The results show that there were significant differences of effective dose values among these phantoms. The calculated effective dose conversion coefficients can be used to estimate radiation risk for the average workers in Korea.

Acknowledgement

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