Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2017

Preliminary Study for Body Shape Deformation of Mesh-type Computational Phantoms

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1. Introduction

Recently a set of mesh-type reference computational phantoms (MRCPs) were developed by the Task Group 103 of the International Commission on Radiological Protection (ICRP), by converting the currently used voxel-type reference computational phantoms into a high-quality mesh format. When compared to the previous voxel-type phantoms, the MRCPs have substantial advantages, including the deformability of the phantoms, which makes it possible to create phantoms in various postures and body shapes. Taking this advantage, the ICRP is now planning to use the MRCPs in the calculation of dose coefficients (DCs) for emergency exposure scenarios in the next term of the commission (2017–2021). However, detailed methodologies for deformation of postures and body shapes of the MRCPs are yet to be developed.

As the first step to develop the methodology for the body shape deformation of the MRCPs, in the present study, the adult male MRCP was deformed to match the 90th percentile body weight and the 90th percentile standing height, respectively, derived from the National Health and Nutrition Examination Survey (NHANES) database in order to identify the difficulties or issues in the body shape deformation. In addition, the deformed phantoms were used to calculate some risk-weighted average doses using the tissue weighting factors (w_T) recommended by the ICRP, and the calculated values were compared with the values calculated with the adult male MRCP.

2. Material and Methods

2.1 Statistical analysis of NHANES data

The adult male MRCP was deformed based on the anthropometric data provided by the NHANES, a survey research program conducted by the National Center for Health Statistics of the Centers for Disease Control and Prevention (CDC). In the present study, the data of Continuous NHANES (1999–2014) were used for the standing heights, body weights, and arm, waist, and thigh circumferences. For the sitting heights and buttocks circumferences, the data of the NHANES III (1988–1994) were used due to the absence of the data in the Continuous NHANES.

The anthropometric target values were derived from the aforementioned NHANES data. The 90th percentile body weight was derived as 111 kg from the lognormal fitting of the body weights of the adult subjects (≥ 20 years old) following the method of Brainard and Burmaster [1]. The 90th percentile standing height was derived as 184 cm from the Gaussian fitting of the standing height of the adult subjects following the method of Johnson et al. [2]. The other anthropometric target values (i.e., arm, waist, buttocks, and thigh circumferences and sitting height) were calculated by averaging the data within a tolerance of ± 0.5 kg in body weight and ± 1 cm in standing height.

2.2 Construction of 90th percentile body weight phantom

The adult male MRCP was deformed to match the 90th percentile body weight (= 111 kg). First, some space for deformation was secured by changing the direction of the arms and legs in the lateral direction. Then, the outer body surface of the MRCP was deformed to match the anthropometric target values by using the Rapidform software (INUS Technology Inc., Korea). Note that during the deformation, only the masses of the residual soft tissue (RST) and the skin were increased, assuming that the other internal organs are independent of the body weight [2-5]. The increased skin mass was calculated, assuming that the skin mass is proportional to the body surface area (BSA), which was estimated by using Equation [6]:

$$\text{BSA}\ (m^2) = 0.024265 \times w^{0.5378} \times h^{0.3964} \qquad (1)$$

where *w* is weight (kg) and *h* is height (cm).

2.3 Construction of 90th percentile standing height phantom

Similarly, the adult male MRCP was deformed to match the 90th percentile standing height (= 184 cm) based on the method of Johnson et al. [2]. First, the head, arms, and torso (including all of the internal organs and tissues) were scaled uniformly in three dimensions to match the target sitting height. The legs were then scaled not only in the z direction to match the target standing height, but also in the x and y directions by applying the scaling factor which linearly changes in the z direction from the sitting-height scaling factor (at the top of the legs) to unity (at the bottom of the legs).

The increase of the standing height resulted in the increase of the body weight by ~8.4 kg, which should be eliminated to maintain the original body weight. For this, the outer body surface of the phantom was deformed to decrease the masses of the RST and the skin, again assuming that internal organs are independent of the body weight [2-5]. This approach, however, was failed

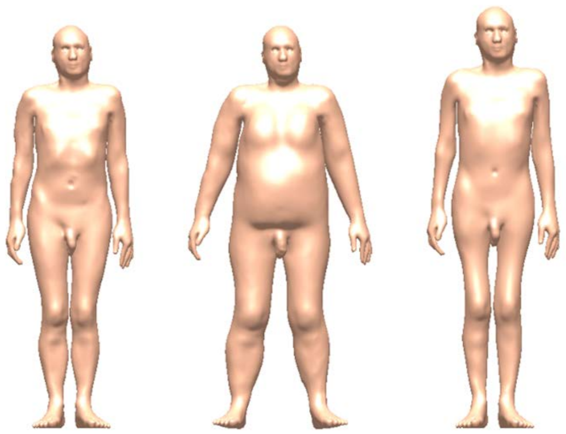

Figure. 1. Original adult male MRCP (left), 90th percentile body weight phantom (middle), and 90th percentile standing height phantom (right).

to avoid the interference of the outer body surface with the muscle and the blood in the large vessels. To address this problem, it was also necessary to deform these tissues while deforming the outer body surface, but this deformation work, due to their complex geometry, is very labor-intensive.

In the present study, therefore, we decided to modify the MRCP by including the muscle and the blood in the large vessels into the RST, recalculating the RST density and elemental compositions. Then, the modified phantom was deformed to match the target standing height. This approach significantly simplifies the deformation procedure, hardly affecting dose calculations considering that the blood is not a radiosensitive tissue and that the muscle is one of the remainder tissues recommended in the ICRP Publication 103 [7]. In addition, the RST can be used as a surrogate of the muscle in muscle dose calculation, which is generally reliable in external exposures considering that both tissues are widely distributed in the whole body [8-9].

3. Results and Discussions

Figure 1 shows the 90th percentile body weight phantom (90WP) and the 90th percentile standing height phantom (90HP) constructed in the present study along with the original adult male MRCP. These phantoms were implemented in Gean4 (ver. 10.02) to calculate risk-weighted average dose for external exposures of monoenergetic photons (0.01–10,000 MeV) at the antero-posterior (AP) direction for comparison. The relative errors of the calculated values were all less than 1%.

Figure 2 shows the calculated values of the risk-weighted average doses for photon exposures at the AP direction. It can be seen that for the photons (< 1 MeV), the dose values of the 90WP are significantly smaller than those of the original MRCP; the maximum difference is as large as ~3.5 times at 0.02 MeV. The

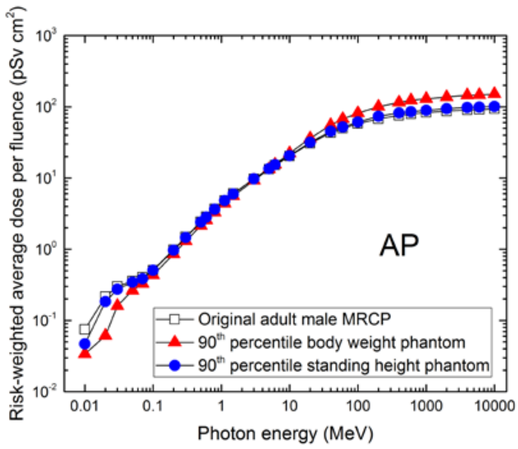

Figure. 2. Risk-weighted average dose per fluence for photon exposures in AP direction: the original adult male MRCP (unfilled square), the 90th percentile body weight phantom (solid triangle), and the 90th percentile standing height phantom (solid circle).

smaller values of the 90WP are mainly due to the increased shielding effect of the thicker RST layer of the 90WP. On the other hand, for the high energy photons (> 10 MeV), the dose values of the 90WP are larger than those of the MRCP; the maximum difference is as large as ~1.6 times at 10,000 MeV. This reversal tendency is due to the fact that the higher energy photons establish the build-up regions deeper in the body where the radiosensitive internal organs are located.

On the other hand, the risk-weighted average doses of the 90HP are generally not much different from the values of the MRCP; the differences are generally less than 9%. At the lowest energy (= 0.01 MeV), there is a relatively large difference of ~40%, which is mainly due to the different dose values of the breast and the testes between the phantoms. In the present study, during the construction of the 90HP, the muscle and the blood in the large vessels were included in the RST to simplify the deformation procedure and thus the density of the RST was increased by ~7%. For the very low energy photons, the increased RST density significantly decreased dose values for superficial organs (e.g., breast and testes) rather than deeper organs.

4. Summary and Conclusion

In the present study, the adult male MRCP was deformed to construct the 90th percentile body weight phantom and the 90th percentile standing height phantom based on the morphometric data of the NHANES. In addition, the risk-weighted average doses calculated with the constructed phantoms for photon exposures were compared with the values calculated with the original MRCP, showing that the body weight is a more significant factor affecting the risk-weighted average doses, ultimately effective doses, rather than the standing height for the AP irradiation geometry. Based on the results of this preliminary study, we will perform a fullscale study to finalize the methodology for the body shape deformation of the MRCPs in the future.

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