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The influence of physique on dose conversion coefficients for idealised external photon exposures: a comparison of doses for Chinese male phantoms with 10th, 50th and 90th percentile anthropometric parameters

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ABSTRACT

For evaluating radiation risk, the construction of anthropomorphic computational phantoms with a variety of physiques can help reduce the uncertainty that is due to anatomical variation. In our previous work, three deformable Chinese reference male phantoms with 10th, 50th and 90th percentile body mass indexes and body circumference physiques (DCRM-10, DCRM-50 and DCRM-90) were constructed to represent underweight, normal weight and overweight Chinese adult males, respectively. In the present study, the phantoms were updated by correcting the fat percentage to improve the precision of radiological dosimetry evaluations. The organ dose conversion coefficients for each phantom were calculated and compared for four idealized external photon exposures from 15 keV to 10 MeV, using the Monte Carlo method. The dosimetric results for the three deformable Chinese reference male phantom (DCRM) phantoms indicated that variations in physique can cause as much as a 20% difference in the organ dose conversion coefficients. When the photon energy was <50 keV, the discrepancy was greater. The irradiation geometry and organ position can also affect the difference in radiological dosimetry between individuals with different physiques. Hence, it is difficult to predict the conversion coefficients of the phantoms from the anthropometric parameters alone. Nevertheless, the complex organ conversion coefficients presented in this report will be helpful for evaluating the radiation risk for large groups of people with various physiques.

KEYWORDS: photon irradiation, conversion coefficient, physique, Chinese computational phantom

INTRODUCTION

In radiological protection, the equivalent dose and effective dose are used to describe the dosimetry of the various organs when irradiated by different particles. However, neither the equivalent dose nor the effective dose can be measured directly. Therefore, the concept of a 'conversion coefficient' has been introduced to relate the organ equivalent dose and effective dose to measurable quantities, e.g. air kerma and particle fluence.

The International Commission on Radiological Protection (ICRP) and the International Commission on Radiation Units and Measurements (ICRU) have updated the values of the organ dose conversion coefficients on several occasions. Each update occurred with the evolution of the computational phantom. Xu [1] exhaustively reviewed the development and implementation of computational phantoms, including abstract stylized phantoms, realistic voxel phantoms and deformable boundary representation (BREP) phantoms. In ICRP Publication 74 [2], the conversion coefficients were calculated using stylized phantoms representing different ages and genders, while ICRP Publication 116 [3] updated the conversion coefficients using the reference male and female voxel phantoms recommended in ICRP Publication 110 [4].

Since the 2000s, some research groups have recognized that the anatomical variations associated with body size and organ shape can cause a large difference in the estimation of organ doses. To reduce the uncertainty in evaluations of radiation dosimetry in individuals, it is necessary to expand the range of reference male phantoms to a larger set with different physiques. Kim *et al.* [5] evaluated the influence of body fat on the effective dose by modifying the thickness of the adipose layer of a stylized torso model. Moreover, a number of family phantoms of different genders, ages and physiques were constructed using the BREP modelling method. Johnson *et al.* [6] constructed underweight, average weight and overweight American adult male phantoms based on the University Florida hybrid adult male phantom [7] and studied the influence of patient size on the dose conversion coefficients in cardiac catheterisation. The research group at Rensselaer Polytechnic Institute (RPI) constructed three pregnant female phantoms in different gestational periods [8] and weight-specific phantoms [9] by deforming the RPI-Adult Male and RPI-Adult Female phantoms; then, the dose conversion coefficients were compared for different phantoms under 0.5-MeV photon irradiation. In addition to the above studies, there are other Caucasian family phantoms such as the Extended Cardiac-Torso (XCAT) family [10] and the Male Adult meSH (MASH) and Female Adult meSH (FASH) family [11].

There are also several Chinese reference adult phantoms that have been used in radiological protection studies. Liu *et al.* [12] constructed a Chinese reference male voxel phantom (CAM) based on the Chinese visible human (CVH) image dataset [13] and calculated the dose conversion coefficients for idealised photon irradiation. Based on the same CVH dataset, Dong *et al.* [14] developed a pair of BREP Chinese reference male and female phantoms and studied the dose conversion coefficients for muons. Meanwhile, Yu *et al.* [15] constructed a deformable Chinese reference male phantom (DCRM) based on the visible Chinese human (VCH) dataset. To the best of our knowledge, Yu *et al.* [15] is the only work that has applied a deformation protocol to the Chinese reference male phantom and constructed three phantoms (e.g. DCRM-10, DCRM-50 and DCRM-90) with 10th, 50th and 90th percentile body mass indexes (BMIs) and body circumference physiques.

The present study optimised the weight adjustment algorithm of the DCRM phantoms so that the percentage of adipose tissue corresponded to the reference value. Then, the optimised DCRM phantoms were implemented in Monte Carlo simulations. The organ dose conversion coefficients were calculated and compared for idealised photon irradiation from 15 keV to 10 MeV. The major goal of the present study was to thoroughly analyse the dosimetric differences between the phantoms with different physiques.

MATERIALS AND METHODS

Chinese male phantoms

The DCRM phantoms used in this study are presented in Fig. 1. The DCRM-50 phantom was constructed first, based on the VCH phantom with a height of 166 cm and a weight of 58 kg. The bone and muscle of the VCH data were scaled to the height of a Chinese reference male, and the organ masses and body circumferences were adjusted according to the reference values [16]. The rest of the

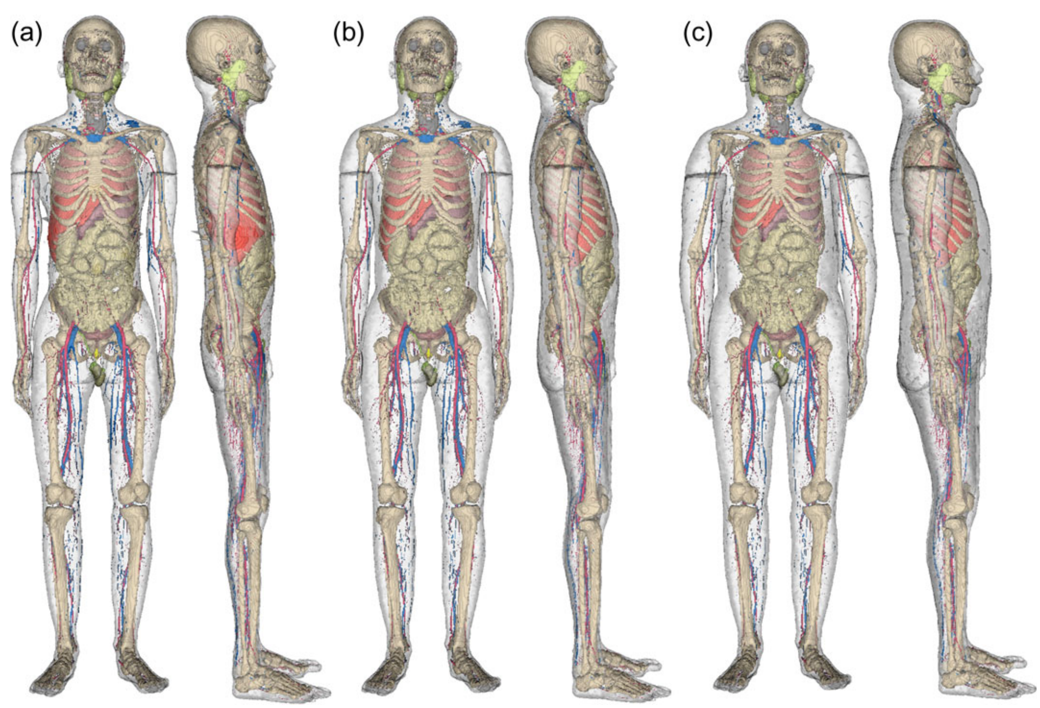

Fig. 1. Anterior and lateral views of the DCRM phantoms. (a) DCRM-10, (b) DCRM-50 and (c) DCRM-90.

Table 1. Original anthropometric values of DCRM-10, DCRM-50 and DCRM-90

	DCRM-10	DCRM-50	DCRM-90
Height (cm)	170.2	170.2	170.2
Weight (kg)	53.3	62.0	75.3
BMI (kg/m^2)	18.4	21.4	26.0
Chest circumference (cm)	78.3	85.6	95.1
Waist circumference (cm)	66.2	74.5	87.8
Hip circumference (cm)	82.7	89.5	98.0
Fat percent (%)	30.1	37.9	48.4

body was considered to be adipose tissue, and its density was modified to achieve the reference body weight. Without adjusting the muscle volume, the percentage of adipose tissue in DCRM-50 was 37.9%, which is noticeably different from the reference value (12.4%). Then, the DCRM-10 and DCRM-90 phantoms were constructed based on the DCRM-50 phantom by directly morphing the body circumferences according to the statistical anthropometric value [17]. Likewise, the volume of fat was modified along with the deformation, while the density of fat was adjusted to achieve the target body weight. The anthropometric values of the DCRM phantoms, including the height, weight, BMI, body circumference and fat percentage, are listed in Table 1.

Finally, the DCRM phantoms were voxelised to a spatial resolution of $2 \times 2 \times 2\,\mathrm{mm}^3$, and the density and elemental compositions of each organ were assigned to the corresponding voxels according to ICRP Publications 70 and 89 [18, 19].

Body fat adjustment

The dose conversion coefficients for the photon exposure of Caucasian phantoms with various physiques have been briefly studied, and the shielding effect of body fat is reported to be significant [9]. However, the percentage of fat in the DCRM-50 phantom diverged from the reference value [16]. Therefore, the percentage of body fat should be corrected to enable a more accurate evaluation of the radiation dose.

The percentage by weight of body fat can be measured or deduced from simple anthropometric parameters. Lean *et al.* [20] developed regression equations (from various combinations of anthropometric measurements) for predicting the percentage of body fat and found that the most robust prediction with the least bias was that obtained from the waist circumference, adjusted for age.

$$\text{Percent (body fat of men)} = 0.567 \times \text{Waist (cm)} + 0.101 \times \text{Age} - 31.8 \quad (1)$$

Body fat primarily consists of subcutaneous adipose tissue (SAT) and visceral adipose tissue (VAT). During the deformation of the DCRM phantom, the volume of the SAT was modified to match the target body circumference, and the density of the VAT was modified so the total body weight agreed with the reference value. Yu *et al.* [15] assumed that the increase in density would have a similar shielding effect to that of the increase in VAT thickness. However, both the density and thickness, which are related to the mass of VAT, play important roles in affecting the ionising radiological dosimetry of internal organs. Hence, an anatomical estimation of the mass of VAT is necessary before modifying its density.

Increases in the amount of VAT have been associated with complications related to obesity, such as insulin resistance, impaired insulin secretion, hypertension, dyslipidemia, and cardiovascular disease [21]. Smith *et al.* [22] concluded that the area of the VAT at the L4–5 slice is a valid parameter for estimating the VAT mass.

$$\text{VAT (kg)} = \text{VAT (cm}^2 \text{ at L4}-\text{L5)} \times 0.038 - 0.452 \quad (2)$$

For the VAT area measured at the L4–5 level, the strongest correlation was age, and the highest partial correlation was the waist–hip ratio (WHR) [23]:

$$\text{VAT (cm}^2 \text{ at L4}-5) = 2.344 \times \text{Age} + 363.427 \times \text{WHR} - 328.159 \quad (3)$$

Based on the two regression equations, the mass of the VAT in the DCRM phantom was assessed, and the density was calculated by dividing the mass by the volume of the VAT in the DCRM phantoms. Then, the volume of the SAT was adjusted by morphological dilation and erosion operations so that the body fat percentage fitted the prediction of Eq. 1. Finally, the body weight was tuned to match the reference value by slightly adjusting the muscle density.

Monte Carlo simulation

Dose conversion coefficients were computed by using the Geant4 Monte Carlo code system [24]. The BREP phantoms with various physiques were converted into voxel phantoms using software that had been coded in-house. All the voxels belonging to one organ were assigned the same ID number. Then, the organ densities and element components were obtained from ICRP Publications 89 and 110 [4, 19]. Photon transport was terminated when the energy fell below 10 eV, and the cut-off energy for the electrons was 500 eV.

Whole-body irradiation with broad parallel photon beams emanating from four directions, i.e. the antero–posterior (AP), postero–anterior (PA), left-side lateral (LLAT), and right-side lateral (RLAT) directions, were simulated in the present study. A total of 5040 organ dose conversion coefficients were calculated for 21 organs, 4 irradiation geometries, 20 energy groups of mono-energetic photons (ranging from 15 keV to 10 MeV) and three Chinese male phantoms with different physiques. The simulations were performed on a workstation with an Intel Xeon 2.27 GHz CPU with 8 GB of RAM and running a 64-bit version of Windows Server 2008. In addition, 1×10^9 photons were tracked in each simulation to reduce the dose uncertainty to 5%.

RESULTS AND DISCUSSION

Adult male phantoms of various physiques

The percentage by weight of body fat (F%) in each phantom was adjusted to fit the theoretical value deduced from the regression equations. Table 2 lists the F% values for phantoms with various physiques, before and after the adjustment. The improvement in F% was remarkable, and the adjusted F% was close to the reference value. The muscle density changed from 1.05 g/cm^3 to 1.08 g/cm^3 after tuning the body weight. We believed that the modification of the muscle density was negligible in the calculation of the radiation dose.

During the construction of the reference human phantom, the body weight was generally adjusted to the reference value by modifying the volume or the density of the fat [9, 11, 15, 25]. However, the adjusted body fat percentage is rarely compared with the reference value in the literature. In the work by Yu *et al.* [15], the density of the VAT was modified from 0.92 g/cm^3 to 2.47 g/cm^3, while the body fat percentage of DCRM-50 was 37.9%, which deviated greatly from the reference value of 12.4% [16]. Given that the abdominal organs are enveloped in VAT, we calculated the conversion coefficients for a 0.5-MeV photon exposure with the VAT densities set to 0.92 g/cm^3 and 2.47 g/cm^3, respectively. Although not presented herein, the results suggest that an increase in the VAT density caused a decrease of ~10% in the abdominal organ conversion coefficients.

The present study estimated the VAT mass and body fat percentage using the reported anatomical regression equation. The body fat percentage in the updated DCRM-50 was consistent with the reference value. The muscle density was modified from 1.05 g/cm^3 to 1.08 g/cm^3. Based on the assumption that an increase in the density has a similar shielding effect to an increase in the volume, the equivalent anthropometric data changed by less than 3% after the modification of the muscle density. We assume that the proposed weight adjustment algorithm in the present study is suitable for calculating the conversion coefficients for a corresponding physique.

Influence of physique on dose conversion coefficients

The dose conversion coefficients for the various organs of the DCRM-10, DCRM-50 and DCRM-90 phantoms are tabulated in the supplementary data. The statistical uncertainties in the Monte Carlo simulation were <3% for photons with incident energies of >30 keV; larger statistical errors are presented for small and deep organs irradiated by photons with energies of <30 keV. Thus, the discussion below mainly focuses on the influence of physique on the dose conversion coefficients when the photon energy is >30 keV.

Table 2. Weight percentage of body fat before and after the adjustment

	DCRM-10th	DCRM-50th	DCRM-90th
Yu *et al.*, 2015 [15]	30.1%	37.9%	48.4%
After adjustment	7.3%	12.7%	20.3%
Reference value		12.4%[a]	

[a]Data from Wang *et al.* [16].

Several trends were observed in the dosimetry results, regardless of the physique. First, the conversion coefficients for those organs closer to the irradiated surface of the phantom were larger, e.g. for DCRM-50 irradiated by 1-MeV photons from the LLAT direction, the conversion coefficient of the stomach was 0.869, while the conversion coefficient of the liver was 0.558. Second, the organ conversion coefficients in AP and PA irradiation geometries were generally larger than those in LAT geometries because of the extra shielding by the arms when the photon was irradiated from the lateral directions. These trends agree with the results of studies that focus on fixed-physique phantoms.

The differences in the conversion coefficients of the eight main organs in the DCRM phantoms are presented in Fig. 2. In general, the organ conversion coefficients were larger for the thinner phantoms because the photons were less scattered and attenuated in the adipose tissue. Those photons with higher energies exhibited lower probabilities of scattering, such that as the energies increased, the difference in the organ doses between the phantoms with different physiques declined. In the following discussions, we analyse the differences in the dose conversion coefficients for both AP/PA irradiation and lateral irradiation geometries.

AP/PA irradiation geometries

The differences in the organ conversion coefficients were relatively small between AP and PA irradiation geometries. For those organs located deep in the torsos of the DCRM-10 and DCRM-90 phantoms [e.g. the red bone marrow (RBM), liver, stomach and bladder] irradiated by photons with an energy of >0.06 MeV, the differences in the dose coefficients relative to DCRM-50 were within 10%. However, as photon energy decreased, this discrepancy increased rapidly, reaching 40% when the photon energy had fallen to 0.03 MeV. For the testicles and brain, the variance in the thickness of the adipose tissue in front of these organs can be ignored in the case of the DCRM phantoms: the coefficients differed by <5% in the AP irradiation geometries. In the case of the testicles, particularly, the difference in the coefficients was <10%, even though the photon energy was 0.03 MeV.

However, an exception occurred in the case of the thyroid, in that the overweight phantom received a higher dose when irradiated by photons with energies of >4 MeV in the AP geometry. This was because the dose deposited by the photons at high-energy levels is mainly due to the secondary electrons produced by Compton scattering. Because of the thinness of the adipose tissue in front of the thyroid in DCRM-10, most of the dose was deposited at a deeper area in the body as a result of the high-energy electrons, which in turn reduced the absorbed dose of the thyroid.

Lateral irradiation geometries

The variations in the amounts of adipose tissue in the arms and legs gave rise to extra discrepancies in the organ dose for lateral irradiation geometries. For those organs shielded by the arms or legs (e.g. the lungs, stomach, liver and testicles), the influence of the

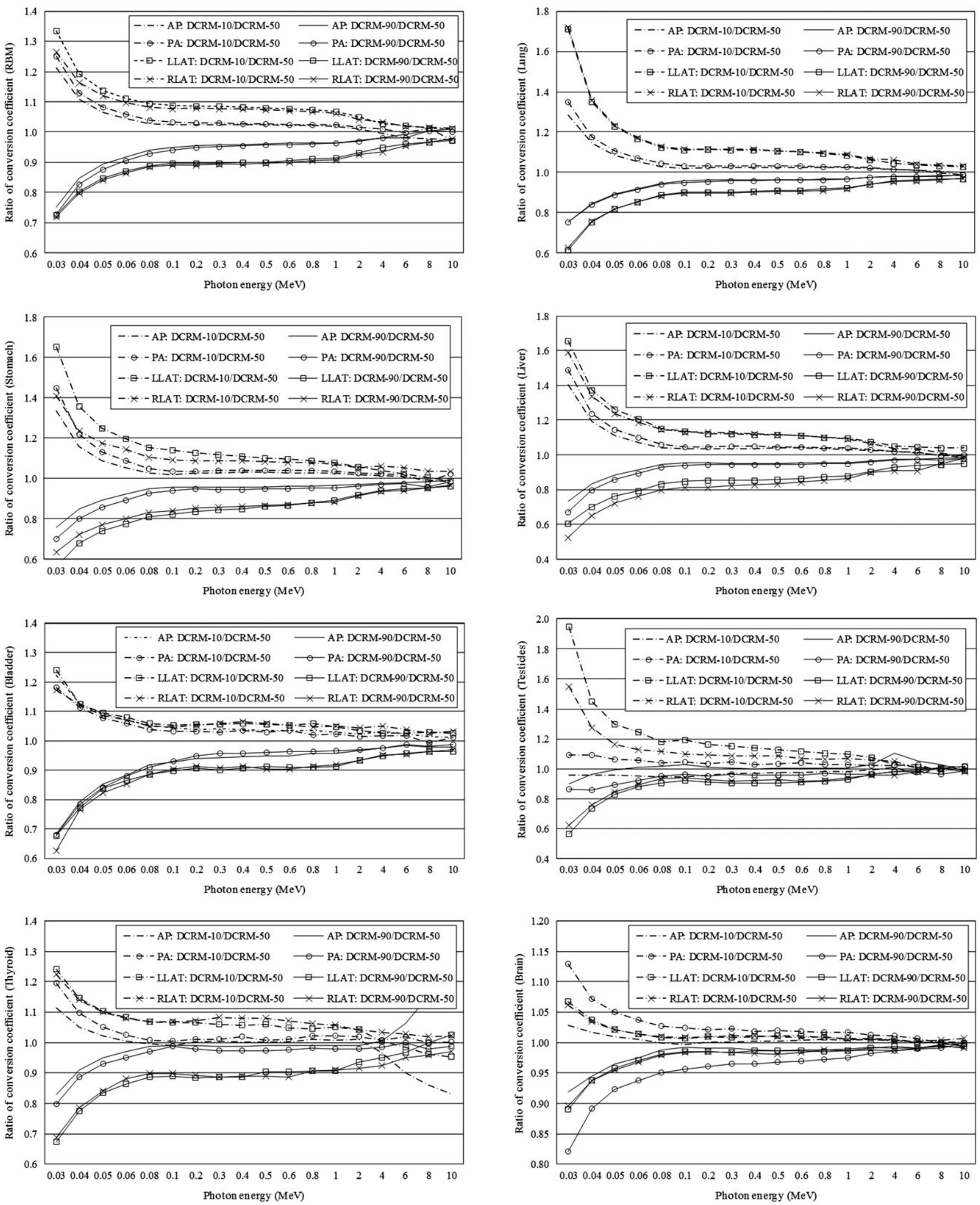

Fig. 2. Comparison of the organ conversion coefficients for the DCRM phantoms.

physique on the conversion coefficients in lateral irradiation geometries was noticeably greater than in AP and PA irradiation geometries: when the photon energy was <0.06 MeV, the difference was >20%, and when the photon energy was between 0.06 MeV and 1 MeV, the difference was >10%. The discrepancy caused by the physique gradually decreased once the photon energy exceeded 1 MeV. However, the influence of irradiation geometry on the coefficient discrepancy was insignificant for organs like the bladder and brain because they were not shielded by the limbs.

The effective dose conversion coefficients for the DCRM phantoms were compared with those of the CAM phantom and those of the ICRP-recommended Caucasian reference male phantom (Fig. 3). The anthropometric data of DCRM-50 and CAM are similar. The heights of the phantoms are the same, and the organ masses are both adjusted according to the Chinese reference values [16]. The weight of the Caucasian phantom is 73 kg and its height is 176 cm. Generally, the effective dose coefficients for the average-weight Chinese phantoms and the ICRP reference phantom in AP and PA irradiation geometries were in good agreement. When photon energy was between 0.06 MeV and 6 MeV, the difference in the effective dose coefficients was <5%. This difference became larger in lateral irradiation geometries because of the different positions of the arms relative to the trunk. For the CAM phantom, the position of the arms relative to the trunk was somewhat further back, so that fewer organs were shielded, leading to higher effective dose conversion coefficients. Na *et al.* [9] reported that slimmer and shorter phantoms receive a higher effective dose; thus, based on the anthropometric parameters of the DCRM-50, CAM and ICRP phantoms, the effective doses of CAM and DCRM-50 should be similar, and higher than that of the ICRP phantom. However, the results of the present study did not fully support this. We supposed that the organ conversion coefficients would not only be influenced by the weight and height, but also by the distribution of the adipose tissue. For the DCRM-50 phantom, the adipose tissue in front of the brain and in the lower abdomen is thicker than that in the ICRP phantom; hence, the coefficients for the brain and bladder of the DCRM-50 phantom are noticeably lower than those for the ICRP phantom (Fig. 4).

A comparison of the DCRM phantoms reveals that the influence of physique on the effective dose conversion coefficients is similar to that on the organs, which is small in AP and PA irradiation geometries (within 5% when the photon energy was >0.05 MeV) and relatively large in lateral irradiation geometries (>10% when photon energy was <0.5 MeV). In addition, as the photon energy increased, the discrepancy between the phantoms with different physiques gradually diminished. Similar trends were reported by Cassola *et al.* [11], who compared the dose conversion coefficients for MASH phantoms of different weights and heights

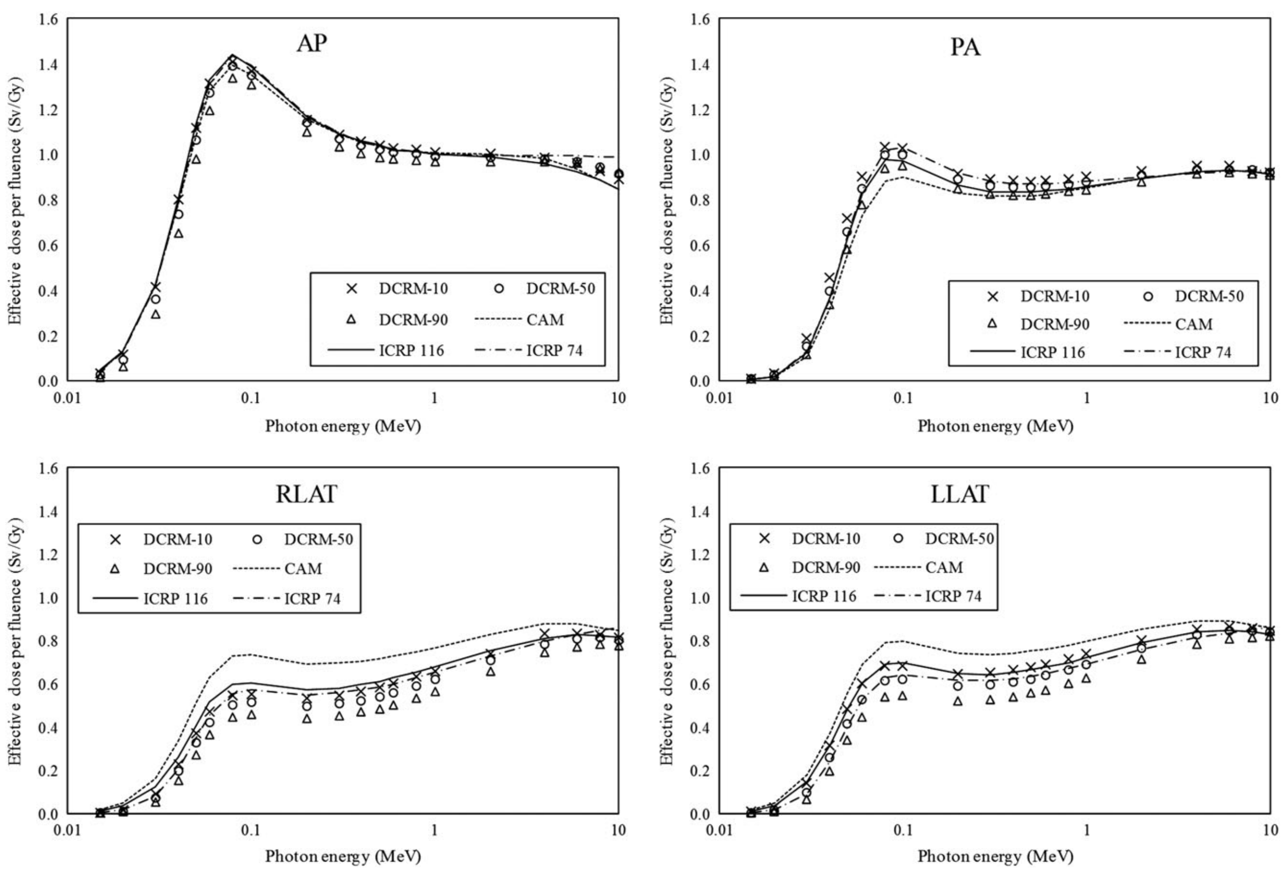

Fig. 3. Comparison of the effective dose conversion coefficients for the DCRM-50, CAM and ICRP phantoms.

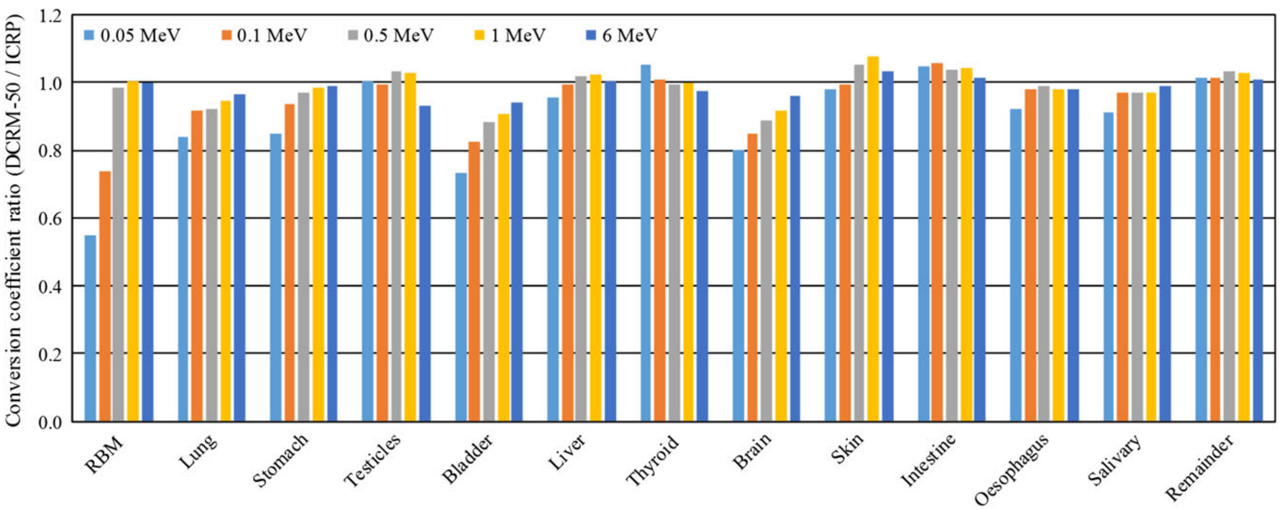

Fig. 4. Comparison of the organ conversion coefficients for the DCRM-50 and ICRP phantoms in AP irradiation geometry.

in AP irradiation geometry. However, the influence of physique on the conversion coefficients was more significant in the MASH phantoms than in the DCRM phantoms. The MASH phantoms are MSTA_m10_h50, MSTA_m50_h50 and MSTA_m90_h50, the weights of which are 66 kg, 79 kg and 98 kg, respectively. The average difference between the conversion coefficient for the colons of MSTA_m10_h50 and MSTA_m90_h50 over the entire energy range was 94%, while the average difference between the DCRM-10 and DCRM-90 phantoms was 23.3%. We supposed that the larger difference in the organ dose conversion coefficient was caused by a larger discrepancy in the body weight. On the other hand, adipose tissue in a male is mainly distributed in the abdomen, and as the body weights of the MASH phantoms are greater than those of the DCRM phantoms, the variation in the amount of adipose tissue shielding the colon is more significant for the MASH phantoms than for the DCRM phantoms. As can be seen in Fig. 2, the differences in abdominal organ dose conversion coefficients between DCRM-10 and DCRM-50 were slightly smaller than the differences between DCRM-90 and DCRM-50, which can also be explained by the above two factors.

A few other studies have discussed the conversion coefficients for phantoms with different physiques [9, 25]. However, these studies only calculated the coefficients for irradiation with 0.5-MeV photons from AP geometry, and were limited to investigating the influence of irradiation geometry and photon energy on the conversion coefficients.

The coefficients recommended in ICRP Publication 74 are also presented in Fig. 3 for comparison because the latest Criteria of National Occupational Hygiene in China continue to cite the conversion coefficients in ICRP Publication 74 [26]. As can be seen, the conversion coefficients provided in ICRP Publication 74 underestimated the effective dose of DCRM-10 in PA and LLAT irradiation geometries. Although not presented herein, the conversion coefficients of most organs were greater than the values in ICRP Publication 74, which suggests that an update of the radiation protection criteria is required for the underweight group.

CONCLUSION

This study updated the DCRM phantoms by using a more anatomically precise weight-adjustment algorithm. The conversion coefficients for underweight, average weight and overweight Chinese adult males were calculated for four idealised external photon exposures from 15 keV to 10 MeV.

In summary, the dose conversion coefficients were found to increase as the body fat percentage decreased, except in the cases of some superficial organs (e.g. the skin, testicles and thyroid). The effective dose conversion coefficients are more influenced by the physique in the case of lateral irradiation geometries than in the case of AP and PA irradiation geometries because of the extra shielding effect provided by the arms. In fact, in the comparison of the DCRM-50 and ICRP phantoms, the conversion coefficients are not only influenced by physique, but also by the distribution of the adipose tissue, organ position, and many other factors. It is difficult to deduce a general function relating the conversion coefficients to anthropometric parameters. However, the detailed conversion coefficients calculated in the present study offer an insight into how the physique influences the dose distribution in photon irradiation, which is helpful for estimating the organ equivalent doses and effective dose in practice.

When the conversion coefficients determined in the present study are compared with the ICRP data, it should be noted that the current criteria of the dose coefficients are inadequate for underweight people. Thus, specific radiological protection plans must be made for underweight people.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

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