Development of Chinese reference man deformable surface phantom and its application to the influence of physique on electromagnetic dosimetry

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Abstract

A reference man is a theoretical individual that represents the average anatomical structure and physiological and metabolic features of a specific group of people and has been widely used in radiation safety research. With the help of an advantage in deformation, the present work proposed a Chinese reference man adult-male polygon-mesh surface phantom based on the Visible Chinese Human segment image dataset by surface rendering and deforming. To investigate the influence of physique on electromagnetic dosimetry in humans, a series of human phantoms with 10th, 50th and 90th body mass index and body circumference percentile physiques for Chinese adult males were further constructed by deforming the Chinese reference man surface phantom. All the surface phantoms were then voxelized to perform electromagnetic field simulation in a frequency range of 20 MHz to 3 GHz using the finite-difference time-domain method and evaluate the whole-body average and organ average specific absorption rate and the ratios of absorbed energy in skin, fat and muscle to the whole body. The results indicate thinner physique leads to higher WBSAR and the volume of subcutaneous fat, the penetration depth of the electromagnetic field in tissues and standing-wave occurrence may be the influence factors of physique on electromagnetic dosimetry.

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(Some figures may appear in colour only in the online journal)

1. Introduction

Human computational phantoms have been widely used in ionizing and non-ionizing radiation safety evaluation, radiation medicine and ergonomics. In some similar researches, to simplify the influence of body size, a featured phantom with representative height, weight and other characteristics for a group of people is needed. The International Commission on Radiological Protection (ICRP) defined a theoretical individual named reference man which had characteristics, including anatomical structure and physiological and metabolic features, for the Western European and North American population (ICRP 1975, 2002). However, the anatomical structures of Caucasians and Chinese people are different. Wang et al (1998) recommended the reference values of the Chinese reference man based on statistical data on physical measurement and a national nutrition survey. Some computational phantoms in agreement with the ICRP reference man have been used to evaluate electromagnetic (EM) dosimetry (Dimbylow 2005). Qiu et al (2008, 2009, 2012) constructed a male Chinese mathematical phantom (CMP) using the Oak Ridge National Laboratory (ORNL) mathematical phantom (Christy et al 1987a, 1987b), Chinese reference man and Reference Asian Man (IAEA 1998a, 1998b, Tanaka et al 1998) data. Liu et al (2009a, 2009b) developed a Chinese reference man voxel phantom, named the Chinese adult man (CAM), based on a Chinese adult male voxel phantom, called CNMAN (Zhang et al 2007a), whose original color image came from the Chinese visible human (CVH) dataset (Zhang et al 2006). Sheng et al (2013) established a Voxel-based Chinese reference female phantom (VCRP-woman) also using the CVH dataset.

Compared to a mathematical phantom, such as the MIRD phantom (Snyder et al 1969) and voxel phantom (Nagaoka et al 2004, Dimbylow 2005), a surface phantom takes advantage in deformation while keeping high anatomical realism. Both non-uniform rational B-Splines (NURBS) (Lee et al 2007) and polygon-mesh surface phantoms have been used to develop human phantoms (Zhang et al 2009, Cassola et al 2011). Dong et al (2015) constructed Chinese Reference adult male and female hybrid phantoms, including NURBS and polygon-mesh surfaces, based on the CVH dataset. However, all the Chinese reference adult male and female phantoms mentioned above were used in ionizing radiation research and did not focus on the body circumferences that were also recommended by the Chinese reference man standard. Hence the first objective of the present work is to construct an adult male computational phantom, used in non-ionizing research, whose mass of internal organs and physiques, including height, weight, and head, chest, waist and hip circumferences, conform to those of the Chinese reference man. Considering the internal organs need to be accurately adjusted with collision detection, the polygon-mesh surface phantom, which has better flexibility in outline control (Na et al 2010), is adopted.

The fast development in wireless communication technology has led to a growing concern about the adverse health effects of EM radiation. The variation of human physique requires more realistic phantoms to accurately evaluate the EM dosimetry of a specific population. A series of human phantoms with different gender, age, height, weight and physique were developed and adopted to analyse influences. The resonance frequency of the human body relates to height (Conil et al 2008). Sandrini et al (2004) suggested the whole-body average specific absorption rate (WBSAR) of adult females is higher than that of adult males due to
thicker subcutaneous fat, which plays the role of a match layer. Christ et al (2006b) found a standing-wave occurred and led to high energy absorption in skin when the thickness of the skin and fat was approximately 1/4 the wavelength in tissues. Lee et al (2012) developed a series of 1-, 3-, 5-, 7- and 20 year-old thin and normal-physique voxel phantoms and found the WBSAR increased due to the reduction of body volume. However, previous phantoms used to evaluate the influences of physique on WBSAR were of different gender (Sandrini et al 2004) or obtained by scaling the whole body (Lee et al 2012). It is necessary to develop phantoms with different physiques while excluding the effects resulting from variation in height and internal organs.

The present work aims to investigate the influence of physique on EM energy absorption using a series of adult male phantoms with the same height and internal organs but different physiques by deforming a new polygon-mesh surface phantom which conforms to the Chinese reference man standards, which include not only the mass of internal organs, but also physique parameters, including height, weight and body circumferences. At first, we constructed an original polygon-mesh surface phantom beginning with the visible Chinese human (VCH) segment image datasets (Li et al 2008). Then the original surface phantom was scaled and deformed to the Chinese reference man phantom, who was then scaled again to meet the 50th height percentile for Chinese adult males, and the body outline was further deformed to a series of phantoms with 10th, 50th and 90th body mass index (BMI) percentile values to represent the underweight, normal and overweight physique population, respectively. Lastly, the series of surface phantoms was voxelized to computational voxel phantoms and utilized to assess the WBSAR and EM energy absorbed by some organs when they are exposed to frontal incidence plane waves to investigate the influence of physique on EM dosimetry.

2. Materials and methods

2.1. Visible Chinese human segment image dataset and polygon-mesh surface phantom

The VCH segment images (Li et al 2008) were applied to reconstruct a deformable polygon-mesh phantom. The VCH project aimed to construct a virtual model of the adult Chinese male and obtained CT, MRI and high-quality cryosectional images from a male cadaver. A total of 8920 cryosectional images were obtained. The pixel resolution is 5440 × 4080. The voxel size is 0.1 × 0.1 × 0.2 mm³. A series of whole-body voxel phantoms based on the VCH segment images had been utilized in ionizing radiation simulations (Zhang et al 2007b, 2008a, 2008b, Liu et al 2011, Ai et al 2014). A head voxel phantom was used to evaluate the influence of dentures on cellphone near-field non-ionizing radiation (Yu et al 2012).

The segment image dataset included 58 tissues and organs. The images were scaled to a resolution of 2 × 2 mm² and applied to reconstruct the original triangle-mesh surface phantoms using the marching cubes algorithm. And then, the Chinese reference man phantom and a series of surface phantoms with different physiques would be reconstructed by deforming the original surface phantoms (figure 1). All the triangle-mesh phantoms were reconstructed and deformed using an in-house C++ program developed with visualization toolkit (VTK).

2.2. Chinese reference man polygon-mesh surface phantom

2.2.1. Reference values of anthropometrics and organ mass for the Chinese reference man. The data of anatomical physiological and metabolic characteristics for Chinese reference man (DAPMCCRM) (Wang et al 1998) provides the recommended reference values of physical measurement parameters for the Chinese male adult (table 1), including height,
weight, head circumference, chest circumference, waist circumference and twelve main organs’ reference mass values, including those for the brain, heart, kidney, liver, lung, pancreas, spleen, adrenal gland, pituitary, testicle, thymus, and thyroid (table 2). The data from DAPMCCRM were adopted to reconstruct the Chinese reference man polygon-mesh surface phantom by deforming the VCH mesh surface phantom.

2.2.2. Polygon-mesh surface phantom deformation algorithm. Two deformation algorithms can be used to adjust the volume and shape of the mesh phantom. The first method is moving points along the ray emitting from a reference point, such as the center of the organ, while the other one is moving along point normal. When scaling the whole body to a specific height, all
the organs were scaled along the ray emitting from the center of the body minimum bounding box. When adjusting the internal organs to the reference mass values, considering collision detection, the deformation algorithm along point normal was employed. The outline physique deformation also used the second method since the connection parts, such as the body and arm, and body and leg, could not be deformed along the ray emitting from a unique reference point.

At first, the VCH triangle-mesh surface phantom was scaled from 166.0 cm to 170.0 cm to meet the recommended height of the Chinese reference man. Then the internal organs, which had the reference mass, were deformed to the reference values. The collision detection algorithm named ray-casting method proposed by Amanatides and Choi (1997) and used by Zhang et al. (2009) was adopted to avoid the internal organs overlapping during deformation. We assumed the organ with higher mass density had higher hardness. So the deformation order was compliant with mass density from hard to soft. The rest of the internal organs without reference mass would not be adjusted. Then the body outline was divided into torso and legs, left arm and right arm to facilitate the calculation of circumference. A horizontal plane at the circumference height was applied to cut the outline mesh to get the contour of the torso. In anthropometric parameter measurement practice, a soft tape was used to measure circumference. The tape would stride the sunken part of the body. To get more realistic measurements of circumference, after calculating the contour of the transverse section of the torso, the convex hull of the contour was computed. The length of the convex hull was regarded as the circumference. The points in the triangle which were cut by the horizontal plane were iteratively adjusted along their normal until the circumferences met the target values. Their move distances were proportional to the thickness of the subcutaneous fat measured in the original cryosectional color images. The move distances of the other points were calculated by cubic spline interpolation to ensure the whole body outline was smooth after deformation. The deformed outline polygon mesh was shrunk along point normals to obtain the inner contour of the skin thickness measured in the original cryosectional color images. However, because the voxel phantom should be covered by at least one layer of skin, considering the resolution, the shrink distance was set to 2 mm.

When the deformations were completed, the body weight perhaps still did not reach the reference value. Similar to what Ding et al. (2012) did, a closed surface which included all the internal organs in the enterocoelia was constructed. The adipose tissue inside this closed

| Organ          | Chinese reference man (g) | Voxel phantom (g) | Var (%) |
|----------------|----------------------------|-------------------|---------|
| Brain          | 1460                       | 1460.4            | 0.0     |
| Heart          | 325                        | 324.0             | -0.3    |
| Kidney         | 290                        | 288.7             | -0.4    |
| Liver          | 1410                       | 1402.3            | -0.5    |
| Lung           | 1250                       | 1253.3            | 0.3     |
| Pancreas       | 120                        | 119.7             | -0.2    |
| Spleen         | 165                        | 162.2             | -1.7    |
| Adrenal gland  | 14                         | 13.9              | -0.7    |
| Pituitary      | 0.7                        | 0.7               | 0.0     |
| Testicle       | 40                         | 39.7              | -0.7    |
| Thymus         | 30                         | 29.7              | -1.0    |
| Thyroid        | 26                         | 25.3              | -2.7    |

Table 2. Reference mass values of the Chinese reference man (Wang et al. 1998) and mass values of voxel phantoms of main internal organs.
surface was defined as visceral fat whose volume was fixed after deformation while density could be changed to obtain the required weight. Hence, the visceral fat density was computed by the fixed volume and the difference between the reference and current weight of the whole body.

Lastly, a series of parallel planes with uniform 2 mm intervals were used to cut all of the polygon-mesh surface phantoms to get the contours. By filling these contours, we obtained a new segment image dataset, which was then utilized to reconstruct the voxel phantoms with a uniform cell size of $2 \times 2 \times 2$ mm$^3$ to perform EM field simulation. The voxel phantoms were checked carefully to ensure the body was covered by skin voxels.

### 2.3. Underweight, normal and overweight Chinese male phantoms

The report on the second national physical fitness surveillance (RSNPFS) (General Administration of Sport of China 2007) provides Chinese anthropometric data, including mean values and statistical distributions. The data on the 20–24 year-old adult male group were chosen as the adult parameters since their average height (170.4 cm) and 50th height percentile value (170.2 cm) were quite close to the height of the Chinese reference man (170.0 cm). Since the RSNPFS didn’t provide the statistical distributions of the weight, chest circumference, waist circumference and hip circumference values at a specific height, the statistical distributions of the BMI, chest circumference/height $\times 100$, waist circumference/height $\times 100$ and hip circumference/height $\times 100$ values were treated as the distributions of weight, chest circumference, waist circumference and hip circumference, respectively. The BMI values of the 10th, 50th and 90th percentile values for the 20–24 year-old adult male group, which were 18.4, 21.4 and 26.0 kg $m^{-2}$ respectively, were chosen because these values were within the BMI range of underweight ($16.0 \leq$ BMI $< 18.5$), normal ($18.5 \leq$ BMI $< 25.0$) and overweight ($25.0 \leq$ BMI $< 30.0$) defined by the World Health Organisation (WHO 2000) and underweight (BMI $< 18.5$), normal ($18.5 \leq$ BMI $< 24.0$) and overweight ($24.0 \leq$ BMI $< 28.0$) defined by the National Health and Family Planning Commission of the People’s Republic of China (2013). Following the definition of the BMI (weight/height$^2$), the 10th, 50th and 90th weight percentile values, which were 53.3, 62.0 and 75.3 kg respectively, were obtained. Hence, using the same method, the 10th, 50th and 90th percentile values of chest circumference, waist circumference and hip circumference for the male with the 50th height percentile (170.2 cm) were derived (table 1). We then assumed people with a specific BMI percentile also had the same percentile values of chest circumference, waist circumference and hip circumference values, which means an underweight male had 10th percentile values of BMI and chest, waist and hip circumference. Hence, the derived anthropometric data could be adopted to adjust the Chinese reference man mesh surface phantoms to underweight-, normal- and overweight-physique Chinese adult male phantoms.

At first, the Chinese reference man surface phantom (170.0 cm) was scaled to the 50th height percentile (170.2 cm) for the Chinese adult male. Meanwhile, all the organs were scaled with the same factor. The internal organs had the same volume in the underweight-, normal- and overweight-physique phantoms, while the outline was further deformed to the target chest, waist and hip circumferences. The RSNPFS provides the hip circumference, but doesn’t provide the head circumference. We still used the same deformation algorithm mentioned above but different circumference datasets to adjust the outline.

We assumed that the difference in physique mainly results from the difference in volume and distribution of subcutaneous fat. Hence, during physique deformation, the shape and position of the internal organs remained constant in all the physique phantoms as far as possible. However, due to the outline shrink, some parts of the internal organs in the
underweight-physique phantom, such as the ribs, muscles, intestines, arteries and veins etc, went outside the body outline. These outside meshes would be moved into the body outline or removed.

The physique adjustment led the palms to leave the torso in the underweight phantom and overlap the torso in the overweight phantom. The arms were rotated to keep the palms touching the torso.

2.4. Electromagnetic field and SAR simulation

Parallel and open-source EM field simulation software named MedFDTD (http://sourceforge.net/projects/medfddtd), which was developed by us based on the finite-difference time-domain (FDTD) (Taflove et al 2005) method, was applied to calculate the EM field and whole-body averaged SAR (WBSAR) in the frequency range of 20 MHz–3 GHz. All the voxel phantoms stood isolated in the center of computational space exposed to a plane wave. The plane waves with a vertically polarized electric field irradiated from the front of phantoms. A seven-layer-thick perfectly matched layer (PML) condition (Berenger 1994) was set around the computational space. The incident power was scaled to 1 W m$^{-2}$ in all simulations. The conductivity and relative permittivity of the tissues and organs were obtained from Gabriel (1996).

The local SAR and WBSAR were evaluated following the Institute of Electrical and Electronic Engineers’ (IEEE) recommended practice (IEEE 2002). Then absorbed energy in the organs and whole body was calculated as $\sum$(local SAR $\times$ voxel mass). The absorbed-energy percentages in skin, fat and muscle located in the superficial part of the body were analysed. Since the mass of these organs and the total absorbed energy, which are affected by body size and shape, were different among the underweight-, normal- and overweight-physique phantoms, the percentages of absorbed energy in the organs to the total absorbed energy in the whole body, rather than the whole-body absorbed energy, were more reasonable for evaluating the redistribution of absorbed energy. The absorbed energy averaged over the organs known as the organ average SAR (OASAR) was also calculated. The WBSAR, OASAR and absorbed-energy ratios were then utilized to investigate the influence of physique on EM energy absorption.

3. Results and discussion

3.1. Chinese reference man and three physique phantoms

A new Chinese reference man deformable surface phantom with a total of 60 tissues and organs (including additional visceral fat and urine) was constructed (figure 2(a)). The deviations of mass of the 12 main internal organs from the reference values are less than 0.5%. However, after voxelization, the absolute deviations of the mass values of some organs in the voxel phantom increase by up to 2.7% (thyroid) due to the staircase-like structure of the voxel phantom, especially in the small organs, such as the thyroid (table 2). The deviations of the head circumference, chest circumference and waist circumference are less than 0.5% after several times of iteration adjustment.

A series of phantoms representing underweight-, normal- and overweight-physique people (figures 2(b)–(d)) were developed by scaling and adjusting the Chinese reference man phantom. In the underweight-physique phantom, some parts of the ribs and muscle around the peritoneal cavity and crista iliaca, arteries and veins went outside of the body. These outside meshes were moved into the outline. There were still some organ meshes outside of the body.
These meshes were then removed and led to a mass loss of 5.1% for the muscle and 0.3% for the bone and bone marrow.

3.2. Influence of subcutaneous fat on EM dosimetry

The WBSAR values of the Chinese reference man and underweight-, normal- and overweight-physique phantoms are in compliance with the safety limits (0.08 W kg\(^{-1}\)) for the general public established by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) (1998) and IEEE (2006) and have similar trends over the frequency range of 20 MHz to 3 GHz (figure 3). The resonance peak values appear at 80 MHz. The height is approximately 0.45 times the EM wavelength at resonance frequency. The ratio is a little higher than those in Dimbylow (2002), Hirata et al (2010) and Lee et al (2012), in which the ratios are in the range between 0.38 and 0.4.

At a specific frequency, the WBSAR increases while the BMI decreases. The WBSAR value of the underweight phantom is higher than the others, especially around the resonance frequency. The maximum difference, which is 0.012 W kg\(^{-1}\), occurs at the resonance frequency, while the largest relative difference, which is 67.3%, appears at 2450 MHz between the underweight and overweight phantoms. The results show similar WBSAR behavior to that reported in Lee et al (2012): smaller body volume leads to a higher WBSAR.

The WBSAR values in the Chinese reference man and normal-physique phantoms are quite close in the whole frequency range due to the similar physique. The largest relative error of WBSAR between them is only up to 4.1% and occurs at 900 MHz. This suggests that the Chinese reference man could be used to well represent the average Chinese adult male in the 50th height, BMI and circumference percentile in WBSAR evaluation.
In the frequency range below 120 MHz, the variation of the whole-body absorbed-energy values is smaller than 5.2% among the phantoms (figure 4). This indicates that the difference in WBSAR is mainly determined by the physique below 120 MHz. At above 120 MHz, an up to 28.2% difference appears. More data are needed to analyse the influence.
The mass percentages of skin, fat and muscle are 5.7%, 35.8% and 30.4% for the Chinese Reference Man, 5.9%, 30.1% and 32.4% for the underweight-physique phantom, 5.5%, 37.9% and 29.4% for the normal-physique phantom and 5.0%, 48.4% and 24.2% for the overweight-physique phantom, respectively. Due to the absorbed-energy redistributions, the absorbed-energy ratios in skin, fat and muscle vary significantly among the different-physique phantoms (figure 5).

Skin, fat and muscle absorb 79.2% – 89.7% of the total absorbed energy in the whole body in all simulations. In particular, muscle absorbs most of the EM energy in almost all simulations except in the frequency range above 2.1 GHz. This may result from the large volume and high water content of muscle. Especially, muscle in the phantoms with less subcutaneous fat has a higher absorbed-energy ratio since EM field attenuation by the more superficial organ, such as skin and subcutaneous fat, is weaker.

At a specific frequency, the absorbed-energy ratios of fat increase with fat volume. The curve fluctuation ranges are only up to 5.6% except for the overweight-physique phantom, whose value increases dramatically at above 900 MHz and leads to a 15.1% variation of absorbed-energy ratio. This increase in the overweight phantom coupled with the reduction in muscle may result from two reasons. The first reason is the subcutaneous fat is thick enough to attenuate the EM field, which leads to a low EM field intensity in the muscle located in the deeper body. Another reason is the EM wave penetration depth decreases while frequency increases.

The variation of the skin absorbed-energy ratio is small in the frequency range below 400 MHz. At above 400 MHz, the ratios increase and the trends are more obvious with frequency increasing. The reasons for the increase may be the EM field penetration depth

Figure 5. Absorbed-energy ratios of skin, fat and muscle to total absorbed energy in the Chinese reference man (Ref) and underweight (10th-BMI), normal (50th-BMI) and overweight (90th-BMI) physique phantoms.
decreasing and a standing-wave occurring when the subcutaneous fat becomes thicker and the wavelength in skin and fat shortens, which both lead to the total thickness of skin and subcutaneous fat getting close to the 1/4 wavelength in subcutaneous fat, which results in higher energy absorbed in skin (Christ et al 2006a, 2006b). When deforming the body outline to the target chest, waist and hip circumferences, the maximum point move distance in the outline of the overweight-physique phantom, which is also the maximum thickness increment of subcutaneous fat, is approximately 27.9 mm while the values are only 6.0 mm in the normal-physique phantom. This means that the overweight-physique phantom has more body surface area may be of the total skin and subcutaneous fat thickness getting into the numerical interval of the 1/4 wavelength of fat over the frequency range of 900 MHz to 3000 MHz (35.5–10.9 mm).

The ratios of the visceral fat mass to the body weight are 7.9%, 7.3% and 5.7% respectively for the underweight-, normal- and overweight-physique phantoms. However, the absorbed-energy percentages are only up to 3.0% in all simulations. This suggests that obtaining the target body weight by adjusting the mass density of visceral fat is reasonable since visceral fat doesn’t have a significant effect on absorbed energy.

The OASAR (figure 6) shows similar trends to those of the WBSAR (figure 3). In the frequency range below 160 MHz, organs in the thinner phantom are of higher OASAR. The peak value and maximum difference appear in the resonance frequency. At above 160 MHz, a small peak occurs in skin. The small peak in the fatter phantom appears at lower frequency, which corresponds to the fact that there is a larger surface area in the fatter phantom whose total thickness of skin and subcutaneous fat is getting close to the 1/4 wavelength of fat. This
indicates that the small-peak OASAR may result from the standing-wave. Since the distribution of subcutaneous fat is complex, it is difficult to determine an accurate thickness which leads to the most significant standing-wave. The small peaks are mainly related to the average effect of the standing-wave in the whole body.

The maximum absolute differences of the whole-body absorbed energy, absorbed-energy ratio and OASAR between the Chinese reference man and normal-physique phantoms are smaller than 3.5% (2450 MHz in figure 4), 4.4% (Skin, 1800 MHz in figure 5) and 8.6% (Fat, 1800 MHz in figure 6), respectively. All of the results verify again that the Chinese reference man phantom can well represent the 50th physique percentile Chinese adult male in EM dosimetry evaluation.

4. Conclusions

In summary, the present work constructed a Chinese reference man polygon-mesh surface phantom based on the VCH segment image dataset and developed an automatic deformation algorithm. A series of adult male phantoms with 10th, 50th and 90th BMI and circumference percentile physique to represent the underweight, normal and overweight physiques among Chinese people were reconstructed by deforming the Chinese reference man surface phantom and used to evaluate EM dosimetry.

The WBSAR values of the underweight-, normal- and overweight-physique phantoms exposed to the vertical polarization plane wave at the same frequency indicate that thinner physique produces higher WBSAR. The variations of the absorbed-energy ratio in skin, fat and muscle suggest that physique, which is mainly decided by the volume of subcutaneous fat, affects the distribution of EM energy in the body. Several effects contribute to the absorbed-energy ratio variations. At the same frequency among the three physique phantoms, with the volume of subcutaneous fat increasing, the absorbed-energy ratio of fat increases with the value of muscle decreasing, which suggests the enhancement of the attenuation effect of subcutaneous fat on the EM field. With frequency increase, EM energy distribution tends to be superficial because the EM field penetration depth decreases. In particular, a standing-wave may occur when the total thickness of skin and subcutaneous fat is close to the 1/4 wavelength in tissues, which leads to a high absorbed energy in skin. The similar WBSAR, whole-body absorbed energy, absorbed-energy ratios of organs and OASAR between the Chinese reference man and 50th size percentile adult male phantoms indicate that the Chinese reference man well represents the average Chinese adult male in EM dosimetry research.

Considering the variation of the volume and complexity of distribution of subcutaneous fat, more realistic human phantoms and a systematic analysis of absorbed energy in different parts of the human body are still needed to evaluate the influence of physique on EM dosimetry in the future.

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References

Ai J, Xie T, Sun W and Liu Q 2014 Red bone marrow dose calculations in radiotherapy of prostate cancer based on the updated VCH adult male phantom Phys. Med. Biol. 59 1815–30
Amanatides J and Choi K 1997 Ray tracing triangular meshes Proc. of the 8th Western Computer Graphics Symp. pp 43–52
Benger J-P 1994 A perfectly matched layer for the absorption of electromagnetic waves J. Comput. Phys. 114 185–200
Cassola V F, Milian F M, Kramer R, Lira C A B D O and Khoury H J 2011 Standing adult human phantoms based on 10th, 50th and 90th mass and height percentiles of male and female Caucasian populations Phys. Med. Biol. 56 3749–72
Christ A, Klingenbock A, Samaras T, Goiceanu C and Kuster N 2006a The dependence of electromagnetic far-field absorption on body tissue composition in the frequency range from 300MHz to 6GHz IEEE Trans. Microw. Theory Tech. 54 2188–95
Christ A, Samaras T, Klingenbock A and Kuster N 2006b Characterization of the electromagnetic near-field absorption in layered biological tissue in the frequency range from 30MHz to 6000MHz Phys. Med. Biol. 51 4951–65
Christy M and Eckerman K F 1987a Specific Absorbed Fractions of Energy at Various Ages from Internal Photon Sources, Part I: Methods ORNL/TM-8381/V1 (Oak Ridge, TN: ORNL)
Christy M and Eckerman K F 1987b Specific Absorbed Fractions of Energy at Various Ages from Internal Photon Sources, Part VII: Adult Male ORNL/TM-8381/V7 (Oak Ridge, TN: ORNL)
Conil E, Hadjem A, Lacroux F, Wong M F and Wiart J 2008 Variability analysis of SAR from 20MHz to 2.4GHz for different adult and child models using finite-difference time-domain Phys. Med. Biol. 53 1511–25
Dimbylow P J 2002 Fine resolution calculations of SAR in the human body for frequencies up to 3GHz Phys. Med. Biol. 47 2835–46
Dimbylow P 2005 Development of the female voxel phantom, NAOMI, and its application to calculations of induced current densities and electric fields from applied low frequency magnetic and electric fields Phys. Med. Biol. 50 1047–70
Ding A, Mille M M, Liu T, Caracappa P F and Xu X G 2012 Extension of RPI-adult male and female computational phantoms to obese patients and a Monte Carlo study of the effect on CT imaging dose Phys. Med. Biol. 57 2441–59
Dong L, Li T and Liu C 2015 Construction of hybrid Chinese reference adult phantoms and estimation of dose conversion coefficients for muons Radiat. Prot. Dosim. 164 219–27
Gabriel C 1996 Compilation of the dielectric properties of body tissues at RF and microwave frequencies Brooks Air Force Technical Report AL/OE-TR-1996-0037
General Administration of Sport of China 2007 Report on the second national physical fitness surveillance (Beijing: People’s Sports Publishing House of China)
Hirata A, Fujiwara O, Nagasaki T and Watanabe S 2010 Estimation of whole-body average SAR in human models due to plane-wave exposure at resonance frequency IEEE Trans. Electromagn. Compat. 52 41–8
IAEA 1998a Compilation of Anatomical, Physiological and Metabolic Characteristics for a Reference Asian Man, Volume 1: Data Summary and Conclusions IAEA-TECDOC-1005 (Vienna: IAEA)
IAEA 1998b Compilation of Anatomical, Physiological and Metabolic Characteristics for a Reference Asian Man, Volume 2: Country Reports IAEA-TECDOC-1005 (Vienna: IAEA)
ICNIRP 1998 Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300GHz) Health Phys. 74 494–522
ICRP 1975 Report of the Task Group on Reference Man (ICRP Publication 23) (Oxford: Pergamon)
ICRP 2002 Basic Anatomical and Physiological Data for Use in Radiological Protection: Reference Values (ICRP Publication 89) (Oxford: Pergamon)
IEEE 2002 IEEE Recommended Practice for Measurements and Computations of Radio Frequency Electromagnetic Fields with Respect to Human Exposure to Such Fields, 100kHz–300GHz Std C95.3-2002 (New York: IEEE)
IEEE 2006 IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz Std C95.1-2005 (New York: IEEE)
Lee A-K and Choi H-D 2012 Determining the influence of Korean population variation on whole-body average SAR Phys. Med. Biol. 57 2709–25
Lee C, Lodwick D, Hasenauer D, Williams J L, Lee C and Bolch W E 2007 Hybrid computational phantoms of the male and female newborn patient: NURBS-based whole-body models Phys. Med. Biol. 52 3309–33
Li A, Liu Q, Zeng S, Tang L, Zhong S and Luo Q 2008 Construction and visualization of high-resolution 3D anatomical structure datasets for Chinese digital human Chin. Sci. Bull. 53 1848–54
Liu L, Zeng Z, Li J, Zhang B, Qiu R and Ma J 2009a An ICRP-based Chinese adult male voxel model and its absorbed dose for idealized photon exposures—the skeleton Phys. Med. Biol. 54 6675–90
Liu L, Zeng Z, Li J, Qiu R, Zhang B, Ma J, Li R, Li W and Bi L 2009b Organ dose conversion coefficients on an ICRP-based Chinese adult male voxel model from idealized external photons exposures Phys. Med. Biol. 54 6645–73
Liu Y, Xie T and Liu Q 2011 Monte Carlo simulation for internal radiation dosimetry based on the high resolution Visible Chinese Human Nucl. Sci. Tech. 22 165–73
Na Y H, Zhang B, Zhang J, Caracappa P F and Xu X G 2010 Deformable adult human phantoms for radiation protection dosimetry: anthropometric data representing size distributions of adult worker populations and software algorithms Phys. Med. Biol. 55 3789–811
Nagaoka T, Watanabe S, Sakurai K, Kumieda E, Watanabe S, Taki M and Yamanaka Y 2004 Development of realistic high-resolution whole-body voxel models of Japanese adult males and females of average height and weight, and application of models to radio-frequency electromagnetic-field dosimetry Phys. Med. Biol. 49 1–15
National Health and Family Planning Commission of the People’s Republic of China 2013 Criteria of weight for adults. Health industry standard of the People’s Republic of China WS/T 428–2013
Qiu R, Li J, Huang S, Bi L and Luo N 2012 Organ dose conversion coefficients for external neutron irradiation based on the Chinese mathematical phantom (CMP) J. Nucl. Sci. Technol. 49 263–71
Qiu R, Li J, Zhang Z, Liu L, Bi L and Ren L 2009 Dose conversion coefficients based on the Chinese mathematical phantom and MCNP code for external photon irradiation Radiat. Prot. Dosim. 134 3–12
Qiu R, Li J, Zhang Z, Wu Z, Zeng Z and Fan J 2008 Photon SAF calculation based on the Chinese mathematical phantom and comparison with the ORNL phantoms Health Phys. 95 716–24
Sandrini L, Vaccari A, Malacarne C, Cristoforetti L and Pontalti R 2004 RF dosimetry: a comparison between power absorption of female and male numerical models from 0.1 to 4 GHz Phys. Med. Biol. 49 5185–201
Sheng Y, Tan L, Ieon J and Xia X 2013 Development of a voxel-based Chinese reference female phantom from color photographs for radiation dosimetry applications Health Phys. 105 512–21
Snyder W, Ford M, Warner G and Watson B 1969 Medical internal radiation dose committee (MIRD) Pamphlet No. 5: estimates of absorbed fractions for monoenergetic photon sources uniformly distributed in various organs of a heterogeneous phantom J. Nucl. Med. 10 (Suppl. 3) 7–52
Taflove A and Hagness S C 2005 Computational Electrodymanics: the Finite-Difference Time-Domain Method 3rd edn (Norwood, MA: Artech House)
Tanaka G, Kawamura H, Griffith R V, Cristy M and Eckerman K F 1998 Reference man models for males and females of six age groups of asian populations Radiat. Prot. Dosim. 79 383–6
Wang J, Chen R, Zhu H, Zhou Y and Ma R 1998 Data of Anatomical Physiological and Metabolic Characteristics for Chinese Reference Man (Beijing: Atomic Energy Press)
WHO 2000 Obesity: Preventing and Managing the Global Epidemic. Report of a WHO Consultation (World Health Organisation Technical Report Series 894 i–xii) (Geneva: WHO) pp 1–253
Yu D, Zhang R and Liu Q 2012 Influence of dentures on SAR in the visible Chinese human head voxel phantom exposed to a mobile phone at 900 and 1800MHz Bioelectromagnetics 33 508–17
Zhang B, Ma J, Liu L and Cheng J 2007a CNMAN: a Chinese adult male voxel phantom constructed from color photographs of a visible anatomical data set Radiat. Prot. Dosim. 124 130–6
Zhang G, Liu Q, Zeng S and Luo Q 2008a Organ dose calculations by Monte Carlo modeling of the updated VCH adult male phantom against idealized external proton exposure Phys. Med. Biol. 53 3697–722
Zhang G, Luo Q, Zeng S and Liu Q 2008b The development and application of the visible Chinese human model for Monte Carlo dose calculations Health Phys. 94 118–25
Zhang G, Liu Q and Luo Q 2007b Monte Carlo simulations for external neutron dosimetry based on the visible Chinese human phantom Phys. Med. Biol. 52 7367–83
Zhang S-X, Heng P-A and Liu Z-J 2006 Chinese visible human project Clin. Anat. 19 204–15
Zhang J, Na Y H, Caracappa F P and Xu X G 2009 RPI-AM and RPI-AF, a pair of mesh-based, size-adjustable adult male and female computational phantoms using ICRP-89 parameters and their calculations for organ doses from monoenergetic photon beams Phys. Med. Biol. 54 5885–908