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Application and Future Prospects of Computational Human Models in Conjunction with Monte Carlo Simulations in Radiation Dosimetry

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Abstract: In the field of radiation dosimetry research, the combination of computer-based human models and Monte Carlo simulation methods has proven to be indispensable and enables a differentiated and detailed approach to studying radiation exposure and its effects. This article examines in depth the application of radiation dosimetry to computer-aided human models combined with Monte Carlo simulations in assessing ionizing radiation doses and illustrates its critical role in this field. This article systematically analyses three main techniques for assessing ionizing radiation dose: direct measurement, phantom model measurement and the advanced method using computer-aided human models with Monte Carlo simulations, highlighting the notable advantages of the latter method. In addition, this article introduces a variety of software tools and discusses the basic principles and wide-ranging applications of computational human models based on Monte Carlo simulations, highlighting their adaptability and effectiveness in this area. Finally, the paper provides a visionary outlook on the evolving landscape and future possibilities of integrating computer-based human models with Monte Carlo simulation methods for radiation dose estimation and predicts significant advances in the field.

1. Introduction

Ionizing radiation, a physical phenomenon that occurs when high-energy particles interact with matter and results in atomic excitation or ionization, is widespread throughout the universe and in nature. The progress and application of radiomedicine, nuclear engineering and space technology have significantly increased the concentration of ionizing radiation in human daily life, making its impact on human health increasingly significant. Prolonged exposure to ionizing radiation can cause DNA mutations, potentially leading to cancer or genetic effects from radiation. Radiation genetic effects are divided into stochastic and deterministic effects. Stochastic effects that are linearly related to radiation dose, can lead to DNA mutations and cancer. Deterministic effects, on the other hand, require the occurrence of a certain dosage threshold, above which they can lead to functional disorders of human organs [1]. Additionally, although non-ionizing radiation such as visible light and microwaves are not powerful enough to ionize matter, they can still have effects on organisms [2].

To accurately assess the effects of radiation on humans, the International Commission on Radiation Units and Measurements (ICRU) and the International Commission on Radiological Protection (ICRP) have developed a comprehensive system for assessing the dose parameters of ionizing radiation. They have also published a number of standards for calculating radiation doses [3-5]. In accordance with these standards, researchers worldwide have developed various radiation dose simulation software and computable human models using the Monte Carlo method. This allows for precise assessment prior to exposure and helps prevent harm to humans from radiation. Therefore, this paper offers a comprehensive overview of the principles, current research, and applications of computable human body models used in radiation dose estimation.

2. Advantages of Combining Computer-Based Models of the Human Body with Monte Carlo Simulation Methods

Ionizing radiation dose assessment primarily involves three methods. The first method involves directly measuring the surface radiation dose by equipping the human body with dosimeters. The second method uses phantom models equipped with microdosimeters at various locations to determine the internal absorbed dose within a radiation field. The third method uses computable models of the human body in combination with Monte Carlo simulation techniques to simulate and determine the absorbed dose of the human body [6]. Direct measurements are carried out using thermoluminescence dosimeters and activation film dosimeters; Phantom models typically use tissue equivalent ionization chambers, Geiger-Müller counters, proportional counters, and semiconductor detectors to measure absorbed doses, dose equivalents, and charged particle energy spectra in real time. Both methods provide intuitive, real-time dose data, but require the subject (human or phantom) to be in an actual radiation environment and equipped with dosimeters. This process is complex and cumbersome and prone to interference from external factors such as humidity, temperature and pressure [7], which has significant limitations.

Integration of computable human body models with Monte Carlo simulation is currently widely used in radiation assessment. Their advantage lies in the use of software to simulate the exposure of the human body to certain radiation conditions. This approach avoids external interference and allows for the advance estimation of radiation doses to various organs before exposure to ionizing radiation [8], thus providing a data and technical basis for radiation protection strategies. The simulation process, as shown in Figure 1, mainly includes: selecting the simulation object, constructing a human body model, configuring a radiation source, setting up a radiation field, and data analysis and evaluation. The creation of the human body model should take into account differences in body tissue, age, gender and physique [8].When setting up radiation sources with Monte Carlo simulation, the source type, location and energy can be changed as needed, taking into account the operating conditions and environment. This allows relatively easy control of relevant variables and the number of simulations and offers a high cost-benefit ratio. Finally, during the data analysis and evaluation phase, the selection of appropriate computational tools to determine radiation doses and other relevant data is crucial, as these form a theoretical basis for radiation protection. The Monte Carlo computational model can describe the properties of radiation fields and the human body structure in detail. The application of this method to various radiation dose assessments demonstrates its significant value.

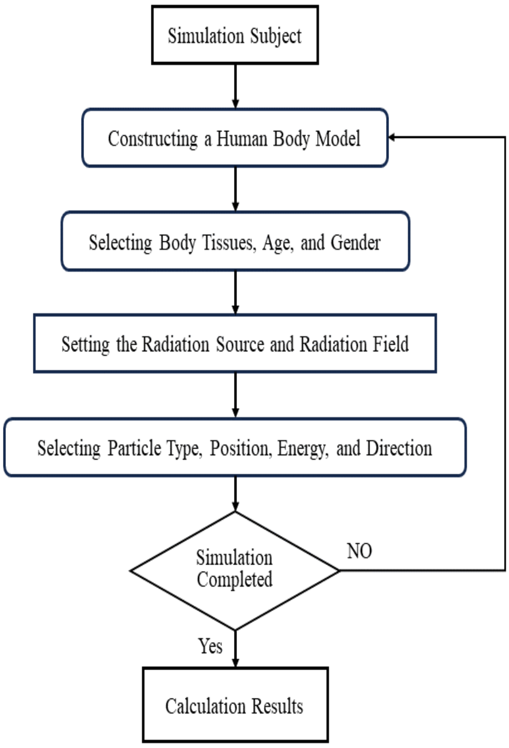

Figure 1: Steps in Combining Computational Human Body Models with Monte Carlo Simulation

3. Radiation Simulation Software and Omputer-Aided Models of the Human Body in Radiation Protection

Using software packages based on the Monte Carlo method, a wide range of targeted software applications and computable human body models have been developed, designed for applications in medical radiation dose assessment, nuclear facility design assessment, and environmental radiation monitoring . These programs and models are now used in several areas and significantly improve the efficiency and precision of radiation protection management.

3.1 Principles and Applications of Radiation Simulation Software

In methods that integrate human body models with Monte Carlo simulation for simulation calculations, the simulation of radiation sources is crucial. Radiation sources are typically divided into artificial and natural radiation. Artificial radiation comes mainly from man-made devices that can emit radiation, such as nuclear power plants. Particle accelerators and nuclear medicine instruments, while natural radiation comes largely from cosmic rays and various radioactive materials in the Earth's crust. In everyday life, the effects of artificial radiation on the human body are greater, so radiation source simulations typically focus only on artificial radiation. The simulation of the radiation source mainly uses the Monte Carlo method, as shown in Figure 2. This method is a statistical approach based on random numbers and probability principles that estimates the expected value of a random variable or the probability of a random event by a large number of random numbers, which becomes more stable as the number of samples increases.

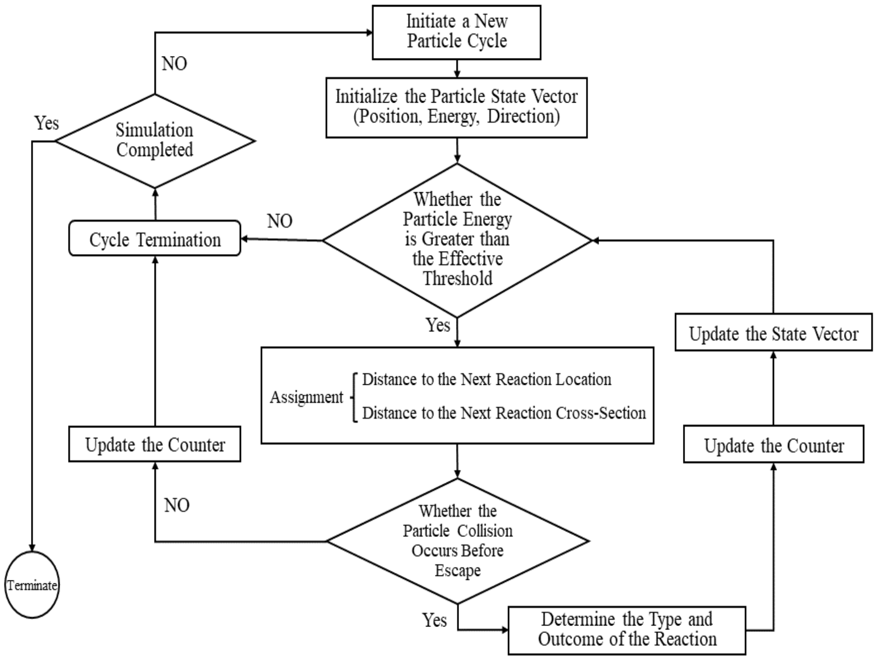

Figure 2: Monte Carlo Radiation Particle Reaction Simulation Flowchart, sourced from Reference [7]

This method, applied to simulate radiation transport processes, is capable of managing complex geometric shapes and various radiation sources and is extensively utilized in cosmic rays, nuclear medicine, nuclear engineering, and radiation protection fields. Common software packages include CORSIKA (Cosmic Ray Simulations for KASCADE), MCNP (Monte Carlo N-Particle Transport Code), and GEANT4 (Geometry and Tracking). CORSIKA is a tool for simulating the transmission of high energy cosmic rays in the atmosphere, initially developed for the KASCADE experiment, it accurately simulates cosmic rays and their secondary particles in the atmosphere, widely used in cosmic ray and high-energy physics research[9]; MCNP, a general-purpose software package based on the Monte Carlo method, calculates neutron, photon, and electron transport in three-dimensional complex geometries, features an array of physical interaction models, used for simulating human radiation exposure and playing a significant role in radiation dose calculations[10]; GEANT4, an open-source software toolkit for Monte Carlo simulation, was developed by the European Organization for Nuclear Research (CERN) using C++ language and is used to simulate particle-matter interactions. It has comprehensive physical models enabling the simulation of particle tracking, detector response, physical processes, geometric descriptions, and data management [11], and is primarily used in areas like radiation protection, radiotherapy, medical imaging, and aerospace engineering.

In the aftermath of the Fukushima nuclear accident in Japan, the safety of nuclear power plants became the focus of global concern, highlighting the critical importance of radiation simulation calculation software. However, previously China lacked radiation simulation software with independent intellectual property rights. The introduction of foreign software was restricted by licenses, prompting China to develop corresponding software to break the international technological monopoly. Since 1999, the Institute of Nuclear Energy Safety Technology of the Chinese Academy of Sciences and the FDS team have independently developed the Super Monte Carlo simulation software system SuperMC. This software supports simulations with a focus on radiation transfer, particularly in complex modeling of radiation source distribution (such as fusion reactor plasma sources) and geometric interactive counting modeling, and also includes multidisciplinary coupled simulations in areas such as thermal hydraulics and structural mechanics, and currently has advances in key technologies such as precise modeling, efficient computing and four-dimensional visualization[12]; Beijing Institute of Applied Physics and Computational Mathematics has developed JMCT Monte Carlo software specializing in complex reactor physics analysis and criticality shielding calculations, and has successfully carried out modeling and simulation calculations for the entire core of Reactor Unit 1 at Daya Bay Nuclear Power Plant Plant achieved results, which closely match those of the MCNP software, and successfully addressed data storage and parallel computation challenges due to tens of millions of geometric grid elements and hundreds of billions of simulated particles. In particular, he demonstrated technical superiority in handling solid-core model problems[13]; RShieldMC (Radiation Shielding Monte Carlo), developed by the Nuclear and Radiation Safety Center of the Chinese Ministry of Ecology and Environment, is a software that simulates the coupled transport of neutrons and photons in complex geometric systems for radiation shielding. The RShieldMC visualization preprocessing module is used to create models for Prepared shielding calculations for radiation monitoring tubes and calculated the neutron flow rate in the midplane and top weld of the radiation monitoring tube of the reactor core in the Qinshan Phase I reactor. The results are consistent with those of MCNP, JMCT-S, TORT and other programs, demonstrating their accuracy and utility in calculating neutron flow rate[14]; Tsinghua University's development of NUCRPD and THUDose software excels in the field of radiation protection design and dose calculation. NUCRPD, developed based on the Geant4 Monte Carlo software package, provides parameterized modeling for commonly used radiation imaging systems and allows users to quickly set up geometries, sources, physical models and statistics for various radiation imaging systems by setting a few parameters at the interface customize, which facilitates parallel computations on servers for simulations, efficiently simulates system performance indices, and provides intuitive graphics to help users comprehensively understand the simulation results[15]; The THUDose software is an innovative radiation protection design and dose calculation tool developed with the Geant4 toolkit, containing pre-processing, Monte Carlo simulation and post-processing modules, as well as a user-friendly interface that allows the setting of materials, geometries, as they sources , physical models and statistical methods for simulations through simple parameter adjustments, and supports server-based parallel computing and visualization of results, allowing users to intuitively analyze results in a short time[16], this software meets most needs in radiation shielding system design and detection system-Parameter accounting, and is characterized by its high accuracy and flexibility. Looking at the development history of China's radiation simulation software, through years of targeted research and development, the company has evolved from initial dependence on foreign software and technology to develop radiation simulation software tailored to domestic needs, and has achieved significant achievements in terms of algorithm optimization, simulation accuracy and user interface Advances have been made, and certain software has become an integral part of the design and operation of nuclear facilities both in China and internationally.

3.2 Principles and Applications of Computer-Based Models of the Human Body

Human body models expressed in computer language represent the three-dimensional anatomical structure of the human body, including the size, shape, position and spatial relationships of various tissues and organs. Human body models are mainly classified into three types: stylized models, voxel models and mesh models. From initial spherical models to stylized models, they have evolved to voxel models based on real human medical images and advanced to the latest polygon mesh models[17]. There are over 120 types of human body models for simulation calculations worldwide, covering diverse populations, including children, adolescents, and adult men and women (including pregnant women)[10], and further development of these models plays a critical role in guiding radiation protection efforts.

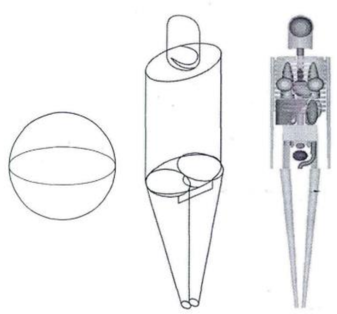

Figure 3: Schematic Models (Left: ICRU Sphere; Center: External Surface of the Adult Model; Right: Skeleton and Internal Organs)[1]

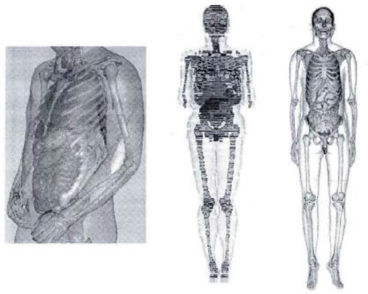

Figure 4: Structure Diagram of Adult Male Voxel Models (Left: VIP-Man Model; Center: KORMAN Model; Right: VCH Model)[2]

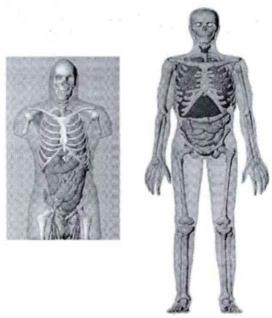

Figure 5: Three-Dimensional Renderings of Human Body Surface Models (Left: NCAT Model; Right: RPI Model)[3]

The stylized models use basic geometric shapes to represent structures and organs of the human body, which simplifies the simulation of the human body through basic formulas and facilitates easy modeling and customization. The model structure is shown in Figure 3. In the 1970s, the Oak Ridge National Laboratory in the United States developed a basic model based on this approach[18] and gradually incorporated organ and body parameters into it, resulting in a reference model that can be adapted to different populations but its simplified forms limited its ability to accurately represent human anatomy, leading to inaccuracies in radiation assessment.

The voxel model is a type of three-dimensional human model based on medical imaging such as CT, MRI, or color tomographic section images, with its model structure shown in Figure 4.These models accurately represent the anatomical structure of the human body by converting

123 sourced from Reference [7]

two-dimensional pixels into three-dimensional voxels, with smaller voxel sizes resulting in more detailed models but also higher computational effort [6]. Starting in the 1980s, voxel model research experienced explosive growth worldwide. The German GSF model family, based on multiple sets of CT images, considers different age groups and genders[19]; Rensselaer Polytechnic Institute in the United States developed the VIP Man model based on the Visible Human Project[20]; Japan has created various population models using CT and MRI data[21]. To accurately represent specific population body types, various countries have developed voxel models tailored to their populations. In China, Tsinghua University and the China Institute of Radiation Protection have developed the CNMAN male model and VPCF female model, based on the "Chinese Visible Human" data [22], making adjustments to the mass of organs and red bone marrow within the CNMAN model; Huazhong University of Science and Technology has constructed both male and female models using the "Visualized Chinese Human" data[23].

The structure of the mesh model, as shown in Figure 5, uses polygonal meshes or Non-Uniform Rational B-splines (NURBS) to delineate human organs. This approach provides a highly accurate method for radiation dose estimation. The University of North Carolina has successfully constructed the NCAT human model (NURBS-based cardiac torso) using NURBS technology and using the VHP dataset, which enables the simulation of 4D human models with heartbeat and respiration[24]; Zhao Ri and colleagues from the China Institute of Radiation Protection applied the tetrahedral division method of the Delaunay algorithm, enabled fast Monte Carlo calculations, and developed an application system for 4D dose calculation[25], making breakthroughs in important technical aspects of 4D dose calculations explored the potential of this technology for precise personal protection in scenarios such as nuclear power plant operations, nuclear decommissioning and medical interventional treatments in the future; The research group at Huazhong University of Science and Technology focuses on developing specific Chinese population models based on VCH data, and further subdivides these models for adult males with different weights[26]; The RPI research group has successfully converted VIP-Man data into polygon mesh models, taking into account the unique case of pregnant women. With the introduction of dynamic mesh models with adjustable posture by the RPI research group, it has provided a crucial tool for assessing radiation exposure in different postures [27]. These models accurately represent human anatomical structures and are more flexible in simulating different body types and postures.

3.3 Current Applications of Computer-Aided Models of the Human Body in Combination with Monte Carlo Simulation Methods

Currently, the integration of computable models of the human body with the Monte Carlo method is applied in nuclear accident scenarios, medical radiation, and environmental radiation dose estimation. In the area of nuclear accidents, simulating the spread of radioactive substances and their absorption by the human body enables the assessment of health risks and supports the development of evacuation and protection strategies. Using Chinese human body models, Li Mingsheng and colleagues successfully simulated the lung measurement efficiency of the detector in the Qinshan Phase III whole-body counter using MCNP, achieving remarkable results[28]; Ding Yanqiu and his team used Geant4 to simulate external radiation and found that the simulated doses to vital organs such as the heart, kidneys and liver were essentially consistent with measurements from thermoluminescence personal dosimeters[29]. In radiation therapy planning, the combination of Monte Carlo simulation and computable models of the human body enables more accurate calculation of doses to both diseased areas and surrounding normal tissue. The research group at Tsinghua University applied the CRAM model to calculate the dynamic dose distribution of 241Am and 60Co in the human body; Tang Xiaobin and colleagues developed a radiation simulation model of the human body consistent with Chinese anatomical and physiological data, and determined the human radiation dose during radiation therapy by integrating with the Monte Carlo method. For monitoring natural radiation environments, such as determining doses to radar operators or people handling natural radioactive substances, this methodology provides a way to assess cumulative doses and potential health risks.

In summary, the development of human modeling in radiation protection has moved from simple geometric simulations to sophisticated models based on state-of-the-art medical imaging techniques. This change not only reflects technological advances, but also highlights the growing demand for increased precision and versatility in these models.

4. Conclusions

As computer technology advances, radiation software is expected to improve its data processing capabilities and simulation capabilities, allowing it to process larger data sets and perform more complex and precise simulation analysis. With increasing requirements in various areas, the need for personalized radiation treatment software is also growing. In the future, radiation simulation software is likely to integrate artificial intelligence and big data technologies to further improve simulation efficiency and accuracy, while opening new opportunities for innovation and breakthroughs in the research field of radiation dose estimation technology.

Continuous advances in medical imaging technology and computing power have led to significant advances in the development and application of models of the human body in the field of radiation protection, resulting in significantly improved accuracy and realism of these models. It is expected that the uses of human body models will become more diverse in the future, not only for dose calculation, but also for evaluating the effects of radiation on the human body, with a greater focus on individual characteristics such as age, gender, body type, etc Models and health status are incorporated into their analysis and construction, so that these models depict the complex structures and physiological changes of the human body more quickly and realistically. The accuracy and scope of human body models will continue to increase, providing more reliable and precise tools for both radiation protection and medical research.

In China, the integration of detailed human body models with the Monte Carlo method is relatively limited in number, and these models are predominantly static, which may affect dose calculations in diagnostic procedures and radiation therapy due to factors such as breathing, although with advances through artificial Intelligence and machine learning will make it possible to accurately estimate the absorbed doses of people exposed to different scenarios, providing a crucial basis for developing and optimizing radiation protection strategies.

References

[1] Bao, Y., Fang, X., Gan, X., et al. (2022). Current research status on the biological mechanisms of non-ionizing radiation-induced damage to male reproductive function. Journal of Naval Medical University, 43(03), 308-313. DOI: 10.16781/j.CN31-2187/R.20200875.

[2] ICRP. (2007). 2007 Recommendations of the International Commission on Radiological Protection (ICRP Publication 103). Oxford, UK: International Commission on Radiological Protection.

[3] ICRU. (1992). Measurement of dose equivalents from external photon and electron radiations. Bethesda, Maryland: International Commission on Radiation Units and Measurements.

[4] ICRP. (2010). Conversion coefficients for radiological protection quantities for external radiation exposure (ICRP Publication 116). Oxford, UK: International Commission on Radiological Protection.

[5] Lü, W. (2017). The influence of human body size on radiation protection dose assessment in photon and proton irradiation (Doctoral dissertation, Huazhong University of Science and Technology).

[6] Sun, W. (2012). Construction of parametric models and surface models based on digital human body and study on external radiation dose (Doctoral dissertation, Huazhong University of Science and Technology).

[7] Xu, G. X. (2014). An exponential growth of computational phantom research in radiation protection, imaging, and radiotherapy: A review of the fifty-year history. Physics in Medicine and Biology, 59(18).
[8] Evans, J. R. (2011). Data model and decision (4th ed.). Renmin University of China Press, 87-108.
[9] Ma, Q., Liu, M. Z., & Liu, D. M. (2017). Research progress on radiation dose estimation in human models based on the Monte Carlo simulation program MCNP. Journal of Preventive Medicine Information, 33(02), 191-194.
[10] Allison, J., Amako, K., Apostolakis, J. E. A., et al. (2006). Geant4 developments and applications. IEEE Transactions on Nuclear Science, 53(1), 270-278.
[11] Wu, Y. C., Song, J., Hu, L. Q., et al. (2016). SuperMC: A super Monte Carlo nuclear computational simulation software system. Nuclear Science and Engineering, 36(01), 62-71.
[12] Deng, L., Li, G., Zhang, B. Y., et al. (2014). Simulation of full-core pin-by-pin model in the JMCT Monte Carlo neutron-photon transport code. Atomic Energy Science and Technology, 48(06), 1061-1066.
[13] Han, J. R., Shi, S. C., Xu, C., et al. (2019). Development and validation of the radiation shielding dedicated Monte Carlo software RShieldMC. Nuclear Technology, 42(03), 68-72.
[14] Wu, X. G., Wu, Z., Ming, S. J., et al. (2017). Development and application of the radiation imaging system simulation software NUCRPD. High Power Laser and Particle Beams, 29(12), 84-92.
[15] Luo, X. Y., Qiu, R., Wu, Z., et al. (2021). Development and application of the radiation protection design and dose calculation software THUDose. Modern Applied Physics, 12(02), 25-30.
[16] Yan, C. C., Qiu, R., Liu, L. Y., et al. (2012). Chinese reference human digital voxel phantoms and their applications in the field of radiation protection. Journal of Tsinghua University (Science and Technology), 52(07), 911-916. DOI: 10.16511/j.cnki.qhdxxb.2012.07.011.
[17] Snyder, W. S., Fisher, H. L., Ford, M. R., et al. (1969). Estimates of absorbed fractions for monoenergetic photon sources uniformly distributed in various organs of a heterogeneous phantom. Journal of Nuclear Medicine, Supplement 3, 7-52.
[18] Petoussi-Henss, N., Zankl, M., Fill, U., et al. (2001). The GSF family of voxel phantoms. Physics in Medicine & Biology, 47(1), 89.
[19] Xu, X. G., Chao, T. C., & Bozkurt, A. (2000). VIP-Man: An image-based whole-body adult male model constructed from color photographs of the Visible Human Project for multi-particle Monte Carlo calculations. Health Physics, 78(5), 476-486.
[20] Saito, K., Wittmann, A., Koga, S., Ida, Y., Kamei, T., Funabiki, J., & Zankl, M. (2001). Construction of a computed tomographic phantom for a Japanese male adult and dose calculation system. Radiation and Environmental Biophysics, 40(1), 69–76.
[21] Zhang, B., Ma, J., Liu, L., et al. (2007). CNMAN: A Chinese adult male voxel phantom constructed from color photographs of a visible anatomical data set. Radiation Protection Dosimetry, 124(2), 130-136.
[22] Sun, W., Jia, X. H., Xie, T. W., et al. (2013). Construction of boundary-surface-based Chinese female astronaut computational phantom and proton dose estimation. Journal of Radiation Research, 54(2), 383-397.
[23] Segars, W. P. (2001). Development and application of the new dynamic NURBS-based cardiac-torso (NCAT) phantom. (Doctoral dissertation, The University of North Carolina at Chapel Hill).
[24] Zhao, R., Liu, Z. X., Liu, N., et al. (2023). Research on 4D human body radiation dose calculation technology. Nuclear Technology, 46(01), 28-34.
[25] Yu, D., Wang, M., & Liu, Q. (2015). Development of Chinese reference man deformable surface phantom and its application to the influence of physique on electromagnetic dosimetry. Physics in Medicine & Biology, 60(17), 6833.
[26] Li, D. M., Jia, S. H., & Li, H. W. (2013). Efficiency simulation study of whole body counter using Chinese human model based on MCNP. Nuclear Electronics and Detection Technology, 2013(12), 1502-1506. DOI: 10.3969/j.issn.0258-0934.2013.12.017.
[27] Ding, Y. Q., Li, M. S., Liu, Y. H., et al. (2015). Research on the method of using simulated human body models to estimate the physical dose of individuals in irradiation places. Chinese Medical Equipment, 2015(2), 8-10. DOI: 10.3969/J.ISSN.1672-8270.2015.02.003.
[28] Liu, L., Franck, D., de Carlan, L., Li, J., (2007). Application of Monte Carlo calculation and OEDIPE software for virtual calibration of an in vivo counting system. Radiation Protection Dosimetry, 127(1-4), 282-286. https://doi.org/10.1093/rpd/ncm469.
[29] Tang, X. B., Geng, C. R., Xie, Q., Chen, D. (2012). Dose calculation research based on NHMAN radiation simulation human model using the Monte Carlo method. Nuclear Electronics and Detection Technology, 32(2), 214-218. DOI: 10.3969/j.issn.1005-202X.2012.02.002.