A STUDY ON THE CONVERSION COEFFICIENTS OF EQUIVALENT BLADDER DOSAGE BASED ON MONTE CARLO SIMULATION

by

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By calculating the dose estimation coefficients for bladder phantoms with varying volumes and equivalent geometric shapes, this study offers guidance for the efficient and accurate assessment of risk organ doses ^{18}F imaging. Based on the modeling of bladder phantoms with four different equivalent geometric shapes, and considering possible treatment conditions, the Monte Carlo method was used to simulate and calculate the absorbed doses and dose conversion coefficients of bladder phantoms of different shapes and sizes. The results show that the absorbed dose of the bladder phantom significantly decreases with the increase of bladder volume, and the absorbed dose of 70 mL is about three times that of 270 mL. The absorbed dose of the conical bladder phantom is significantly different from other shapes, with a relative deviation of 6 to 30 times that of other shapes. The ratio of bladder wall volume to surface area of the conical bladder phantom is significantly different from other shapes, with a relative deviation of 5 to 20 times that of other shapes. Therefore, when using bladder phantoms to calculate dose estimation coefficients, it is necessary to consider not only the ratio of phantom volume to surface area but also the actual shape and volume of the bladder.

Key words: positron emission tomography, Monte Carlo, nuclear medicine, radiation dosimetry

INTRODUCTION

Positron emission computed tomography (PET), is highly advanced imaging technology for precise medical diagnostics. It is widely applied in clinical cancer diagnosis, with radiographic imaging agents containing the radioactive isotope ^{18}F making up over 90 % of total clinical applications. During its decay from an unstable to a ground state, ^{18}F releases a positron, which rapidly annihilates with free electrons in the target material, emitting a pair of oppositely directed gamma photons, each with an energy of 0.511 MeV [1-6]. Any ^{18}F that does not decay at the lesion site is metabolized and excreted through the bladder. When retained in the bladder as primary urine, the ^{18}F decay-emitted photons will cause an additional dose burden on the bladder wall and surrounding organs. Therefore, accurately estimating risk organs doses, especially for the bladder, using Monte Carlo simulation is a trending topic in radiation protection, dosimetry, and nuclear medicine [7-12].

Most current studies estimate the bladder wall dose using the medical internal radiation dose (MIRD) method [13]. However, MIRD does not account for dynamic changes in parameters such as bladder wall volume during primary urine retention, leading to inaccurate results. To this end, Wu *et al*. [14] proposed a dynamic balloon-bladder phantom, modeling the bladder at different times as a fixed-shaped ellipsoid. However, since the actual bladder shape changes with urine filling, this simplification may introduce additional errors in bladder wall dose estimation [15, 16].

This study aims to propose a bladder phantom group modeled based on the GEANT4 software. Using simulation calculations, we compared the absorbed doses in bladder walls with different volumes and shapes [17], and differences in dose conversion coefficients, thereby providing a basis for selecting a more accurate equivalent geometric shape for bladder dose estimation. The results of this study will help to choose medication conditions that can reduce the dose received by risk organs, which is of great significance for improving the level of radiation protection in nuclear medicine and reducing the extra dose received by patients.

MATERIAL AND METHOD

Bladder phantom model

The shape and volume of the bladder change depending on the degree of urine filling. When empty, it has a conical form. As urine continues to fill, it gradually becomes ellipsoidal and finally approximates a

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Table 1. Geometric parameters of bladder models

Volume [mL]	Ellipsoid			Sphere	Cone		Cylinder	
	Semiaxis a [cm]	Semiaxis b [cm]	Semiaxis c [cm]	Radius [cm]	High [cm]	Bottom radius [cm]	High [cm]	Bottom radius [cm]
70	2.45	2.50	2.45	2.50	5.00	3.54	5.00	2.04
120	2.96	3.00	2.96	3.00	6.00	4.24	6.00	2.45
180	3.46	3.50	3.46	3.50	7.00	4.95	7.00	2.83
270	3.87	4.00	3.87	4.00	8.00	5.66	8.00	3.27

spherical shape. The thickness of the bladder wall is usually 4~6 mm [18, 19]. This study sets up four groups of bladder phantoms with volumes of 70 mL, 120 mL, 180 mL, and 270 mL, respectively, to evaluate the absorbed dose at different filling stages. Each volume includes four shapes: conical, frustum, ellipsoidal, and spherical, resulting in 16 (4 × 4) model parameters, as shown in tab. 1, with a constant bladder wall thickness of 5 mm assumed at each stage.

In the clinical cancer diagnosis of PET [20], the radioactive activity of ^{18}F in the patient's body is generally 185~370 MBq, of which about 20 % is concentrated in the bladder. Therefore, this study sets the radioactive specific activity of urine at 0.3 MBq (mL)$^{-1}$ to estimate the absorbed dose of the bladder wall.

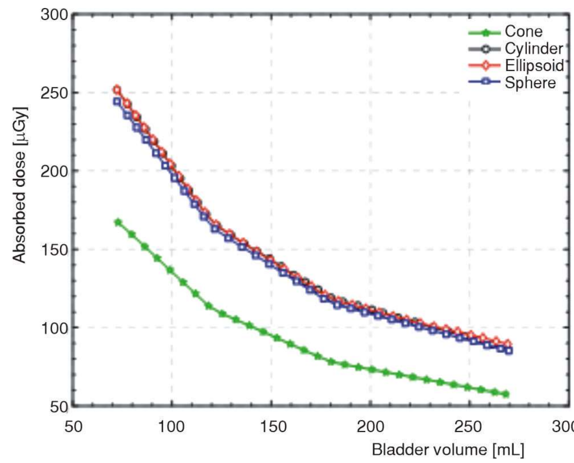

Figure 1. Absorbed dose in 16 groups of bladders

Monte Carlo simulation calculation

The GEANT4 can handle various types of particles including photons, neutrons, and charged particles. GEANT4 is widely used in scientific research and engineering applications, including high-energy physics experiments, medical physics, nuclear engineering, earth science, and space science. For photon transport problems, GEANT4 accurately models various microscopic physical processes in detail [21-23]. In this study, GEANT 4 version 11.2 is used, with QBBC as the selected physics list. The bladder phantom used in this paper has a regular shape, and the modeling is completed by Boolean operation cutting. The G4GeneralParticleSource Class of GEANT4 sets a 0.511 MeV photon volume source with an isotropic emission direction. The number of particles used in each simulation is set to 10^{10} to ensure that the error caused by statistical fluctuations is <5 %. The G4UserAction Class of Geant4 is used to analyze statistically the energy deposition situation of the bladder wall, and the known radioactive activity is used to calculate the bladder dose conversion coefficient for correction.

RESULTS AND DISCUSSION

Absorbed dose of bladder phantom model

Figure 1 shows the change in the absorbed dose of four bladder phantom models with different shapes as the bladder volume changes. As shown in fig. 1, for any shape of bladder phantom, its absorbed dose shows a significant downward trend as bladder volume increases. However, there is a certain difference in the absolute value of the absorbed dose of different shape phantoms at the same volume. Taking the dose obtained by the spherical phantom as a reference value, within the range of 70~270 mL, the relative standard deviation of the dose for the cylindrical and ellipsoidal phantoms is only 1 % to 5 %. However, the relative deviation of the absorbed dose obtained by the conical phantom simulation is as high as 30 % to 32 %, and there is a possibility of serious underestimation of the absorbed dose This difference may be because various bladder phantom shapes have distinct ratios of bladder volume to external surface area at different volumes, which further causes an uneven spatial distribution of target tissues.

The ratio of bladder wall volume to phantom external surface area

To further investigate the cause of dose differences among differently shaped phantoms, fig. 2 illustrates how the ratio k of bladder wall volume to external surface area changes with bladder volume. As shown in fig. 2, except for the ellipsoid, the k values of various phantom shapes exhibit only slight variation with volume. Moreover, the deviation in k values between different phantoms remains relatively constant, aligning with the results in fig. 1, which indicate that the relative standard deviation of absorbed dose

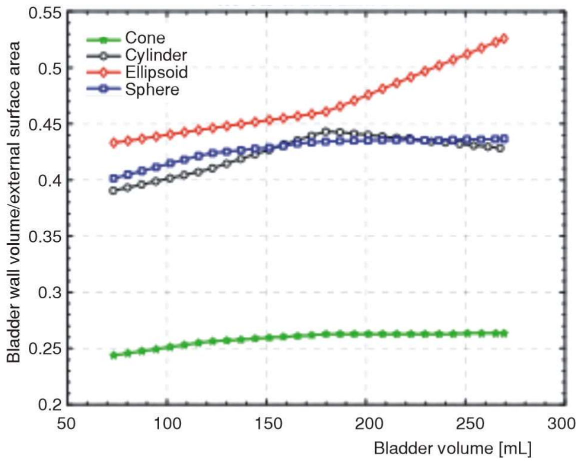

Figure 2. The ratio of bladder wall volume to external surface area in 16 groups

among phantoms shows minimal variation with volume. At the same bladder volume, using the absorbed dose from the spherical phantom as a reference, the relative standard deviation of the dose in the cylindrical and ellipsoidal phantoms ranges from 2 % to 8 %. Meanwhile, the relative deviation of the *k* value in the conical phantom is significantly higher, reaching 38 % to 40 %. This confirms that the difference in the ratio of bladder wall volume to phantom external surface area is the main reason for the difference in the absorbed dose of phantoms with different shapes.

Absorbed dose conversion coefficient

In most cases, the estimation of the absorbed dose of the inner wall of the bladder is completed by the dose conversion coefficient (*S* value). Therefore, the *S* value under various phantom shapes is calculated as

$$S = \frac{D}{A} \tag{1}$$

where *D* is the absorbed dose obtained by simulation calculation and *A* – the radioactive activity in the phantom. The *S* values of the 16 phantom groups are presented in tab. 2. As seen in tab. 1, when the volume remains constant, the *S* values of the cylinder, ellipse, and sphere are nearly identical, except for the cone. When the phantom volume is distributed between 70 mL and 270 mL, the *S* value is distributed within (4.7 – 20.6) $\times 10^{-2}$ μGy(MBq)$^{-1}$ and significantly decreases as the volume increases. This indicates that maintaining a certain filling degree of the bladder before taking the drug will effectively reduce the dose received by the bladder wall. However, there is a certain difference compared to the *S* value obtained by Hu *et al*. [24]. Further optimization of the relationship between bladder wall thickness and bladder volume, along with increased electron dose calculations, will effectively reduce this difference.

Table 2. The *S* values of 16 phantom groups

	Dose conversion coefficient *S* value [10^{-2} μGy(MBq)$^{-1}$]			
Volume [mL]	Cone	Cylinder	Ellipsoid	Sphere
70	13.8	20.5	20.6	19.9
120	9.1	13.5	13.5	13.2
180	6.4	9.6	9.5	9.4
270	4.7	7.0	7.3	6.9

DISCUSSION AND CONCLUSION

With the widespread clinical application of imaging agents containing ^{18}F, the measurement of absorbed doses to organs at risk, particularly the bladder, has received significant attention. Currently, the main approach to obtaining equivalent bladder wall S values is by measuring dose conversion coefficients using phantoms with fixed shapes, which significantly differ from the actual physiological morphology of the bladder. In this study, we used GEANT4 software to model four bladder phantoms with different morphological characteristics. We conducted an in-depth investigation into how absorbed dose relates to phantom morphology and filling status. The findings indicate that, regardless of the shape of the bladder phantom, the absorbed dose decreases as volume increases, which is highly consistent with the results of Wu *et al*. [14]. Analysis also showed that the dose conversion coefficient obtained by the conical phantom deviates from other equivalent bladder shapes, with a maximum relative difference of up to 32 %. Additionally, the volume-to-surface area ratio of the phantom appears to be a key factor contributing to this difference. Therefore, relying on overly simplified phantom shapes, such as ellipsoidal phantoms, in equivalent dose transfer coefficient calculations for the real human bladder warrants careful consideration. The morphological parameters of the real human bladder are complex and variable. Using voxelized phantoms for dose calculations can help identify simplified bladder phantom shapes, enabling rapid, accurate, and cost-effective measurement of *S* values. This approach may also help minimize the dose to organs at risk, thereby lowering stochastic effects in patients.

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REFERENCES

[1] Cheng, Q.-Z., *et al.*, Differential Diagnostic Value of 18F-FDG PET/CT Imaging for Multiple Myeloma and Bone Metastases, *Chinese Journal of Experimental Hematology, 28* (2020), 4, 5

[2] Zhu, Y., *et al.*, A Meta-Analysis of the Chemical Synthesis Module Process of ^{18}F-FDG for PET Imaging, Journal of Beijing Normal University: *Natural Science Edition, 56* (2020), 1, 5

[3] Wang, X. G., *et al*., Biodistribution of ^{18}F Ethylcholine, ^{11}C Choline, ^{18}F-FDG and PET Tumor Imaging in Human Hepatocellular Carcinoma HepG2 Cells in Tumor-Bearing Nude Mice, *Journal of Graduate Medicine,* (2022), 004, 035

[4] Wang, J., *et al*., Progress of ^{68}Ga-FAPIs, a Novel Tumor Imaging Agent, *Chinese Journal of Nuclear Medicine and Molecular Imaging, 41* (2021), 6, 4

[5] Peng, P., *et al*., Value of ^{18}F-Deoxyglucose Positron Emission Computed Tomography for Pre-Treatment Evaluation of Extranodal NK/T-Cell Lymphoma, *Chinese Journal of Oncology, 44* (2022), 4, 7

[6] Ji, J., *et al*., ^{18}F-FDG Micro-PET Scanning of Extracellular NK/T-Cell Lymphoma, *Chinese Journal of Radiation Medicine and Protection, 40* (2020), 9, 6

[7] Li, K. X., *et al*., Effects of Bladder Volume Changes on Target Area and Organs at Risk and Interventions During Intensity-Modulated Radiation Therapy for Cervical Cancer, *Biomedical Engineering and Clinics,* (2022), 002, 026

[8] Ge, B., *et al*., Effect of Bladder Filling Difference on Dose in Radiation Therapy for Cervical Cancer, *Biomedical Engineering and Clinics, 25* (2021), 5, pp. 569-574

[9] Dowd, M. T., *et al*., Radiation Dose to the Bladder Wall from 2-[^{18}F]-Fluoro-2-Deoxy-D Glucose in Adult Humans, *Journal of Nuclear Medicine, 32* (1991), pp. 707-712

[10] Sahmaran, T., *et al*., Investigation of Radiological Properties of Imaging Agents Used in Nuclear Medicine with Different Methods and GATE/GEANT4 Simulation Program, *Nucl Technol Radiat, 38* (2023), 2, pp. 116-124

[11] Tang X.-Q., *et al*., Simulation and Measurement of X-Ray Scattered Radiation In Radiodiagnosis, *Nucl Technol Radiat, 38* (2023), 2, pp. 125-134

[12] Faj, D., *et al*., Monte Carlo Simulation of Photon Breast Radiotherapy of the Pregnant Patient, Beam Characteristics, *Nucl Technol Radiat, 39* (2024), 2, pp. 154-159

[13] Wang, Z. T., *et al*., Mathematical Modeling of Chinese Reference Persons Based on a Series of Standards for Radiation Protection, *Chinese Journal of Maritime Medicine and Hyperbaric Medicine, 29* (2022), 3, pp. 363-366

[14] Wu, T., *et al*., Dynamic Evaluation of Absorbed Dose to the Bladder Wall with a Balloon-Bladder Phantom During a Study Using [^{18}F]-Fluoro-Deoxy-Glucose Positron Emission Imaging, *Nuclear Medicine Communications, 23* (2002), 8

[15] Wang, H., *et al*., Influence of Bladder Volume Changes on Target Area Irradiation Dose in Intensity-Modulated Radiotherapy After Radical Surgery for Cervical Cancer, *Clinical Medicine Research and Practice, 5* (2020), 31, 3

[16] Xu, Z., *et al*., Effect of Bladder Volume Change on Brachytherapy for Cervical Cancer, *Modern Medical Oncology, 27* (2019), 23, pp. 4269-4272

[17] Hou, L., *et al*., Monte Carlo-Based Method to Simulate the Effect of Different Bladder Filling Degree on Brachytherapy for Cervical Cancer, *Chinese Journal of Medical Physics, 34* (2017), 11, pp. 1096-1101

[18] Li, M., *et al*., Study on the Effect of Bladder Volume on Dose Distribution in Three-Dimensional Postloading for Cervical Cancer, *Journal of Clinical Military Medicine, 43* (2015), 6, pp. 571-573

[19] Xiao, D., *et al*., Research on Three-Dimensional Segmentation Method of Bladder Tumor Suspected Region Based on Thickness Feature Fuzzy C-Mean Algorithm, *Medical and Health Equipment, 36* (2015), 3, pp. 14-31

[20] Liu, X., *et al*., Research on the Measurement of Radiopharmaceutical Activity and Injection Method, *China Medical Equipment, 14* (2017), 3, pp. 101-104

[21] Allison, J., *et al*., Recent Developments in Geant4, *Nucl. Instrum. Meth. A, 835* (2016), Nov., pp. 186-225

[22] Allison, J., *et al.*, Geant4 Developments and Applications, *IEEE Trans. Nucl. Sci, 53* (2006), 1, pp. 270-278

[23] Agostinelli, S., *et al*., Geant4 - A Simulation Toolkit, *Nucl. Instrum. Meth. A, 506* (2003), 3, pp. 250-303

[24] Hu, P., *et al*., Internal Dosimetry in F-18 FDG PET Examinations Based on Long-Time Measured Organ Activities Using Total-Body PET/CT: *Does It Make Any Difference from a Short-Time Measurement, EJNMMI Physics, 8* (2021), 51

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СТУДИЈА О КОЕФИЦИЈЕНТИМА КОНВЕРЗИЈЕ ЕКВИВАЛЕНТНЕ ДОЗЕ У БЕШИЦИ НА ОСНОВУ МОНТЕ КАРЛО СИМУЛАЦИЈЕ

Израчунавањем коефицијената процене дозе за фантоме бешике различитих запремина и еквивалентних геометријских облика, ова студија нуди смернице за ефикасну и тачну процену доза ^{18}F за ризичне органе. На основу моделовања фантома бешике са четири различита еквивалентна геометријска облика и узимајући у обзир могуће услове лечења, коришћена је Монте Карло метода за симулацију и израчунавање апсорбованих доза и коефицијената конверзије дозе фантома бешике различитих облика и величина. Резултати показују да апсорбована доза фантома бешике опада са повећањем запремине бешике, а апсорбована доза за 70 mL је око три пута већа од дозе за 270 mL. Апсорбована доза коничног фантома бешике значајно се разликује од других облика, са релативним одступањем од 6 до 30 пута у односу на друге облике. Однос запремине зида бешике и површине коничног фантома бешике разликује се од других облика, са релативним одступањем од 5 до 20 пута у односу на њих. Стога, када се користе фантоми бешике за израчунавање коефицијената процене дозе, потребно је узети у обзир не само однос запремине фантома и површине, већ и стварни облик и запремину бешике.

Кључне речи: позитронска емисиона томографија, Монте Карло, нуклеарна медицина, дозиметрија зрачења