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Development and validation of a fast voxel-based dose evaluation system in nuclear medicine

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HIGHLIGHTS

- We develop and validate a voxel-based Monte Carlo toolkit based on SimSET using in nuclear medicine dosimetry.
- 3D dose distribution can be provided by SIMDose.
- The timeframe of simulation that is less than one minute may be acceptable for patient-specific dose evaluation of nuclear medicine examinations.

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ABSTRACT

PET imaging has been widely used in the detection and staging of malignancies and the evaluation of patient-specific dosimetry for PET scans is important in nuclear medicine. However, patient-specific dosimetry can be estimated only by Monte Carlo methods which are usually time-consuming. The purpose of this study is to develop a fast dose evaluation system namely SimDOSE. SimDOSE is a Monte Carlo code embedded in SimSET with a dose scoring routine to record the deposited energy of the photons and electrons.

Fluorine-18 is one of the most commonly used radionuclides that decay predominantly by positron emission. Only a 635 keV (Emax) positron and two annihilation photons should be concerned in F-18 radiation dosimetry, hence simulation is relatively simple. To evaluate the effects of resolution, an F-18 point source placed in a 20 cm diameter sphere filled with water was simulated by SimDOSE and GATE v6.1. Grid sizes of 1 mm, 3 mm, and 5 mm were tested and each was simulated with a total of 10^7 decays. The resultant dose distribution functions were compared. Dose evaluation on ORNL phantom was also performed to validate the accuracy of SimDOSE. The grid size of phantom was set as 3 mm and the number of decays was 10^7. The *S*-values of liver computed by SimDOSE were compared with GATE and OLINDA (Organ Level INternal Dose Assessment) for ^{11}C, ^{15}O, and ^{18}F.Finally, the CPU time of simulations was compared between SimDOSE and GATE.

The dose profiles show the absorption doses located 3 mm outside the center are similar between SimDOSE and GATE. However, 71% (19%) difference of the center dose between SimDOSE and GATE are observed for 1 mm (3 mm) grid. The differences of the profile lie in the assumption in SimDOSE that all kinetic energies of electrons are locally absorbed. The ratios of *S* values of (SimDOSE/OLINDA) range from 0.95 to 1.11 with a mean value of 1.02 ± 0.043. To compare simulation time from SimDOSE to GATE for calculation of 1 mm, 3 mm, 5 mm gird point source and *S* values of ORNL phantom are 1.3%, 1.2%, 1.2% and 1.2%, respectively.

In conclusion, SimDOSE is an efficient and accurate toolkit to generate patient-specific dose distribution in clinical PET application.

1. Introduction

Nuclear medicine examinations are widely used in clinical diagnosis and therapy, and grow annually in clinical practices

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(Mettler et al., 2008a). Whole-body F-18-fluorodeoxyglucose (FDG) PET for tumor staging, restaging, and detection of unknown primary tumors are the most commonly used examinations of PET in nuclear medicine. PET accounted for about 5% of all nuclear medicine procedures in Taiwan in 2008 (Tung et al., 2011) and the effective dose of PET scan is 14.1 mSv and it is higher than most of others (Mettler et al., 2008b). Although cancer risks from single PET/CT examination may be of less impact (Huang et al., 2009), cancer patients after treatment may undergo multiple PET/CT or other nuclear medicine examinations for the follow-up. Therefore, it is an important issue to estimate patient dose of PET/CT.

The patient dose can be specified by CTDI for each person under a CT examination and the dose in nuclear medicine is estimated by MIRD method (Brix et al., 2005). However, MIRD method uses reference man to calculate patient dose which is not patient-specific. Monte Carlo (MC) method can provide patient-specific dosimetry (Chiavassa et al., 2006; Visvikis et al., 2006); however it is time-consuming for clinical applications. Moreover, clinical imaging devices provide voxelized images, and MC codes directly handling these data format can facilitate the clinical applications (Visvikis et al., 2006). The purpose of our study is to develop and validate a fast Monte Carlo toolkit for voxelized patient-specific dose evaluation in the clinic.

2. Material and method

2.1. SimDOSE

The Simulation System for Emission Tomography (SimSET) package developed by the University of Washington is an efficient toolkit in emission imaging (Harrison et al., 1993). Based on SimSET, we developed a patient-specific Monte Carlo toolkit namely SimDOSE for nuclear medicine dosimetry. A routine including subroutines of electron generation and energy deposition scoring which is shown in dash line parts in Fig 1 was added. Electrons are generated through the interactions of photons with materials: photoelectric absorption and Compton scattering. Photoelectrons are generated with energies equal to that of incident photons (neglect the binding energy). The kinetic energies of Compton electrons are the energies of incident photons subtracting those of the scattered photons. The photons tracking processes in SimSET remained intact and all electrons and positrons were assumed to deposit all their energies at the location where they were generated.

2.2. GATE

GATE (GEANT4-based Application for Emission Tomography) (Jan et al., 2004) is a well-validated Monte Carlo simulation platform for nuclear medicine imaging and dosimetry (Maigne et al., 2011; Visvikis et al., 2006). The results from GATE 6.1 will be compared with those of SimDOSE.

2.3. Spherical water phantom

A 20 cm water sphere with grid sizes of 1 mm, 3 mm, and 5 mm were used in the simulation. Then, an ^{18}F point source was placed in the center of the phantom to generate the dose distribution. F-18 is a pure positron-emitting nuclide, and only a positron with 635 keV (Emax) and two annihilation photons should need to be considered for radiation dosimetry. Hence, simulation is simplified and absorbed dose contributed from the photons and positrons could be compared separately. Decay cascade, positron range, and non-collinearity of F-18 source were simulated as well. An ideal point source at the center of the voxel, and voxel sources with radioactive isotopes distributed uniformly in the voxel were simulated as in realistic situation.

2.4. The ORNL phantom

The ORNL mathematical phantom, developed by Oak Ridge National Laboratory, is a stylized phantom which provides complete information about the body structure and internal organs (Cristy and Eckerman 1987). The adult man phantom (cut at upper thigh) was voxelized for the SimSET code with matrix size $168 \times 168 \times 400$ and voxel size $0.3 \times 0.3 \times 0.3$ cm^3. We used liver as source organs to calculate the S values of target organs and the results of ^{11}C, ^{15}O and ^{18}F simulated by SimDOSE will be compared with GATE and OLINDA. The activity was assumed to be distributed uniformly inside each source organ and decay number was set as 10^7. The S values calculated

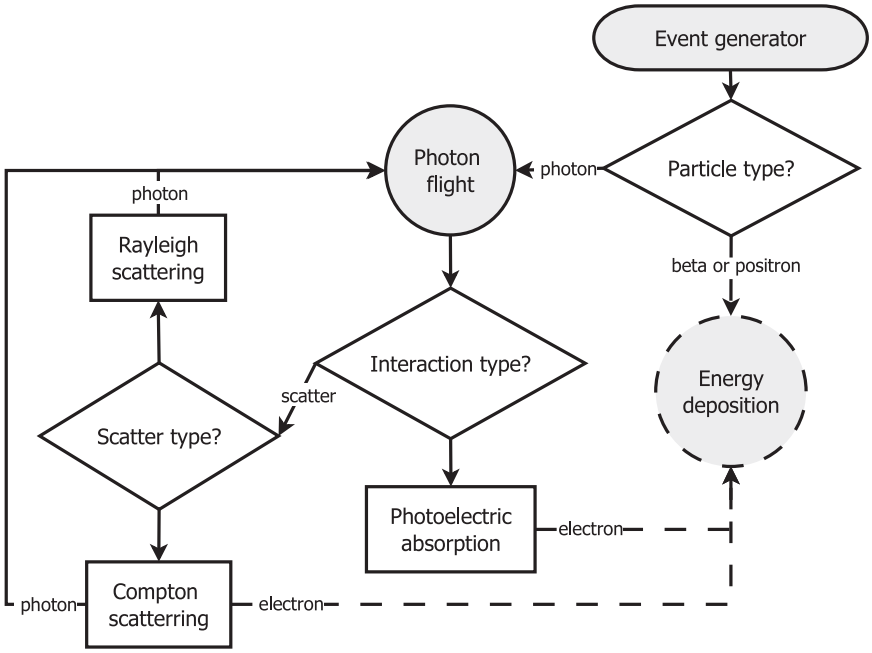

Fig. 1. Flowchart for transporting processes of photons and positrons. Dashed line shows the energy deposition of electrons and positrons.