Evaluation of prompt gamma and positron emitter properties for in-vivo dose verification of carbon-ion therapy: A Monte Carlo study

[1]Department of Radiation Convergence Engineering, Yonsei University, Wonju 26493, Republic of Korea

Bo-Wi Cheon[1], Hyun-Joon Choi[1], Wook-Geun Shin[1], Hyo-Jun Park[1], and Chul Hee Min[1,*]

Purpose:

Since the carbon-ions deliver most of its energy in the region near the Bragg peak, it is important to predict the exact beam range and patient dose distribution to avoid delivering a high dose to normal tissues. Prompt gamma (PG) imaging and positron emission tomography (PET) are suggested as representative methods to evaluate the beam range in real-time and after the treatment, respectively. Our research team has been developed a PG-PET system that combines the advantages of the two modalities for in-vivo dose verification in proton therapy. However, to fully deploy the PG-PET system clinically, it still requires defining the properties of the PG and positron emitter (PE) from carbon-ion beams.

The aim of this study is to evaluate the clinical applicability of the PG-PET system by investigating the characteristics of PG and PE produced due to the carbon-ion beam in the Geant4 Monte Carlo toolkit.

Materials and Methods:

In the simulations, a homogeneous PMMA phantom was employed to evaluate the characteristics of PG and PE productions by the carbon-ion beams with various energies. The elemental composition of the phantom was $C_5H_8O_2$ with a density of 1.19 g cm^{-3}. The phantom defined 10 × 10 × 60 cm^3 with a voxel size of 10 × 10 × 0.1 cm^3. Carbon-ion beams of three different energies (148.5, 290.5, and 350 MeV/u.) were delivered to the phantom at each case. The distance between the source and the phantom was decided as 10 cm. The beam had a 1-mm radius of 10^7 carbon-ions. BIC and INCLXX hadron physics models were used in the simulations and the potential level for the ionization of the PMMA was fixed at 74 eV. Only gammas produced in 10 ns after the carbon inelastic process were defined as the prompt gamma.

Production of the PGs was evaluated in terms of the phantom depths with comparison to the depth dose distribution of the carbon-ions. The energy spectrum of the PGs was also obtained to decide PG energies to be detected by the PG-PET system. In the case of PE, productions of three kinds of PEs (^{11}C, ^{10}C, and ^{15}O) were selectively evaluated because they dominant PEs in the carbon-ion irradiations. The amount of each PE in the phantom according to time duration from the irradiations was calculated by considering the generation rate and the half-life of the emitters.

Results:

The peak energy at PG was determined as 0.5, 0.8, 1, 1.7, 4.5, and 5.3 MeV. Among the PGs with different energies, PGs of 4.5 MeV and 5.3 MeV are expected to have the most dominant effect on the resolution of the PG image. The beam range of the PGs showed good accuracy in which the range difference was less than 1 mm compared to that of the depth dose distribution of carbon-ion beam. In addition, the dose distribution before the Bragg peak showed similarity with the PG distribution.

For the PE distributions, the beam range showed 5 – 15 mm differences from the depth dose distribution depending on the incident energy and PE type. The higher the carbon energy, the expansion of the difference in the depth distribution. Among the PEs, the amount of ^{11}C was evaluated at least 8.2 times larger with less decay compared to ^{10}C and ^{15}O. The decay rate of ^{10}C, ^{11}C, and ^{15}O after 5 minutes was evaluated that more than 99%, 16%, and 82% respectively. Therefore, the most dominant PE that affected the PET image was ^{11}C.

Conclusions:

We evaluated the properties of the PG and PE for range verification in the carbon-ion therapy by using Geant4. It was expected that the determination of the relationship between secondary emissions distribution and dose distribution can contribute to the development of an accurate dose verification system.

Keywords:

Prompt Gamma, Positron Emitter, Carbon-ion, Monte Carlo simulation