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Monte Carlo simulation for calculation of fragments produced by 400 MeV/u carbon ion beam in water

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ABSTRACT

Monte Carlo simulation was an important approach to obtain accurate characteristics of radiotherapy. In this work, a 400 MeV/u carbon ion beam incident on water phantom was simulated with Gate/Geant4 tools. The authors obtained the dose distributions of H, He, Li, Be, B, C and their isotopes in water phantom, and drew a conclusion that the dose of ^{11}C was the main reason of causing the embossment of total dose curve around 252 mm depth. The authors also studied detailedly the dose contribution distributions, yield distributions and average energy distributions of all kinds of fragments. The information of four distributions was very meaningful for understanding the effect of fragments in carbon ion beam radiotherapy. The method of this simulation was easy to extend. For example, for obtaining a special result, we may change the particle energy, particle type, target material, target geometry, physics process, detector, etc.

1. Introduction

In recent years, the application of carbon ion in tumor therapy has attracted more attention in many countries. The number of patients treated with carbon ion radiotherapy has been gradually increasing. While the accuracy of radiotherapy treatment planning played a very important role in radiotherapy quality [1]. Monte Carlo simulation was an important approach to obtain accurate radiotherapy parameters. And water was considered as a kind of matter which was very approximate to body tissue. So, it was important and significative to simulate carbon ion beam incident on water.

The fragments produced by carbon ion beam in water transfered in water and produced dose deposits. The dose of fragments, compared with that of carbon ion beam, was no small proportion [2]. To understand fully the characteristics of fragments was very helpful for understanding carbon ion radiotherapy. These characteristics included mainly dose distribution, dose contribution distribution, yield distribution and average energy distribution, etc.

2. Simulation scheme

2.1. Simulation tools

Geant4 and Gate were chosen as simulation tools for this work. Geant4 [3,4] was a Monte Carlo simulation tool to simulate energetic particles through materials. It can be used in high energy physics, nuclear physics and accelerator physics, can also be used in medical physics [5–8] and space science. The other tool, Gate [9–13], an opensource software, was a toolbox based on Geant4. It was mainly used for numerical simulations in medical imaging and radiotherapy. Some articles [14–16] had showed the applications of Gate in radiation therapy. We adopted the Gate6.2 and Geant4.9.5 in this work.

2.2. Model settings

As shown in Fig. 1, water phantom of this simulation was a cuboid, of which the geometric size was 20 cm × 20 cm × 40 cm and material parameter of which was set to G4_WATER. Carbon ion beam was incident vertically on the center of left end surface of water phantom.The settings of carbon ion beam were consistent with the source parameters of Haettner [17] experiment. The carbon ion beam was set to monoenergic 400 MeV/u, Gaussian distribution and $\delta_x = \delta_y = 2.12$ mm (the full width at half maximum

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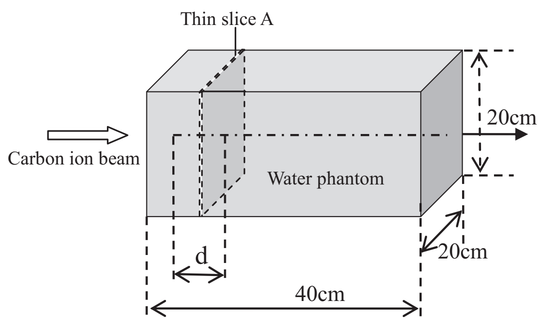

Fig. 1. Schematic diagram of carbon ion beam incident on water phantom.

(FWHM) was equivalent to 5 mm), of which the angle scattering parameter was $\delta_{ang} = 1\,\mathrm{mrad}$. The number of carbon ions in this simulation was set to 1×10^5.The detector geometry was thin slice A in Fig. 1, of which the geometric size was 200 mm × 200 mm × 0.02 mm and the material parameter of which was also set to G4_WATER. The thin slice A was used for collecting some information such as particle number and average energy. As shown in Fig. 1, the distance between the center of thin slice A and the incident point was set to d.

2.3. Gate method

The script file of Gate included several aspects: source and particle management, defining geometry and material, setting up the physics, actor management. The source, particle, geometry and material had been described ahead. The physics processes of this simulation were set to default settings of particle radiotherapy in Gate. The default settings included the standard Electromagnetic processes for leptons, the Electromagnetic processes for hadrons and Hadronic processes for hadrons. Actors of Gate was used for collecting information during simulating. DoseActors was used to record the particle dose distribution. PhaseSpaceActors was used to record the particle type, energy and location. SecondaryProductionActors was used to record the secondary particles. ParticleFilter was used to filter particles.

3. Results

3.1. Dose distributions of fragments

The fragments produced by carbon ion beam in water, included ionized electrons, photons, neutrons, and H, He, Li, Be, B, C, N, O, F, Ne elements (including their isotopes). The same as primary ^{12}C ion, all fragments transfered in water and produced dose deposits. Relative dose distributions of carbon ion beam, primary ^{12}C ion and fragments in water phantom were shown in Fig. 2. The solid line was total dose distribution of carbon ion beam, the dashed line was dose distribution of primary ^{12}C ion and the dotted line was dose distribution of all fragments. In this simulation, the Bragg peak position of 400 MeV/u carbon ion beam in water was 274.5 mm (corresponding to the depth value of the position of peak height 80%). This was consistent with the Haettner [17] experimental result 274.7 ± 1.0 mm.

Fragments dose reached its maximum at 252 mm depth before the Bragg peak. After the Bragg peak, fragments dose line and total dose line were almost entirely overlapping. This was because the primary ^{12}C ion contributed almost nothing after the Bragg peak, the tail of total dose was primarily due to the contribution of fragments.

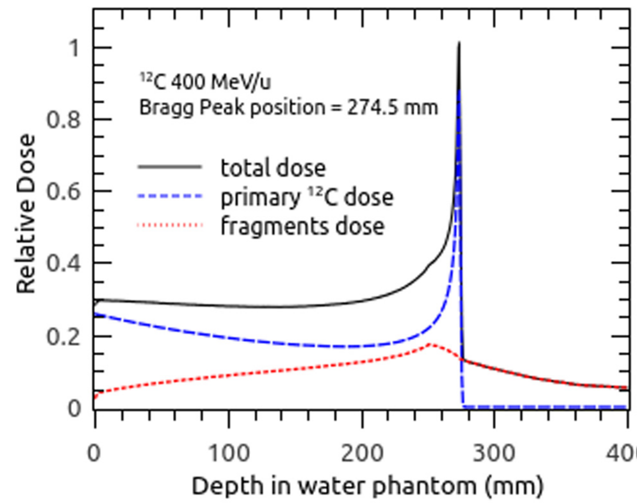

Fig. 2. Relative dose distributions of carbon ion beam, primary ^{12}C ion and fragments in water phantom (with the Bragg peak value of total dose as normalization factor).

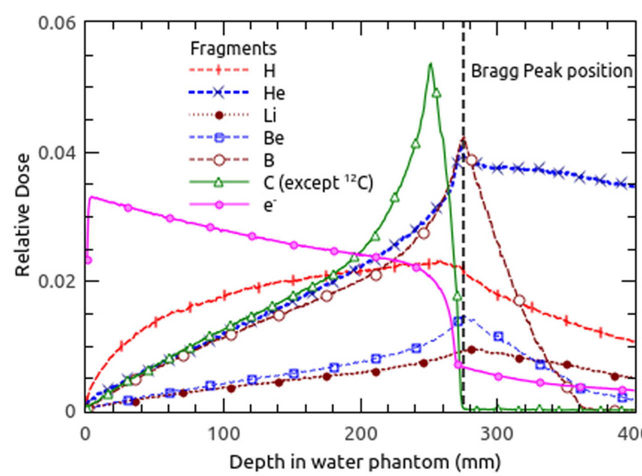

Fig. 3. Dose distributions of H, He, Li, Be, B, C (except ^{12}C), e^- in water phantom (with the Bragg peak value of total dose as normalization factor).

As shown in Fig. 3, each fragment element or particle formed its own dose distribution in water phantom. The lines with symbol indicated the dose distributions of H, He, Li, Be, B, C (except ^{12}C), e^- respectively. Because the doses formed by N, O, F, Ne and γ were very small [18], their curves not be shown.

As can be seen from Fig. 3, the dose curves of H, He, Li, Be, B reached their peaks nearby the Bragg peak position. While the dose curve of C (except ^{12}C) reached its peak at 252 mm depth. Electron dose curve was also very special. It began to fall sharply at about 250 mm depth, and became relatively flat again after the Bragg peak position.

It also can be seen from Fig. 3 that the doses of H, He, B, C and e^- maintained a relatively high level before the Bragg peak position, while the doses of Li, Be were relatively low. After the Bragg peak position the dose of He remained high level, while the dose of B fell steeply. Gunzert-Marx [19] gave the similar results of 200 MeV/u carbon ion beam using the PHITS codes.

The dose distributions of H, He, Li, Be, B, C (except ^{12}C) and their isotopes in water phantom were shown in Fig. 4(a) to (f), respectively. The solid line in each figure indicated dose distribution of each element of H, He, Li, Be, B, C (except ^{12}C). The rest lines with