SIMULATION OF HEAVY ION THERAPY SYSTEM USING GEANT4

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Abstract

We implemented the geometry of a new beamline of HIMAC (Heavy Ion Medical Accelerator in Chiba) in Geant4 [1], and simulated the dose distribution in a water target irradiated with carbon beam. The simulation well reproduced the Bragg peak for the beam energy of 290 MeV and 400 MeV while leaving room for improvement in the agreement for the spread-out Bragg peak produced with the ridge filter inserted in the beam path. This work provides a basis to establish a simulation framework that allows comprehensive and accurate treatment planning in heavy ion therapy.

INTRODUCTION

Nowadays, effectiveness of heavy ion beam for medical treatment has been recognized and number of facilities for heavy ion therapy are in operation or being planned around the world. Distinct advantage of the heavy ion beam is the capability to localize dose. The dose given by a heavy charged particle penetrating matter rises sharply at the end of the range while that by a photon beam are maximal near the surface. This sharp peak in the dose distribution is known as Bragg peak. If the beam energy is chosen so that the particle stops at the depth of lesion, the dose can be concentrated on the spot with minor exposure of adjacent normal tissue. In addition, heavy ion beam is expected to be effective even aganist radiation-resistant cells due to higher biological effect over photon or proton beam.

The heavy ion beam involves more complex processes in matter as compared to photon beam used in conventional radiation therapy. The heavy ion beam suffers fragmentation into lighter nuclei with longer ranges, giving tail dose beyond the Bragg peak. This unwanted dose also needs to be precisely evaluated in treatment planning. In addition, taking advantage of the heavy ion beam employs a variety of instruments specifically designed for the purpose. To extract such parameters of these instruments that optimize the clinical effect, a reliable simulator is essential. We launched a project aimed at providing a simulation framework for heavy ion therapy using Geant4.

This paper presents the implementation of the geometry of a newly developed heavy ion beam line of NIRS-HIMAC as a part of the project, and the validation of the simulator through comparison with experimental data.

BEAMLINE

HIMAC was constructed at NIRS, national institute of radiological science in Japan, as the first heavy ion accelerator dedicated to medical treatment in the world. Over 2,000 cases have been treated so far and accumulated data are showing heavy ion therapy to be promising for cancer treatment.

In HIMAC, broad beam method was developed so that desired volume inside a human body is irradiated with the heavy ion beam. Fig. 1 shows the beamline instruments and the experimental target implemented and visualized in the simulation. The broad beam method combines a pair of dipole magnets (wobbler magnets) and scattering material to produce uniform radiation field at treatment position. The magnetic fields are modulated in such a way that the beam is moved periodically painting circular-shaped dose distribution. The detailed description of the wobbler system is found elsewhere [2].

Secondary emission monitor, installed in front of the wobbler magnets, consists of parallel aluminum foils enclosed by vacuum windows. Electrons emanating from the foils are collected to measure the beam intensity. The beam line is equipped with two ionization chambers with identical structure to monitor dose and beam profile.

The Bragg peak is spread by having the beam pass through a plate made of many ridges (ridge filter) enough to cover the target thickness. The ridge filter is designed to flatten the dose over the spread-out Bragg peak with the biological effectiveness being ignored specifically for this experiment.

Plates with various thickness (range shifter) may be in-

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serted in the beam path to ajust the residual range although not used in the present experiment. Lateral beam profile is shaped by collimators. Multi-leaf collimator is the one with many movable leaves to change the aperture shape and trim the beam dynamically. Note that this beamline was constructed for research and development, in which the configuration of the components are different from that used in the actual treatment.

The water in an acrylic vessel was placed at the treatment center (isocenter) to imitate the human body. The target was irradiated with ^{12}C beam and dose distribution in the water was measured with multi-channel dosimeter. In the simulation, the water target was divided into voxels according to the segmentation of the dosimeter, and energy deposit in each of them was accumulated.

SIMULATION

Geant4 version 8.0 was used in the present work. Geant4 physics models were configured to enable ionization, multiple scatternig, and inelasitc hadronic reactions for ions. The inelastic reaction is invoked according to the inclusive cross section based on emprical formulae, and the rest of the process is treated as intranuclear cascade. Radioactive decay is invoked when an unstable nucleus is generated. For secondary particles, available electromagnetic interactions and hadronic interactions were applied.

RESULTS AND DISCUSSION

Fig. 2 shows the depth-dose distribution in the water for the beam energy of 290 MeV/n. The left figure shows the monochromatic Bragg peak where the ridge filter was not used. The right figure shows the spread-out Bragg peak (SOBP) produced by using the ridge filter. The Geant4 simulation is shown with solid lines and the experimental data are plotted with red circles. The simulated data are fitted to the measured dose curve with the offset and the scale as parameters. The fitting resulted in the offset less than the voxel length in the depth direction (1 mm), which indicates that the range of the carbon beam in water is reproduced pretty well. However the tail dose beyond the Bragg peak seems to be underestimated in the SOBP. Further investigation is required to determine whether the discrepancy is built up of the slight underestimation in the monochromatic peak or resulting from the placement of the ridge filter.

The comparison between the simulation and the measurement for the beam energy of 400 MeV/n is shown in Fig.3 alike. Although the spectral shapes are in good agreement with the measurement, the ranges are found to be underestimated by 1.2 mm and by 2.8 mm for the monochromatic and the spread-out Bragg peak, respectively. The different behavior between the enegies of 290 MeV/n and 400 MeV/n may suggest energy dependent problem of the Geant4 physics models for ions.

SUMMARY

We have proposed to utilize Geant4 for the treatment planning in heavy ion therapy, starting with the implementation of the new beamline of NIRS-HIMAC in Geant4. The Geant4 simulation successfully reproduced the Bragg peaks in the water bombarded with ^{12}C beam with the energy of 290 MeV/n and 400 MeV/n. On the other hand, the tail dose beyond the spread-out Bragg peak produced with 290 MeV/n beam tends to be underestimated while the depth of the peak position is slightly underestimated for 400 MeV/n beam. We will proceed to improve the simulation capability especially for the case where the ridge filter is inserted. It would be helpful to carry out more thorough experiment including the identification of secondary particles to validate the Geant4 physics models for ions in detail.

REFERENCES

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[2] T. Kanai M. Komori, T. Furukawa and K. Noda. Optimization of spiral-wobbler system for heavy-ion radiotherapy. *Japanese Journal of Applied Physics*, 43:6463–6467, 2004.

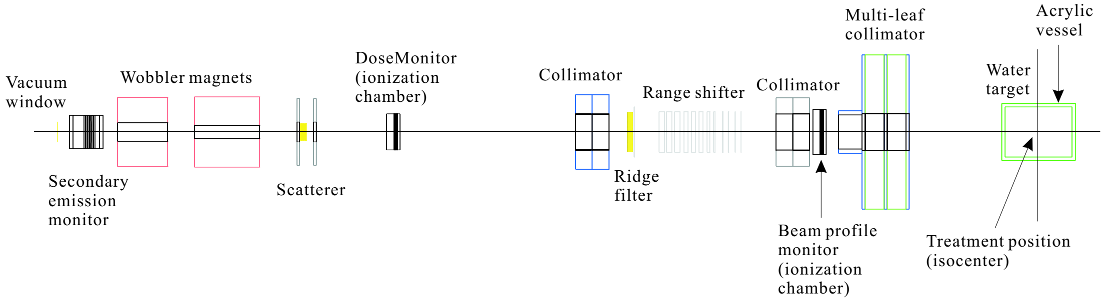

Figure 1: Heavy ion beam line of HIMAC modeled in Geant4 simiulation

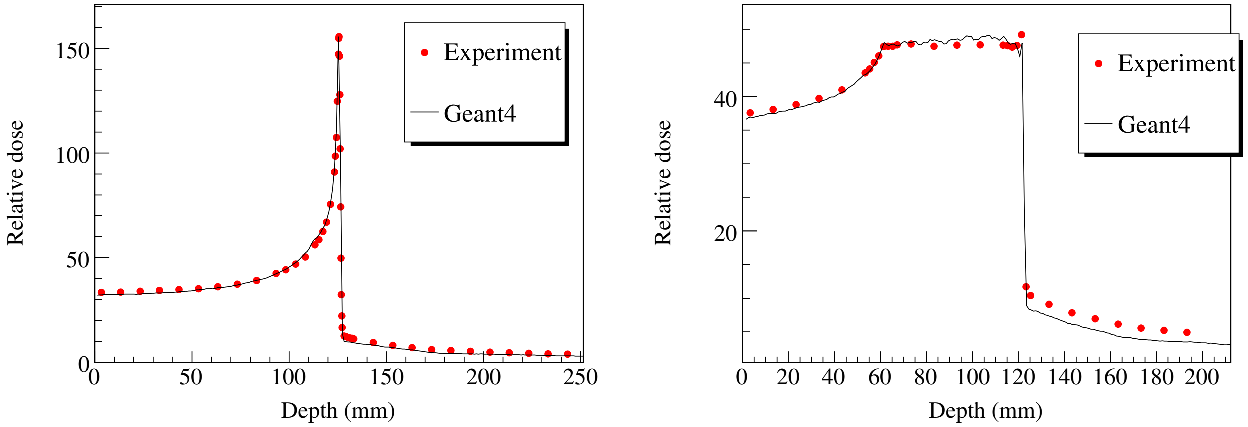

Figure 2: Measured and simulated depth-dose distribution in the water irradiated with 290 MeV/n ^{12}C beam

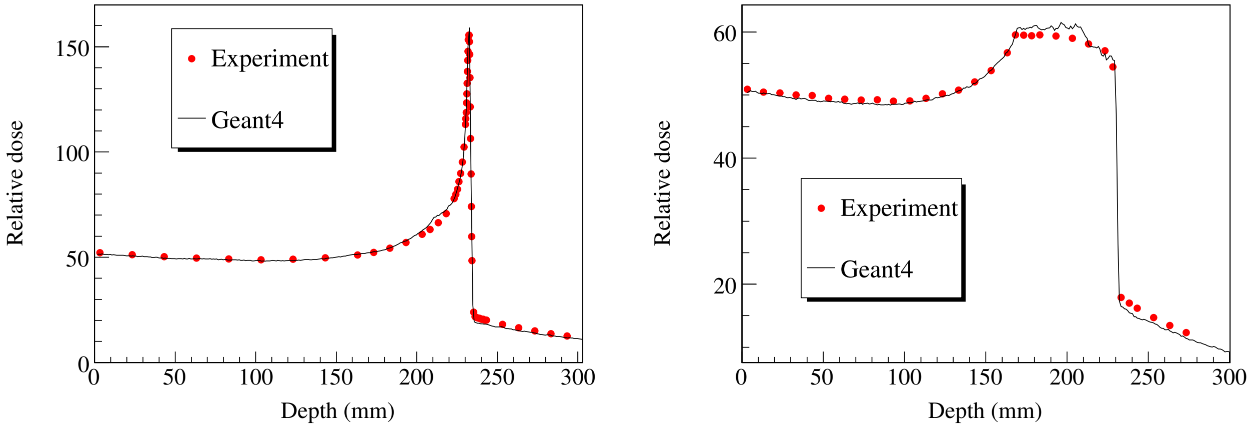

Figure 3: Measured and simulated depth-dose distribution in the water irradiated with 400 MeV/n ^{12}C beam