A GEANT4 based simulation for proton therapy

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A GEANT4 based simulation for proton therapy

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Abstract. The GENAT4 based simulation framework for hadron therapy has been developed. Three types of irradiation systems for proton therapy were successfully implemented on the top of the framework; those are the gantry treatment nozzle at Hyogo Ion Beam Medical Center (HIBMC), the gantry treatment nozzle at National Cancer Center (NCC), and the eye treatment facility of UC San Francisco at Crocker Nuclear Laboratory cyclotron, UC Davis (CNL). The validations of the developed simulation were performed for Bragg peak and Spread-out Bragg Peak with the measurements taken at HIBMC and NCC.

1. Introduction

The GEANT4[1] Monte Carlo code provides many powerful functions for conducting particle transport simulations with great reliability and flexibility. GEANT4 has been extending the application fields for not only the high energy physics but also medical physics. Using the reliable simulation for the radiation therapy, it will become possible to validate treatment planning and select the most effective one. For the use of a simulation in the clinical application, the simulation has to reproduce the dose distributions in three-dimensions with the best accuracy for ensuring the patient safety. The most of treatment planning systems (TPS) in hadron therapy facilities calculates dose distributions using a pencil beam algorithm derived from experiments and analytical formula. Monte Carlo simulation is expected to reproduce precise influences of complex geometry and material varieties which are difficult to introduce to the pencil beam algorithm. In Japan, six hadron therapy facilities have already started the treatment and three facilities are under construction. Many hadron therapy facilities desire to develop a simulation for the treatment planning system.

The simulation framework has been developed in order to provide a GEANT4 simulation for hadron therapy facilities. The simulation framework is capable to deal with more than one irradiation system and to modify the geometrical parameters of beam components. Three types of irradiation

systems for proton therapy were successfully implemented on the top of this framework. Using the developed simulation, the validations were performed for dose distributions of Bragg peak and Spread-out Bragg peak with the measurements taken at Hyogo Ion Beam Medical Center (HIBMC) and National Cancer Center (NCC). In this report a belief description of the developed simulation and the comparisons of simulated dose distributions with measurements are described.

2. Hadron therapy

In a cancer treatment, a treatment may be chosen from surgery, chemotherapy, or radiation therapy. The radiation therapy is expected to keep quality of life (QOL) of a patient compared to the other kind of therapies. The radiation therapy using X-rays becomes popular in the world. However, the hadron therapy takes an advantage of a treatment of tumors at deep position. The X-ray deposits the highest dose around the entrance and then it decrease, while hadrons deposits the maximum dose at a deeper position where the hadron stops. This characteristic is known as Bragg peak. Hadron therapy can reduce dose at healthy tissue while maximize the effect at the deeper tumor volume. Table 1 shows comparison of X-ray, Proton, and Carbon ion therapies. Carbon ion takes a large relative biological effect (RBE), a low Oxygen Enhancement Ratio (OCR), and excellent localization of dose by the sharp Bragg peak. These characteristics are most suitable for canter treatment while the hadron interactions concerning to the nuclear-nuclear interactions are very complex. Proton takes almost same effects as X-ray at the point of RBE and OER, but dose localization is still good by the Bragg peak. The physics interactions of proton are rather simpler than that of carbon ion. The validation of proton physics is important for not only proton therapy but also understanding complex interactions in carbon ion.

In Japan, many hadron therapy facilities are currently used for treatment or under construction (Table 2.). Figure 1 shows the basic design of irradiation system for hadron therapy [2]. The purpose of the beam irradiation system is to adjust the beam to give sufficient dose into the tumor volume while minimizing dose in healthy tissues. In figure 1, the wobbler magnets and a scatter widen the beam to achieve enough irradiation fields. The wobbler magnets cause the beam to follow circular trace and then the beam scattered by a scatter. By choosing the wobbler radius and scatter thickness, flat irradiation field is obtained. The lateral irradiation field of tumor shape is finally clipped by a multi-leaf collimator (MLC). The ridge filter is a range modulator used to produce spread-out Bragg peak (SOBP) in depth-dose distribution. The range of beam is finally adjusted by range compensator corresponding to the depth of tumor volume. The other technologies are being developed. A double scattering method [3] and a spiral wobbling system [4] are established in order to realize shorter irradiation system. The most advanced method [5] is a beam scanning system using small beam spot and variable beam energy. However most of beam components are similar in many facilities.

Table 1. Comparison of radiation therapy by particles

	X-ray	Proton	Carbon ion
RBE	1	1.1	3
OER	3	3	1.8
Dose localization	Tomography	Bragg peak	Bragg peak
Physics process	Electromagnetic	Electromagnetic and hadron interaction	Electromagnetic and hadron interaction

Table 2. Hadron therapy facilities in Japan (2007 Summer)

| Facility	Beam particle	Status
National Institute of Radiological Science	Carbon	operated
National Cancer Center	Proton	operated
Proton Medical Research Center, Univ. of Tsukuba	Proton	operated
Hyogo Ion Beam Medical Center	Proton/Carbon	operated
Wakasa wan Energy Research Center	Proton	operated
Shizuoka Cancer Center	Proton	operated
Fukui Prefecture Hospital	Proton	Constructing
Southern Tohoku Research Institute for Neuroscience	Proton	Constructing
Gumma University	Carbon	Constructing
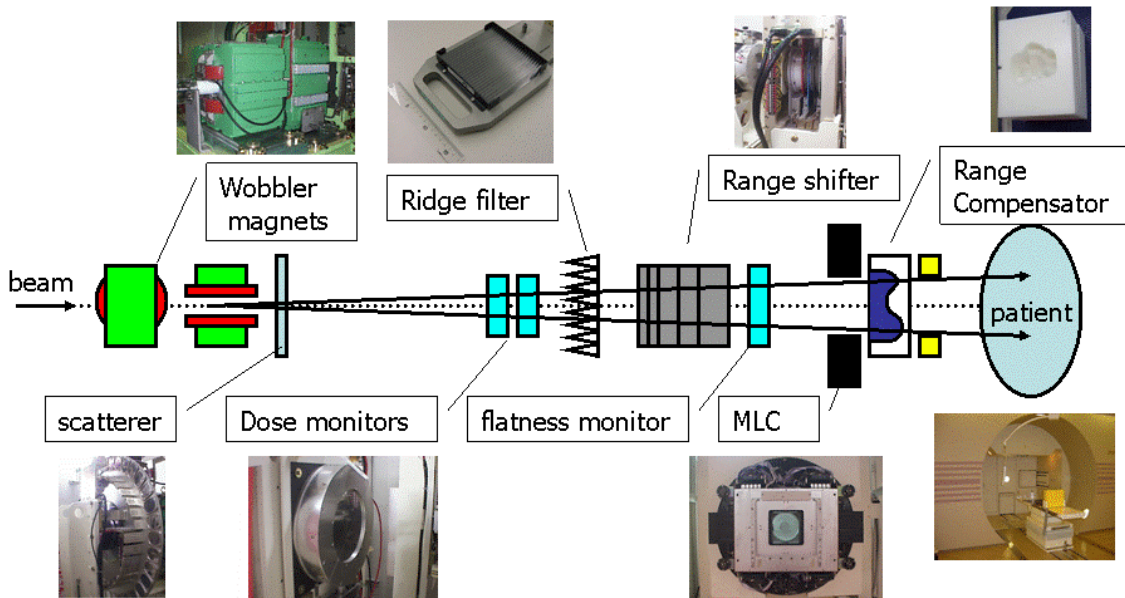
Figure 1. Basic design of irradiation system for hadron therapy.

3. Particle therapy simulation framework

The framework is required to describe different irradiation systems independent to facilities, because it will be used by medical physicists of many facilities for designing beam delivery system and validating a treatment planning. According to these requirements, an irradiation system has to be configured in the framework but the coding effort has to be minimized for beginners of C++ and GEANT4.

The developed simulation for particle therapy system (PTSsim) offers users to configure the irradiation system and the geometrical parameters of beam modules by using user interface (UI) commands. The PTSsim consists of modules and data files. The modules are categorized to a beam

module, a scoring module, and a DICOM module [6,7]. The configuration parameters of beam modules are described in ASCII data files, which allow the configuration to be changed easily without recompiling. An irradiation system is composed by specifying a set of beam modules and a primary generator. The G4MVParticleTherapySystem is an abstract base class to represent a particular irradiation system and holds a list of available beam modules which are derived from an abstract base class G4MVBeamModule. Those beam modules are installed on the beam line as geometry or uninstalled from the geometry. The translation and rotation of a beam module are also handled. These modifications are invoked by using UI commands.

The beam characteristics depend on the specification of the facility and are very important to obtain realistic results in the simulation. A proper primary generator should be assigned to the irradiation system by using UI commands.

The irradiation systems for three proton therapy facilities and one carbon ion facility have been successfully developed on the framework. The example of those irradiation systems are shown in figure 2 for the irradiation systems of proton therapy are the gantry treatment nozzle at the Hyogo Ion Beam Medical Center (HIBMC), the gantry treatment nozzle at the National Cancer Center (NCC), the eye treatment facility of UC San Francisco at the Crocker Nuclear Laboratory cyclotron, UC Davis (CNL).
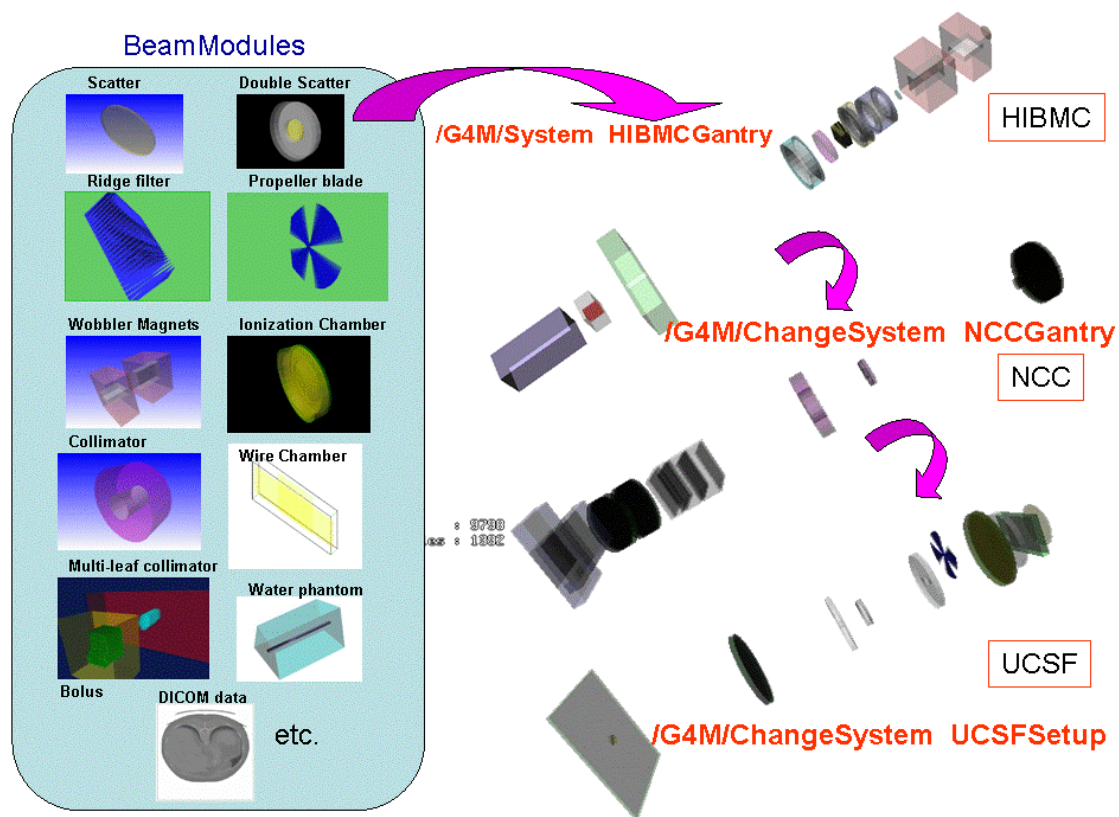

Figure 2. Example implementations of irradiation systems for proton therapy.

4. Physics validation
The validation of the simulation was performed in proton range for important materials in the beam line, and in the lateral uniformity of the radiation field at the isocenter. Dose distributions based on GEANT4 were verified with measurements of the Bragg peak and the spread-out Bragg peak. Those

results had already been published in [8]. The verification shows that the simulations are in good agreement with measurements.

The other verification is in progress with cooperative work with NCC. Pristine Bragg peak was examined with two different initial beam conditions in order to study the influence of beam parameters. Since the beam energy is not exactly defined, we estimated the beam energy to reproduce the depth of the Bragg peak in the measured depth-dose distribution. The energy fluctuation was estimated from measurements.

The effect of the beam was studied using two different primary generators. G4MBeamGun and G4MFocusGun classes are designed for generating the parallel beam with respect to beam axis and the cone beam with two focusing point independently for x and y plane on z axis, respectively. The initial beam spot size in x-y plane was adjusted in G4MBeamGun to reproduce the measured lateral distribution at the isocenter. The focusing points on z axis and the divergences of the beam were adopted from the measured results. Figure 3 shows the depth-dose distribution. The open circle is the measurement. The red and blue lines are the parallel beam and the cone beam, respectively. Table 3 shows the comparison of the distributions in important parameters. Apparently, the cone beam reproduces the measured distribution better than the parallel beam. The result indicates that the beam condition has be taken carefully in the beam scanning irradiation system which piles pristine Bragg peak together.
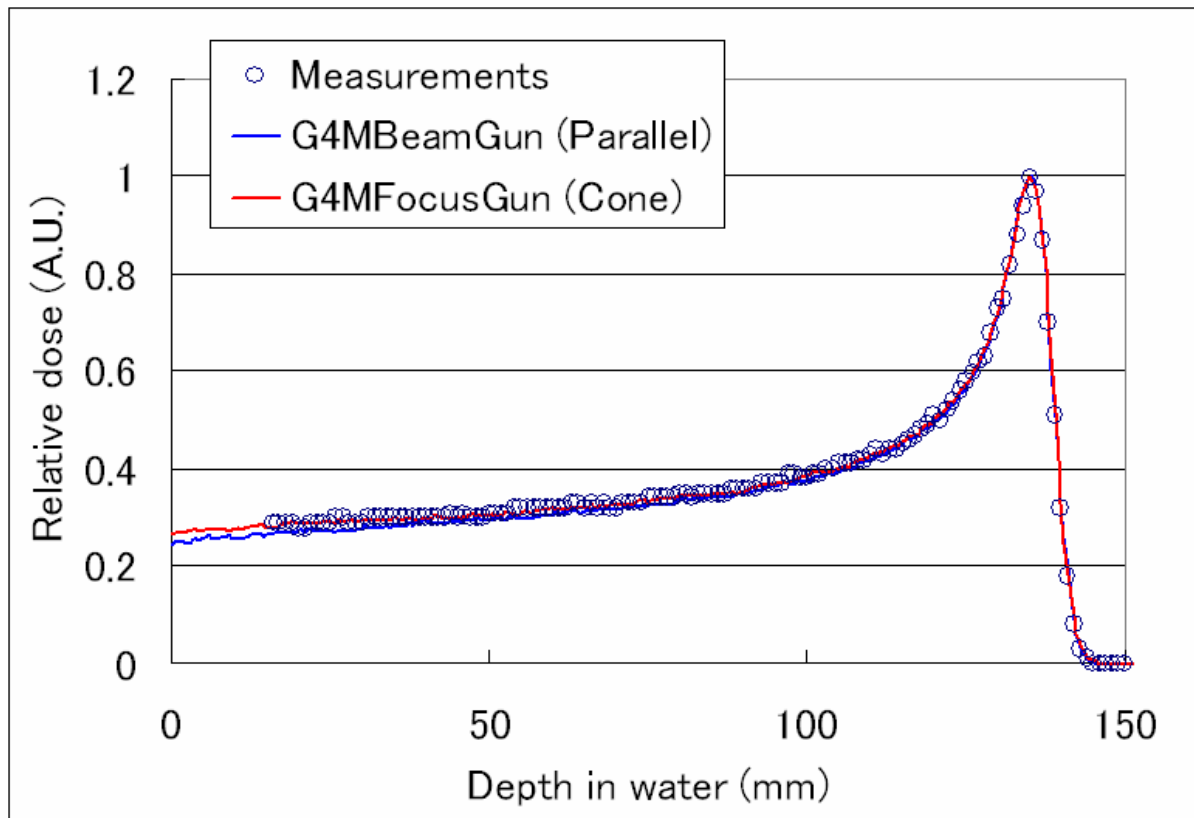

Figure 3. Depth-dose distribution for different beam parameters.

Table 3. Comparison of depth-dose distribution

	Measurements	Parallel beam	Cone beam
Plateau-peak ratio	0.290	0.267	0.280
FWHM [mm]	19.55	18.60	19.29
Distal dose 90%-10% [mm]	5.07	5.02	5.15

5. Summary

The GEANT4 based simulation framework for particle therapy system has been developed. The configuration of the irradiation system is easily changed using UI commands by users such as medical physicists who are not familiar to C++ language and GEANT4. Three proton irradiation systems were successfully implemented on the framework. The depth-dose distribution of simulation was studied with the measurement taken at National Cancer Center in Japan. The result shows the initial beam condition affects the depth-dose distribution. This framework is sufficiently used for a simulation of irradiation system independent to facility specifications.

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