Validation of the Dose Distributions with Monte Carlo Simulation for Carbon Ion Cancer Therapy

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Abstract— Charged particle therapy with carbon ions has advantages over conventional radiotherapy using x-ray beams. The application of charged particle therapy has rapidly increased over the last decades. This is due to its characteristic Bragg peak which has relatively low entrance doses and favourable doses distribution. In this research work, Geant4 based Monte Carlo simulation (MC) method has been used to calculate the radiation transportation and dose distributions in tissue-like media. The main objective of the work was to compare the Geant4 simulated depth dose distributions with experimental measurements and verify the capability of the geant4 simulation toolkit. The carbon ion beams for the therapeutic energy of 350 MeV/u and 400 MeV/u respectively were simulated, with the same settings as the experimental work carried out at the treatment room at Heavy Ion Medical Accelerator (HIMAC), National Institute of Radiological Sciences (NIRS), Chiba, Japan. The simulation results were verified with measurements data. The work was to measure the accuracy and quality of the dose distributions by Geant4 MC methods. The results show that the Bragg peak and spread out Bragg peak (SOBP) distributions in simulation has fairly good agreement with measurements.

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1 INTRODUCTION

Charged particle therapy is an advanced type of radiation treatment that uses proton or carbon ions beams to irradiate or deliver high energy radiation directly to the tumour, destroying cancer cells while sparing surrounding healthy tissues and other critical areas or vital organs. With conventional radiation therapy, x-ray beams pass through both healthy and cancerous tissues, destroying cancerous tissues and damaging some of normal healthy tissues in the path of the x-ray beams. Thus giving high ionization radiation to patients causes both the cancerous tissues and the surrounding healthy tissues to be damaged. Carbon ion therapy can potentially deliver maximal doses while minimizing irradiation of surrounding tissues. It can be more effective or less harmful than other forms of radiotherapy for some cancers. Charged particle beam therapy especially in proton and carbon-ion therapy has been clinically available since 1954 [1] and more and more charged particle centres have been built worldwide.

Carbon ions has advantages over conventional radiotherapy using x-ray beams; due to its characteristic Bragg peak which has relatively low entrance doses and favourable doses distribution [2-3]. Carbon ions beam can effectively destroy deeply-seated tumours that are difficult to reach because they are near or within vital areas or located in sensitive areas of the body. Carbon ions enter the body with a low dose of radiation, stop at the tumour site, conform to the tumour's shape and volume or depth, and deposit almost all their energy right at the tumour site.

Charged particle therapy has been used extensively in radiotherapy application [4-8]. This physical characteristic of carbon ion is very suitable for radiation therapy to treat cancer tumour. Till end of 2015, more than 154203 patients have been treated worldwide with charged particles [1]. In this research work, the depth dose distributions for carbon ions in tissue-like media were presented by Geant4 simulation method. For the verification of the Geant4 simulated dose distributions, the simulated data were compared with measurements data at Heavy Ion Medical Accelerator (HIMAC) at the National Institute of Radiological Sciences, NIRS, Chiba, Japan by using different therapeutic beam energies.

1.1 Geant4 Simulation toolkit

When charged particle traverse through medium, they may undergo one million interactions per cm. This is a complex transport kinematics. Simulation software should be capable of handling such works. Accurate and comprehensive simulations are necessary for a large number of scientific applications, ranging from elementary particle physics to space science and medical physics. There are a number of very powerful software packages or code system being made available and the majority of them are distributed free.

There are some codes for charge particle simulation such as EGSnrc, Penelope or Geant4. In this study, GEANT4 (Geometry ANd Tracking) Monte Carlo code [9-10] is used because of its powerful abilities to simulate all type of particles, greater flexibility, and its ability in simulating various geometric variations. Geant4 Monte Carlo toolkit has been widely used in radiation transport for charged particle and many literatures show the Geant4 simulations had good agreement with experimental results [11-14].

2 MATERIALS AND METHODS

2.1 Simulation

The transportation of carbon-ion beams of 350 and 400 MeV/u were simulated by ad-hoc Geant4 Monte Carlo toolkit, version 4.9.4 Patch 01 in a Polymethyl Methacrylate (PMMA) phantom. The Bragg peak depth-dose distributions and spread-out Bragg peaks (SOBP) depth-dose distributions were studied and compared with the measurement values. The PMMA phantom with a volume of 30 cm x 30 cm x 30 cm and the position in the same way as measurements. The scoring of dose and linear energy transfer were performed using a cubic voxelised phantom placed at the end of the beam line.

The initial characteristics of the beams were defined to match the characteristics (peak to plateau ratio, Full Width Half Maximum, peak position, in particular) of the simulated Bragg peak distribution with the experimental data. The primary beam was generated from a circular spot, from which particles were emitted with a mono-energetic distribution with a standard deviation (defining the energy spread of the beam) of 0.3%. No divergence of the primary beam has been considered, in agreement with the cyclotron specification. The simulation of the Bragg peak distribution, the 100,000 mono-energetic carbon-ion beam was passed through a tantalum scatterer which has 0.4 mm thickness. The detectors divided into small-sized units call voxels, the voxels have dimensions of 100 mm × 100 mm × 0.1 mm, the total number of 200 voxels with dimensions of 0.1 mm thickness placed perpendicular to the beam axis and the energy deposited in each voxel was accumulated and the results were read by ASCII file.

Several more carbon ion energies were simulated in this work for better understanding of the depth dose distribution and energy dependence of Bragg peak position. Carbon ion beam at energies 170, 230, 290, 350, 400 and 450 in PMMA phantom were simulated. The wide range of energies are selected so that all the therapeutic energy for various accelerator facilities can be covered. Therefore, the results obtained can be used as a reference and is useful for further comparison with measurements.

The simulation of the spread-out Bragg peaks (SOBP), the complete components of the Broad-Beam delivery system including the scattering and collimator system, the range shifter (to degrade the beam energy), the ridge filter as a range modulator (forming a SOBP) and the detectors have been implemented. The geometrical and physical characteristics of the elements and the characteristics of the incident beam such as beam energy, energy spread, beam spot size and angular spread can be easily defined and changed. The bar shape of aluminium ridge filter is a range modulator used to spread out the Bragg peak. The ridge filter parameters such as the ridge filter width, length, high pitch and position were adjusted precisely to match the measurement data as close as possible. The detectors have volume of $20 \times 20 \times 1$ mm^3, total of 200 voxels with respect to the beam axis. Total number of 100, 000 primary beams was used. The energy deposited in each voxel was accumulated and the results read by ASCII file.

For the physics and hadronic interaction, the QGSP_BIC_EMY Reference Physics List was used in this simulation. This is pre-compiled and a ready-to-use set of physics models and contains a set of physics models. The Reference Physics List is a collection of Physics Lists and contain both the electromagnetic and hadronic models. Including Physics Lists for the electromagnetic physics, hadronic elastic and hadronic inelastic physics for hadronic interactions. QGSP_BIC_EMY is an acronym that briefly explains all the physics models activated when it is called: QGSP (Quark Gluon String Pre-compound) which defines the hadronic models for nucleons; BIC (Binary Ion

Cascade) which defines the inelastic models for ions and EMY (ElectroMagnetic Y) which defines the electromagnetic models used by all the particles (Y indicates a particular EM physics particularly tailored for the use in medical physics).

The QGSP_BIC_EMY Reference Physics List that has been tested and specifically created to address simulation problems for which high level of accuracy is requested [15]. The production of secondary fragmentation in the electromagnetic processes can lead to very huge numbers of small energy such as electrons and gammas; thus it is important to have a production threshold to suppress the generation of large numbers of soft electrons and gammas. In Geant4, charged particles are tracked to the end of their ranges, so that the range is used to suppress the particle production. This is so-called the range cut or simply call cuts in Geant4. Since the energy of non-produced particles is transferred from the discrete process to the continuous process, the dose distribution depends on the range cut. Therefore, the production threshold is needed to limit the large number of secondary particles. The range cuts was set to 1 mm in this study, means the tracking of secondary particles will stop if the secondary particles cannot travel more than 1mm distance.

2.2 Experiment

To validate and examine the accuracy of the Geant4 MC simulation, the experimental work was carried out in National Institute of Radiological Sciences, NIRS, Chiba, Japan by using the Heavy Ion Medical Accelerator, HIMAC. Figure 1 shows the geometry implementation of experimental beam line in HIMAC, NIRS [16]. The nozzle comprises a lateral beam-spreading system, beam monitors, a bar ridge filter, and a multi-leaf collimator. The lateral beam spreading system consists of a pair of wobbler (dipole) magnets and a scatterer. The wobbler magnets make a carbon ion beam draw a circular trace; a lead scatterer placed behind the magnets broaden the beam to produce a uniform circular dose distribution. These beam lines are also equipped with ionisation chambers for monitoring the intensity and beam profile.

For the spread out Bragg peak measurement, the bar ridge filter was added as a range modulator and is used to spread out the Bragg peak (SOBP) in the depth-dose distribution. So the uniform physical dose area is obtained in the SOBP region three-dimensionally.

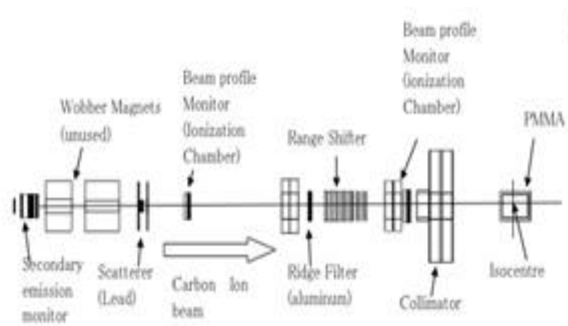

Figure 1: Heavy ion beamline of HIMAC

The broadened beam was trimmed by two collimators with circular and square apertures, and shaped by a multi- leaf collimator installed at the end of the beamline. The beamline was equipped with a secondary-emission monitor and two ionization chambers for monitoring the intensity and lateral profile of the beam.

The therapeutic carbon-ion beam of 350 and 400 MeV/u was irradiated and the absorbed dose distribution was measured by using a Marcus parallel-plate ionization chamber (Type 23343, PTW-Freiburg), the thin entrance window allows measurements in solid state phantoms up to the surface positioned at the isocenter 10 m from the effective source. The stack of PMMA was inserted just upstream of the ionisation chamber to represent water-equivalent thickness. The depth dose distributions profile was obtained by varying the thickness of the PMMA along the beam direction. More detailed description of the HIMAC beam line can be found in literatures [17].

3 RESULTS AND DISCUSSION

The depth dose distribution in the Geant4 MC simulation were obtained by summing up the doses in each voxels at different depths, then compared with the measurement data. When the radiation field produced by carbon ions passing through tissue, the interaction is relatively complex due to nuclear fragmentation reactions along their path, the fragmentation reactions leads to the attenuation of the incident ions, ionization and excitation processes and to the build-up secondary fragments. Secondary release their energy ionizing the tissue traversed and create other particles which have longer ranges and cause the tail dose downstream of Bragg peak.

However, depth dose distributions are the main parameter of comparison because they play very important role in hadrontherapy and give crucial information about some dosimetric quantities used for treatment planning. Bragg peak is the most accurate way to indicates how the Genat4 Monte Carlo simulations can well reproduce the energy loss process suffered by the primary and secondary particles.

Besides that, the comparison and agreement can be also evaluated by *Peak-plateau ratio*, also call *peak-to-entrance ratio*, the ratio of the deposited energy at the peak position and at the entrance, *Full width at half maximum (FWHM)*, the width of the Bragg peak at the points corresponding to the 50% of the maximum dose value. *Distal dose fall-off*, the distance between the points of 80% and 20% of absorbed dose along the beam axis beyond the Bragg peak. The *peak-to-entrance ratio* is the most common used dosimetric quantities for the Bragg peak evaluation in general. The analysis of these parameters was discussed in this session as well.

The depth dose profiles as relative dose versus penetration depth (mm) for both simulations and measurements are plotted. Figure 2 (a) and (b) show the Bragg peak depth dose distribution produced by 350 and 400 MeV/u ion beams respectively with ridge filter. The Bragg curves have been normalised such that both measurement and simulation coincide with the area.

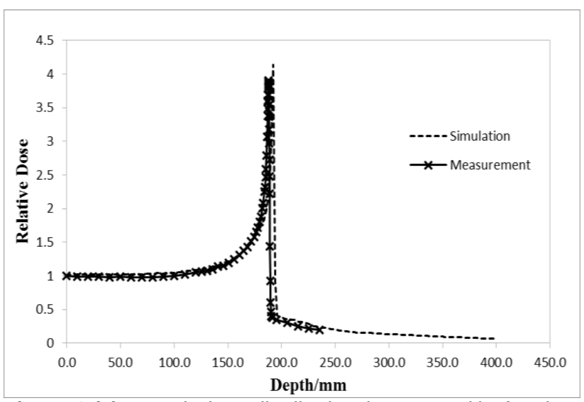

Figure 2 (a): Depth dose distribution (Bragg peak) of carbon ion beam for measurements and simulations with 350 MeV/u

As we can observe in Figure 2, overall the Geant4 based simulations can describe the shape of the experimental depth-dose curves with fairly well precision for all energies. The superimposition of the curves can be seen in the entrance channel (plateau) 350 MeV/u, where the simulation slightly overestimates in the entrance channel for the energy 400 MeV/u. The tail doses of the simulations slightly overestimate compared with the measurements data for both energies, the slight difference may be due to the beam divergence and emissions of fragment particles.

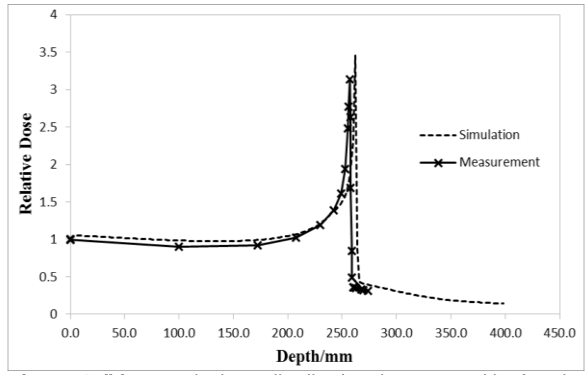

Figure 2 (b): Depth dose distribution (Bragg peak) of carbon ion beam for measurements and simulations with 400 MeV/u

However, the biological effects of the tail dose or fragment nuclei are not significant and far less than the primary carbon ion. Table I shows the deviation (Δz) of Bragg peak positions between measurement and simulation.

The deviation is lower for low energies and increases towards higher energies. Overall, the deviation of the Bragg peak positions between measurements and simulations are in satisfactory agreement. The maximum deviation of about 5 mm has been found at the incident beam 400 MeV/u. The main reason of discrepancy is due to simulation beam parameter setup. More comprehensive analysis of important parameters for the Bragg peak are summarized in Table II.

A discrepancy in the peak-plateau ratio of 0.31 mm (9.87%) has been found at energy level 400 MeV/u; this value is larger than the values at energy 350 MeV/u which have uncertainties of 5.88%. As mentioned above, the discrepancy is mainly due to the geometry beam parameter setup and physical interaction in simulation. The small change in beam parameter such as thickness of scatterer, beam position spread and angular momentum can cause a large difference in the Bragg curve value. This is because the simulation of beams transportation can easily be affected by many factors thus influencing the collection of energy depositions. Full width at half maximum (FWHM) and distal fall-off show a fairly good agreement between measurement and simulation in both energies with the difference less than 1 mm except 1.31 mm for FWHM at energy 400 MeV/u. The main possibility is due to the uncertainty in calculation especially the values of FWHM and distal fall-off for the measurement data. Besides that, other possible experimental reason of discrepancies may also be due to the uncertainty of the initial energy spread, heterogeneity of the scatter and electrode in the monitor. The depth dose profiles at various low energies from 170 to 450 MeV/u as relative dose versus penetration depth (mm) are plotted in Figure 3.

Table I: The deviation of Bragg peak position

Energy (MeV/u)	Measurement/mm	Simulation/mm	Different(ΔZ)/mm	% Different
350.00	187.90	192.00	-4.10	2.18
400.00	256.90	262.00	-5.10	1.99

Table II: Comparison between different parameters obtained with the simulation and measurement

350 MeV/u	Simulation	Measurement	Different (Δd)	% Different
Peak-plateau ratio	4.14	3.91	0.23	5.88
FWHM /mm	6.47	7.43	0.96	12.92
Distal fall-off/mm	1.82	1.11	0.71	63.96
400 MeV/u				
Peak-plateau ratio	3.45	3.14	0.31	9.87
FWHM /mm	7.49	8.80	1.31	14.89
Distal fall-off/mm	2.28	1.41	0.87	61.70

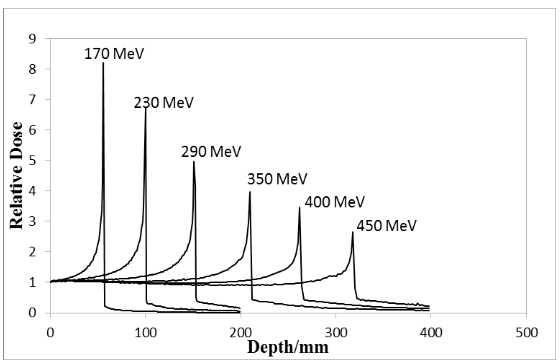

Figure 3: Depth dose distribution of carbon ion beams in water at various low energies by Geant4 simulation

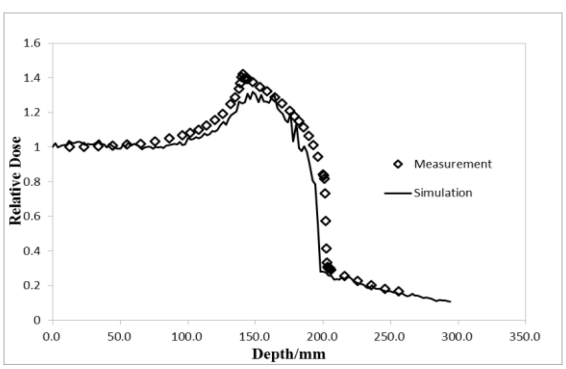

Figure 4 (a): Depth dose distribution (SOBP) of carbon ion beam for measurements and simulations with 350 MeV/u

From Figure 3, we can see more clearly the peak height is highest for lowest energy, 170 MeV/u and the peak height decreases constantly with the increase in energy levels. Energy ranging from 170 to 290 MeV/u may be suitable for tumours lying in the outer layer of the human body up to 150mm depth and energy ranging from 290 to 450 MeV/u are suitable for more deeply-seated tumours. Beam energies more than 450 MeV/u are not suitable for charged particle therapy and cannot be utilized as the range of particles will cross the human body, the results also agree with the previous similar study [18].

Figure 4 (a) and (b) show the spread-out Bragg peaks (SOBP) width of 50 mm produced by 350 and 400 MeV/u therapeutic beams respectively, with complete components of the Broad-Beam delivery system. The SOBP depth dose profiles have been normalized such that both measurement and simulation coincide with the area. The depth dose profiles as relative dose versus penetration depth (mm) are plotted. This work shows that the simulation results are similar to the measurements data for energy 350 MeV/u. Fairly good agreement of entrance dose and tail dose can be found between simulations and measurements for the energy 350 MeV/u, but simulations dose is slightly underestimated at the spread-out Bragg peak

(SOBP) regions compared with the measurement.

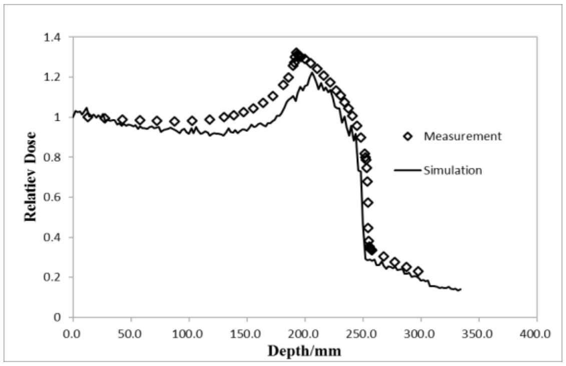

Figure 4 (b): Depth dose distribution (SOBP) of carbon ion beam for measurements and simulations with 400 MeV/u

The maximum deviations at the peak regions between simulation and measurement for energy 350 MeV/u is 12% at the depth about 141 mm. For the beam energy 400 MeV/u, the simulated curves did not match the measurement dose pattern well overall, include tail dose and it is more obvious at the spread out Bragg peak region. Maximum deviation of 18% has been found at the depth about 193 mm (peak region) between simulation and measurement. However, the biological effects of the secondary particles are far smaller than primary carbon, therefore the underestimation of the tail dose is not a serious problem in practice.

The reproducibility of SOBP shows slight disagreement for 400 MeV/u. They are due to several factors including the geometry implementation. Other than that, there is also the need to improve the model at high projectile energies. Many factors can contribute significant influences to the simulated results such as the geometrical adjustments of the scatterer, range shifter and ridge filter in the Geant4 simulation code. The main reason of the underestimates for simulated data compared with the measured data at the peak region for SOBP is due to the parameter setup of the ridge filter. Small changes in the ridge filter can bring significant effects to the simulation results.

Therefore, a very sensitive adjustment for the bar shape of ridge filter is needed to improve the simulation data in future works. Besides that, the results can be possibly improved by using more precise beam parameter such as beam position spread, spot size, angular momentum and so on.

4 CONCLUSIONS

This study gives the validation and comparison of depth dose distribution between simulations and experiments for carbon ions beam, at two therapeutic energies of 350 MeV/u and 400 MeV/u respectively in order to ascertain the reliability and ability of the Geant4. The dose distribution of the simulation agreed well with the real carbon ions doses and the results demonstrated the ability of Geant4 simulation to be applied in charged particle therapy.

Bragg peak of the carbon ions beam plays a pivotal role in the clinical practice of hadron cancer therapy. The doses distributions of the simulation fairly agreed with the measured dose for Bragg peak but still has room for improvement for the spread-out Bragg peaks (SOBP) dose distributions. This results demonstrates the ability of the Geant4 simulation which can be fully applied in the charged therapy cancer treatment. Furthermore, the pretty good simulation results also verified the abilities of the Geant4 toolkit done by Toshito et at [13] and Cirrone et at [15]. Further works will be carried out to refine and improve the Geant4 MC simulations.

CONFLICTS OF INTEREST

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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