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MONTE CARLO SIMULATION FOR EVALUATION OF DOSE DISTRIBUTION IN PROTON THERAPY*

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Abstract. This paper presents dose calculation in proton therapy using Monte Carlo method and comparison with experimental data obtained at TOHOKU University's cyclotron and isotope center in Japan. In this way, two Monte Carlo codes, FLUKA and MCNPX, has been employed to calculate percentage depth dose, lateral dose profiles, isodose curves and secondary particles production for proton pencil and broad beam in PMMA phantom.

By going deeply through and showing the accuracy of the data the capability of Monte Carlo method in proton therapy modeling has been demonstrated.

Our results reveal a good agreement between simulated and measured dose which are 3% differences for the maximum dose. The results presented herein shows the applicability of Monte Carlo models for predicting and evaluating the dose distribution in proton therapy. Also, despite differences in algorithm and atomic and nuclear library between MCNPX and FLUKA, these two codes showed good consistency.

Keywords: Proton therapy, Monte Carlo method, percentage depth dose, lateral dose profiles, isodose curves.

1. INTRODUCTION

Radiotherapy is the use of ionizing particles to reduce or trim down the size of cancerous tissues. Currently utilizing photons and electrons are the most preferred particles in radiotherapy but using Hadrons (protons, neutrons and pions) and heavy particles have shown promising results in cancer treatment.

In treatment with charged particles the energy range is 80 MeV to 400 MeV which are produced by an elastic collision of protons with the electrons of the target. Due to their small angular distribution and much localized depth dose

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deposition, protons deliver high dose to a small volume of cancerous tissue while the healthy structures will be spared during proton radiation therapy. Protons are extensively used in treatment of inoperable tumors and/or in treatment of cancer in children. Clinical studies have been carried out using this method in treatment of Retinoblastoma, Striated Muscle Sarcoma and tumors of: head and neck, Brain, Prostate and Lungs. Protons are accelerated with high energy in Cyclotrons or synchrotrons [1].

Like all developed methods in radiation therapy, modeling of dose deposition is the essential process in proton therapy. Since measuring the parameters of dose distribution is an important step in treatment planning system, Monte Carlo method can be a powerful tool for precise simulation of dose deposition in proton therapy. [1, 34].

Monte Carlo model follows the propagation of a proton beam in the medium by considering almost all possible interactions of particles with matter. Each interaction for each particle is considered on the basis of models and/or experimental and evaluated databases for electromagnetic and hadronic interactions at all levels (molecular, atomic and nuclear) [5].

2. METHODS AND MATERIALS

This study is focused on the applicability of Monte Carlo method in estimation of dose distribution in proton therapy by comparison with experimental data obtained at TOHOKU University's cyclotron and isotope center (CYRIC) in Japan [6]. To do this, two Monte Carlo codes, MCNPX and FLUKA, in field of radiation therapy is employed to calculate depth dose, lateral dose profiles, isodose curves and secondary particles production for both proton pencil and broad beam in PMMA (Ploy methyl methacrylic) phantom.

CYRIC Proton therapy facility includes a horizontal beam line which is currently used for research experiments and consists of beam wobbling system, beam monitoring system, different types of ridge filter, range shifter, collimators, detectors and other required devices for doing experiment.

In this center, protons are accelerated by AVF (Azimuthally Varying Field) cyclotron and their energy reach to 80 MeV which is suitable for experiments on small animals [7, 8].

Fig. 1 shows a schematic layout of horizontal beam line and required devices in beam path in order to create a desired treatment area on target volume.

While protons enter scatterer material, they scatter mainly by interaction with atomic nuclei rather than electrons, because collisions with electrons hardly deflect the massive protons. They leave scatterer in a range of angles as a net result of interactions in their paths due to the process of multiple coulomb scattering. The distribution of these angles is very close to Gaussian distribution with a specific

FWHM (Full Width at Half Maximum). Therefore, the narrow pencil beam will be expanded into a larger beam with an approximately Gaussian transverse profile [8].

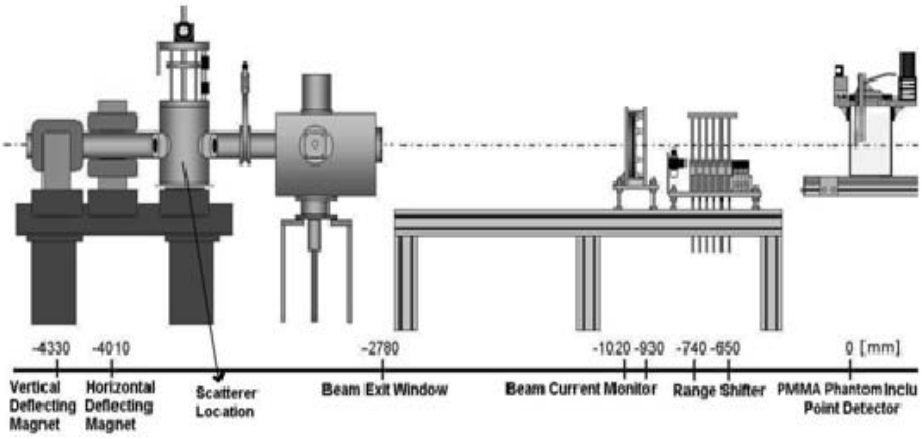

Fig. 1 – Schematic layout of proton beam path in Proton therapy facility, CYRIC [8].

The current of proton beam is measured online by beam current monitor, which operates as parallel plate ionization chamber. Range shifter is used in proton beam path to adjust the position of the Bragg Peak inside the target. This system includes six plates (100 mm×100 mm) made of PMMA. Pin Point Ionization Chamber type 31014 has been used to measure precisely the deposited dose in the phantom [8].

Two general-purpose Monte Carlo radiation transport codes MCNPX 2.6 and FLUKA 2011 have been chosen as a tool for the simulations presented in this paper due to their extensive usage in radiation therapy applications and user-friendly handling.

MCNPX is a radiation transportation code of Monte Carlo Method which simulates the interaction of nearly all particles in all energies. This Code is the new generation of Monte Carlo Method which has been publicized in 1994 to cover all particles in all energies with an enhanced physical based simulating method and comprehensive photonuclear libraries up to 150 MeV and also a new method for variance reduction and data analysis

This code uses tabulated cross-sectional data up to a maximum energy, which is particle and material dependent, and beyond this maximum energy, the program uses model based transport parameters [9].

Fluka is a general purpose tool based on Monte Carlo Method which is used in calculations of particle transport and interaction with matter. It is capable of simulating the interaction of 60 different particles, Heavy particles, interaction of Hadrons-hadrons and Hadrons-Nuclei. Quite the opposite of MCNPX it has been created based on Fortran 77 and it's operable on linux-unix operating system [10].

With the help of these two codes proton beams up to several TeV can be simulated.

Moreover, the results from two codes will be redone for pionic source and compare with treatment with photon. By going deeply through and showing the accuracy of the data the capability of the codes in modeling such problems will be demonstrated.

3. RESULTS

Fig. 2 represents the measured and simulated data of depth dose (Bragg peak profiles) created with 80 MeV protons in PMMA phantom. Experimental results show sharper peak and dose fall faster than simulated data.

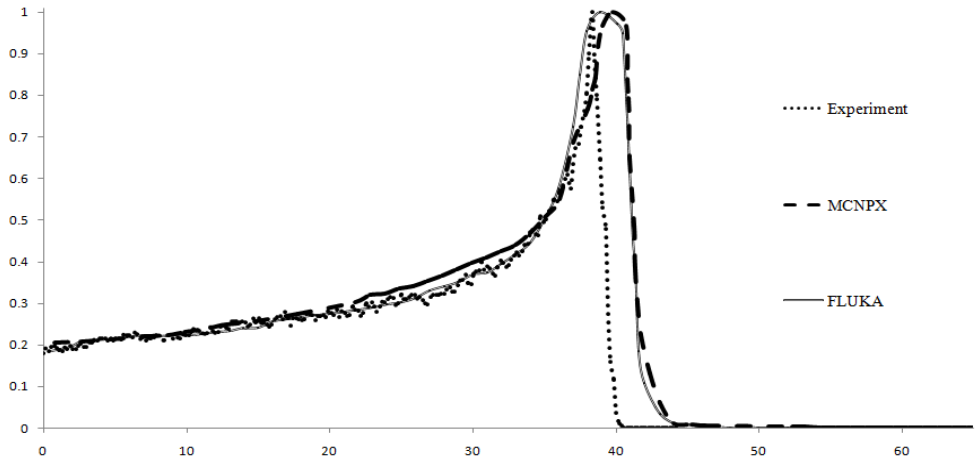

Fig. 2 – Percentage depth dose in PMMA phantom; Monte Carlo Simulation vs. experimental result.

There is 3% to 4% difference in Bragg peak and the maximum difference between simulated and experimented results is 6% in distal part of depth dose profiles. The results show that dose decreases to half approximately in 0.8 mm after the peak and about 1.5 mm after peak dose will drop off to 10%. Figure 3 shows the lateral profile of pencil beam. The main characteristics of a pencil beam are energy and FWHM. In this case beam FWHM is 0.5 MeV for proton energy of 80 MeV. It should be considered the atomic compositions of the air which exist in beam path causes a few scattering on proton beam with a narrow Gaussian profile.

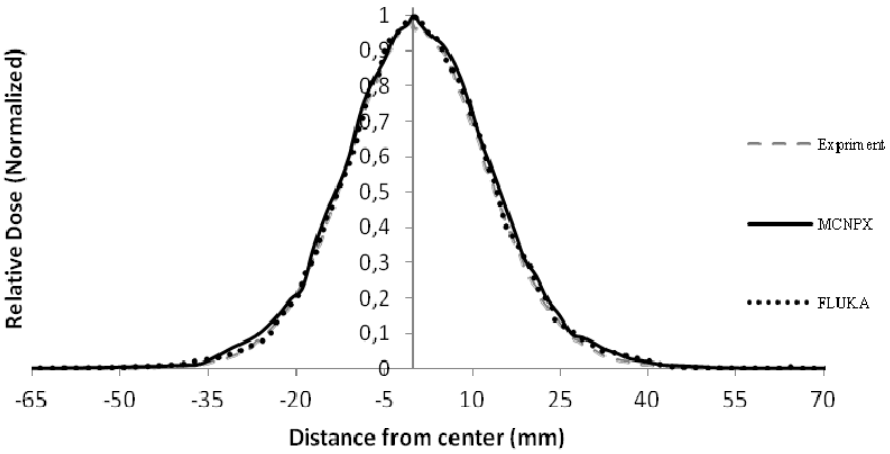

Fig. 3 – Lateral dose profile for pencil beam in longitudinal direction. Comparison between experimental data and Monte Carlo simulation. The solid line corresponds to the measured data; the round dot and dash present dose profile as calculated with FLUKA and MCNPX results respectively.

The maximum difference between the results is related to borders and penumbra. Since the phantom is homogenous and symmetric in longitudinal and transverse directions the results in these two directions reveal no significant difference.

Broad beam is created by inserting a Lead foil with 0.1 mm thickness in front of proton beam. After irradiating protons to scatterer, the narrow pencil beam will be expanded into a larger beam with an approximately Gaussian transverse profile. Fig. 4 depicts the comparison results of FLUKA and MCNPX code and experiment. It should be noticed that the information of broad beam such as FWHM and beam divergence can be imported in BEAM card directly. For MCNP/X by defining a parameter (p), the characteristics of flat beam are imported:

$$p\,(E) = C \exp[\,((E-b)/a)^2] \tag{1}$$

where a is the width and b is the mean value of energy. a can be calculated from equation 2.

$$FWHM = a\left(\ln 2\right)^{\frac{1}{2}}. \tag{2}$$

Treatment area is the area between two 80% dose before and after peak [11]. This area can be extracted from Fig. 4 and the values in both two directions which are determine the thickness of curable tumor and difference between the results of two Monte Carlo codes and experimental data is shown in Table 1 and Table 2. Results show that a tumor with thickness of 4 to 5 cm properly receives high dose from 80 MeV proton.

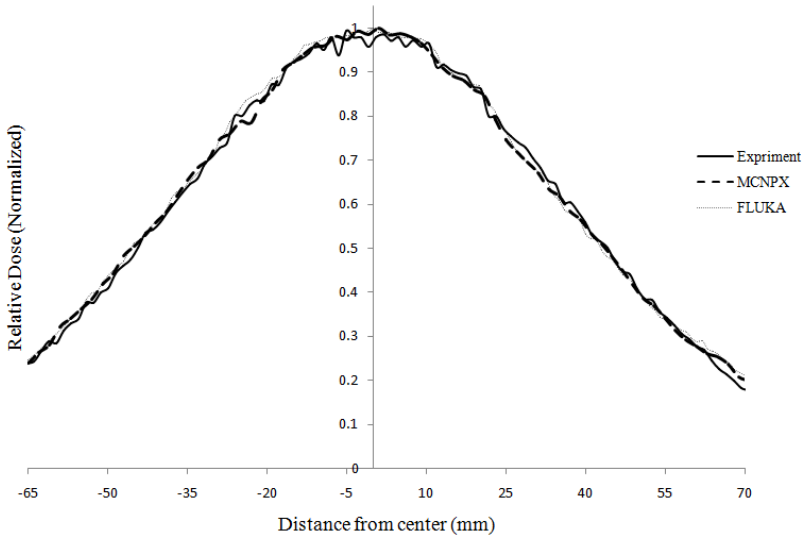

Fig. 4 – Lateral dose profile of flat beam in longitudinal direction. The results have been compared between Monte Carlo method and data from experiment. Again, solid line shows the measured data; the round dot and dash correspond to the dose profile as calculated with FLUKA and MCNPX results respectively.

Table 1

Treatment area for broad beam in X axis (longitudinal)

	Treatment area (mm)	Difference
Experiment	47.81	
MCNPX	46.67	2.38%
FLUKA	49.36	3.14%

Table 2

Treatment area for broad beam in Y axis (transverse)

	Treatment area (mm)	Difference
Experiment	46.8	
MCNPX	48.15	2.80%
FLUKA	48.73	3.91%

The deposition of dose within PMMA phantom is visualized through the use of isodose curves [12]. Fig. 5 depicts the isodose curve in two X-Z and Y-Z plane which are plotted by tecplot software. The trend of dose deposition in phantom can be visualized using these curves.

Moreover, 2D and 3D dose distribution in phantom in Fig. 6 and Fig. 7 respectively. The values of dose are expressed in unit of MeV/g/primary particle.

Finally, secondary neutron production causes by interaction of proton with nuclei is shown in Fig. 8.

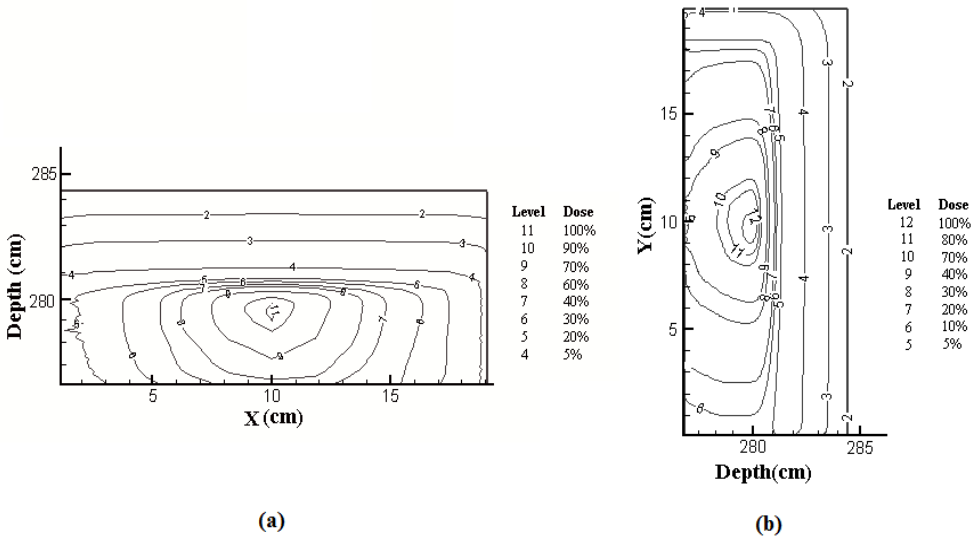

Fig. 5 – Isodose curves in X-Z plane (a) and in Y-Z plane (b), plotted by MCNPX (tecplot).

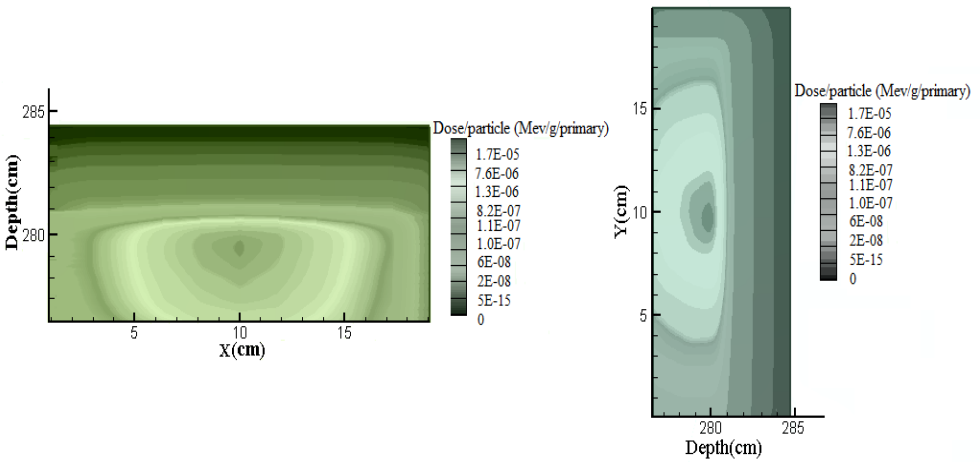

Fig. 6 – 2D dose distribution in PMMA phantom X-Z plane (a) and Y-Z plane (b), plotted by MCNPX (tecplot)

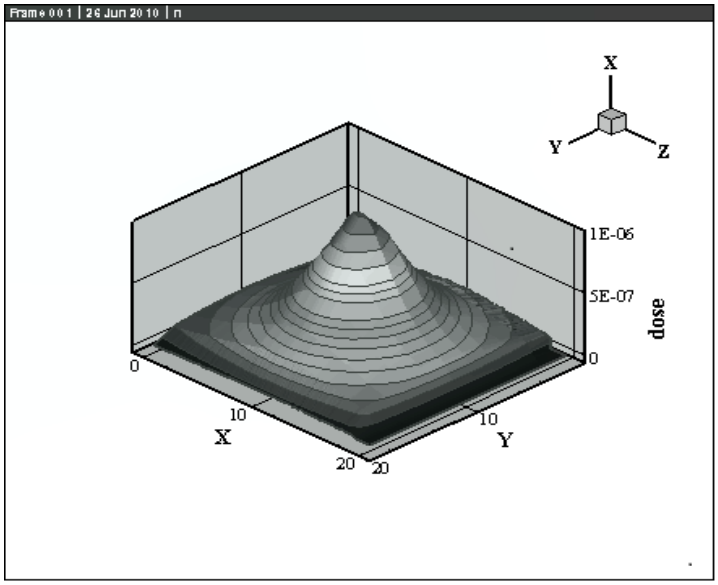

Fig. 7 – 3D dose distribution in PMMA phantom.

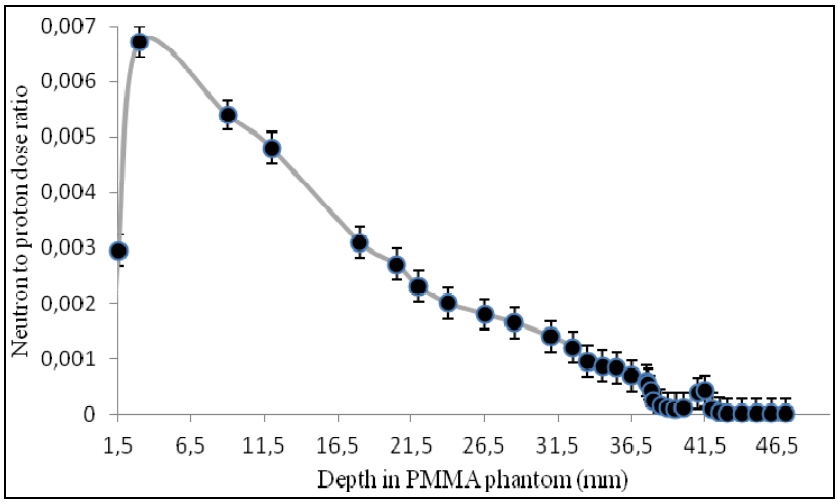

Fig. 8 – Ratio of neutron dose to proton dose in PMMA phantom.

4. CONCLUSION

In this study, we confirmed the dosimetric accuracy of the Monte Carlo model by comparison with experimental data which are obtained in SYRIC for percentage depth dose and lateral dose profiles. The results show the maximum 3-

4% difference between Monte Carlo and experiment. Moreover, the results from two Monte Carlo codes reveal good consistency despite difference in algorithms and libraries.

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