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Tissue inhomogeneity in proton therapy and investigation of its effects on BRAGG peak by using MCNPX code

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ABSTRACT

Background: Hadron therapy for malignant tumor is becoming increasingly popular. There are many factors which effect on implementation of a proper treatment planning. The purpose of this work is to investigate the inhomogeneity effects as affecting factor on proton range, Full width at half maximum (FWHM) and 20% position of penumbra (P20) by MCNPX code. ***Materials and Methods:*** An inhomogeneous tissue (Bone or Adipose) with a variable thickness (0.1 cm, 0.5cm and 1.0 cm) was inserted into a phantom. Then this phantom was irradiated by 108.8 MeV proton beam located at 10 cm away from it. Particle energy deposition (PEDEP) in mesh tally card was used for simulation of Bragg curve and obtaining the proton range, FWHM and 20% position of penumbra (P20). Finally, the MCNPX results were compared with GEANT4. ***Results:*** The results of MCNPX for water phantom including 1cm adipose for range and P20 were 8.87 and 9.10 cm respectively, and for 1cm bone, range and P20 were 8.52 and 8.58 cm. By increasing the adipose thickness, range and P20 were reduced but it was vice versa for increasing the bone thickness. Also FWHM does not show a regular variation in both bone and adipose tissues. ***Conclusion:*** The results show that the location of the inhomogeneous tissues does not affect the variation of the whole shape of the Bragg curve, while it radically affects the dose in the Bragg curve. The comparison between MCNPX and GEANT4 results showed that the MCNPX results have the closer values than GEANT4 to references.

Keywords: *Proton therapy, MCNPX, GEANT4, brag peak, plateau.*

INTRODUCTION

There are very clear advantages to the use of proton therapy either alone or in conjunction with other modalities. It can be used in conjunction with photon treatments to provide patients with a wider variety of treatment options. The proton beam deposits most of its energy immediately before it stops to form a depth dose distribution called a Bragg curve; this predictable deposition of dose can be utilized to spare normal tissues and kill malignant cells [1-4]. Due to the range straggling, not all protons of the same energy have the same range. Thus, the range needs to be defined for a beam of protons resulting in a broadened Bragg peak or a spread-out Bragg peak (SOBP) [3,4].

The Monte Carlo method is very time consuming during proton therapy treatment planning, the accuracy of the Monte Carlo method has been reported by many researchers [5-10]. MCNPX, PENELOPE, FLUKA and GEANT are the well-known codes based on the Monte Carlo method. In order to compare the verification and validation of GEANT4 results of the effects of inhomogeneity in proton path length of the two states mentioned above, MCNPX code was considered in this research (5-10).

MCNP code is a general-purpose Monte Carlo radiation transport code for modeling the interaction of radiation with matter. It utilizes the nuclear cross section libraries and uses physics models for particle interactions and gives the required quantity with certain error (11, 12).

GEANT4 is software developed at CERN that stands for "Geometry and Tracking". GEANT is coded entirely in C++ and was initially designed to perform high energy physics Monte Carlo simulations (13,14).

Generally, the dose distributions achievable with protons are very sensitive to the changes in radiological depths along the beam path (15, 16). However, so far not any study has been focused on the effects of dose distributions according to the position of inhomogeneous materials. This study makes a comparison between the results of the two different Monte Carlo codes which simulate the effects of inhomogenous tissues inserted in water phantom (15, 16).

The dose conformity is influenced by the inhomogeneous tissues placed on the path of the proton beam. The effects of inhomogeneities are serious when high density material is placed in the Bragg peak region, which results in the degradation of the Bragg peak and the range (15). Proton beams could have a non-uniform dose distribution, if the effect of inhomogeneities would not be adequately compensated. Because the proton brag peak or maximum dose may be placed on the other organs excluded from the process, Schneider et al. and Szymanowski represented a development of analytical models that include the effects of density heterogeneity (17,18). The aim of this study is to investigate the effect of inhomogeneous tissue placed in the region of the Plateau and Bragg peak in proton therapy by the MCNPX code. The factors such as range, defined as the distance between the entrance surface of the beam and the distal point of the 80% dose, full width at half maximum (FWHM) by means of the MCNPX simulation code are calculated and compared with GEANT4 available data (15).

Each of the above mentioned parameters could be calculated by mesh tallies in MCNPX code. A mesh tally is a tally available within MCNPX. Mesh tallies provide a convenient way to visualize in 3-dimensions what is not possible with a traditional segment.

In an appropriate radiation therapy, tissue homogeneity can help to have a simple and good treatment planning. There are many factors which affect the implementation of a proper treatment planning. One of the factors is the existence of an inhomogenity in tissue (e.g. bone and adipose) which creates a disturbance in treatment planning. In this research, the effect of inhomogeneous tissues (bone and adipose in different thicknesses) placed in the Plateau and Bragg peak regions of the Bragg curve in water phantom is investigated by MCNPX code and compared with available GEANT4 data.

MATERIALS AND METHODS

The Simulation of water phantom without inhomogeneous tissues

The proposed geometry consisted of a cubic water phantom of 40 × 30 × 30 cm^3, because the Bragg curve in the water phantom was acquired as reference data for comparing the altered parameter by the effects of inhomogeneous condition. The beam penetration axis was determined as an appropriate maximum range for proton therapy and the field size was set as 30 × 30 cm^2. The cubic voxel size was selected with dimensions of 1 mm for obtaining the necessary data. The environment except the mentioned phantom was filled with air. Materials of the phantom in the geometry were adopted from National Institute of Standards and Technology (NIST) data. Finally, the water phantom was centered in an air cube for variance reduction. Anything outside the air cube was considered void into which MCNPX could not make efficient transport.

The cyclotron proton source was modeled as a directional plane source in a vacuum. This 108.8 MeV proton source was located 10cm away from the entry plane of the mentioned water cube. The initial direction of proton source was parallel to the beam axis. The output of MCNPX mesh tally from 108.8 MeV proton beam was compared with GEANT4 data in a water phantom in order to ensure the reliability of the simulation. Comparisons of MCNPX and GEANT4 data were made with respect to the three factors: range, penumbra width as the distance between points of 80% and 20% absorbed dose in the distal region of the Bragg curve; and FWHM, as full width at one-half of maximum as shown in figure. 1.

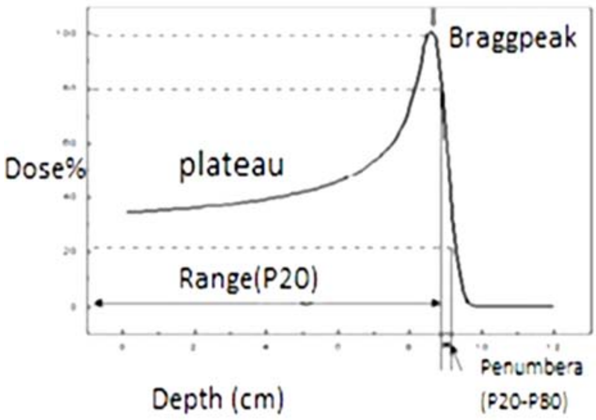

Figure 1. A Bragg peak with the three factors: range, penumbra width as the distance between points of 80% and 20% absorbed dose in the distal region of the Bragg curve; and FWHM, as full width at one-half of maximum.

The simulation of water phantom with inhomogeneous tissues

The effect of inhomogeneities was simulated with respect to the inserted position, density and thickness of tissues. The inhomogenities of interest comprised the bone (Density= 1.85 g/cm^3) and adipose tissue (Density= 0.92 g/cm^3) which were inserted in the water phantom.

In this research, the bone and adipose tissues were selected with three thicknesses 0.1, 0.5 and 1.0 cm. In addition, the energy of proton beams was 108.8 MeV. The position of the proton source was 10 cm away from the surface of the water phantom. The output of MCNPX mesh tally from 108.8 MeV proton beam was compared with GEANT4 data in a water phantom in order to demonstrate the reliability of the simulation. Comparisons of MCNPX and GEANT4 data were made with respect to the three factors: range, penumbra width as the distance between the points of 80% and 20% absorbed dose in the distal region of the Bragg curve; and FWHM, as a full width at one-half of maximum. The schematic representation of inhomogeneous geometry is shown in figure 2.

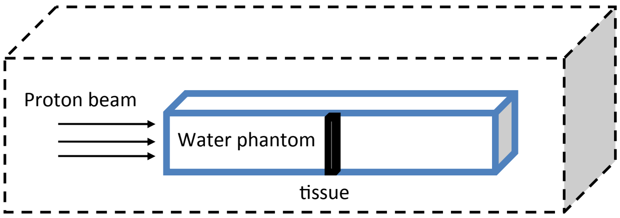

Figure 2. The schematic figure of inhomogeneous geometry in this study.

RESULTS

When the bone tissue was inserted in the region of plateau and Bragg peak, the range was decreased by approximately 3.5 mm for the bone with 1.0 cm thickness, and it has not been changed by inserting the adipose tissue. The variation of range by inserting the bone in the reference phantom in the GEANT4 simulation was considerable (7mm), so the MCNPX results have a closer agreement to reference relative to GEANT4. Table 1 shows the obtained results for the range, penumbra width (P20 and P80) and FWHM in reference water phantom. Comparisons of MCNPX and GEANT4 dose distribution results were made for 108.8 MeV proton beams.

Table 1. The MCNPX and GEANT4 results for parameters of bragg curve in reference water phantom.

	Range or P80	FWHM	P20
GEANT4[15]	8.61 cm	4.95 cm	9.16 cm
MCNPX	8.87 cm	4. 25 cm	9.04 cm
Difference	-0.26 cm	0.7 cm	0.12 cm

Table 2 shows the results of MCNPX and GEANT4 for the range, penumbra width (P20 and P80) and FWHM in water phantom including inhomogeneous tissues (bone and adipose) with 0.1, 0.5 and 1cm thicknesses. The proton ranges (P80) and P20 expand by the increase in the inhomogeneous layer thickness for the adipose tissue in Bragg peak albeit contrary to the bone tissue, which reacts vice versa.

Table 2. The parameters of Bragg curve in 108.8 MeV proton beams by inserted inhomogeneous materials in bragg peak (MCNPX and GEANT4 results).

	MCNP						GEANT4					
	Adipose tissue			Bone			Adipose tissue			Bone		
Inhomogenity Thickness (cm)	0.1	0.5	1	0.1	0.5	1	0.1	0.5	1	0.1	0.5	1
Range (P80) (cm)	8.78	8.84	8.87	8.75	8.64	8.52	8.71	8.73	8.74	8.63	8.33	7.97
FWHM (cm)	4.34	4.32	4.29	4.47	4.40	-	5.06	5.13	5.00	5.19	5.11	-
P 20 (cm)	9.02	9.08	9.1	8.87	8.81	8.58	9.23	9.28	9.30	9.18	8.88	8.52

Figures 3 and 4 show the changes in the position of range (P80), FWHM and P20, when the bone and adipose layer (three layer thicknesses 0.1, 0.5 and 1 cm) as an inhomogeneity are inserted in the Bragg peak of reference water phantom.

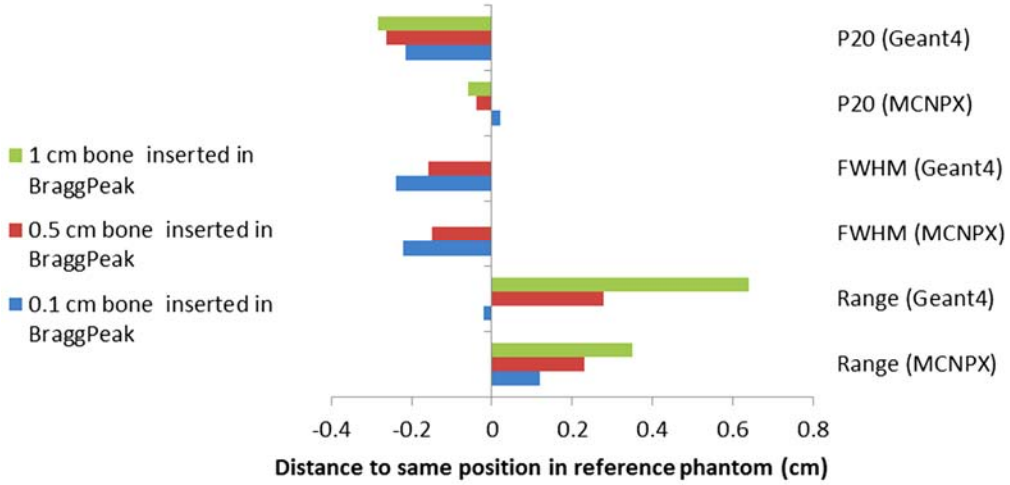

Figure 3. The difference between MCNPX and GEANT4 results for parameters of bragg curve in water phantom with the bone tissue (in bragg peak).

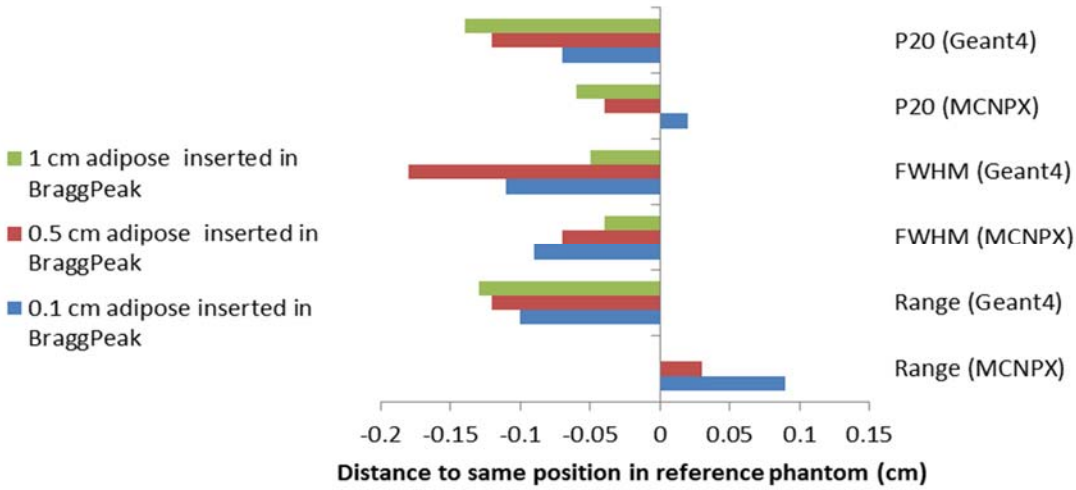

Figure 4. The difference between MCNPX and GEANT4 results for parameters of Bragg curve in water phantom with the adipose tissue (in Bragg peak).

Table 3 shows the results of MCNPX for the range, penumbra width (P20 and P80) and FWHM in the water phantom including inhomogeneous tissue (the bone and adipose) with 0.1, 0.5 and 1cm thicknesses. The range (P80) and P20 increase by the increase in the inhomogeneous layer thickness for the adipose tissue in Plateau but is vice versa for the bone tissue.

Figures 5 and 6 show the changes in the position of range (P80), FWHM and P20, when the bone and adipose layer (three layer thicknesses 0.1, 0.5 and 1 cm) as an inhomogeneity are inserted in the Plateau of reference water phantom.

Table 3. The parameters of Bragg curve in 108.8 MeV proton beams by the inserted inhomogeneous materials in Plateau (MCNPX and GEANT4 results).

	MCNP						GEANT4					
	Adipose tissue			Bone			Adipose tissue			Bone		
Inhomogenity Thickness (cm)	0.1	0.5	1	0.1	0.5	1	0.1	0.5	1	0.1	0.5	1
Range (P80) (cm)	8.78	8.84	8.87	8.75	8.64	8.52	8.71	8.72	8.74	8.62	8.33	8.00
FWHM (cm)	4.35	4.41	4.40	4.30	4.39	4.39	5.07	5.12	5.11	5.01	5.12	5.11
P 20 (cm)	9.02	9.08	9.10	8.87	8.81	8.58	9.23	9.27	9.30	9.18	8.88	8.52

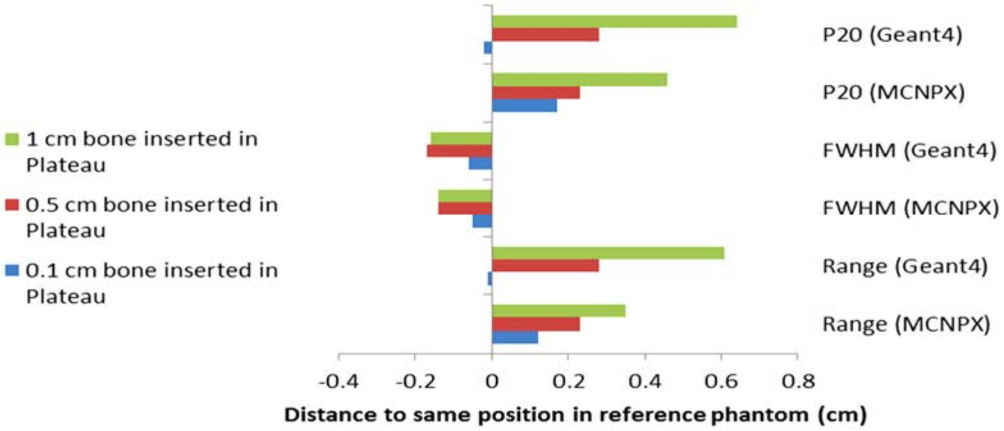

Figure 5. The difference between MCNPX and GEANT4 results for parameters of Bragg curve in the water phantom with the bone tissue (in Plateau).

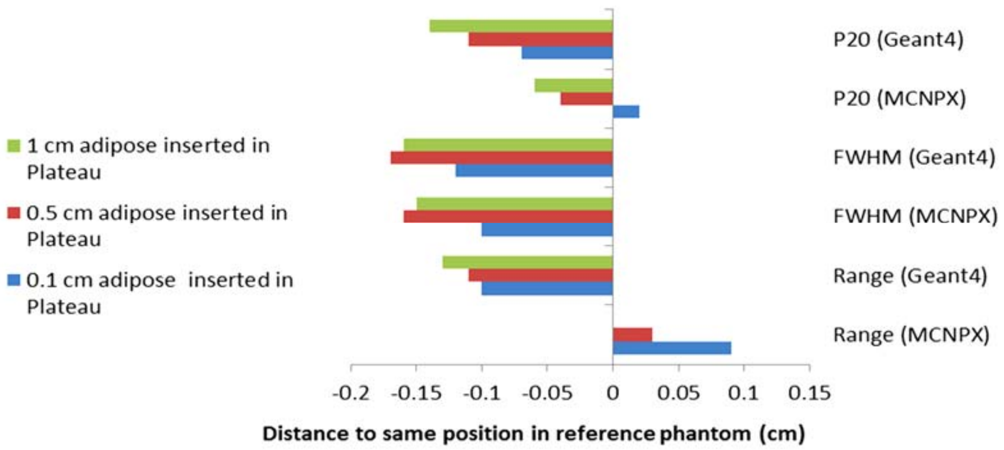

Figure 6. The difference between MCNPX and GEANT4 results for parameters of Bragg curve in the water phantom with the adipose tissue (in Plateau).

When the adipose with a low thickness is inserted in the region of Plateau and Bragg peak, the range (P80) and P20 reduce. But by increasing the adipose thickness, the range (P80) and P20 increase. By inserting the bone layers in the region of Plateau and Bragg peak, the range (P80) and P20 reduce. FWHM is always increased by increasing the inhomogeniety thickness (bone and adipose).

DISCUSSION

Protons, like all charged particles, record a rapid energy loss at the end of their tracks. In radiotherapy, especially hadron therapy, tissue homogeneity has advantages over inhomogenous tissues for doing a proper treatment planning. Inhomogenous tissues create a perturbation in treatment planning. So-Hyun Park and coworkers [15] investigated the effects of the bone and adipose tissue as an inhomogeneity using GEANT4 Monte Carlo code. Their results indicated that the location of inhomogenous tissues does not affect the variation of the whole shape of the Bragg curve, while it basically affects the dose in the bragg curve. Also the placing of inhomogenous tissues affects dose variation when high density tissue is put within a homogeneous matrix.

The data by Marcia Urie and coworkers in 1985 showed that if the bone as a inhomogeneous tissue is put in the Bragg peak entrance, the value of FWHM is disturbeded and also the density difference within tissues causes degradation of the Bragg peak [19]. Also Paganetti indicated that these inhomogeneities can change the form of energy distribution when the protons pass through the materials [20].

In our research, we demonstrated the effect of inhomogeneous materials such as the bone and adipose tissue on the region of the plateau and Bragg peak on the Bragg curve. The analysis included the range (P80), FWHM, P20 and the location of these in the presence of inhomogeneities (bone and adipose). Although there were no significant differences in the parameters of Bragg curve, the results showed the change of the dose associated with the thickness or the density of inhomogeneous material in the Bragg curve. When the bone is put into the region of the Bragg peak, the reduced range makes the Bragg peak enter into the region of the bone at the expense of a great deal of energy which is not absorbed into the bone. The analysis of each result is as follows: the protons have sharp Bragg peak and a finite range that are dependent on the initial proton energy and the density distribution of the materials along the beam direction. The density difference between materials causes degradation of the Bragg peak [18]. The above mentioned parameters were simulated by using the two codes MCNPX and GEANT4. In comparison of MCNPX and GEANT4, the results of MCNPX for water phantom including adipose layer showed a better agreement with the parameters of reference water phantom than GEANT4 (in the presence of 1cm adipose, range (reference: 8.87 cm) and P20 (reference: 9.04 cm)) they are 8.87 and 9.10 cm, while the GEANT4 results showed a little consistency with reference system (range (reference: 8.61 cm) and P20 (reference: 9.61 cm) in the presence of 1 cm adipose are 8.74 and 9.30 cm). The comparison showed a fairly good agreement between the MCNPX and the results published by So-Hyun Park [15] for the range (P80), FWHM and P20 in 108.8 MeV.

CONCLUSSION

This work validates the usefulness of MCNPX results as a reasonably fast and accurate tool for quality assurance in planning proton therapy. This study showed that the location of the inhomogeneous tissues does not affect the variation of the whole shape of the Bragg curve, while it radically affects the dose in the Bragg curve. Also the comparison demonstrated that there is a reasonable agreement between the two Monte Carlo codes MCNPX and GEANT4 for proton transport.

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Conflict of interest: *Declared none.*

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