Iran. J. Radiat. Res., 2006; 4 (3): 115-120

Monte Carlo computation of dose deposited by carbon ions in radiation therapy

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Background: High-velocity carbon ion beams represent the most advanced tool for radiotherapy of deep-seated tumors. Currently, the superiority of carbon ion therapy is more prominent on lung cancer or hepatomas. ***Materials and Methods:*** The data for lateral straggling and projected range of monoenergetic 290 MeV/u (3.48 GeV) carbon ions in muscle tissue were obtained from the stopping and range of ions in matter (SRIM) computer code. The data were transformed to determine the carbon ion trajectories in tissue by means of the Monte Carlo method. Consequently, the lateral dose distributions in the Bragg peak as well as the thickness of a thin disc-shaped tumor in the lateral direction were computed. The absorbed dose in the tissue was obtained as a function of the diameter of a carbon ion pencil beam. ***Results:*** More than 90% of the radiation dose in the lateral direction is deposited in the Bragg peak. The simulation results are in agreement with the existing data. ***Conclusion:*** It was confirmed that this method is reliable for estimation of dose deposited in human tissue by carbon ion beams. **Iran. J. Radiat. Res., 2006; 4 (3): 115-120**

Keywords: *Monte Carlo, carbon ion therapy, absorbed dose, SRIM code.*

INTRODUCTION

Heavy charged particles interact with matter predominantly through inelastic collisions with atomic electrons. Slower particles give more energy to the electrons in comparison with faster particles; therefore, the delivered dose increases while the particle energy decreases. The point at which the particles deposit most of their energy is called the Bragg peak. The presence of a Bragg peak makes heavy charged particles very useful to treat deep-seated tumors. By varying the energy of a charged particle beam, radiation oncologists can spread this peak to match the contours of tumors or other targets. The advantages of heavy ion therapy over the conventional photon, and proton therapies are due to the better physical dose distributions achievable, tumor-conform treatment (1), and the radiobiological characteristics of heavy ions.

Carbon ion beams appear to have the most optimal characteristics in physical and biological efficiencies comparing with other heavy ions. On the other hand, the relative biological effectiveness (RBE) of carbon ions widely varies as a function of depth in a medium, whereas it is similar to the RBE of neutrons only around the Bragg peak. Beams of high-velocity carbon ions provide an excellent physical depth-dose profile with an increased RBE (2) in the target volume. Millimeter precision at any depth is another additional advantage of carbon ion beam therapy of deep-seated tumors. Hence, radiation therapy with carbon ion beam is recommended when an advanced physical precision is of great importance, such as treating a solid tumor close to sensitive organs, as well as tumors in the head and neck region (3). At present, for therapeutic purposes, carbon ions are accelerated up to 430 MeV/u (4).

The study of ion trajectories in tissue is essential in the fields of radiation dosimetry, health physics, radiation biology, and ion beam therapy. The precision of a Monte Carlo technique for computation of ion trajectories in matter depends mainly on the precision of the calculation of the stopping power properties of the matter (5). Stopping powers of charged particles in elements can be

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predicted at intermediate to high energies using the Bethe-Bloch formula [6]. A direct calculation of proton stopping powers in tissue is practically possible by using the SRIM [7] computer program.

In this paper, the Monte Carlo method used for simulation of proton tracks in tissue [8] has been developed to be employed for simulation of radiation therapy with other heavy charged particles. Afterwards, the trajectories of 290 MeV/u carbon ions in muscle tissue for a point-like beam and a pencil beam (parallel beam) as well as the corresponding lateral dose distributions in the Bragg peak have been determined. Furthermore, for a 290 MeV/u carbon ion pencil beam, the thickness of a thin disc-shaped tumor in the lateral direction and the physical dose rate delivered to the tissue have been computed. The results obtained from this method have been in agreement with the experimental values.

MATERIALS AND METHODS

Computations were carried out for a 290 MeV/u carbon ion pencil beam traversing muscle tissue with the corresponding range of 162.2 mm. This has been the energy used at the Heavy Ion Medical Accelerator in Chiba (HIMAC), Japan, to obtain some experimental results [9]. According to the SRIM code, the density of muscle tissue and its molecular composition were considered as 1 g/cm^3 and H (63%) + C (6%) + N (1%) + O (28%), respectively.

For the transport of ions in matter, the straggling distribution follows a Gaussian function [10]. In order to compute the dose deposited in tissue, one should obtain the projected range as well as the standard deviation of the lateral straggling distribution (σ) for charged particles traversing the tissue [11]. For carbon ions traveling in muscle tissue, these data were obtained from the SRIM code, and were stored as a library to feed the computer program written for this purpose. In this program, the projected range and lateral straggling of charged particles were used to determine the trajectories of the particles, as well as the dose deposited in human tissue. The corresponding value of 1094 μm for σ was obtained from the SRIM code for the total path length of a point-like beam of 290 MeV/u carbon ions in muscle tissue. In this code, the range of ions in matter has been divided into several subintervals, so that the quantities lying in each subinterval can be properly considered to vary linearly.

To study ion beam therapy, one should initially compute the trajectories of ions in the tissue. For this purpose, the standard deviations (σ_i) for the lateral stragglings in each subinterval should be precisely determined. This is possible by running the Monte Carlo program for a point-like beam of 290 MeV/u carbon ions traversing muscle tissue. For simplicity, the same values for σ_i's in each subinterval were considered. These quantities were obtained so that the value of σ for the total path length of a point-like beam of 290 MeV/u carbon ions in muscle tissue, namely 1094 μm, could be reproduced by the Monte Carlo program; therefore, the values of the σ_i's were calculated to be 22 ± 0.3 μm for each subinterval. In other words, considering 22 ± 0.3 μm for the σ_i's, one can also compute the corresponding value 1094 μm for σ, which is determined by the SRIM code. Consequently, the computations were made for 290 MeV/u carbon ion pencil beams with definite diameters. In this simulation, the number of carbon ions was considered as 10^6.

RESULTS

Figure 1 shows the depth-dose distribution including the Bragg peak for 290 MeV/u carbon ions in muscle tissue obtained from the SRIM code. Figures 2 and 3 show the trajectories for a point-like beam of 290 MeV/u carbon ions in the tissue and the lateral distribution of the dose in the Bragg peak obtained from this Monte Carlo computation, respectively.

For therapeutic applications, carbon ion

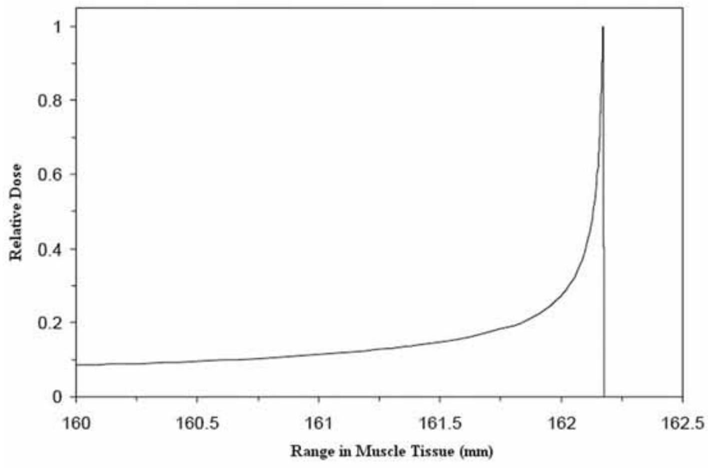

Figure 1. Depth-dose distribution for 290 MeV/u carbon ions in muscle tissue obtained from the SRIM computer program.

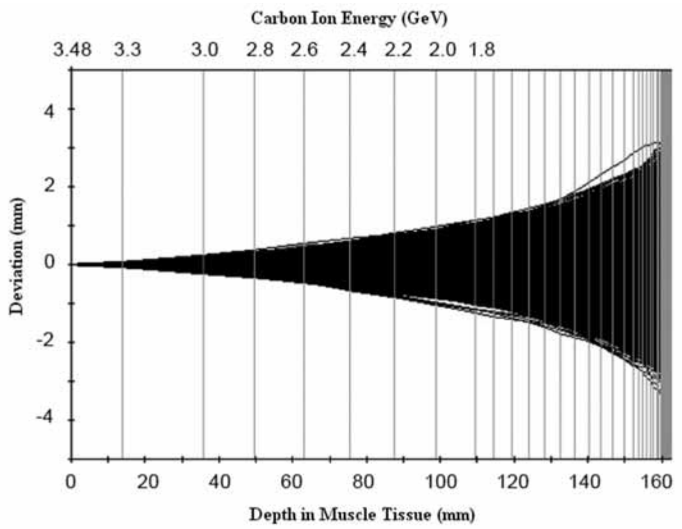

Figure 2. Trajectories for a point-like beam of 290 MeV/u carbon ions traversing muscle tissue obtained from the Monte Carlo simulation.

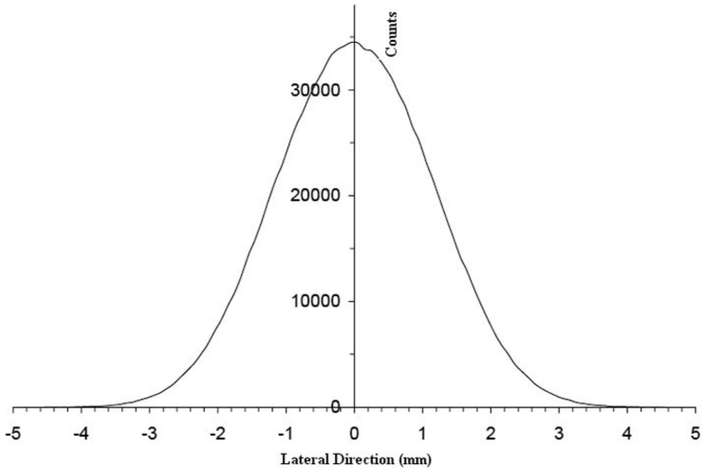

Figure 3. The lateral dose distribution in the Bragg peak for a point-like beam of 290 MeV/u carbon ions in muscle tissue obtained from the Monte Carlo computation.

beams with definite diameters were used. The pencil beams used at ion beam therapy centers, such as the HIMAC at the National Institute of Radiological Sciences in Japan, Lawrence Berkeley Laboratory in the United States, and the Gesellschaft für Schwerionenforschung (GSI) in Germany, have not been point-like beam. For GSI, the diameter of a typical carbon ion pencil beam was greater than 2 mm (Kraft, personal communication). Figure 4 shows the trajectories of 290 MeV/u carbon ions in muscle tissue for a pencil beam with the beam diameter of 2 mm obtained from the Monte Carlo method. Thus, for a 290 MeV/u carbon ion pencil beam with a 20 mm diameter (d = 20 mm), the trajectories of the carbon ions in muscle tissue, and the physical dose rate as well as the lateral dose distribution in the Bragg peak were computed. Figure 5 shows the lateral distribution of the dose delivered to muscle tissue (in the Bragg peak) by a pencil beam of 290 MeV/u carbon ions with d = 20 mm. The lateral dose distribution in the Bragg peak provided an appropriate estimate of the size of a tumor located at the end of the path length. For a fixed energy carbon ion pencil beam, the Bragg peak is extremely sharp. Thus, in order to irradiate a typical tumor properly, the thickness of the tumor in the beam direction must be small. Alternatively, its thickness in the lateral direction should be equal to the full-width at half-maximum (FWHM) corresponding to the lateral distribution of the dose in the Bragg peak.

A monoenergetic carbon ion pencil beam is able to irradiate a thin disc-shaped tumor. Figure 6 shows the diameter of a thin disc-shaped tumor, which could be properly irradiated by a pencil beam of 290 MeV/u carbon ions versus the corresponding diameter of the beam.

Figure 7 shows the absorbed dose rate

deposited in muscle tissue as a function of the diameter of a 290 MeV/u carbon ion pencil beam obtained from the Monte Carlo simulation in logarithmic scale. Furthermore, in order to compare the data with the experimental values, the figure includes the results for a 60 MeV proton pencil beam and also the experimental value reported in the literature [12].

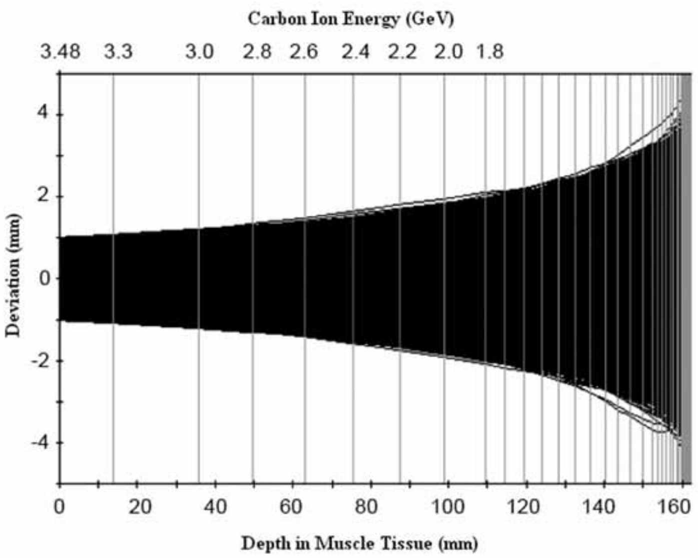

Figure 4. Trajectories for a 290 MeV/u carbon ion pencil beam with a 2 mm diameter traversing muscle tissue obtained from the Monte Carlo simulation.

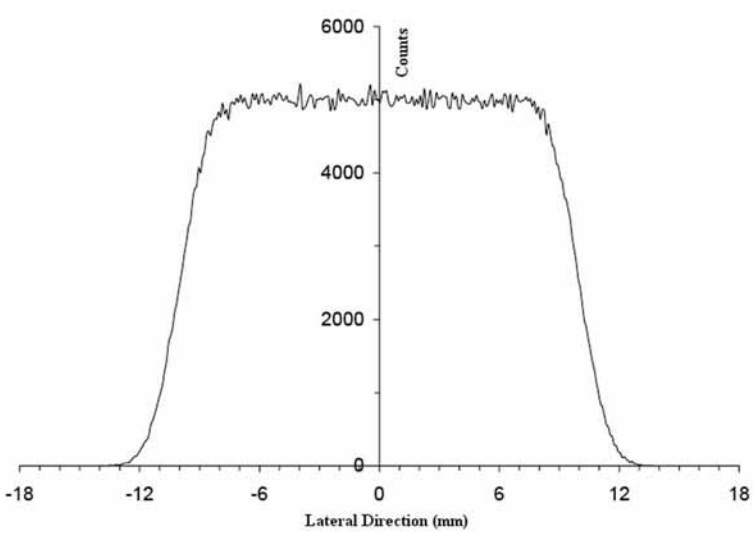

Figure 5. The lateral dose distribution in the Bragg peak for a 290 MeV/u carbon ion pencil beam with a 20 mm diameter in muscle tissue obtained from the Monte Carlo computation.

DISCUSSION

It is well-known that the lateral displacement of a beam of charged particles at various depths follows Molière's theory [13]. For the point-like beam shown in figure 1, the extent of lateral scattering was obtained to be about 6 mm, which was in agreement with the theoretical expectation of Molière's theory within the uncertainty of 8%. One can also see that the lateral dose distribution for a point-like beam follows a Gaussian function with an FWHM of 2.8±0.1 mm.

It should be noted that unlike the protons, some of carbon ions have been disintegrated to fragment particles. The fragments also carried dose, and caused extra spatial distribution. This effect was also taken into account through the application of the data obtained from SRIM computer code for lateral straggling and projected range of carbon ions in muscle tissue. To irradiate a tumor with considerable thickness in the beam direction (which is not discussed in this paper), a beam should be selected with an appropriate distribution of carbon ion energies.

In figure 5, the FWHM for the distribution has been calculated to be 20.3 ± 0.9 mm. It means that a thin disc-shaped tumor with the corresponding diameter of 20.3 ± 0.9 mm, located at the end of the path length, could be irradiated by a 290 MeV/u carbon ion pencil beam having a diameter of 20 mm. Under these conditions, (94 ± 1.3)% of the dose in the Bragg peak would have been deposited in the tumor tissue.

The error due to the uncertainties in obtaining the desired parameters, also the statistical errors due to the Monte Carlo simulation was estimated to be 4.7%. The error was mainly related to random sampling from the Gaussian distribution for

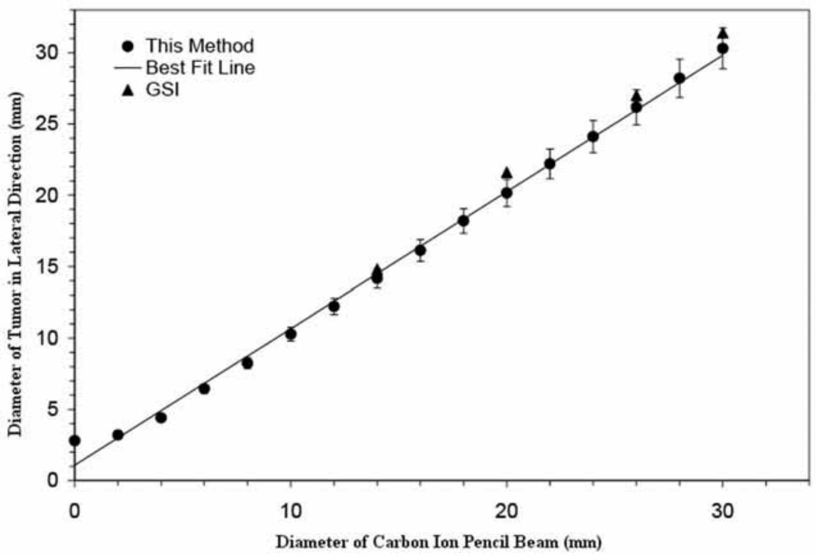

Figure 6. Results obtained from the Monte Carlo simulation for 290 MeV/u carbon ion pencil beams traversing muscle tissue.

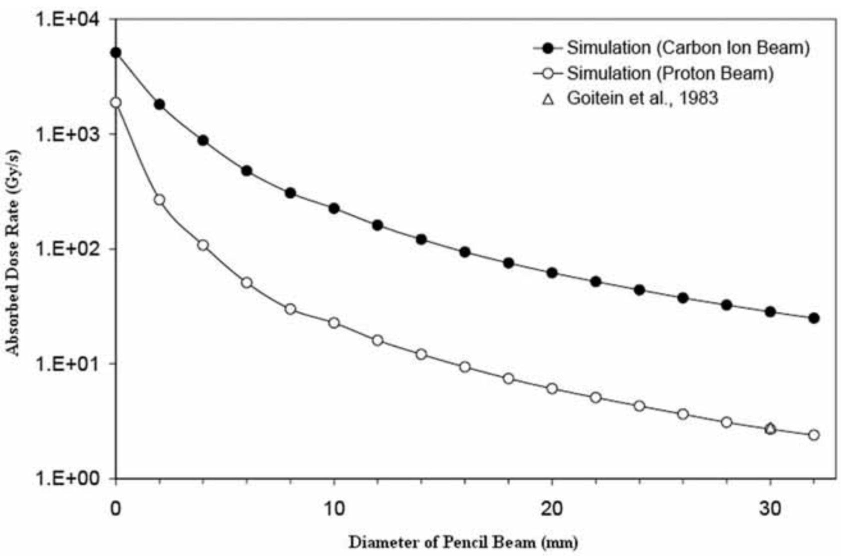

Figure 7. Physical dose rate deposited in muscle tissue obtained from the Monte Carlo simulation for a 290 MeV/u carbon ion pencil beam and a 60 MeV proton pencil beam.

obtaining the lateral straggling data in each subinterval using the Monte Carlo method. This was determined from by the error propagation formula. The results obtained from this computation have been compared with the experimental values which are currently used for therapeutic purposes at the GSI (Kraft, personal communication). It should be noted that, GSI does not use a monoenergetic beam, and it applies to a mixed-energetic beam by inserting a ridge filter to a beam line. Nevertheless, one can conclude that for any point of a tumor, and at a specific distance from the beam, the thickness of the tumor in the lateral direction at that point corresponds to a specific energy of the beam. This means that for a monoenergetic carbon ion pencil beam, it is possible to determine the thickness of a tumor in lateral direction in order to be properly irradiated by the beam. Desirable agreements are shown in figure 6 between the Monte Carlo results and the corresponding values.

It is worthwhile to note that the absorbed dose directly depends on the volumes of the regions like those shown in figures 2 and 4. As pointed out earlier, the agreements with the Molière's theory show the reliability of this computation in obtaining physical dose delivered to the tissue by carbon ion beams. For $d > 4$ mm, one can see that the absorbed dose rate for a carbon ion beam is about 10 times greater than that of a proton beam with the same diameter. In this calculation, the uncertainty due to the statistical errors was estimated to be 7.6%. The main error was attributed to the uncertainty in calculation of the volumes of the regions like those shown in figures 2 and 4. Each computation was performed with a beam current of 1 nA, which is a typical value being used for charged particle therapy.

In conclusion the results presented here show that this method can be used as a fairly simple and precise technique for computation of dose deposited in human tissue by carbon ions in radiation therapy.

ACKNOWLEDGMENTS

The author takes this opportunity to thank Prof. M. Lamehi-Rachti for his useful comments and discussions during this work.

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