AbstractID: 9701 Title: Monte Carlo Simulation of depth dose in water phantom for multi-energy protons

I. Introduction

For proton therapy, the depth dose peak can be "spread out" by using multi-energy proton beams. The dose distribution could be adapted to the defined target volume. The shape of dose distribution profile is very sensitive to the spectral distribution of the beam. An estimation of the depth dose distribution for a multi-energy proton beam was done in this study based on a mathematical linear approximation based on a set of depth dose curves pre-calculated for mono-energetic proton beams. Monte Carlo calculation using the same energy spectrum provides accurate three-dimensional (3D) depth dose matrix and offers basic and benchmarking data to compare the mathematical calculation.

To define a uniform dose distribution to a sphere target, a multi-energy proton beam with symmetric energy spectrum from 100MeV to 140MeV was used and a 3D dose calculation for the multi-energy proton beam was done, based on Monte Carlo code MCNPX and a voxelized cubic water phantom. The dose distribution was superimposed to the CT scan of the water phantom. The isodose lines and the dose volume histogram for the target were shown.

II. Material and Methods

A. Monte Carlo dose calculation algorithm for proton radiotherapy

Energy deposit per mass is calculated using the equation[1]:

$$H_t = \frac{\rho_a}{m}\int dE\int dt\int dV\int d\Omega\sigma_t(E)H(E)\psi(\vec{r},\Omega,E,t) \quad \text{(I)}$$

where: Ht = total energy deposition in a cell (MeV/g);

ρ_a = atom density (atoms/barn-cm);

m = cell mass (g);

$\sigma_t(E)$ = microscopic total cross section (barns);

H(E) = heating number (MeV/collision);

$\vec{r},\hat{\Omega},E,t$ = particle position vector (cm), direction vector, energy (MeV), and time (sh; 1sh = 10-8 s) respectively;

The dose distribution in water was calculated based on a cubic water phantom which was voxelized to cells with size 2 mm x 2 mm x 1 mm. Dose deposited in each cell was calculated and recorded as the 3D dose matrix.

B. Target and proton spectrum

This study used a parallel proton beam with uniform spatial distribution to cover a sphere target with diameter 2.5 cm and positioned at 8 cm below water. The proton beam size and spectral distribution could be roughly estimated according to the target defined.

A parallel beam with diameter 4cm was used. Figure 1(a) shows a few proton depth dose curves for several mono-energetic proton beams calculated by MCNPX (protons with energies from 100 MeV to 140 MeV might be needed to produce a depth dose peak at 8cm below surface. In this study, a symmetric spectral was used, as shown in Figure 1 (b).

III. Results and Discussion

A. Mathematical linear approximation of depth dose distribution for a multi-energy proton beam

Using linear approximation between the set of depth dose curves for mono-energetic beams, we can get the relative depth dose curve for the multi-energy proton beams. Figure 1(b) shows the depth dose curve calculated by mathematical approximation and Monte Carlo simulation. The coefficient of determination (R-square) between these two methods was 0.9998.

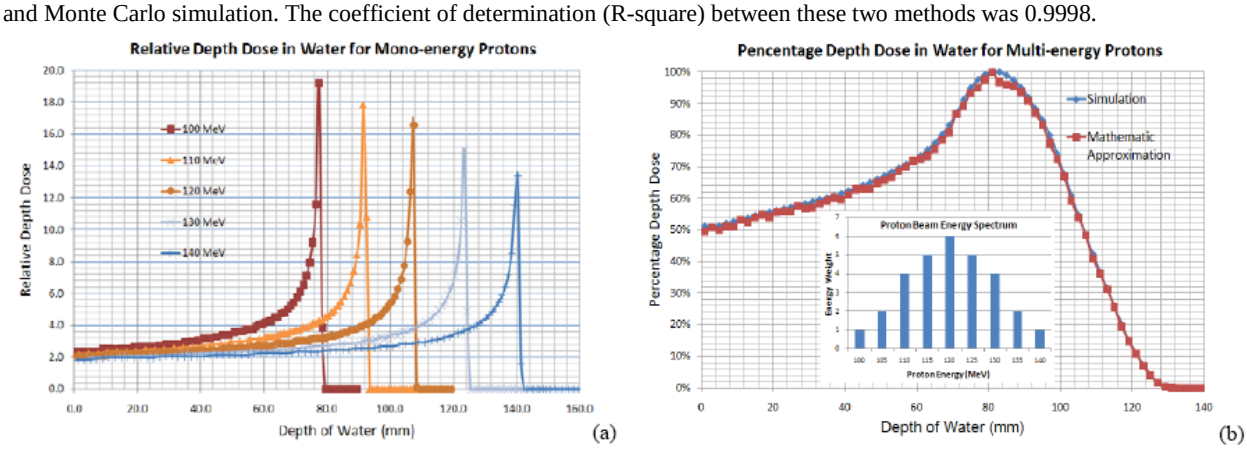

Figure 1 (a) Relative depth dose distribution for a set of mono-energetic proton beams in water; (b) Relative depth dose distribution generated by a multi-energy proton beam with spectrum shown, a comparison between the mathematic linear approximation and Monte Carlo calculation

B. 3D dose distribution generated by the multi-energy proton beam

The 3D dose distribution in water phantom by the multi-energy proton beam specified above was shown in Figure 2(a). Three slices in the axial, coronal and sagittal plane "cut the phantom open" so we can clearly view the inside dose distribution. Figure 2 (b) is an enlargement of 2-D dose distribution near the peak in coronal plane. The uniformity of dose distribution within the target and the dose gradient outside target could be appreciated.

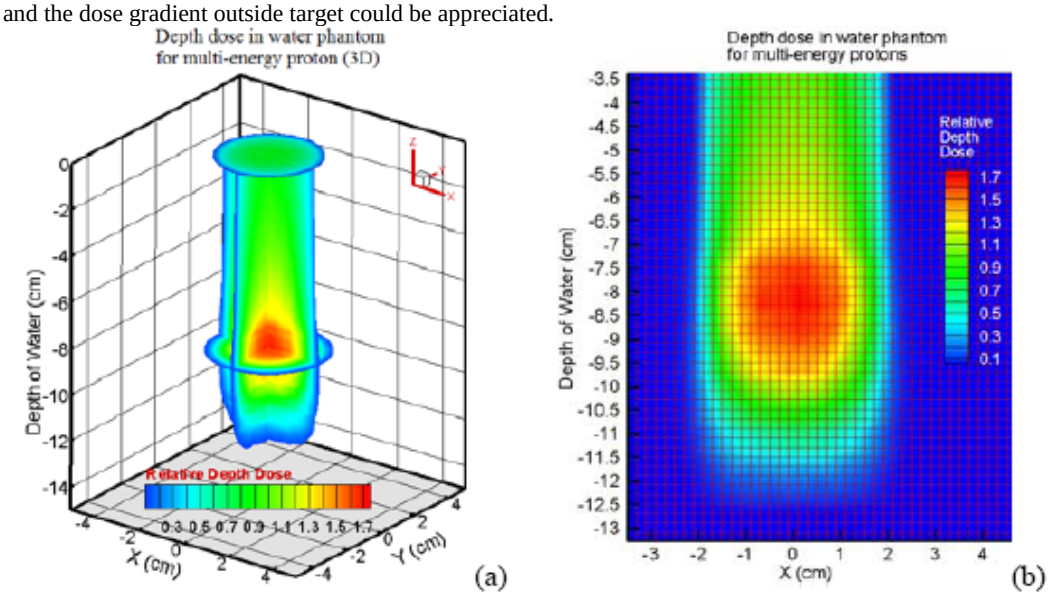

Figure 2 dose distributions for the multi-energy proton beam in water; the proton beam has a spectrum shown in Figure 1(a) and a uniform spatial distribution with beam diameter as 4cm, (a) 3D dose distribution shown at axial, coronal and sagittal plane, (b) detailed dose profile on coronal plane

C. Superimpose 3D dose distribution to CT image.

Combining the 3D dose matrix calculated by Monte Carlo method and the CT scan of phantom would give a more quantified evaluation of the dosimetric characteristics. Figure 3 (a), (b) and (c) are the isodose lines in axial, coronal, sagittal planes, separately, and Figure 3 (d) is the dose volume histogram (DVH) for target.

By using only gantry angle of proton beams, the target received a conformal dose. Meanwhile, the surrounding tissues receive very low dose due to the proton unique feature of deposit its energy in a very narrow range.

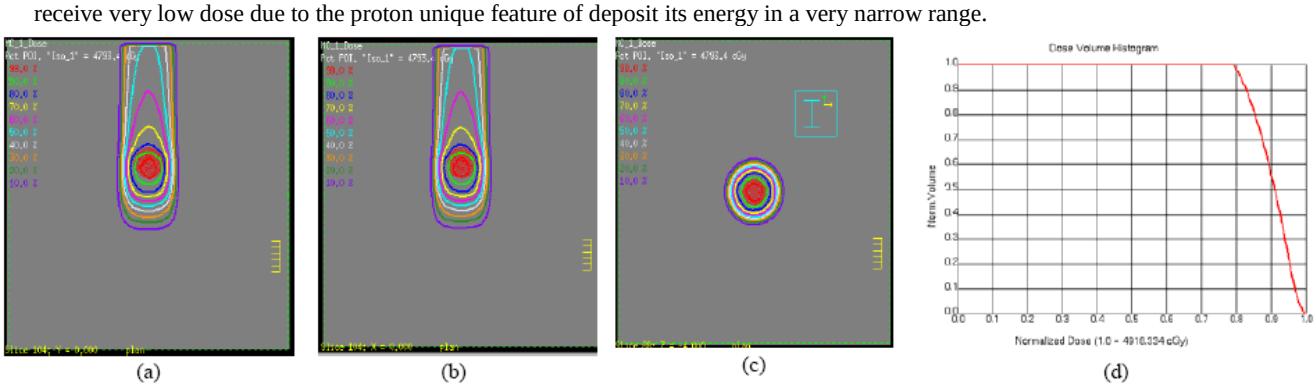

Figure 3 the result of superimposing the dose calculated by Monte Carlo method and the CT scan of the phantom, the isodose lines on the axial plane (a), the coronal plane (b) and the sagittal plane (c); (d) the DVH for target

IV. Conclusion

Proton therapy can deliver high uniform dose to target while sparing dose to the surrounding health tissue. By varying the energy spectrum of proton beams, the depth dose peak range can be adjusted according to the target shape. Monte Carlo method provides a reliable tool for dose calculation for multi-energy proton beams. Monte Carlo calculation provides an accurate 3D depth dose distribution and offers basic and benchmarking data to compare the mathematical calculation.

Reference

[1] MCNPX User's Manual Version 2.3.0, LA-UR-02_2607, edited by L. S. Waters, Los Alamos National Laboratory, Los Alamos, NM, 2002