Monte Carlo Calculation of the Dose Profiles for a 6 MeV Electron Beam with Longitudinal Magnetic Fields

Dong Hyeok Jeong[a*], Young Kee Oh[b], Jhin Kee Kim[c], Jeung Kee Kim[d], Kyo Chul Shin[e], Ki Hwan Kim[f], Jeong Ok Lee[g], Jeong Ku Kang[h], Sun Rock Moon[a], Bu Gil Kim[c], and Sung Kyu Kim[i]

[a]Dept. of Rad. Onc., Wonkwang Univ. Hospital, Iksan, Korea
[b]Dept. of Rad. Onc., Kyungpook Nat. Univ. Hospital, Taegu, Korea
[c]Medical Sci. Inst., Chonbuk Nat. Univ. Hospital, Jeonju, Korea
[d]Dept. of Rad. Onc., Dong-A Univ. Hospital, Pusan, Korea
[e]Dept. of Therapeutic Radiology, Dankook Univ. Hospital, Cheonan, Korea
[f]Dept. of Therapeutic Radiology, Chungnam Nat. Univ. Hospital, Teajeon Korea,
[g]Dept. of Radiotec., Wonkwang Health Science College, Iksan, Korea
[h]Dept. of Rad. Onc., Presbyterian Medical Center, Jeonju, Korea
[i]Dept. of Rad. Onc., Yeungnam Univ. Hospital, Taegu, Korea
*Corresponding author: *e-mail: physics@wmc.wonkwang.ac.kr*

ABSTRACT

Using Monte Carlo calculations the effects of longitudinal magnetic fields on the beam profiles produced by clinical electron beam were studied. The Monte Carlo calculations were performed using the EGS4 code system modified to account for external magnetic fields. The beam profiles for a 6 MeV electron beam with longitudinal magnetic fields of 0.5-3.0 T were calculated. As a result of these calculations we found that the penumbra widths can be reduced with increased magnetic fields. This means that the electron therapy benefits from the external magnetic fields.

Keywords: Monte Carlo calculation, beam profile, magnetic field

1. INTRODUCTION

Several investigators have presented the effects of external magnetic fields on the dose distributions for clinical electron and photon beams[1-4]. Their studies are summarized that the penumbra widths can be reduced by the strong longitudinal magnetic fields and the dose deposition on central axis can be enhanced by the strong transverse magnetic fields. This study is similar to the former studies except that we focus the low energy electron beam with more lateral scatter. It is the reason that the reductions of the penumbra region are induced by the skewness of the laterally scattered electrons along the direction of magnetic field lines. The principle of dose enhancements in the penumbra region is to deflect the laterally scattered electrons from its initial direction by Lorentz force under longitudinal magnetic field. In this study we calculated the beam profiles for an clinical electron beam of 6 MeV with longitudinal magnetic fields of 0.5-3.0 T using a Monte Carlo code. In next section we roughly described the Monte Carlo code and calculation structures.

2. MATERIALS AND METHODS

The equation of motion for a charged particle of charge q and of velocity $\vec{v}$ in a magnetic field $\vec{B}$ is

$$\vec{F}_m = q\vec{v} \times \vec{B} \qquad (1)$$

where $\vec{F}_m$ is a external force(Lorentz force) due to applied magnetic field[5]. Fig. 1 shows the projections onto the $x-y$ plane of the motions for a charged particle in an uniform magnetic field, $\vec{B}$, to the z direction. In this figure $\vec{v}_\perp$ is the component of velocity perpendicular to the magnetic field, the θ and R are orbit angle and its radius of the charged particle. We can consider Eq. (1) to be the equation of motion in a vacuum therefore there is no energy loss

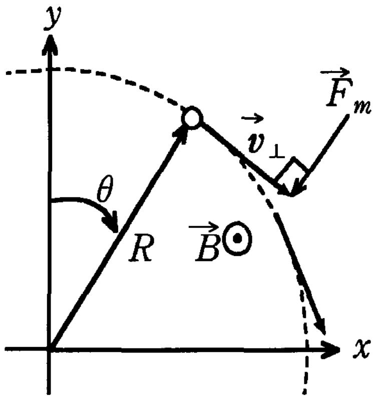

Fig. 1. The analysis of motion for a charged particle in a magnetic field.

while traveling in magnetic field. But we can suppose that a charged particle moving through material undergoes energy lose and direction change by the Coulomb force. The energy loss and direction change of the charged particle are described in terms of stopping power and multiple scattering respectively. Therefore the equation of motion for a charged particle in a medium with external magnetic field can be expressed as

$$\vec{F} = \vec{F}_s + \vec{F}_{ms} + \vec{F}_m \text{ ,} \qquad (2)$$

here $\vec{F}_s$ and $\vec{F}_{ms}$ are the forces due to energy loss and multiple scattering. The particle transport for $\vec{F}_s$ and $\vec{F}_{ms}$ in a medium can be performed by using general Monte Carlo codes. The additional term of $\vec{F}_m$ in a medium can be considered by inserting a statement for direction change in a magnetic field into the Monte Carlo code. In our calculations we use a coupled electron and photon transport code of EGS4 code system[6)]. An EGS4 user code was developed that simulates the irradiation of cylindrical water phantom in a typical point source configuration. The geometrical configurations of this simulation are shown in Fig. 2. In order to account for the effects of an externally applied magnetic field, the macros for the change of direction angles as a function of energy and external magnetic field strength were inserted in our user code. The change of direction angles can be calculated by solving Eq. (1) for $q = -e$, $\vec{B} = B\hat{k}$, and $\vec{v} = v_x\hat{i} + v_y\hat{j} + v_z\hat{k}$, where $\hat{i}$, $\hat{j}$, and $\hat{k}$ are unit vectors parallel to the x, y, and z axes. Solving the equations with changing to the cylindrical coordinate system, the $\vec{v}$ and its components are given by

$$\vec{v} = v\sin\phi\cos\theta\hat{i} - v\sin\phi\sin\theta\hat{j} + v\cos\phi\hat{k} \text{ ,} \qquad (3)$$

where ϕ is the angle between the velocity and magnetic field vector and θ as shown in Fig. 1 is the angle as a function of electron's energy, magnetic field, and step size. The ϕ is constant for given initial direction of the velocity vector. Therefore the θ represents the direction change of velocity vector on $x-y$ plane. We can describe direction change in terms of direction cosines of $U = v_x\hat{i}/v$, $V = v_y\hat{j}/v$, and $W = v_z\hat{k}/v$ when initial direction cosines for an electron incident on the magnetic field area are given by U_0, V_0, and W_0. We can calculate the transport parameters of the EGS4 system under the magnetic field by solving Eq. (3). In this calculation $\theta = \omega t$, where $\omega = eB/m$ is angular velocity, m is electron's mass, and $t = S/v$ is time to travel step length S with speed v. Where S is calculated from the condensed step algorithm in EGS4 system. The calculations are performed for static, uniform, and longitudinal magnetic fields of 0.5-3.0 T confined to a cylindrical water phantom irradiated by monoenergetic 6 MeV electrons. We calculated the beam profiles for a 5 cm field in diameter with longitudinal magnetic fields of 0.5-3.0 T at the depths of 1.5(R100), 2.0(R90), and 2.4 cm(R50).

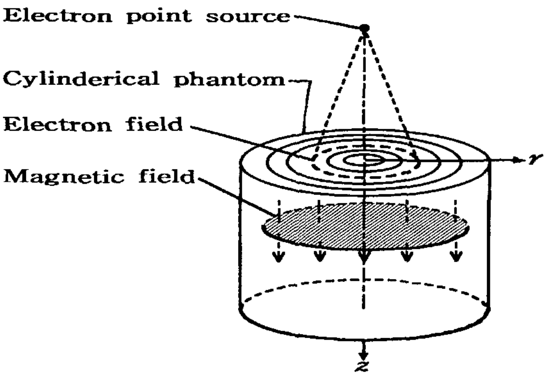

Fig. 2. Geometrical configuration used in Monte Carlo calculation.

3. RESULTS

To discuss the dose enhancement effect on the penumbra area from the calculated results, we introduced the simple term of penumbra reduction ratio(PR), which is defined as the percentage difference between the penumbra width without magnetic field, W_0, and the penumbra width with magnetic field, W_B, at the same depth.

$$PR_B = \frac{W_0 - W_B}{W_0} \times 100\% \qquad (4)$$

The Fig. 3 is the calculated dose profiles for a 6 MeV electron point source at a depth of 2.4 cm in the presence of uniform longitudinal magnetic fields with strength 0, 0.5, 1.0, 2.0, and 3.0 T. The penumbra widths and PR_B at the depths of 1.5(R100), 2.0(R90), and 2.4 cm(R50) are listed in table 1. We found that the average $PR_B = 33\%$, and 49% over the depths of 1.5, 2.0, and 2.4cm for the magnetic fields of 2.0 and 3.0 T respectively. For the case of 0.5 and 1.0 T the effects of magnetic filed were not observed significantly.

Table 1. Calculated penumbra width(W_B) and penumbra reduction ratio(PR_B) as a function of longitudinal magnetic field B, where W_0 and W_B are penumbra widths for without and with magnetic.

Depth in water(cm)	$W_{0.5}$ / $PR_{0.5}$	$W_{1.0}$ / $PR_{1.0}$	$W_{2.0}$ / $PR_{2.0}$	$W_{3.0}$ / $PR_{3.0}$
1.5 (W_0=1.1 cm)	1.1 / 0%	1.1 / 0%	0.8 / 27%	0.6 / 46%
2.0 (W_0=1.4 cm)	1.4 / 0%	1.2 / 14%	0.9 / 36%	0.7 / 50%
2.4 (W_0=1.4 cm)	1.4 / 0%	1.2 / 14%	0.9 / 36%	0.7 / 50%

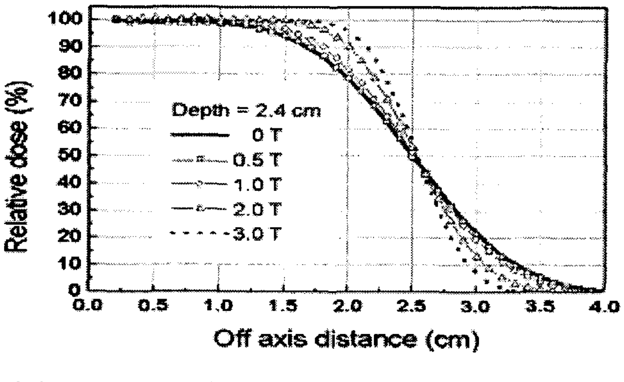

Fig. 3. Calculated electron dose profiles at 2.4 cm depth in the presence of uniform magnetic fields.

4. DISCUSSIONS AND CONCLUSIONS

As a result of these calculations we found that the penumbra widths can be reduced with increased magnetic fields. This penumbra reduction is explained as a result of electron lateral spread outside the geometrical edges of the beam in a longitudinal magnetic field. This means that the electron therapy benefits from the external magnetic fields. In order to obtain the dose enhancement effects by the external magnetic field, we think that its strength should be more than 2 T approximately. Theoretically the advantages are clear, in addition experiments also can be performed to verify the effects, but it generally depends on the difficulty of producing strong uniform magnetic fields.

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