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Original Article

Electron Beam Dose Distribution in the Presence of Non-Uniform Magnetic Field

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Abstract

Introduction
Magnetic fields are capable of altering the trajectory of electron beams andcan be used in radiation therapy.Theaim of this study was to produce regions with dose enhancement and reduction in the medium.
Materials and Methods
The NdFeB permanent magnets were arranged on the electron applicator in several configurations. Then, after the passage of the electron beams (9 and 15 MeV Varian 2100C/D) through the non-uniform magnetic field, the Percentage Depth Dose(PDDs) on central axis and dose profiles in three depths for each energy were measured in a 3D water phantom.
Results
For all magnet arrangements and for two different energies, the surface dose increment and shift in depth of maximum dose (dmax) were observed. In addition, the pattern of dose distribution in buildup region was changed. Measurement of dose profile showed dose localization and spreading in some other regions.
Conclusion
The results of this study confirms that using magnetic field can alter the dose deposition patterns and as a result can produce dose enhancement as well as dose reduction in the medium using high-energy electron beams. These effects provide dose distribution with arbitrary shapes for use in radiation therapy.

Keywords: Electron Beam; Magnetic Field; Radiation Therapy.

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1. Introduction

In the absence of electric field, the force (F) on a movingelectronwithvelocity(v)andcharge(e) in a magnetic field (B)becomes[1]:

$$F = m\frac{dv}{dt} = ev \times B \quad (1)$$

In the situation where the magnetic field is in the Zaxis (parallel to central axis of electron beam), the Zcomponent of the velocity along the magnetic field is not affected , but the Xand Ycomponents of the velocity vector vary as[2]:

$$\frac{dv_x}{dt} = (\frac{e}{m})B_z v_y \quad \text{And} \quad \frac{dv_y}{dt} = \left(\frac{e}{m}\right)B_z v_x \quad (3)$$

This equation shows the electrons that normally would have been released their energy in the off-axis, in the absence of the magnetic field enter to the region near the central axis. In the other hand, studyingionizing radiation on biological systems shows that radiation exposures induce biological damage in DNA of cells. Successful cell killing occurs when a sufficient number of breaks in DNA occur within close proximity[3, 4]. This begs the question of whether magnetic field can be used to alter the path of charged particles (electrons in this research) in such a way to focus them on tumors as a target in electron radiation therapy. Evaluation of the effect of magnetic field on dose distribution has been studied for along time. Bostike was the first person whoproposed that the dose distribution can be improve by placing the media in magnetic field[5].

The electron beams enter the transverse magnetic field following a spiral motion that tends to reduce the velocity of the electrons. The results of this process are to increase the maximum doseandchange the location of buildup region and skin sparing as a result of the reduction in the surface dose [6-8].Someresearchershaveshownthatthedosedepositioncan beforcedby the transverse magnetic fieldto followarapiddrop-off [9, 10]. This field can be used to increase the dose to the tumor and reduce the dose to adjacent normal tissues.The enhancement of dose refersto the trapping of electrons in a specific area and the dose reduction is due to the loss of transient charged particle equilibrium downstream from the magnetic field[11, 12].

Somestudies suggest that the magnetic field can be used in conjunction with electron therapy and demonstrated that lateral spread of 10 and 20 MeV could be reduced from many centimeters to a few millimeters. These magnetic fields, due to the lateral confinement of the electron trajectories in the phantom, can be used to reduce the undesirable effects caused by loss in charged particle equilibrium (CPE) near air cavities[13, 14].

Although the magnetic field has a direct effect on the dose deposition patterns of electron beams, dosimetric properties of photon beams can be modified by applying the magnetic field. Because of the influence of secondary electrons, the magnetic field can significantly reduce the lateral spread of scattered and secondary electrons that will lead to a change in the penumbra for photon beam irradiation[15]. The main issue in the magnetic field, conjunction with photon beam, is that the magnetic field cannot directly affect the photon beam. For this reason, the magnetic field must be applied tothe phantom and in these circumstances; the magnetic poles are far away from each other. To compensate this loss, a high-intensity magnetic field should be used but consequently the magnet weight will go up and the cost would be prohibitive [7, 16, 17].

Magnetic field effects on the electron beams in some studies have been considered usingMonte Carlo methods.It is shown that the longitudinal non-uniform magnetic field can significantly improve electron beam dose deposition [18, 19]. It is also observed that uniform longitudinal magnetic field of 0.5 T strength can be used to reduce secondary electron out-scatter caused by the presence of an air gap, and thus improve the dose at the distal surface of air cavities[20]. The aim of this study was to verify the influence of magnetic field on the electron trajectories in order to create the desired dose distribution pattern.

2. Materials and Methods

2.1. Beam generation and dosimetry

The experiments were performed at high-energy clinac center, Ahvaz Golestan Hospital using Varian clinac 2100 C/D. 9and 15MeV electron beams were used in this study. Percentage depth dose(PDD) and profiles measurements were obtained usinga 50×50×50 cm^3water phantom(scanditronixwellhöfer, Germany),electrometer CU500 (scanditronixwellhöfer, Germany), and cylindrical ion chambers (CC13 ,6186 and CC13, 6187) for field and reference dosimeter, respectively. Data analysis was undertaken using the Omni-Pro software (IBA Company). The IAEA TRS 398 dosimetry protocol was used in this study[21].

2.2. Beam shaping

The square cerrobend cutouts 4.7×4.7 cm^2 was made to produce 5×5cm^2 field size on phantom surface (SSD=100 cm).This cutout was used in 15×15cm^2 standard applicator with a gap of 5 cm to the phantom surface. The thickness of each cutout was 2 cm.

2.3. Magnetic field

The magnetic field that used in this research was produced by NdFeB permanent magnet with 60×50×20 cm^3 dimensions. The permanent magnets were placed around the aluminum frame on the cerrobend cutout edge(Figure 1). These magnets wereconfiguredin 3 designs: 1) use of one magnet, 2) use of 2 parallel magnets with like poles, and 3) use of 2 parallel magnets with unlike poles. The intensity of magnetic field was measured by standard and calibrated gauss meter (BROCKHAUS Messtechnik model 410).Measurement showed that the strength of magnetic field in ion chamber site was zero so there was no concern about effect of magnetic field on ion chamber response.

Figure 1.The applicator and aluminum frame that magnet was placed on.

3. Results

Magnetic field distribution inside the frame withthepermanent magnet attachmentis shown in Figure 2.

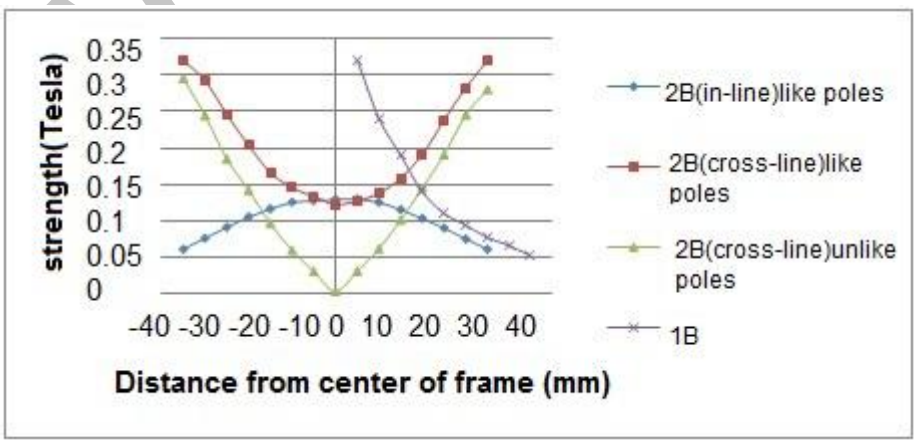

Figure 2. Magnetic field distribution for all arrangements.

When using one magnet (1B), the maximum magnetic field was measured 0.320T inside the frame and this strength decreased from the magnet toward the other side of the frame. For case of 2B (unlike poles), the maximum magnetic field at cross-line was 0.320T whichdecreased toward the center of the frame.This quantity at in-line was 0.129T and decreased by distance from center. For case of 2B, using unlike poles, the maximum magnetic field at cross-line was 0.296T. In this case, the magnetic field around the center of frame and at in-line direction was approximately zero.

Figures 3 and 4 show the 9and15MeV electron beams central axis depth dose when the experiments arranged with and without magnetic setup. For evaluating the effect of magnetic field on dose distribution,the measurements of percentage depth dose in all situations were normalized to the maximum PDD of nonmagnetic setup. As the PDDcurves demonstrates, in addition tothe amount of increase in the maximum dose, the depth of this maximum was also shifted. However, the PDDmeasurement showed thatfor 15MeV, the PDD have a rational rise and fall-off in the region before and after the $d_{max.}$The PDD of 9MeV for case of 1B and 2B (like poles) in the build-up region have an unexpected behavior. However,for case of 2B (unlike poles), the d_{max}occurred in10.2mm with PDD= 184.8% and for this case, the PDD in buildup region have a normal rise and fall-off.

The PDDmeasurement showed that for all magnetic conditions, the surface dose and the dose in the buildup region were increased. This effect for 15MeV electron beam, after applying the magnetic field demonstrated a systematic enhancement. While for the 9MeV, electron beam surface dose enhancement in 2B (like poles) situation wasless than case of 1B and 2B (unlike poles), respectively. Dose measurement in the central axis direction for 9MeV showed noticeable event about 1B, in addition to the increasein the dose of surface and buildup region.After d_{max}, the dose reductionexperienceda rapidgradient rather than the non-magnetic conditions.

In order to evaluate the effect of magnetic field on dose distribution around the central axis, the in-line and cross-line profiles in deferent depths were measured. Depths for 9MeV were 20.2, 25, and 35 mm and for 15MeV were 37, 55, and 65mm, respectively (due to increase the number of graphs the curves for middle depth is not shown).

Profile measurement in the in-line direction for 9MeV indicates that the magnetic field was able to increase the dose in the region near the central axis. Figure 5 shows that this increase, which coupled with the converging profile, is more considerable for two shallow depths. For greatest depth as Figure 6 shows, although the profile is still largely converged, the dose enhancement cannot occur in compare with non-magnetic condition.

Scan of in-line direction(figures 7 and 8)for 15MeV in agreement with the 9MeV verifies the focusing effect and dose enhancement due to application of magnetic field even for deeper depths. As can be seen in the in-line figures, for the 15MeV electron beam, the shift of the d_{max}wasnot significant in comparison with 9MeV. It should be noted that the phase difference between in-line and cross-line direction is 90 degrees. As can be seen in the cross-line measurements (Figures9 and 10 for 9MeV and 11 and 12 for 15MeV)the dose distribution has lost its discipline and regularityandatendency to lateral spread can be observed. Such conditions show the penumbra enhancement and indicate the electron being sent to areas outside of treatment field. Under 2B magnetic conditions, the 9MeV dose deposition at depthof 20.2and25mm regardless to distortion, was increased. In the two recent depths, the 1B condition increased the dose at right side and decreased the left side of cross-line profile. As shown in Figures11, 12although the 15MeV cross-line profiles have been shifted to the lateral side, the less distortion is seen rather than the 9MeV. The other remarkable note in the cross-line measurement was formation of like-wedge profile for 1B condition, while this profile for 9MeV was formed in all three depth but for 15MeV only at depth =37mm.

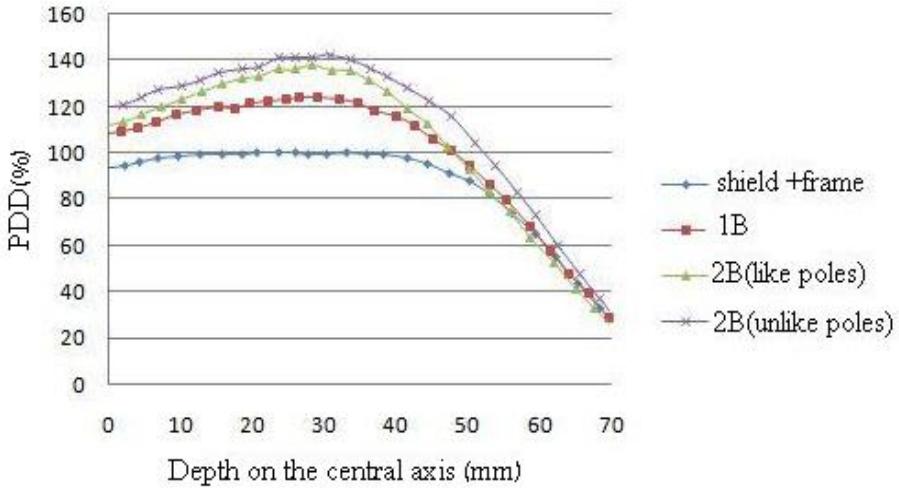

Figure 3. PDDs measurement of 15MeV electron beam for with and without magnetic setup.

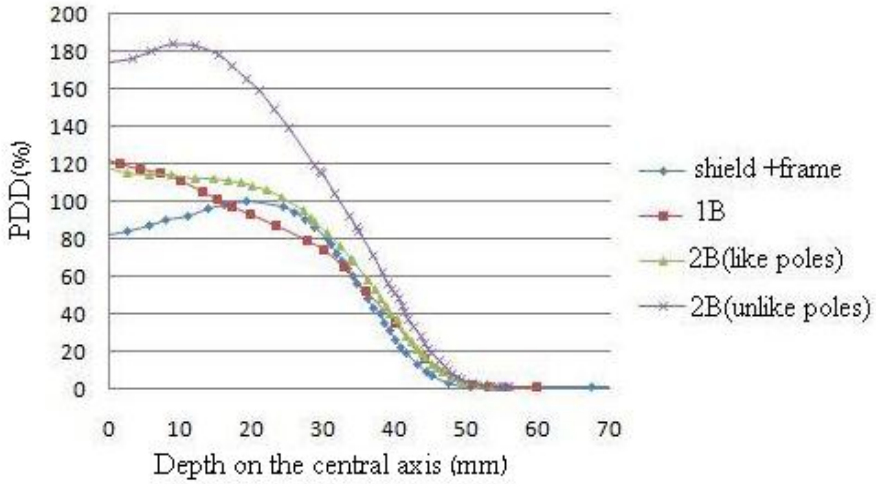

Figure 4. PDDs measurement of 9MeV electron beam for with and without magnetic setup.

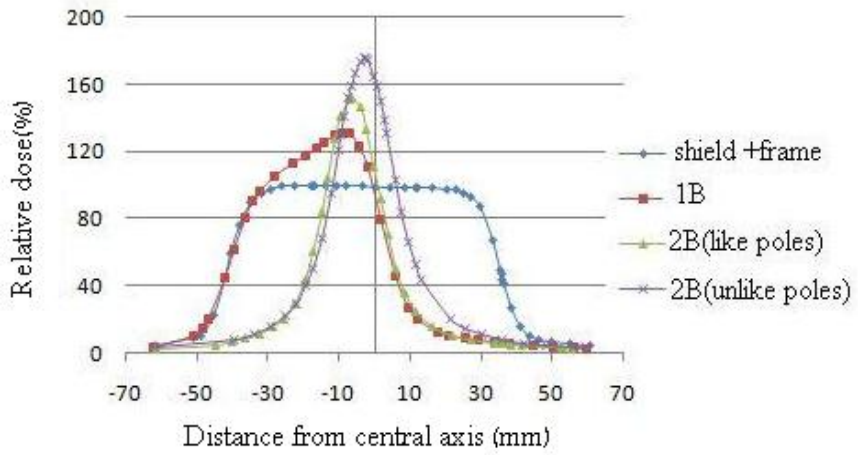

Figure 5. In-line dose distribution at depth=20.2mm for 9MeV electron beam.

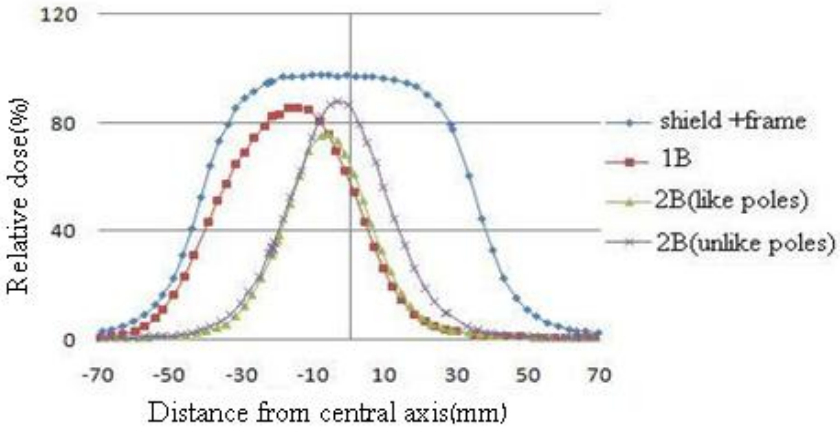

Figure 6. In-line dose distribution at depth=35mm for 9MeV electron beam.

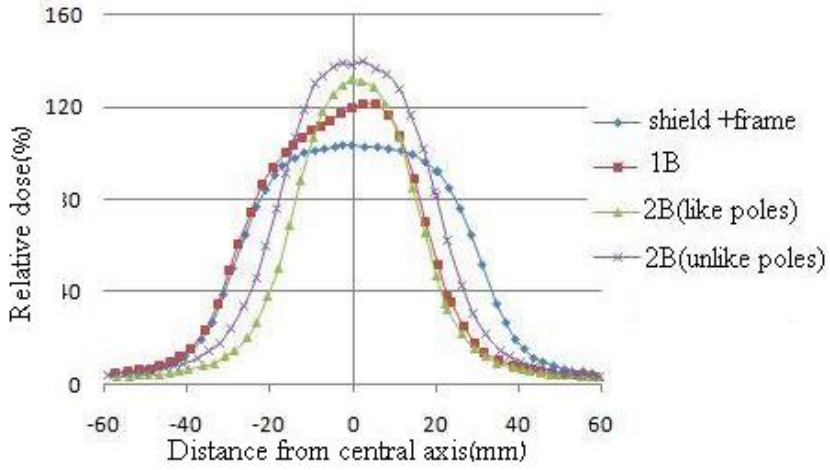

Figure 7: In-line dose distribution at depth=37mm for 15MeV electron beam.

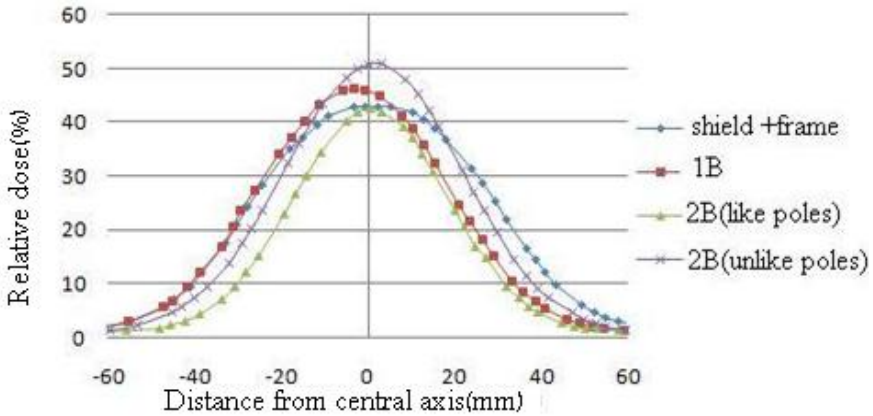

Figure 8. In-line dose distribution at depth=65mm for 15MeV electron beam.

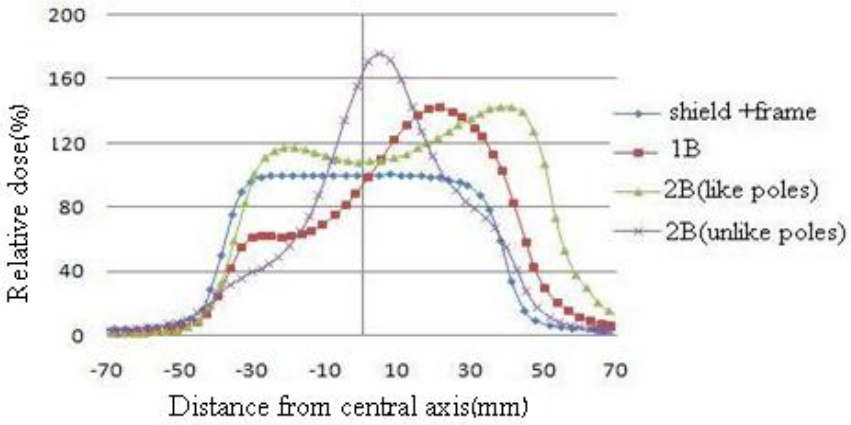

Figure 9. Cross-line dose distribution at depth=20.2mm for 9MeV electron beam.

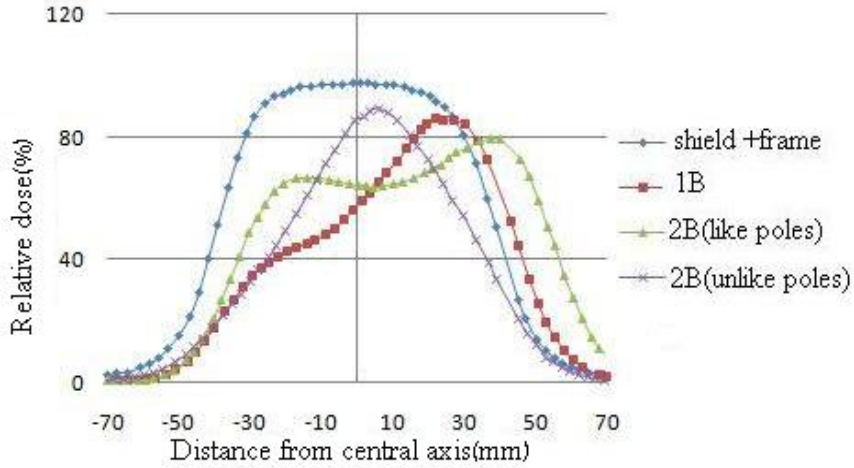

Figure 10. Cross-line dose distribution at depth=35mm for 9MeV electron beam.

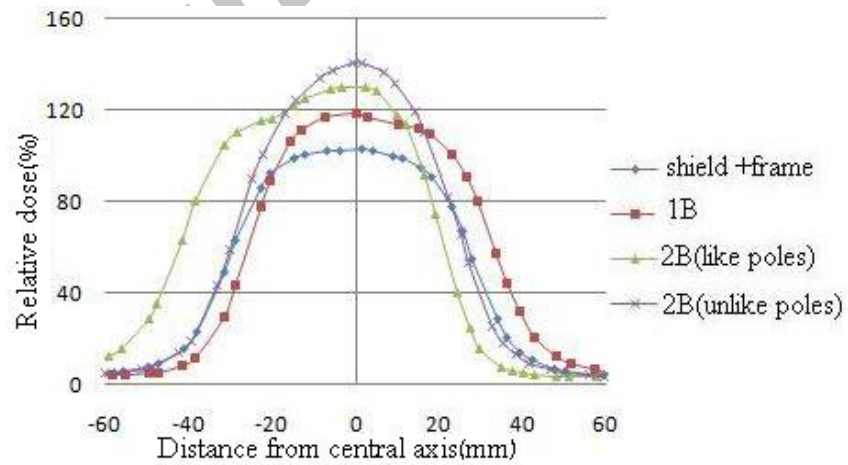

Figure 11.Cross-line dose distribution at depth=37mm for 15MeV electron beam.

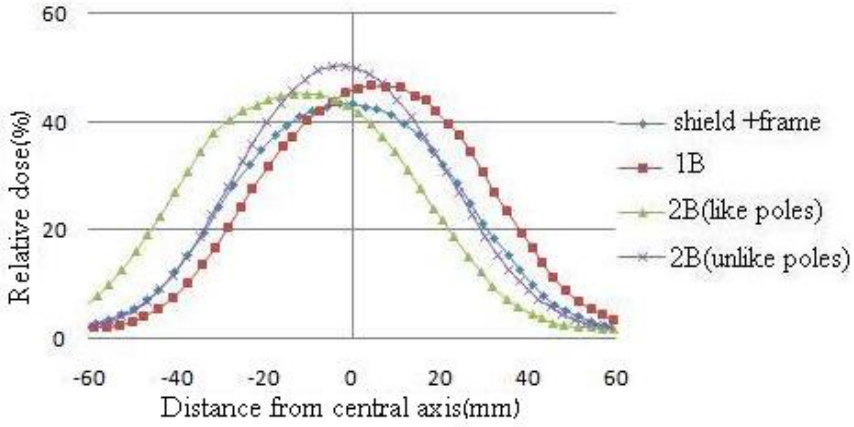

Figure 12. Cross-line dose distribution at depth=65mm for 15MeV electron beam.

4. Discussion

The PDD measurements are presented in Figures3 and4.Due to the collecting and focusing effect of the magnetic field, the electron flux density increased, leading to increases in the energy deposition around the central axis. From this result, it is seen that the magnetic field shifts the region of maximum dose distribution to the localized volume and this arises from the facts that a particle, which moves along a curved magnetic field line, experiences a centripetal force on its guiding path.

For 2B (unlike poles), the magnetic field near the magnets are much stronger.Because electrons can experience a more force towards the center between the poles, they are pushed and havemore tendency toward the central axis. Particularly, in the energy 9MeV electrons with less velocity cause an increase in the time that it has been faced with the magnetic field. Therefore, unlike 15MeV energy, the 9MeVelectrons have less opportunity to escape from the magnetic field, and as can be seen, the dose deposition in this energy represents a significant increase.

Under 1B magnetic condition, comparing the PDD curves show significant difference for both energy. As can be seen in these curves, unlike 15MeV energy,the PDD for 9MeV was reducedwith linear gradient from the surface to the depth. Under this arrangement and gradient, it appears that slower electrons are not able to pass throughthe magnetic field.Therefore, the electrons are forced to deposit their energy in the beginning of the path. The 40% increase in surface dose and rapid dose reduction in the build-up region confirms the argument. It should be noted that there is also such a gradient for 15MeVelectron beams, but higher velocity for these electrons helps them to pass from the magnetic trap.

The angle of the particle trajectory with the vector of magnetic field is called pitch angle. When the pitch angle becomes 90 degree, the parallel component of velocity vector is reflected from lateral sides toward the center of the treatment field (This process is called mirror mechanism) [22].It is noted that in all arrangements, the surface dose for both 9MeV and 15MeV electron beams was intensified when magnetic field was applied. The PDD measurement in Figures 2 and3 indicate that this was due to the magnetic trapping and focusing primary electrons that reflected backward due to the mirror effect. In addition, the confinement and focusing effect of magnetic field can provide reduction of lateral scattering of the electrons.

Dosimetry in the in-line direction for both electron beams indicates, magnetic field results in a noticeable focusing of the primary electron beam, and in addition, confines the resulting dose profile. Particularly, the large penumbra generally associated with electron beams, which limits their use in radiotherapy, is significantly reduced. Magnetic in-line dose distribution compared with absence of magnetic conditions particularly increased the dose in the volume near the depth of the

maximum dose (at depth 20.2and 25mm for 9MeV).

For the lower beam energy in our investigation, in-line measurement at depth of 35mm indicates that magnetic field can return the electron beam from the deeper depth toward the surface. This could be the result of applying the mirror effect of magnetic field on the electron beam that tends to influence toward depth. Noticeable result for case of 1B in the in-line measurement is the production of wedge profile.This property as shown in the plots was more illustrious for near surface depths. Comparison between in-line measurement shows that production of wedge profile with 1B arrangement for 9MeV was intensifier than 15MeVelectron beam. Dose profile with magnetic field produced by our 3 arrangements showed significant difference. While the 1B condition can provide confinement, it also deflects the incident electron beam, rather than focus. In contrast, the magnetic field generated by 2B conditions(both like and unlike poles)on the beam axis acts as a magnetic lens and provides both focusing properties and confinement. The focusing property can influence the electron beams parallel to the central axis and confinement feature can impress the secondary electrons that previously released their energy in the lateral border of the treatment field.

Findings of the present work is in agreement with result of some researches that used Monte Carlo methods or experimental setup particularlyresearches that emphasize on the dose enhancement for the region near the surface of the phantom or reduction in deeper depth. Furthermore, some researchers believethat the magnetic field can reduce the penumbra in the edge of the field sizebut our findings (Figures 7 and 8 for 9MeV and Figures 11 and12 for 15MeV) indicate that in some areas, there is penumbra increase while there is a reduction in some other areas [15, 22, 23]. These differences could arise from differences in the selection of scan direction and attributed to the fact that increasing the dose to an area can be related to the decreasing dose in adjacent regions.

Although some researchers assert that the magnetic field can reduce surface dose[24], the most obvious finding to emerge from the present study wasthat the magnetic field can increase the surface dose for all their arrangements. These differences can be caused by the strength and type (e.g., longitudinal, transverse, complex) of magnetic field or revert to region that the magnetic field is applied. This explanation does not include photon beams. As showed in other studies, the reduction of surface dose in photon beams encounter to magnetic field is due to the elimination of electron contamination [25, 26].

5. Conclusion

NdFeB rare earth permanent magnets can produce strong magnetic field restricted to small area with a rapid fall-off. Our finding showsthat use of magnetic field can change the dose-deposition patterns, so by this effect can produce dose enhancement as well as dose reduction in localized regions for high-energy electron beams. The locations of these high- and low-dose regions are potentially adjustable to enhance the dose to the target volume and decrease the dose to normal tissues in radiation therapy.

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