Effect of transverse magnetic fields on a simulated in-line 6 MV linac

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Abstract
The effects of a transverse magnetic field on an in-line side-coupled 6 MV linear accelerator are given. The results are directly applicable to a linac–MR system used for real-time image guided adaptive radiotherapy. Our previously designed end-to-end linac simulation incorporated the results from the axisymmetric 2D electron gun program EGN2w. However, since the magnetic fields being investigated are non-axisymmetric in nature for the work presented here, the electron gun simulation was performed using OPERA-3d/SCALA. The simulation results from OPERA-3d/SCALA showed excellent agreement with previous results. Upon the addition of external magnetic fields to our fully 3D linac simulation, it was found that a transverse magnetic field of 6 G resulted in a 45 \(\pm\) 1\% beam loss, and by 14 G, no electrons were incident on the target. Transverse magnetic fields on the linac simulation produced a highly asymmetric focal spot at the target, which translated into a 13\% profile asymmetry at 6 G. Upon translating the focal spot with respect to the target coordinates, profile symmetry was regained at the expense of a lateral shift in the dose profiles. It was found that all points in the penumbra failed a 1\%/1 mm acceptance criterion for fields between 4 and 6 G. However, it was also found that the lateral profile shifts were corrected by adjusting the jaw positions asymmetrically.

1. Introduction

Image guided radiotherapy is currently performed by imaging the patient immediately prior to treatment to correct for patient setup variations. During the course of treatment however, the tumor and organs at risk locations can move in unpredictable ways. Tumor motion requires the clinician to outline a larger planning target volume (PTV) to ensure the tumor is receiving
the full prescription dose at all times in its motion trajectory. As a consequence, a larger volume of normal tissue is irradiated, which increases the probability of side effects and complications to the patient. In order to reduce the volume of the PTV to more closely conform to the clinical tumor volume (CTV), real-time intra-treatment imaging is required to track the location of the tumor as well as all organs at risk during treatment. The coupling of a magnetic resonance (MR) imager and a linear accelerator (linac) provides the means to image in real-time, providing information on the location of the tumor and organs at risk during treatment. Two different linac–MR systems have been proposed with our group coupling a 6 MV linac to a low field 0.2 T bi-planar MR imager (Fallone et al 2007, 2009), and another group coupling a 6 MV linac to a 1.5 T superconducting solenoid MR imager (Raaymakers et al 2009).

The work presented here builds on our work of a linac simulation published previously (St Aubin et al 2010a, 2010b) by further investigating its operation in the presence of transverse magnetic fields. To date only one investigation has been published on the effects of magnetic fringe fields on a medical linac (Kok et al 2009). They investigated the effects of the magnetic fringe fields from a 1.5 T linac–MR system on 2 m long accelerating waveguides in adjacent vaults. The linacs in that study were positioned 8 and 12 m away from the MR magnet, and the built-in beam control systems, which correct for the changes in the earth’s magnetic field at different gantry angles, were exploited to correct the effects of the additional fringe fields from the MR. In contrast, the linac generating the x-rays for the linac–MR system is in close proximity to the MR imager with the target at approximately 1.5 m from the magnet isocenter. At this distance, the electron gun is expected to experience field strengths of 30–50 G, which increases to 80–100 G at the target for our low field linac–MR system. In addition, the linacs proposed for use with linac–MR systems do not include built-in beam control systems since they use much shorter in-line side-coupled 6 MV waveguides. Because our institute has limited access to dedicated research linacs on which magnetic field studies could be performed, magnetic field measurements on an actual in-line 6 MV linac were not possible. Thus the full in-line side-coupled 6 MV linac simulation designed and validated previously (St Aubin et al 2010a, 2010b) was used. Using the simulation has the added advantage of performing investigations on linac operation in the most extreme cases with field strengths resulting in 100% beam loss where measurements may be unpractical.

With no built-in beam control mechanism for the 6 MV linac, alternative solutions for correcting or avoiding any deleterious effects on the linac from the magnetic fringe fields are required. These solutions will only come after an understanding of the 6 MV linac’s performance within an external magnetic field is obtained. The two proposed linac–MR systems (Fallone et al 2009, Raaymakers et al 2009) are designed such that the magnetic fringe fields cross through the 6 MV linac perpendicular to its length with a minimal longitudinal component. Our previously validated linac simulation (St Aubin et al 2010a, 2010b) incorporated the widely used 2D axisymmetric program EGN2w (Stanford Linear Accelerator Center, CA) (Herrmannsfeldt 1988) together with the finite element program (FEM) COMSOL (Burlington, MA) and the particle in cell program PARMELA (Los Alamos National Lab, NM) (Young 2005). However, EGN2w cannot be used directly for the investigation of a linac’s performance in an external transverse magnetic field that crosses through the linac; it only allows for the addition of axisymmetric magnetic fields. Thus the fully 3D FEM electron gun program OPERA-3d/SCALA (Kidlington, UK) was used in its stead. An investigation was performed to determine the effects on the electron beam calculated at the target as well as the dosimetric effects caused by a transverse magnetic field. The effect of magnetic fields directed parallel to the waveguide is the subject of future work.
2. Methods

2.1. Simulation of the linear accelerator in the presence of transverse magnetic fields

The linac simulation used to investigate the effect of transverse magnetic fields was fully 3D in nature incorporating a 3D electron gun simulation using OPERA-3d/SCALA, 3D radio-frequency (RF) solution within the waveguide from COMSOL (St Aubin et al 2010a) and 3D particle tracking in PARMELA. The geometry of the EGN2w electron gun design published previously (St Aubin et al 2010b) was replicated in OPERA-3d to obtain the FEM electrostatic field solution, and SCALA was used to calculate space charge effects with electron emission at the cathode set by Child’s law

\[ j_e = \frac{4\varepsilon_o}{9} \sqrt{\frac{2q}{m_e}} \frac{V^{3/2}}{d^2}, \]

where \( j_e \) is the current density emitted from the cathode, \( q \) is the charge of the electron, \( m_e \) is the electron mass, \( \varepsilon_o \) is the permittivity of free space, \( V \) is the potential difference and \( d \) is the normal sampling distance (assumed to be small compared to the radius of curvature of the cathode). Transverse magnetic fields were added to the linac simulation in OPERA-3d/SCALA (hereafter referred to as SCALA) and PARMELA, and the electrons were tracked from the electron gun cathode to the target. As shown by work performed previously by this group, nominal linac operation inherently yields a 63 ± 1% electron beam loss. The subsequent beam loss percentages quoted throughout this paper will refer to relative beam losses above the nominal 63%.

2.2. Dosimetric effects

Before Monte Carlo simulations were performed, the electron spatial intensity distribution at the target, generated from the PARMELA phase space, was translated laterally with respect to the center of the flattening filter. This translation was performed to ensure that the dose profiles were symmetric as required for a clinical radiation beam and is analogous to the commissioning process performed when the waveguide is first installed in the linac head.

The geometry of the linac head shown in figure 1 was modeled in BEAMnrcMP 2007 (BEAM) (Rogers et al 1995) using Varian 600C information supplied from the manufacturer. Roughly \( 5 \times 10^8 \) initial histories were run and directional bremsstrahlung...
splitting was used with a splitting number of 1000 with the splitting field source-to-surface distance set to 100 cm. The splitting field radius was chosen to be equal to the field size and Russian roulette was turned on with the splitting plane chosen to be 0.16 cm above the bottom of the flattening filter. The values for the electron energy cutoff (ECUT) and photon energy cutoff (PCUT) were set to 0.70 MeV and 0.01 MeV respectively, and range rejection was turned on with an ESAVE value of 0.7 MeV in the target and 2.0 MeV for the rest of the linac components with no photon forcing. With the ECUT and PCUT values set to 0.70 MeV at the target less than 0.3% of the PARMELA phase space electrons were rejected.

BEAM and DOSXYZnrc 2007 (DOSXYZ) were run in unison using the *i*source 9 input in DOSXYZ for the 40 × 40 and 20 × 20 cm² fields and thus no phase space was required to be scored. The depth of the voxels for all depth dose (DD) simulations was 0.2 cm down to a depth of 1.5 cm and then 0.5 cm to a depth of 30 cm while the lateral dimensions were set to 1 × 1 cm². The total size of the water tank simulated was 66 × 66 × 48 cm³, approximating the size of the IBA Dosimetry (Bartlett, TN) water tank used for measurements. The voxel in which the dose was scored for the profiles varied in size depending on the field size that was simulated. They were created such that their width in the penumbra was 0.5 cm in order to approximate the volume averaging effect of the ion chamber used for the measurements (St Aubin et al 2010b). In order to ensure that a sufficient resolution was obtained in the penumbra, all profiles were obtained through two simulations, with the voxel centers staggered to create points every 0.25 cm. The ECUT and PCUT values were set to 0.70 MeV and 0.01 MeV respectively for the DOSXYZ simulation and no range rejection was used. All of the dose profiles were normalized to the central axis dose (DCAX) and the DD curves were normalized to the dose at 10 cm depth (D10). The simulated profiles were initially smoothed using a median filter, followed by piecewise cubic interpolation. In order to evaluate the effect of the transverse magnetic fields on the simulated profiles, they were compared to a validated simulation profile at 0 G (St Aubin et al 2010b). By comparing to a validated simulation profile, only changes caused by the transverse magnetic fields are quantified. The goodness of agreement analysis was performed through the creation of a gamma index (Daniel et al 1998) with a 1%/1 mm acceptance criterion. No magnetic fields were added to the Monte Carlo simulations in order to solely investigate the effect of the magnetic field on the linac structure (electron gun and waveguide). The results presented here are thus solely due to the transverse magnetic field intersecting the linac structure.

3. Results and discussion

3.1. Validation of the 3D SCALA electron gun

The geometry of the EGN2w electron gun was replicated in SCALA (figure 2) and the simulation results were compared. The emission current of the SCALA electron gun was determined to be roughly 20% greater than EGN2w predicted. Both programs determine the emission current from Child’s law where the net potential at the cathode (which is the sum of the anode–cathode potential and the space charge potential) is zero. Thus the determination of emission current is critically dependent on the resolution of the electrostatic field at the cathode. SCALA uses isoparametric mesh elements to conform to curved geometries (such as the cathode). It also has the advantage of using quadratic basis functions in the determination of the electrostatic field solution and the space charge field creating a more accurate solution (Jin 2002). EGN2w on the other hand uses a square mesh and a finite difference approximation for the electrostatic field solution. The higher field resolution and conformal meshing is thought
to explain the differences in emission current between the two electron gun programs. The higher emission current in SCALA required a slight modification of the cathode to regain the measured emission current of a Varian (Palo Alto, CA) 600C linac of 0.36 ± 0.01 A (St Aubin et al. 2010b). The cathode radius was reduced by 7.6% from 2.5 to 2.31 mm giving an emission current of 0.361 ± 0.002 A. The emittance of the electron beam generated in SCALA was calculated to be 0.357 π mm mrad compared to 0.148 π mm mrad from EGN2w. The 3D SCALA electron gun was used as an input into our linac waveguide simulation and the particle trajectories were calculated in PARMELA at 0 G. The target current was calculated to be 0.131 ± 0.002 A with a maximum discrepancy in electron energy and beam centroid at the target of 0.015 MeV and 0.01 mm, respectively, as compared to the simulation utilizing EGN2w. When the 3D SCALA electron gun was used as an injector to our linac simulation and Monte Carlo simulations were performed, the simulated dose distributions were found to agree with measurement to the same accuracy as was presented previously (St Aubin et al. 2010b).

3.2. Linac response to homogeneous transverse magnetic fields

The simulated linac responded to increasingly larger transverse magnetic fields by exhibiting increased beam loss. Homogeneous magnetic fields of 2, 4 and 6 G were added to the simulated linac and the resulting beam loss is shown in figure 3(a). The additional beam loss calculated at the target from the 2, 4 and 6 G transverse fields was determined to be 6 ± 1, 19 ± 1 and 45 ± 1% respectively. The first points on the left of the dotted line in figure 3(a) at each magnetic field value correspond to beam losses within the electron gun. It is observed from figure 3(a) that as the transverse field strength increases, less beam loss is experienced within the electron gun since the electrons that would normally be accelerated back toward the gun are lost elsewhere in the waveguide. Thus while the 6 G field contributes to the largest beam loss within the waveguide, it contributes to the least beam loss within the electron gun. The electron spatial distributions at the target for 0, 2, 4 and 6 G transverse field simulations are given in figure 3(b). Fields larger than 6 G caused the electron distribution peak to be lost.
Figure 3. (a) The beam loss within the simulated linac is given for increasing homogeneous transverse magnetic field strengths with the intensities normalized to the 0 G intensity count. The first points on the left of the dotted line are the beam loss values taken within the electron gun. (b) The electron spatial intensity distributions (normalized to 0 G) at the target resulting from the addition of the 0, 2, 4 and 6 G transverse magnetic fields are given.

resulting in greater than 60% beam loss and a fairly flat distribution at the target. The 6 G field yields the most asymmetric spatial distribution at the target and thus has the largest effect on the dose distributions.

The wide field dose distributions derived from the simulated phase space resulting from the addition of the 2, 4 and 6 G transverse magnetic fields are shown in figures 4(a)–(c) along with the gamma index for a 1%/1 mm acceptance criterion. Since the peak shift away from center, shown in figure 3(b), becomes more drastic as the magnetic field is increased, a larger lateral translation of the spatial distribution at the target was required to maintain the profile symmetry. It was determined that a lateral translation of 0.07, 0.14 and 0.24 cm in the y direction for the 2, 4 and 6 G magnetic field simulations respectively was required to maintain the profile symmetry. The gamma index analysis found that 4.2, 10.8 and 14.4% of all points failed a 1%/1 mm criterion for the 2, 4 and 6 G field simulations respectively, with nearly all the failed points positioned in the penumbra as seen in figures 4(a)–(c). When the acceptance criterion was changed to 3%/3 mm, all points for the 2 and 4 G magnetic field simulations met the new criterion while the 6 G field simulation had 0.9% of the points fail.

The maximum energy of the electrons impacting the target showed no change with increasing magnetic field, but the mean energy increased slightly to 5.64 MeV, 5.71 MeV and 5.74 MeV for the 2, 4 and 6 G simulations respectively. The increase in mean energy is a result of more low energy electrons being lost as the transverse magnetic field increases. With these very small changes in the mean energy no differences greater than 1.3% were seen in the DD curves shown in figure 4(d). This is expected since the DD curves have been shown to be quite insensitive to small changes in the electron beam energy (Libby et al 1999, Lovelock et al 1995).

The points failing the acceptance criterion were predominantly in the penumbra due to a lateral profile shift. The lateral shift in the dose profile as measured by the location of the 50% dose is directly caused by the lateral shift in the focal spot due to the commissioning process (figure 5). Thus if the symmetry is maintained it is at the expense of a laterally shifted dose profile. If on the other hand there was no lateral shift in the profile (by not translating the spatial distribution at the target), the asymmetry in the 40 × 40 cm² field was calculated to be 13%, well outside clinical specifications. As explained previously, homogeneous fields larger
than 6 G cause the electron distribution peak to be lost within the waveguide resulting in a relatively flat and spatially homogeneous distribution at the target. Thus the largest effects on the dose distributions come from a homogeneous field of around 6 G. As an extension to the applicability of this study, any transverse magnetic field configuration (homogeneous or otherwise) that yields the beam centroid shifts as shown in figure 3(b) would yield the
Figure 6. The reduction in target current for increasing homogeneous magnetic field strengths is given. At 14 G, none of the electrons impact the target.

Figure 7. (a) A large lateral shift of the dose profile for the 6 G simulation is seen causing large discrepancies from a typical clinical profile as seen by the gamma index. (b) The use of asymmetric jaw placements almost fully corrects the lateral shift.

Dosimetric results given in figure 4. Thus the results presented here can be applied to various transverse magnetic field configurations.

A further analysis was performed to determine the target current at increasingly larger field strengths for completeness. The results are presented in figure 6 and show that by 14 G, all electrons are lost within the electron gun and waveguide and none reach the target.

3.3. Reduction of the magnetic field effects on the dose distributions

The lateral shift in the dose profiles seen in figures 4(a)–(c) can be reduced significantly through the use of asymmetric jaw positions. The effectiveness of using asymmetric jaw positions for a $20 \times 20$ cm$^2$ field size is demonstrated in figure 7 to correct the largest lateral shift caused by the 6 G field. By changing the left and right jaw placements from $-10$ and 10 cm respectively to $-10.15$ and 9.85 cm (a shift of 1.5 mm to the left), the lateral shift seen in figure 7(a) is almost completely removed (figure 7(b)) with only 0.5% of the points failing the 1%/1 mm criterion. Appropriate positioning of the $x$ and $y$ jaws can compensate the lateral shift even for collimator rotations. It should be noted that the multi-leaf collimators (MLCs) could also correct the lateral shift. However, the largest $40 \times 40$ cm$^2$ field cannot be used
since the jaws are limited to a maximum position of ±20 cm, so the maximum field size must be slightly smaller, but only by a few millimeters at most.

As an alternative solution to using the jaws to compensate the dosimetric effects resulting from the transverse magnetic fields on the linac, beam control systems similar to a high energy unit may be added. These control systems would be designed to redirect the electron beam to the target. Alternatively, passive or active magnetic shielding could reduce the magnetic fringe fields at the linac sufficiently to achieve minimal beam deflection. The design of magnetic shielding is currently being investigated by our group.

4. Conclusion

The 2D axisymmetric electron gun program EGN2w was replaced by the 3D electron gun program OPERA-3d/SCALa in our validated linac simulation. The emission current from the 3D gun was found to be 20% larger than EGN2w calculated, requiring a 7.6% reduction in the cathode radius to ensure its output matched measurement. The linac simulation was re-validated using this updated design giving our previously achieved agreements to measurement. Upon the addition of increasing homogeneous magnetic field strengths, larger beam losses were calculated within the linac due to the increasing transverse electron deflections. The large electron deflections lead to a spatially shifted electron distribution at the target resulting in either clinically unacceptable profile symmetry, or if maintaining symmetry, a laterally shifted dose profile. The laterally shifted dose profiles at homogeneous fields of 4 and 6 G failed to meet a 1%/1 mm acceptance criterion with all points in the penumbra causing the failure. It was found that using asymmetric jaw locations created an opposite shift that almost completely eliminated the lateral shifts in the dose profiles caused by the external fields. It was also found that at a transverse homogeneous field of 14 G no electrons impacted the target resulting in 100% beam loss.

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