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

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(Received 5 May 2010; revised 2 August 2010; accepted for publication 3 August 2010; published 24 August 2010)

Purpose: Linac-magnetic resonance (MR) systems have been proposed in order to achieve real-time image guided radiotherapy. The design of a new linac-MR system with the in-line 6 MV linac generating x-rays along the symmetry axis of an open MR imager is outlined. This new design allows for a greater MR field strength to achieve better quality images while reducing hot and cold spots in treatment planning. An investigation of linac’s performance in the longitudinal fringe magnetic fields of the MR imager is given.

Methods: The open MR imager fringe magnetic field was modeled using the analytic solution of the magnetic field generated from current carrying loops. The derived solution was matched to the magnetic fringe field isolines provided for a 0.5 T open MR imager through Monte Carlo optimization. The optimized field solution was then added to the previously validated 6 MV linac simulation to quantify linac’s performance in the fringe magnetic field of a 0.5 T MR imager. To further the investigation, linac’s performance in large fringe fields expected from other imagers was investigated through the addition of homogeneous longitudinal fields.

Results: The Monte Carlo optimization of the analytic current loop solution provided good agreement with the magnetic fringe field isolines supplied by the manufacturer. The range of magnetic fields the linac is expected to experience when coupled to the 0.5 T MR imager was determined to be from 0.0022 to 0.011 T as calculated at the electron gun cathode. The effect of the longitudinal magnetic field on the electron beam was observed to be only in the electron gun. The longitudinal field changed the electron gun optics, affecting beam characteristics, such as a slight increase in the injection current and beam diameter, and an increasingly nonlaminar transverse phase space. Although the target phase space showed little change in its energy spectrum from the altered injection phase space, a reduction in the target current and spatial distribution peak intensity was observed. Despite these changes, the target phase space had little effect on the depth dose curves or dose profiles calculated for a 40 × 40 cm² field at 1.5 cm depth. At longitudinal fields larger than 0.012 T, a drastic reduction in the injection current from the electron gun was observed due to a large fraction of electrons striking the anode. This further reduced the target current, which reached a minimum of 28 ± 2 mA at 0.06 T. A slow increase in the injection and target currents was observed at fields larger than 0.06 T due to greater beam collimation in the anode beam tube.

Conclusions: In an effort to achieve higher quality images and a reduction in hot and cold spots in the treatment plan, a parallel configuration linac-MR system is presented. The longitudinal magnetic fields of the MR imager caused large beam losses within the electron gun. These losses may be eliminated through a redesign of the electron gun optics incorporating a longitudinal magnetic field, or through magnetic shielding, which has already been proven successful for the transverse configuration.

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Key words: linac-MR, linear accelerator, electron gun, magnetic fringe fields, longitudinal
I. INTRODUCTION

Magnetic resonance (MR) image guided radiation therapy has been proposed by a variety of groups in order to achieve true real-time image guided radiation therapy.\textsuperscript{1-3} The linac-MR system designed by our group provides two options for the placement of the linac with respect to the MR imager.\textsuperscript{1} One is a transverse design where the linac is coupled to the MR imager such that the x-rays travel perpendicular to the main magnetic field. Two proof-of-concept linac-MR systems have been presented previously that produce x-rays perpendicular to the main magnetic field of the MR imager.\textsuperscript{4,5} The existence of both of these proof-of-concept systems proves that all engineering difficulties relating to the transverse case can be overcome. However, despite overcoming engineering difficulties, the transverse case produces hot and cold spots at tissue-air interfaces in the treatment plan due to the significant deflection in low density media of the high energy electrons generated by Compton scattering, etc.\textsuperscript{6} At 1.5 T, these effects produce large deviations away from a nominal treatment plan with no magnetic field. However, it has also been shown that at lower magnetic field strengths, such as 0.2 T, the hot and cold spots at tissue-air interfaces is largely reduced.\textsuperscript{6} The minimization of electron deflections in low density media at lower field strengths is simply a result of a reduction in the transverse magnetic force on the particles.

The second option that our design allows is a parallel arrangement, where the linac is coupled to the MR imager such that the x-rays travel parallel to the main magnetic field. The parallel design for a linac-MR system was first presented by our group in 2009.\textsuperscript{7,8} Our group has shown that in using the parallel design, there is a significant reduction in hot and cold spots at the tissue-air interface and that the highest magnetic field strength with minimum creation of hot and cold spots is approximately 0.5 T.\textsuperscript{7,9} The image quality at 0.5 T would be superior to that at 0.2 T. Work has shown that a parallel configuration also results in a smaller penumbra.\textsuperscript{9,10}

Since an in-line side-coupled 6 MV linac is proposed to be the source of x-rays directed parallel to the main magnetic field of the MR imager, the accelerating electrons within the linac will be subjected to longitudinal magnetic fringe fields. The longitudinal magnetic fields are not expected to deflect the electrons away from the target as a transverse field would, but the effects on the electron beam resulting from altered beam optics at the electron gun and throughout the waveguide require quantification. In addition to quantifying changes to the electron beam, the resulting changes in the dose distributions also require quantification. An investigation of these effects, due to longitudinal magnetic fields, is presented here.

II. METHODS

The outline of the work presented here is as follows. A continuous magnetic fringe field solution approximating discrete isoline data supplied by an open MR imager manufacturer was first generated. The reasoning and methodology behind this calculation are explained in Sec. II A. The approximated continuous fringe field was then added to our linac simulation.\textsuperscript{11-13} Our linac simulation, described in Sec. II B, was previously validated against measurement as reported in Ref. 11 and 13. The electron phase space at the linac target produced as a result of our linac simulation was then used as an input into a Monte Carlo simulation to calculate the associated dose distribution in a water tank, which is discussed in Sec. II C. Our Monte Carlo model of a linac was also validated against measurements as reported in Ref. 13.

II.A. Magnetic fringe field calculations

The parallel linac-MR design (Fig. 1) can be implemented with various open commercial MR imagers. Examples of open MR imagers include PARAmed MRopen\textsuperscript{TM}, GE Signa SP\textsuperscript{TM}, Phillips Panorama\textsuperscript{TM}, Siemens Magnetom Concerto\textsuperscript{TM}, and the Hitachi Elite\textsuperscript{TM}. As an example for what can be performed, an investigation of linac’s performance in a longitudinal magnetic field was performed using fringe field isoline data supplied by PARAmed for its MRopen\textsuperscript{TM} system. The final location of the linac with respect to this MR imager is expected to lie within a target-isocenter distance ranging from 1 to 2.2 m. Within this range of target-isocenter distances, the longitudinal magnetic field at the cathode of the electron gun is expected to range from 0.0022 to 0.011 T.

It was necessary to approximate the discrete fringe field isoline data through the generation of a full magnetic field solution from the superposition of a single current loop. This was done because our linac simulation requires a fully continuous field solution including vector components, and this cannot be adequately performed by simply inserting the provided discrete field values. The analytic solution of the magnetic field $B$ in tesla (T), in cylindrical coordinates for a single current loop, is
\[
B_x(r,z) = -\frac{I\mu_0(z-h)}{2\pi\sqrt{(r+a)^2 + (z-h)^2}} \\
\times \left[ f + \frac{2aE(k)}{[(r+a)^2 + (z-h)^2](1-k^2)} \right], \tag{1a}
\]
\[
B_y(r,z) = \frac{I\mu_0}{2\pi\sqrt{(r+a)^2 + (z-h)^2}} \left[ K(k) + E(k) \right] \\
\times \left( \frac{2a(r+a)}{[(r+a)^2 + (z-h)^2](1-k^2)} - \frac{1}{1-k^2} \right), \tag{1b}
\]
with
\[
k = \sqrt{\frac{4ar}{(r+a)^2 + (z-h)^2}} \tag{1c}
\]
and
\[
f = \frac{4a}{(r+a)^2 + (z-h)^2} \int_0^{\pi/2} \frac{\sin^2 \alpha - 1}{(1-k^2)^2 \sqrt{1-k^2 \sin^2 \alpha}} d\alpha. \tag{1d}
\]

In Eq. (1), \( h \) is the height above the \( z=0 \) plane, \( a \) is the loop radius, \( I \) is the current, \( \mu_0 \) is the permeability of free space, and \( K(k) \) and \( E(k) \) are complete elliptic integrals of the first and second kinds, respectively. The cylindrically symmetric solutions given in Eq. (1) were transformed into Cartesian \( xyz \) coordinates by the following transformations:

\[
B_x(x,y,z) = \pm B_x \cdot \frac{1}{\sqrt{1+(y/x)^2}}, \tag{2a}
\]
\[
B_y(x,y,z) = \pm B_y \cdot \frac{y}{x\sqrt{1+(y/x)^2}}, \tag{2b}
\]
and
\[
r = \sqrt{x^2 + y^2}, \tag{2c}
\]

with the \( \pm \) set depending on which quadrant in the \( xy \) plane the solution was determined. Thus, through a superposition of solutions from Eq. (1) and the transformation of Eq. (2), the magnetic field from any number of current loops can be determined.

The current \( I \), separation \( h \), and radius \( a \) for the current loop pair were optimized in order to minimize the square root of the mean squared difference between the calculated magnetic field solution and the isoline data supplied from PARAmed using a Monte Carlo optimizer. An initial value for \( I, h, \) and \( a \) was input into the optimization algorithm and the square root of the mean squared difference between the calculated solution and the isoline data was determined. The Monte Carlo optimizer then used random numbers to make fluctuations in \( I, h, \) and \( a \). By applying larger amplitude fluctuations to \( I, h, \) and \( a \), the region around the minimized square root of the mean squared difference was first located. Once located, smaller amplitude fluctuations were used to find the minimized square root of the mean squared difference. Once the minimized square root of the mean squared difference was determined for a given number of current loop pairs, an additional loop pair was added to the model in an attempt to further minimize differences between the calculated solution and the isoline data. The optimization of \( I, h, \) and \( a \) for each loop pair was then repeated. If the addition of a current loop pair reduced the square root of the mean squared difference by less than 1% of the previous solution, the optimization was completed and the model with the lower number of loop pairs was chosen as the optimal solution for simplicity. The use of a Monte Carlo optimizer on the current loop solution guarantees the divergence of the field to be zero (i.e., giving a physical solution). Regular fitting techniques such as chi-squared minimization or other polynomial based fitting techniques would not guarantee a physical solution.

The optimized continuous magnetic field solution was then added to our previously validated linac simulation\textsuperscript{11-13} such that the field at the electron gun cathode was calculated to be 0.0022, 0.0046, and 0.011 T. These field strengths correspond to target-isocenter distances of 2.2, 1.6, and 1.0 m, respectively. In addition to this investigation, homogeneous fields up to 0.2 T were used to simulate the effects of other possible open slit solenoid MR imagers, which may have larger fringe fields due to poor or nonexistent magnetic shielding.

II.B. 6 MV linac simulation

Our validated 6 MV linac simulation was designed in two parts. The first part was an electron gun simulation that consisted of a 3D finite element method (FEM) solution for the electrostatic field within the gun and a particle simulation. The second part was a waveguide simulation that included a 3D FEM radio-frequency (RF) field solution and a particle simulation. The details of these programs are given below.

The 3D FEM program OPERA-3D/SCALA from Cobham Technical Services (Kidlington, UK) uses a user defined electron gun design and calculates its electrostatic field from a given cathode-anode potential along with the electron beam current and trajectory. The initial design of the electron gun used was presented previously in 2D in Ref. 13 with the slight cathode modification for the 3D OPERA-3D/SCALA electron gun model specified in Ref. 11. Further details on the FEM as applied to electromagnetics are given by Jin.\textsuperscript{15} The electron gun beam current is calculated in an iterative fashion using Child’s law to simulate electron emission off the cathode. Child’s law is given below
\[
\dot{j}_e = \frac{4e_0}{9} \sqrt{\frac{2qV^{3/2}}{m_e d^2}}, \tag{3}
\]
where \( \dot{j}_e \) represents the electron current density emitted from the cathode, \( e_0 \) is the permittivity of free space, \( q \) is the electronic charge, \( m_e \) is the electron mass, \( V \) is the potential difference, and \( d \) is the normal sampling distance for the current density calculation set to be 0.5 mm from the cathode. On the first iteration, \( V \) is taken solely as the applied cathode-anode potential and a beam current is calculated along with the electron beam trajectory. Using the calculated beam current, the corresponding space charge potential is...
calculated and added to the cathode-anode potential. Using this new potential $V$, an updated beam current and trajectory are calculated. This process continues until the calculated beam current varies by less than $1 \times 10^{-6}$ A from the previous iteration. The output of the 3D FEM electron gun program OPERA-3D/SCALA is a six dimensional (6D) phase space. The six dimensions are specified by the particle’s $x$, $y$, $z$ position as well as its $v_x$, $v_y$, $v_z$ relativistic velocity components. This 6D phase space represents the electrons to be injected into the linac waveguide and served as an input into our waveguide simulation.

Our waveguide simulation consists of a waveguide design in which a 3D FEM RF field solution is calculated using COMSOL MULTIPHYSICS (Burlington, MA). Details on our waveguide design and RF field solution have been published previously. The 3D RF field solution serves as an input into the particle simulation program PARMELA (Los Alamos National Laboratory, NM). PARMELA uses the calculated 6D electron gun phase space to determine the initial conditions for the electrons being injected into the waveguide and uses a 3D particle-in-cell algorithm to calculate the electron trajectories subject to the inputted RF field as well as a space charge field. The space charge field is calculated in PARMELA on a user defined 3D grid using a cloud-in-cell method to interpolate charges and forces on the grid. Details on particle-in-cell calculations and the cloud-in-cell interpolation method are given by Hockney. With the forces calculated, time integration is performed using the leap-frog method in order to calculate the electron trajectories as they travel through the waveguide. The output of PARMELA is a 6D phase space for the electrons incident on the linac target. From this 6D phase space, the electron focal spot and energy spectrum at the linac target are determined. The 6D electron phase space at the linac target was then used as an input into the Monte Carlo program BEAMnrcMP 2007 (BEAM), which models commercial medical linac heads (including the target, collimators, flattening filter, monitor chamber, etc.). The Monte Carlo program DOSXYZnrc 2007 (DOSXYZ) then used the output of BEAM to calculate dose distributions in a water tank. The linac simulation from electron gun to target, and including dose distributions in a water tank was validated previously against measurement.

Figure 2 summarizes the simulation process and includes the input and output of each program used.

II.C. Monte Carlo simulations

A Varian (Palo Alto, CA) 600C linac head was modeled in BEAM using the information supplied from the manufacturer. Roughly $3 \times 10^8$ initial histories using the PARMELA output phase space as an initial condition were run in BEAM for a $40 \times 40$ cm$^2$ field size. A $40 \times 40$ cm$^2$ field size was chosen due to its sensitivity to changes in the electron focal spot size and energy. Directional bremsstrahlung splitting was used as a variance reduction technique with a splitting field source-to-surface distance of 100 cm. Thus, for every bremsstrahlung photon generated, 1000 more were created with random initial directions, each with a weight of 1/1000.

Greater detail of the bremsstrahlung splitting algorithm is given by Kawrakow. The splitting field radius for the bremsstrahlung splitting was chosen to be 30 cm, and “Russian roulette” was turned on with the splitting plane 0.16 cm above the bottom of the flattening filter. Russian roulette is a random process which has a probability of removing any particle traveling away from the chosen splitting field. The values of electron (ECUT) and photon (PCUT) transport cut-off energies were 0.70 and 0.01 MeV, respectively, for all field sizes and range rejection was used with an ESAVE value of 0.70 MeV in the target and 2.0 MeV for the rest of the linac components with no photon forcing. With the given ESAVE value, electrons with total energies less than 0.70 MeV deposit their energy locally and are not tracked any further. Greater detail of these Monte Carlo parameters in BEAM are given by Kawrakow et al. With ESAVE and ECUT both set to 0.70 MeV in the target, less than 0.3% of the PARMELA phase space electrons were rejected.

The dose distributions in a $66 \times 66 \times 48$ cm$^3$ water tank using the output of the BEAM simulation were calculated using DOSXYZ. A total of $7.8 \times 10^9$ histories was run in DOSXYZ. 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 $1 \times 1$ cm$^2$. The voxel sizes in which the dose was scored for the profiles had dimensions of $1 \times 1 \times 0.5$ cm$^3$ except in the penumbra where the voxel size was reduced to $0.2 \times 1 \times 0.5$ cm$^3$. The ECUT and PCUT values were set to 0.70 and 0.01 MeV for the DOSXYZ simulation, but this time no range rejection was used. All DD curves were normalized to the dose at 10 cm depth ($D_{10}$) and dose profiles were normalized to the central axis dose ($D_{CAX}$). In order to evaluate the differences between the profiles derived from the linac simulation with and without magnetic fields, all profiles were initially smoothed using a median filter, and interpolated with a piecewise cubic polynomial. The comparison
between profiles was performed through the creation of a gamma index using a 1%/1 mm acceptance criterion.

III. RESULTS AND DISCUSSION

III.A. Effect of MRopen™ fringe magnetic fields on the linac

The results of the Monte Carlo optimization provided an accurate approximation of the 0.5 T MR when comparing magnetic fringe field isolines over the region where the linac is expected to be located using two current carrying loop pairs. The continuous field solution derived from the discrete field values supplied for the MRopen™ system from PARAmed is shown in Fig. 3. A maximum discrepancy of 12% was calculated at the 0.002 T field point. Elsewhere, the discrepancy was less than 2%.

The longitudinal MR field was seen to have a large effect on the injection electron phase space as seen in Fig. 4. The phase space becomes highly nonlaminar prior to injection into the linac for all longitudinal field strengths investigated. The normalized root-mean-square (rms) emittance at the exit of the electron gun for the 0, 0.0022, 0.0046, and 0.011 T magnetic field simulations was calculated to be 0.358, 0.810, 1.573, and 3.255π mm mrad, respectively. In addition to the nonlaminar phase space, the diameter of the injected electron beam grew from 0.178 cm at 0 T to 0.183, 0.194, and 0.22 cm at 0.0022, 0.0046, and 0.011 T, respectively. The changes in the electron beam at the electron gun are a result of the longitudinal magnetic field changing the optics of the electron gun, which was originally designed for use in a nearly 0 T field environment. Despite the change in optics, at up to 0.011 T no beam loss was calculated within the electron gun.

The electron spatial intensity distribution and energy spectrum at the target resulting from the MR field are given in Fig. 5. Beam losses above nominal of 1%, 2%, and 16% were calculated for the 0.0022, 0.0046, and 0.011 T fields, respectively. As can be seen, the spatial distribution changes drastically with the addition of longitudinal magnetic fields as quantified by the full width half maximum (FWHM). The FWHM of the spatial distribution, calculated to be 0.012 cm at 0 T, grew to 0.074, 0.143, and 0.254 cm for the 0.0022, 0.0046, and 0.011 T fields, respectively. The maximum and mean energy of the electron beam incident on the target remained unchanged at 6.32 and 5.57 MeV, respectively, at 0.0022 and 0.0046 T. However, at 0.011 T, despite the maximum energy being unchanged, the mean energy increased slightly to 5.60 MeV. In order to separate the effects of the longitudinal magnetic field on the gun from those within the waveguide, a longitudinal magnetic field was placed on the electron gun only and not on the linac waveguide and the target phase space was analyzed. The beam loss, energy, and spatial intensity distribution were the same for these simulations compared to those with the field on both the electron gun and waveguide. This shows that the only effect of a longitudinal magnetic field (up to 0.011 T) on a linac is at the electron gun. The simulation results presented here were found to be the same if the magnetic fringe field direction was reversed. A reversal of field direction would occur if the MR magnet poles were reversed with respect to the linac.

![Fig. 3](image3.png) **Fig. 3.** The derived magnetic fringe field solution resulting from Monte Carlo optimization of current loops. Two coil pairs were used to generate the above continuous field solution.

![Fig. 4](image4.png) **Fig. 4.** The transverse phase space at the exit of the electron gun is given when subjected to (a) 0 T, (b) 0.0022 T, (c) 0.0046 T, and (d) 0.011 T longitudinal magnetic fields.

![Fig. 5](image5.png) **Fig. 5.** (a) Spatial intensity distribution and (b) energy spectrum at the linac target for simulations of 0, 0.0022, 0.0046, and 0.011 T longitudinal magnetic fields over the electron gun and linac waveguide.
Our Monte Carlo model of a Varian 600C linac, which was previously validated against measurements,13 generated dose profiles and DD curves as seen in Fig. 6. Figures 6(a)–6(c) show the in-line \(40 \times 40 \) cm\(^2\) dose profiles at 1.5 cm depth, and Fig. 6(d) shows DD curves derived from the electron phase space at the linac target for the simulations in 0.0022, 0.0046, and 0.011 T longitudinal magnetic fields. Only the in-line profiles are shown since the crossline profiles showed the same agreements. A comparison of the profiles at 0.0022, 0.0046, and 0.011 T to the 0 T profiles resulted in 96% of all points meeting a 1%/1 mm acceptance criterion at all field strengths. The DD curves in longitudinal magnetic fields all matched the 0 T curve to within 1% at all depths down to 30 cm deep. Thus, the addition of longitudinal magnetic fields does not have a large effect on the dose distributions in fields up to 0.011 T.

An investigation was also performed to determine the linac sensitivity to lateral misalignments away from the symmetry axis of the MR imager. If the linac is installed with a misalignment away from the central axis, it is subjected to larger transverse fields. A 1 cm misalignment corresponded to a maximum transverse field strength of \(10^{-5}\) T, up from \(10^{-5}\) T with no misalignment. At a target-isocenter distance of 1.0 m, a 1 cm misalignment in the \(x\) or \(y\) direction produced an 18 \(\pm 2\) % beam loss. The 2% increase compared to the simulation on the symmetry axis is a result of the larger transverse magnetic fields. The simulations incorporating the misalignments also produced a 0.012 cm shift of the beam centroid compared to no misalignment and a maximum discrepancy of 12 keV in the mean electron beam energy. After linac commissioning is performed by translating the target focal spot with respect to the flattening filter,13 these lateral misalignments for the MR imager modeled would have no effect on the dose distributions. Typical misalignments are expected to be on the order of a few millimeters at most and not the exaggerated 1 cm offset investigated here. However, this investigation shows that even for a 1 cm misalignment, linac’s performance is minimally affected.

### III.B. Effect of strong longitudinal magnetic fields on the linac

Homogeneous longitudinal magnetic fields up to 0.2 T were added to the linac simulation to investigate their effect on the electron gun as well as on the waveguide. A slight increase in the emission current, which was calculated using Child’s law, was observed for longitudinal fields of increasing field strength. This increase may be explained by a reduction in space charge potential near the cathode due to the larger beam diameter. A reduction in space charge means more current can flow from the cathode at the same cathode-anode potential. The injection current saw the same increases up to around 0.012 T. However, further increases in field strength lead to a reduction in the injection current since the beam diameter became larger than the anode radius. The injection current dropped to its minimum value of \(75 \pm 2\) mA at 0.06 T (a 79% beam loss), but began increasing slowly at larger longitudinal field strengths due to greater beam collimation within the anode beam tube. Figure 7 shows the 3D electron gun model together with the calculated electron beam at 0.06 T field strength. Figure 8 highlights the results of the calculated emission and injection currents for increasing longitudinal magnetic field strengths up to 0.2 T. The effects of the longitudinal magnetic field within the electron gun directly translate into a reduction in the linac target current as seen in Fig. 9. Even though the injection current slightly increases up to 0.012 T, the target current is reduced over the same range. The changing beam characteristics quantified by the normalized rms emittance and shown in Fig. 4 explain this drop. Changes in these characteristics of the injected beam have been shown previously to affect the overall capture efficiency of the linac, which is defined as the...
target current over the electron gun emission current. At fields larger than 0.012 T, the injection current decreases, causing a further decrease in the target current where at 0.06 T the linac experiences a maximum beam loss of 92% corresponding to a target current of 28 mA. These large beam losses must be addressed before the linac can be subjected to strong longitudinal fields. Since the total beam loss over nominal has been shown to be largely due to losses within the electron gun, magnetically shielding the electron gun, or redesigning the electron gun optics to incorporate longitudinal magnetic fields of a known strength could minimize or eliminate these large losses.

IV. CONCLUSIONS

The next generation linac-MR system at the Cross Cancer Institute consists of a 6 MV linac coupled to a 0.5 T superconducting open MR imager. This configuration will allow for the x-ray beam to be generated in the same direction as the main magnetic field of the MR imager leading to a reduction in hot and cold spots in the dosimetry at tissue-air interfaces. As an example, depending on the final linac position, the longitudinal magnetic fringe fields at the cathode are expected to range from 0.0022 to 0.011 T according to isoline data provided for an MROpen™ imager. A continuous field solution was optimized using Monte Carlo to match the fringe field isoline data for use in our in-line 6 MV linac simulation. The optimized longitudinal magnetic field on the linac has been shown to affect the electron optics of the electron gun, creating an increasingly nonlaminar electron beam with a larger beam radius being injected into the linac waveguide. This, in turn, causes a drastic reduction in the intensity of the peak of the electron spatial distribution at the target and an increase in beam loss which was calculated to be 1%, 2%, and 16% at 0.0022, 0.0046, and 0.011 T, respectively. However, the altered electron focal spot at the target had little effect on the dose distributions with 96% of all points meeting a 1%/1 mm acceptance criterion when compared to a 0 T distribution and an agreement of better than 1% in the DD curves at all depths. Fields larger than 0.011 T, representing a range of fringe field magnitudes for other open MR systems, produced large beam losses within the electron gun. Specifically, a sharp decline in injection current for the designed electron gun was observed for field strengths between 0.012 and 0.06 T at which point the injection current was a minimum of 75 mA. After 0.06 T, the injection current increased slowly due to increased beam collimation in the anode beam tube. The linac target current calculated was observed to follow a similar trend to the injection current with its minimum value of 28 mA achieved at 0.06 T. These excessive beam losses at the target need to be addressed by a modification of the electron gun optics, or in the form of magnetic shielding (which has already been proven successful with the transverse configuration) before the linac can be operated efficiently in strong longitudinal magnetic fields.
ACKNOWLEDGMENTS

The authors thank PARAmed Medical Systems, Inc. (North Andover, MA) for allowing access to data for Fig. 3. Partial funding for this work was provided by the Alberta Cancer Foundation and the Natural Sciences and Engineering Research Council of Canada.

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