Magnetic decoupling of the linac in a low field biplanar linac-MR system

J. St. Aubin
Department of Physics, University of Alberta, 11322-89 Avenue, Edmonton, Alberta T6G 2G7, Canada
and Department of Oncology, Medical Physics Division, University of Alberta, 11560 University Avenue, Edmonton, Alberta T6G 1Z2, Canada

S. Steciw
Department of Medical Physics, Cross Cancer Institute, 11560 University Avenue, Edmonton, Alberta T6G 1Z2, Canada and Department of Oncology, Medical Physics Division, University of Alberta, 11560 University Avenue, Edmonton, Alberta T6G 1Z2, Canada

B. G. Fallone
Department of Physics, University of Alberta, 11322-89 Avenue, Edmonton, Alberta T6G 2G7, Canada; Department of Medical Physics, Cross Cancer Institute, 11560 University Avenue, Edmonton, Alberta T6G 1Z2, Canada; and Department of Oncology, Medical Physics Division, University of Alberta, 11560 University Avenue, Edmonton, Alberta T6G 1Z2, Canada

(Received 26 April 2010; revised 26 July 2010; accepted for publication 27 July 2010; published 17 August 2010)

Purpose: The integration of a low field biplanar magnetic resonance (MR) imager and linear accelerator (linac) causes magnetic interference at the linac due to the MR fringe fields. In order to eliminate this interference, passive and active magnetic shielding designs are investigated.

Methods: The optimized design of passive magnetic shielding was performed using the finite element method. The design was required to achieve no greater than a 20% electron beam loss within the linac waveguide and electron gun, no greater than 0.06 T at the multileaf collimator (MLC) motors, and generate a distortion of the main MR imaging volume of no greater than 300 ppm. Through the superposition of the analytical solution for a single current carrying wire loop, active shielding designs in the form of three and four sets of coil pairs surrounding the linac waveguide and electron gun were also investigated. The optimized current and coil center locations that yielded the best cancellation of the MR fringe fields at the linac were determined using sequential quadratic programming.

Results: Optimized passive shielding in the form of two steel cylinders was designed to meet the required constraints. When shielding the MLC motors along with the waveguide and electron gun, the thickness of the cylinders was less than 1 mm. If magnetically insensitive MLC motors are used, no MLC shielding would be required and the waveguide shield (shielding the waveguide and electron gun) became 1.58 mm thick. In addition, the optimized current and coil spacing for active shielding was determined for both three and four coil pair configurations. The results of the active shielding optimization produced no beam loss within the waveguide and electron gun and a maximum MR field distortion of 91 ppm over a 30 cm diameter spherical volume.

Conclusions: Very simple passive and active shielding designs have been shown to magnetically decouple the linac from the MR imager in a low field biplanar linac-MR system. The MLC passive shielding produced the largest distortion of the MR field over the imaging volume. With the use of magnetically insensitive motors, the MR field distortion drops substantially since no MLC shield is required. The active shielding designs yielded no electron beam loss within the linac. © 2010 American Association of Physicists in Medicine. [DOI: 10.1118/1.3480482]

Key words: linac-MR, linear accelerator, finite element analysis, magnetic shielding

I. INTRODUCTION

The inability to track tumors and critical structures during treatment has motivated the design of linac-MR systems.1-3 Magnetic resonance (MR) imaging provides superior soft tissue contrast and multiple contrast mechanisms and is being used more and more in simulation and treatment planning for radiation therapy. Using the MR imager to visualize the tumor and critical structure locations in real-time during treatment, a more conformal treatment can be planned compared to current x-ray treatments. Continuous imaging of the tumor and organs at risk during treatment could then enable adaptive treatments with reduced margins. This could in turn allow for greater dose escalation at the tumor and greater normal tissue sparing.

The integration of the MR imager and linear accelerator (linac) creates several technical issues, among which is the magnetic interference of the linac. The close proximity of the linac to the MR imager causes its magnetic fringe fields to intersect the linac. The linac-MR system design proposed by our group consists of a low field 0.2 T biplanar magnet coupled to an in-line 6 MV linac. A functioning 0.29 m bore
proof of concept linac-MR system has been designed and presented previously. This paper furthers this work by presenting optimized magnetic shielding designs for a larger 0.7 m bore linac-MR system. This configuration has the linac to the side of the biplanar magnets with the x-ray beam penetrating the open MR bore. This causes the linac to be intersected by the magnetic fringe field perpendicular to its length. The transverse magnetic fringe fields cause the electrons accelerating within the waveguide to deflect from their straight course according to the Lorentz force, possibly causing an unusable radiation beam. The linac-MR system presented by Raaymakers et al. also has the linac submerged in transverse magnetic fringe fields, but from a 1.5 T MR imager in their design. Their proposed magnetic shielding design is to alter the active shielding of the MR imager to create a region of low magnetic field at the electron gun. However, if the active shielding does not reduce the magnetic fringe fields sufficiently, additional passive or active shielding may be required. The design of passive and active shielding presented here can be applied to any situation in which similar magnetic field strengths are directed perpendicular to an in-line 6 MV linac.

Passive shielding as a method to reduce the electron deflections within the waveguide was initially presented by our group according to the constraint that the linac could only operate in a maximum $0.5 \times 10^{-4}$ T field, about the Earth’s magnetic field strength. However, since that time, investigations performed on linac operation within a transverse magnetic field have shown this constraint to be overly restrictive. The newly understood linac tolerances to an external transverse magnetic field allows for passive shielding designs to be reoptimized. The process of reoptimization allowed for a significant reduction in the shielding weight, a shorter target-to-isocenter distance, and reduced inhomogeneity of the main magnetic field. The larger linac tolerances to an external transverse magnetic field also admit simple active shielding designs as a method to reduce the magnitude of the magnet fringe fields. Designs based on a strict $0.5 \times 10^{-4}$ T net field limit would be extremely complicated or impossible. A study of the effectiveness of a simple passive shielding design to reduce the magnetic fringe fields at the linac culminating in an optimized design is presented. In addition to the presentation of an optimized passive shielding design, a study to determine the feasibility and effectiveness of the use of a simple active shielding design is performed. The results of these two studies show the ease in which the linac can be magnetically decoupled from the MR imager in a low field biplanar linac-MR system.

II. METHODS

II.A. Linac operational tolerance

If the magnetic fringe fields at the location of the waveguide and electron gun are large enough to cause sufficient deflections of the accelerating electrons to cause an unusable x-ray beam, magnetic shielding would be required to shield the electrons from the external magnetic fields. In order to optimize passive magnetic shielding, a constraint dictating the maximum acceptable electron beam loss within the linac was chosen. The optimization of the passive magnetic shielding minimized the amount of shielding required while meeting the chosen beam loss constraint. Less magnetic shielding material translates into less perturbation of the main magnetic field of the MR imager. An operational constraint of the maximum beam loss acceptable due to the magnetic field was set to an additional 20% beam loss over nominal in this investigation. Asymmetry in the electron focal spot for an approximately 20% beam loss was presented previously. After proper linac commissioning (see Ref. 4), the lateral shift in the dose profile was calculated to be 1 mm. This is easily compensated by using appropriate jaw or MLC shifts. The calculation of beam loss was performed using the particle-in-cell program PARMELA (Los Alamos National Laboratory, NM). The details of its application to our developed linac simulation, including calculation of magnetic field effects, have been presented previously.

It should be noted that the 2.10 m width (and the resulting center to edge distance of 1.05 m) of the biplanar MR imager makes the minimum possible target-isocenter distance approximately 1.72 m. Thus, including the dose rate reduction caused by the larger target-isocenter distance and the 20% beam loss, the nominal 250 MU/min dose rate of a Varian (Palo Alto, CA) 600C linac would be reduced to around 68 MU/min. The focus of this investigation, however, is the reduction of magnetic field effects on linac operation and these low dose rates are mostly a result of the target-isocenter distances dictated by geometry. However, up to a 20% reduction in dose rate may be compensated by the yield and dose rate servos of the 600C, although this means running the linac outside of the manufacturer specifications. This could bring the dose rate up to 85 MU/min. Despite not being investigated here, the dose rate could be increased further by restricting the field size and making the flattening filter thinner, or by removing the flattening filter altogether and performing intensity modulated radiation therapy. An increase in dose rate could also be achieved by interchanging the Varian 600C linac with a Varian 600C/D or 6EX whose nominal dose rates are up to 600 MU/min. However, since these other linacs have the same length and energy as the 600C, the same shielding requirements and designs presented here are expected to apply.

II.B. Finite element analysis and passive shielding

The finite element method (FEM) program COMSOL MULTIPHYSICS (Burlington, MA) was used to simulate the magnetic fields of a low field (0.2 T) biplanar magnet and to optimize passive shielding designs. All FEM simulations were performed using Delaunay triangulation, quadratic basis functions, and sufficient mesh elements in high gradient areas to ensure the maximum possible accuracy of the solution in the regions of interest. The low field 0.2 T MR imager modeled (Fig. 1) was a permanent magnetic system, 1.98 m in height with a $2.10 \times 2.10$ m² base. Passive shielding was designed as a 40 cm long and 80 cm inner diameter steel cylinder surrounding the multileaf collimators (MLCs) to-
gether with a 60 cm long and 36 cm inner diameter steel cylinder surrounding the linac waveguide and electron gun (seen in Fig. 1). The steel mounting flange modeled is axisymmetric with a radius of 29 cm and an equivalent thickness of 6 cm. It separates the waveguide and primary collimator from the rest of the linac components including the MLCs. The magnetic shielding is divided into two sections separated by the steel mounting flange. The first section closest to the magnet (MLC shield) is required to shield the MLC motors, but also encompasses the jaws and monitor chamber. The second section further back from the magnet (waveguide shield) is designed to shield the waveguide and electron gun, but also surrounds the primary collimator. The holes in the waveguide shield (Fig. 1) are required to connect the wires from the electron gun to the modulator cabinet and feed the accelerating RF into the linac waveguide through a rectangular transmission waveguide. The hole in the MLC shield provides an opening for the x-ray beam to pass unattenuated. The addition of these holes is contrary to the optimal shielding design of a completely closed container, drawing in the largest number of field lines and thus creating the maximum possible shielding effect. An investigation of the effectiveness of the cylindrical shielding design incorporating the required holes was performed by varying the cylinder thickness as well as its distance away from the magnet edge. The close proximity of the steel magnetic shielding and the MR imager causes increased inhomogeneity of the main magnetic field over the imaging volume. By mirroring the shielding structure on the opposite side of the MR imager (as seen in Fig. 1), the inhomogeneity can be reduced by creating a more symmetric distortion of the magnetic field. Large inhomogeneities would manifest as image distortions, reducing the accuracy in which the tumor or critical structure could be localized.

The optimal passive shielding design was required to meet three major constraints. First, the waveguide shield was required to reduce the magnetic field throughout, such that a maximum beam loss of 20% was not exceeded during linac operation. Second, the MLC shield was required to reduce the field at the MLC motors to below 0.06 T.9 The third constraint imposed a minimum thickness of shielding at the shortest target-isocenter distance that yielded a preshim inhomogeneity of the main magnetic field below 300 ppm over a 30 cm diameter spherical volume (DSV). The maximum preshim inhomogeneity of 300 ppm was chosen after discussions with the National Research Council of Canada (Winnipeg, Canada). From experience, they consider a 300 ppm distortion over the 30 cm DSV manageable with current shimming methods.10

II.C. Active shielding

Active shielding in the form of a current driven independently through three or four coil pairs (Fig. 2) was investigated as a possible alternative to passive shielding. The advantage of active shielding is the possible elimination of any electron beam loss within the linac. A disadvantage of active shielding, however, is the added complexity and cost. The design of the active shielding was constrained to three or four coil pairs. All coils in the “three coil pair” configuration had diameters of 20 cm while the coils in the “four coil pair” configuration had diameters of 10 cm. The vertical separation between two adjacent coils was set to 5 cm (Fig. 2) in order to eliminate any possible physical overlapping of coils. The smallest separation between coils in a coil pair was 17 cm, just larger than the diameter of the waveguide including the coupling cavities, and the adjacent coil pair had a separation of 27 cm.

The net active shielding magnetic field solution, normalized per unit current, was generated using superposition of the solution for a single current loop calculated from the following formulas:

![Fig. 1](image1.png)

**Fig. 1.** The design and configuration of the biplanar magnet and a cutaway section of the proposed passive shielding. The presence of the shielding on the opposite side the biplanar MR reduces the inhomogeneity of the main magnetic field.

![Fig. 2](image2.png)

**Fig. 2.** The active shielding designs surrounding a cut-away section of the linac electron gun and waveguide for (a) the three coil pair and (b) the four coil pair configurations.
In Eq. (52), the coordinates by the following transformations:

\[
\begin{align*}
B_z(r, z) &= -\frac{\mu_0(z-h)}{2\pi\sqrt{(r+a)^2 + (z-h)^2}} \left[ f + \frac{2aE(k)}{[(r+a)^2 + (z-h)^2](1-k^2)} \right], \\
B_r(r, z) &= \frac{\mu_0}{2\pi\sqrt{(r+a)^2 + (z-h)^2}} \times \left[ K(k) + E(k) \times \left( \frac{2a(r+a)}{[(r+a)^2 + (z-h)^2](1-k^2)} - \frac{1}{1-k^2} \right) \right].
\end{align*}
\]

(1a, 1b)

with \( k = \sqrt{\frac{4ar}{(r+a)^2 + (z-h)^2}} \)

(1c)

and

\[
f = \frac{4a}{(r+a)^2 + (z-h)^2} \int_0^{\pi/2} \frac{\sin^2 \alpha - 1}{(1-k^2)^{\frac{3}{2}} - \sin^2 \alpha} d\alpha.
\]

(1d)

In Eq. (1), \( h \) is the height above the \( z=0 \) plane, \( a \) is the ring radius, \( \mu_0 \) is the permeability of free space, and \( K(k) \) and \( E(k) \) are complete elliptic integrals of the first and second kinds, respectively.\(^{11} \) The cylindrically symmetric solutions given in Eq. (1) were transformed into Cartesian \( xyz \) coordinates by the following transformations:

\[
B_x(x, y, z) = \pm B_r \cdot \frac{1}{\sqrt{1 + (y/x)^2}},
\]

(2a)

\[
B_y(x, y, z) = \pm B_r \cdot \frac{y}{x \sqrt{1 + (y/x)^2}},
\]

(2b)

and \( r = \sqrt{x^2 + y^2} \).

(2c)

with the \( \pm \) set depending on which quadrant in the \( xy \) plane the solution was determined in. Thus, through a superposition of the solutions from Eq. (1) and the transformation of Eq. (2), the net active shielding field could be determined for the three or four coil pairs with varied lateral separations (\( z \) positions). The \( z \) location of each coil pair along the waveguide and electron gun, together with the total current \( nI \), was optimized using the sequential quadratic programming routine in the Mathworks program MATLAB (Natick, MA) to create the best cancellation of the magnetic fringe fields. The total current \( nI \) represents the number of wire turns \( n \) and the driving current \( I \).

III. RESULTS AND DISCUSSION

III.A. No shielding

The magnetic fringe fields from the biplanar MR imager are shown in Fig. 3. As shown in the inset of Fig. 3(b), the electron gun experiences 0.0033 T at the cathode and 0.0092 T at the target. These fields create substantial electron deflections within the electron gun and waveguide, resulting in all electrons impacting the electron gun and waveguide walls and none reaching the target. The FEM biplanar magnet with its rose ring design provided a calculated preshime distortion of the main magnetic field of 81 ppm over a 30 cm DSV. The field strength at the location of the MLC motors (around 1.1 m from isocenter) was calculated to be 0.1273 T, well over their tolerance limit.\(^{9} \)

III.B. Passive shielding

The magnetic field strength at the linac calculated for different separations between the magnet edge and MLC shielding at various shielding thicknesses is given in Fig. 4. The target-isocenter distance for a 0 m separation [Fig. 4(a)] is 1.72 m. Figure 4 also clearly shows that the effectiveness of the passive shielding decreases as the field strength decreases. The field decrease observed by increasing the steel shielding thickness from 0.75 to 2 mm is larger than the decrease from 5 to 10 mm. Thus, the difficulty of trying to restrict the magnetic field within the linac to less than 0.5 \( \times 10^{-4} \) T becomes readily apparent. Very large slabs of steel and even the introduction of extremely high permeability material such as Mu-metal\textsuperscript{TM} are required. Under the assumption that the entire linac required shielding to 0.5 \( \times 10^{-4} \) T, our group initially presented a passive shielding.
design resulting in a 2.1 m target-isocenter distance and a homogeneity of 321 ppm over a 30 cm DSV.

In contrast to the shielding design restricting the field at the linac to $0.5 \times 10^{-4}$ T, a more optimal design can be determined with the use of the known linac response to an external magnetic field. According to the constraints listed in Sec. II B, the optimal shielding configuration was determined to be a 0.9 mm thick waveguide shield together with a 0.75 mm thick MLC shield located 2.0 cm from the magnet edge resulting in a target-isocenter distance of 1.74 m. Figure 5(a) gives the magnetic field distribution around the MR imager including the effects of the optimized shielding. Figure 5(b) shows the magnetic field at the linac within the optimized shielding. This shielding design resulted in a 0.04472 T field at the MLC motors, an inhomogeneity of 298 ppm over a 30 cm DSV, and a $20 \pm 1\%$ beam loss. This more optimal shielding design represents three times reduction in shielding weight and a 46% increase in dose rate caused by the closer target-to-isocenter distance compared to the initial design. A 0.75 mm thin MLC cylinder was the thinnest ge-

---

**Fig. 4.** The magnetic field within the linac calculated for 0.75, 2, 5, and 10 mm thicknesses of the MLC and waveguide shield (Fig. 1) at separations between the magnet edge and MLC shield of (a) 0, (b) 0.05, (c) 0.1, (d) 0.15, and (e) 0.2 m. The target is located at 0 m and the electron gun cathode at 0.3 m.

**Fig. 5.** (a) A 2D field map of the linac-MR system including the MLC optimized shielding overlaid on the finite element mesh. (b) The magnetic field strength at the location of the linac resulting from the magnetic shielding. The target is located at 0 m and the electron gun cathode at 0.3 m.

**Fig. 6.** (a) A 2D field map of the linac-MR system overlaid on the finite element mesh. (b) The magnetic field strength at the location of the linac resulting from the magnetic shielding. The target is located at 0 m and the electron gun cathode at 0.3 m.
Figure 7. The fringe field of the biplanar magnet, the individual coil magnetic fields, and the sum of the coil fields are shown for (a) the three coil pair configuration [Fig. 2(a)] and (b) the four coil pair configuration [Fig. 2(b)]. The net field at the linac is shown directly under the field plots. The target is located at 0 m and the electron gun cathode at 0.3 m.

ometry that could be meshed while maintaining the accuracy of the solution resulting in the slight over shielding of the MLCs.

The MLC shield was the main contributor to the inhomogeneity of the main magnetic field. Under the assumption that all magnetic parts of the MLC were changed to nonmagnetic ones (e.g., the steel backplate changed to stainless steel) and by replacing the typical brushed permanent magnet DC MLC motors with motors designed for use in MR environments,12 there would be no need for MLC shielding. With no MLC shielding, the optimal waveguide shield thickness became 1.58 mm with no separation between the MLCs and the magnet edge yielding a $20 \pm 1\%$ beam loss. This design represents a significantly reduced inhomogeneity which was calculated to be 85 ppm over a 30 cm DSV. It also provides an additional 10% reduction in weight, and with its target-isocenter distance of 1.72 m, it provides a further 2.3% increase in dose rate compared to the design with a MLC shield. Figure 6(a) gives the magnetic field distribution around the MR imager including the effects of the optimized shielding. Figure 6(b) shows the magnetic field at the linac within the optimized shielding.

### III.C. Active shielding

Under the assumption that no MLC shielding was required and the steel mounting flange was removed, active shielding was optimized to reduce the fringe fields within linac. The results from the optimization for the three and four coil pair active shielding are given in Fig. 7 for a 1.72 m target-isocenter distance. The optimized locations and total currents for both active shield configurations are summarized in Table I. Using the net field as an input into our linac simulation,4,7,13 both the three and four coil pair configurations proved to provide sufficient cancellation of the fringe field such that no electron beam loss was observed. In addition, compared to our simulation without a magnetic field,7 the beam centroid at the target shifted by 0.01 and 0.001 cm for the three and four coil pair configurations, respectively. These small beam centroid shifts have no impact on the dose distributions as presented previously,7 with Monte Carlo studies showing greater than 99% of all points meet a 1%/1 mm acceptance criterion at a 40 x 40 cm$^2$ field size. The four coil pair configuration provided the best cancellation of the fringe field as seen from the smaller beam centroid shift at the target and the smaller net magnetic field at the linac [Fig. 7(b)]. Both three and four coil optimized configurations can be manufactured and require nothing but adequate ventilation during use. After calculating the field variation caused by the active shielding fringe fields over the 30 cm DSV, the inhomogeneity is expected to be approximately 91 ppm for the three coil configuration and 87 ppm for the four coil configuration.

### IV. CONCLUSION

Simple and effective means of magnetically decoupling a 6 MV in-line linac for use in a biplanar linac-MR system have been presented. Using current MLC systems which incorporate brushed permanent magnet DC motors, a 0.75 mm thick cylinder of steel was all that is required to allow the MLCs to operate in close proximity to a low field biplanar linac-MR system. With this MLC shield in place, the steel mounting flange together with a 0.9 mm thick cylinder around the waveguide and the electron gun produced a $20 \pm 1\%$ electron beam loss. With this MLC, flange, and waveguide shield combination, a preshim distortion of the main magnetic field of the MR imager was calculated to be 298 ppm over a 30 cm DSV. With the use of magnetically insensitive motors, no MLC shield would be required and the thickness of the waveguide shield behind the steel flange

| Table I. The optimized total current (nI) and location of each coil pair in both configurations shown in Fig. 2 is given. The optimized locations are measured with respect to the target location at 0 m. |
|---|---|---|---|
| **Total current (nI)** | **Coil center location (m)** |
| **Three coil pair configuration** | 1111.3 | 2380.8 | 583.8 |
| | −0.0562 | 0.0938 | 0.2813 |
| **Four coil pair configuration** | 2077.6 | 5909.2 | 728.7 | 3119.9 |
| | −0.0260 | 0.0763 | 0.1851 | 0.2889 |

Medical Physics, Vol. 37, No. 9, September 2010
grew to 1.58 mm, maintaining a $20 \pm 1\%$ electron beam loss. With only the steel flange and waveguide passive shield, the distortion of the main magnetic field was calculated to be 85 ppm over a 30 cm DSV. As an alternative to passive shielding, with no MLC shield or steel flange, active shielding was optimized. The optimizations of coil current and location for the active shielding designs studied produced excellent results with no beam loss within the linac and a maximum distortion of the MR field of 91 ppm over a 30 cm DSV.

---

Electronic mail: ginofall@cancerboard.ab.ca


