Dosimetry in the presence of strong magnetic fields

D J O’Brien1, N Schupp2, S Pencea2, J Dolan2 and G O Sawakuchi1
1Department of Radiation Physics, University of Texas MD Anderson Cancer Center, Houston, TX 77030, USA
2Elekta Software, Elekta A. B., Maryland Heights, MO 63043, USA

E-mail: dobrien@mdanderson.org; gsawakuchi@mdanderson.org

Abstract. Magnetic resonance imaging–guided radiotherapy (MRIgRT) is an emerging technology that requires the use of radiation fields in the presence of magnetic (B) fields. In the presence of B-fields the Lorentz force influences the trajectories of the secondary electrons, which in turn affects both the dose distribution in water and the dose-response of ionization chambers and several other detectors. Thus, dosimetry in the presence of a B-field requires understanding both the B-field effects on the dose distribution and the response of detectors. In this paper we present measured data to show effects of the B-field on the dose distributions, response of ionization chambers, and presence of air-gaps surrounding the sensitive volume of the detector.

1. Introduction
Magnetic resonance imaging–guided radiotherapy (MRIgRT) integrates an MRI scanner with a radiotherapy source such as a linear accelerator or 60Co for volumetric imaging guidance of the radiation beam. MRIgRT provides real-time imaging during patient treatment. MRIgRT also provides much higher soft-tissue contrast than that of conventional computed tomography (CT)-based image guided radiotherapy (IGRT) techniques such as cone-beam CT or CT on rails [1, 2]. As a result, there is great interest in developing new external-beam radiotherapy machines with integrated MRI [3-7]. However, since MRI requires magnetic (B) fields, the Lorentz force influences the trajectories of the secondary electrons, which in turn affects both the dose distribution in water [1, 8, 9] and the dose-response of ionization chambers [6, 10-12] and several other detectors [13, 14]. Thus, dosimetry in the presence of a B-field requires understanding both the B-field effects on the dose distribution and the response of detectors.

Further, how the detector is positioned relative to the B-field orientation and the beam direction also influences its response. The detector orientation relative to the Lorentz force deserves attention because of variations in the design of new MRIgRT units. The Cross Cancer Institute in Canada is developing a linac-based MRIgRT unit in which B-field orientation can be switched either longitudinally or transversely relative to the beam direction [5]. Elekta is designing a linac-based MRIgRT unit with a 1.5-T B-field fixed in a transverse configuration relative to the beam direction [15]. The Ingham Research Institute is developing an open-bore linac-based MRIgRT [7]. ViewRay has a 60Co-based MRIgRT unit with low B-field strength (0.35 T) transverse to the plane of three 60Co sources [3, 4] and is now developing a linac-based unit.

In this paper we present measured data to show the effects of the B-field on the dose distributions and on the response of ionization chambers, including the effect of air-gaps surrounding the sensitive volume of the detector.
2. Methods

Measurements were performed at The University of Texas MD Anderson Cancer Center using the Elekta MR-linac system. The Elekta MR-linac has a 7-MV flattening filter free beam and closed-bore design with a 1.5-T B-field. The isocenter is at 143.5 cm from the source. We performed measurements using either an in-house Elekta MRI-compatible 3D water phantom (63 × 43 × 24 cm³) or a mixture of 30 × 30 cm² water-equivalent plastic slabs (Solid Water, Gammex RMI, Middleton, WI; and Virtual Water, Standard Imaging, Middleton, WI). We performed measurements with the magnet both ramped up at 1.5 T and ramped down at 0 T to compare the dose distributions in the presence and absence of a 1.5-T B-field.

All measurements performed in this work were done at a source-to-surface distance (SSD) of 133.5 cm. The isocenter was located at a water equivalent depth of 10 cm at a source-to-axis distance (SAD) of 143.5 cm. A 10 × 10 cm² field size defined at isocenter was used for all measurements. At least 10 cm of backscatter material was also present. Detectors were aligned by using an on-board MV imaging system.

Percentage depth dose (PDDs) and lateral profiles were measured in water using a PTW 60019 microDiamond detector and a PTW TANDEM electrometer. PDDs were scanned from the water surface to just beyond a depth of 10 cm. Profiles were measured at a depth of 10 cm.

The effect of air-gaps in plastic phantoms on the signal from three Farmer-type ionization chambers (PTW 30013, PTW 30010 and NE2571) was assessed with water-equivalent plastic slabs with the chamber placed inside a machined hole that conformed to the shape of the chamber. Each ionization chamber was rotated about its axis in increments of 45° and the response as a function of rotation angle was recorded both with and without the magnetic field.

3. Results and Discussions

3.1. PDD and Dose Profiles

Figure 1 shows PDDs for a 10 × 10 cm² field measured with and without a 1.5-T B-field. The depth of maximum dose \( d_{\text{max}} \) is 1.3 cm and 1.7 cm, respectively. The B-field shifts \( d_{\text{max}} \) 4-5 mm towards the water surface. The trajectories of the secondary electrons are curved by the Lorentz force, which reduces their overall range and leads to compression of the build-up region. Beyond the build-up region, the reduced electron range has shifted the depth dose curve closer to the depth kerma curve. This shift results in a 0.5% lower dose at these depths for the same photon fluence [12]. More significantly, the compression of the build-up region enhances the dose at \( d_{\text{max}} \) by 1.9%. Both of these effects have a corresponding effect on the PDD (Figure 1). As a result, the use of the PDD as a beam quality specifier must be re-examined in the presence of a B-field in terms of its relationship to the stopping power ratios. In contrast, alternative beam quality specifiers, such as the \( TPR_{10}^{20} \), that depend on dose ratios in the transient equilibrium region are relatively unaffected by the B-field [12].

Note that in closed bore systems, such as the Elekta MR-linac, the cryostat acts as an additional source of contaminant electrons which also have the effect of shifting \( d_{\text{max}} \) closer to the surface [12]. These electrons are swept away when a transverse B-field is present and do not significantly influence the surface dose. Since electron contamination increases with field size, the relative shift in \( d_{\text{max}} \) between with and without a B-field is greater for field sizes smaller than 10 × 10 cm² and less for larger fields. The opposite may be true with inline MR-linac configurations where the beam and B-field are parallel, as the confining effect of the B-field on contaminant electrons in this configuration enhances the surface dose and changes the PDD relative to the case without a B-field [16].

Figure 2 shows lateral dose profiles with and without the B-field at a depth of 10 cm for a 10 × 10 cm² field size. In the presence of the B-field, the lateral dose profile is shifted by approximately 1 mm in the direction of the Lorentz force and the penumbra becomes asymmetric. Going from left to right on Figure 2, the penumbra starts sharp but becomes broader than the 0 T case as it enters the beam,
whereas on the other side of the profile the opposite is true. Profiles measured in the direction parallel to the B-field are not significantly affected by the B-field.

![Figure 1](image-url)

**Figure 1.** Percentage depth dose curves measured for a 10 × 10 cm² field with and without a 1.5 T magnetic field. These measurements were taken with a PTW 60019 microDiamond detector in a water phantom.

### 3.2. Ionization chamber response

Meijsing et al. [10] showed that the presence of a B-field can change the response of a Farmer-type ionization chamber by up to 11% depending on the B-field strength and on the orientation of the B-field with respect to the beam. The magnitude of the effect reaches a maximum at approximately 1 T over the range of B-fields that has been studied (≤2 T). The reason for this change in response was explained by Meijsing et al. as the result of the curving of the electron trajectories inside the air cavity of the ionization chamber, which resulted in the average path lengths of electrons traversing the cavity changing as a function of B-field strength and cavity geometry.

Reynolds et al. [11] found results similar to those of Meijsing et al. and showed that the orientation of the B-field with respect to the chamber itself also has an effect. They also found that the response of ionization chambers was relatively stable for inline MR-linacs where the B-field is parallel to the beam. In that case, they found that the chamber response did not require correction for B-fields up to 1 T regardless of the orientation of the chamber. O’Brien et al. [12] proposed a general formalism for reference dosimetry in the presence of a B-field, and they also calculated correction factors for a range of Farmer chambers for the transverse 1.5-T Elekta MR-linac system, where the beam is always perpendicular to the magnetic field. In this configuration, they showed that the correction for chambers that are aligned parallel to the B-field (1.5 T) (Figure 3a) is less than 1%. However, they also found a distinction between the two perpendicular orientations depicted in Figure 3b and Figure 3c. In Figure 3b, the chamber is rotated 90° clockwise from the parallel orientation and in this configuration the correction for the chamber response is about 4% for each of the chambers that were examined. However, in Figure 3c, the chamber is rotated 90° counter-clockwise from the parallel orientation, and in this configuration the chamber response correction was found to vary between 2.4% and 4.4% depending on the chamber model.

The reason for this discrepancy is because, in the perpendicular orientations, the chamber geometry is asymmetric with respect to the direction of the Lorentz force (which is perpendicular to the B-field). In the clockwise orientation, the Lorentz force is directed towards the stem of the chamber, whereas in the counter-clockwise orientation the Lorentz force is directed away from the chamber stem. Consequently, the geometry and materials used in the electrode and stem (which
vary between different chamber models) become more important in the counter-clockwise orientation, as electrons generated in the stem are directed towards the sensitive volume of the chamber by the Lorentz force. Therefore, it is important to be aware of which perpendicular orientation is being used, and it is advisable to use the parallel orientation instead wherever possible.

![Figure 2](image_url)

**Figure 2.** Lateral dose profiles measured for a $10 \times 10 \text{ cm}^2$ field at 10 cm depth with and without a 1.5-T B-field. These measurements were taken with a PTW 60019 microDiamond detector in a water phantom.

### 3.3. Air gaps

Plastic phantoms are a convenient tool for routine quality assurance (QA) owing to their portability and ease of setup. In the case of MR-linacs, they are particularly attractive because of the limited space available inside the MRI bore. However, Hackett et al. [17] recently showed that ionization chambers exhibit a significantly increased rotational dependence in the presence of a B-field when used in plastic phantoms. This effect was attributed to the presence of sub-millimeter air gaps surrounding the chamber inside the phantom insert cavity. This was established by virtue of the fact that this effect was not observed when measured in water phantoms or when the insert cavity was filled with water.

Figure 4 shows the variation of three different Farmer chambers (PTW 30013, PTW 30010, and NE2571) as they were rotated about their long axis inside a plastic phantom when no B-field was present. In almost every case, the variation from the mean value was less than 0.1%. However, when a 1.5-T B-field is applied (Figure 5), some of the variations are greater than ±1% of the mean value depending on the detector and phantom used.

This is a problem for performing reference dosimetry with non-waterproof ionization chambers, in which either plastic sleeves or water phantoms with plastic inserts are used, because this variation exceeds the recommended tolerance of 0.5% [18]. It also presents a problem for performing routine QA in plastic phantoms, as consistent readings cannot be guaranteed. The air gaps responsible for these effects are very small, with Hackett et al. demonstrating an effect with a gap on the order of 0.1 mm thick.

Figure 5 shows that the effect can vary between two similarly constructed ionization chambers in the same phantom (the outer geometry of the PTW 30010 and PTW 30013 Farmer chambers are almost identical). Figure 5 also suggests that phantom/chamber combinations can be designed that reduce this effect to less than the 0.5% tolerance value, as was the case for the NE2571 chamber in phantom B. However, this would probably be difficult to achieve in general given the detector-to-detector variations.
Figure 3. Three distinct ionization chamber orientations with respect to the magnetic field: (a) chamber parallel with magnetic field, (b) chamber rotated 90° clockwise from the magnetic field and (c) chamber rotated 90° counter-clockwise from the magnetic field.

Consequently, for any work involving the use of plastic phantoms in a B-field, the presence and effect of any sub-millimeter air gaps near the dosimeter must be carefully assessed and characterized.

Figure 4. Variation of Farmer chamber response relative to the mean as a function of rotation about the detectors’ long axis inside a plastic phantom with no magnetic field. Three detectors in two phantoms are shown.
Figure 5. Variation of Farmer chamber response relative to the mean as a function of rotation about the detectors’ long axis inside a plastic phantom in a 1.5 T magnetic field. Three detectors in two phantoms are shown. For clarity of presentation, the phase of oscillation of each data set has been aligned.

4. Conclusions
In the presence of B-fields, the Lorentz force perturbs the dose distribution by altering the trajectory of charged particles, which in turn affects the response of detectors. The results presented here are meant to highlight several basic effects that must be accounted for when performing dosimetry measurements in B-fields. The effects presented here are not comprehensive, and more research is needed to understand whether the standard dosimetric methods can be used in the same way in the presence of B-fields. Specific topics to be investigated include the calculation and validation of B-field correction factors for commercially available ionization chambers, investigation of the definition of the effective point of measurement in B-fields, and the study of polarity and ion recombination effects. B-field effects similar to those observed with ionization chambers may also need to be considered when using other detectors. Thus, more research is needed to develop and implement detectors to facilitate machine and patient treatment QA. Detailed investigations of these effects are important to understand the limitations of standard radiation detectors when used in B-fields as well as to develop new procedures to calibrate and perform dosimetric QA of new MRgRT units. Particularly for QA of the MR-linac beam and patient plans, accurate dose distribution measurements are required. However, to date, only a few two-dimensional (2D) dosimetry systems have been investigated for use in the presence of B-fields [19, 20], and not many detection systems are commercially available. Therefore, development of new detectors that could be used in the presence of B-fields is essential to advance the field. Van Zijp et al. [21] have shown that many of the B-field effects on QA devices can be removed for the purposes of QA by incorporating electron-dense materials such as copper into their design. Because the MR-linac will require adaptive treatments with every fraction, QA of the adapted plans will be important. Thus, dosimetric systems that could provide accurate and fast 3D dose distribution measurements would be important for plan verification. Understanding the limitations of current dosimetric techniques in the presence of B-fields and developing new techniques to address current limitations are necessary for the safe implementation and full potential use of MRgRT.

5. Acknowledgments
This work was partially supported by Elekta.
6. References

[1] Raaymakers B W et al 2004 Phys. Med. Biol. 49 4109-18
[2] Lagendijk J J W et al 2008 Radiother. Oncol. 88 25-9
[3] Dempsey J F et al 2005 Int. J. Radiat. Oncol. 63 S202
[4] Dempsey J et al 2006 Med. Phys. 33 2254
[5] Fallone B G et al 2009 Med. Phys. 36 2084-8
[6] Smit K et al 2013 Phys. Med. Biol. 58 5945-57
[7] Oborn B M et al 2014 Med. Phys. 41 051708
[8] Raaijmakers A J E et al 2005 Phys. Med. Biol. 50 1363-76
[9] Raaijmakers A J E et al 2007 Phys. Med. Biol. 52 929-39
[10] Meijsing I et al 2009 Phys. Med. Biol. 54 2993-3002
[11] Reynolds M et al 2013 Med. Phys. 40 042102
[12] O’Brien D J et al 2016 Med. Phys. 43 4915-27
[13] Reynolds M et al 2014 Med. Phys. 41 092103
[14] Stefanowicz S et al 2013 Radiat. Meas. 56 357-60
[15] Raaymakers B W et al 2009 Phys. Med. Biol. 54 N229-37
[16] Liney G P et al 2016 Med. Phys. 43 5188-94
[17] Hackett S L et al 2016 Med. Phys. 43 3961-8
[18] International Electrotechnical Commission 1997 Medical electrical equipment – dosimeters with ionization chambers as used in radiotherapy (Genève) IEC 60731
[19] Smit K et al 2014 Phys. Med. Biol. 59 1845-55
[20] Houweling A C et al 2016 Phys. Med. Biol. 80 N80
[21] van Zijp H M et al 2016 Phys. Med. Biol. 50 N50