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Novel Theoretical Concepts for Supporting Reference Dosimetry of MRgRT Beams

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ABSTRACT

Key concepts of radiation dosimetry in the presence of a magnetic field are studied and linked to fundamental principles to support radiotherapy guided by magnetic resonance imaging (MRgRT) clinical dosimetry.

Monte Carlo simulations are used to investigate the breakdown of standard cavity theory in MRgRT through Fano's theorem and to characterize the extent of the dosimetric impact of airgaps.

Scaling the magnitude of the magnetic field with the electron density of the geometry re-establishes Fano's conditions and eliminates absorbed dose perturbations at heterogeneous interfaces. The impact of airgaps is shown to extend beyond the CSDA range of the electrons involved in the Electron Return Effect (ERE).

The present study provides valuable theoretical insights that support AAPM's TG-351 and IPEM's addendum Codes of Practice (CoP) and illustrates the challenges associated with clinical dosimetry of MRgRT beams.

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INTRODUCTION

Magnetic resonance guided radiation therapy (MRgRT) combines an MRI system with a medical linac to enable continuous anatomical imaging during treatment delivery. While MRgRT has undeniable advantages over conventional x-ray based IGRT, it poses challenges related to beam characterization and calibration due to the presence of the magnetic field at all times.

Under MV photon beam reference conditions without a magnetic field, an air cavity minimally perturbs the electron fluence crossing it. Thus, absorbed dose to water can be obtained from absorbed dose in the detector with small corrections. However, similarly to small and modulated photon beams, MRgRT beams produce conditions in which the detector can introduce severe electron fluence perturbations, breaking down the predictions of cavity theory and the underlying intuition required for clinical dosimetry.

In this work, Monte Carlo simulations are used to address and clarify fundamental concepts of dosimetry in the presence of a magnetic field, supporting the new Codes of Practice (CoP) for MRgRT reference dosimetry, i.e., AAPM's TG-351 [1] and IPEM's addendum [2], as well as future developments in MRgRT clinical dosimetry.

METHODS AND MATERIALS

Monte Carlo simulations are performed using EGSnrc v2025a. The magnetic field is implemented using the EEMF macro developed by Malkov and Rogers [3], with a 1.5 T magnetic field perpendicular to the irradiation beam for the presented simulations. A 6 MV photon beam spectrum from Mohan et al. [4] was used as the incident radiation source.

Percent depth doses (PDD) are scored with *egs_chamber* in a water phantom containing a heterogeneous region of variable density. Simulations are repeated first with a constant magnetic field across the geometry, then with a magnetic field that scales with the electron density of the medium, to evaluate the consequences of Fano's theorem violation.

Analytical track-length calculations are used to predict perturbations in the electron fluence differential in energy at low-density interfaces linked to the Electron Return Effect (ERE). Monte Carlo simulations of the fluence differential in energy of the electrons using *egs_VolumetricFluence* are used to support those predictions.

The impact of airgaps on secondary buildup distances is investigated as a function of gap size, using the dose-to-collisional-kerma metric (D/K_{coll}). Collisional kerma is calculated with *egs_kerma*.

RESULTS

Monte Carlo simulations of PDDs show dose perturbations at heterogeneous interfaces under a constant magnetic field strength. Scaling the magnetic field strength with the electron density eliminates these perturbations, as expected under the special Fano conditions. This behavior is observed for both high and low-density heterogeneities.

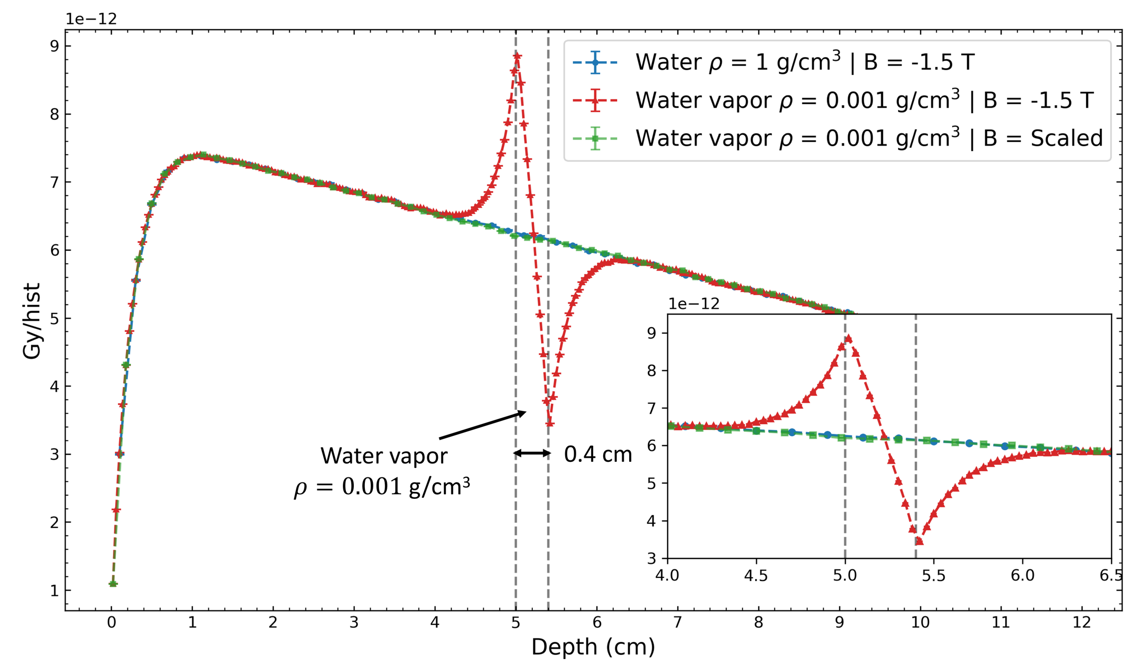

Figure 1. Effect of scaling the magnetic field with the electron density of the medium on a depth dose curve in water containing a heterogenous region (5.0-5.4 cm).

The Electron Return Effect (ERE) is characterized by three distinct regimes: (1) ERE with reduced electron path length, (2) ERE with increased electron path length, and (3) the absence of ERE. Analytical calculations of electron trajectories in vacuum provide a good approximation of the electron track length modification induced by the magnetic field and accurately predict the transition between these regimes.

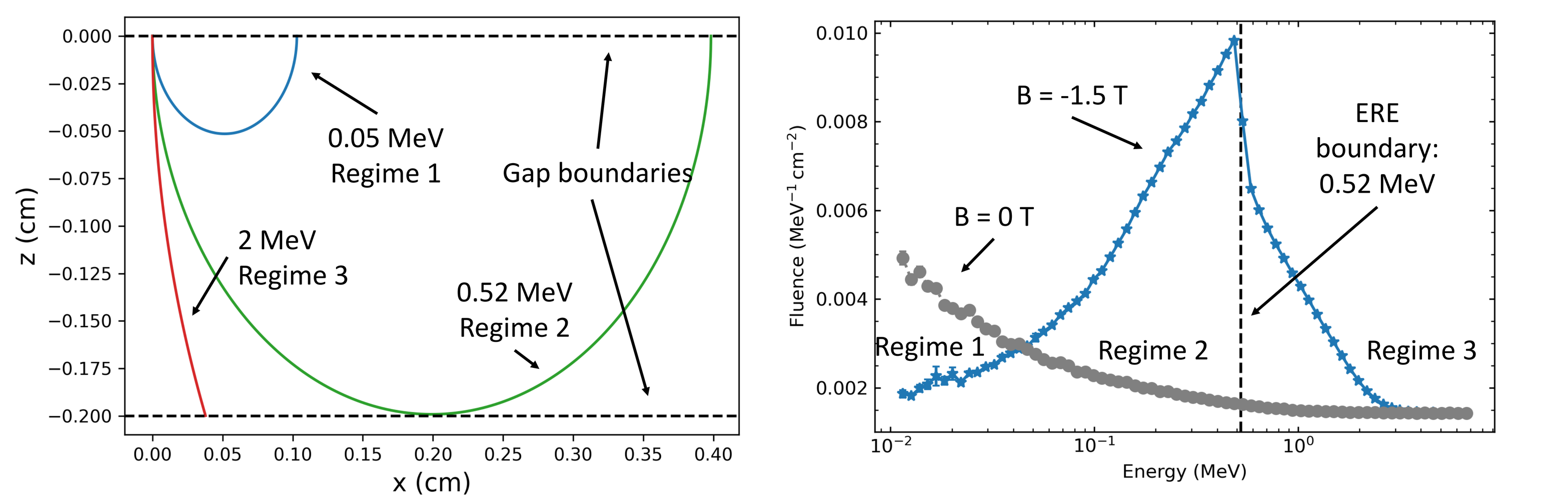

Figure 2. Electron tracks in a 0.2 cm gap with a magnetic field (-1.5 T) representing the three regimes: analytical calculation (left), and Monte Carlo simulation (right)

Air gaps alter the electron fluence spectrum, leading to a loss of charged particle equilibrium (CPE), the formation of a disequilibrium region upstream of the gap, and a secondary buildup region downstream of the gap. The extent of these regions increases with gap size before reaching a plateau for gaps larger than 0.4 cm. Both the upstream disequilibrium distance and the downstream secondary buildup distance remain shorter than d_{max}.

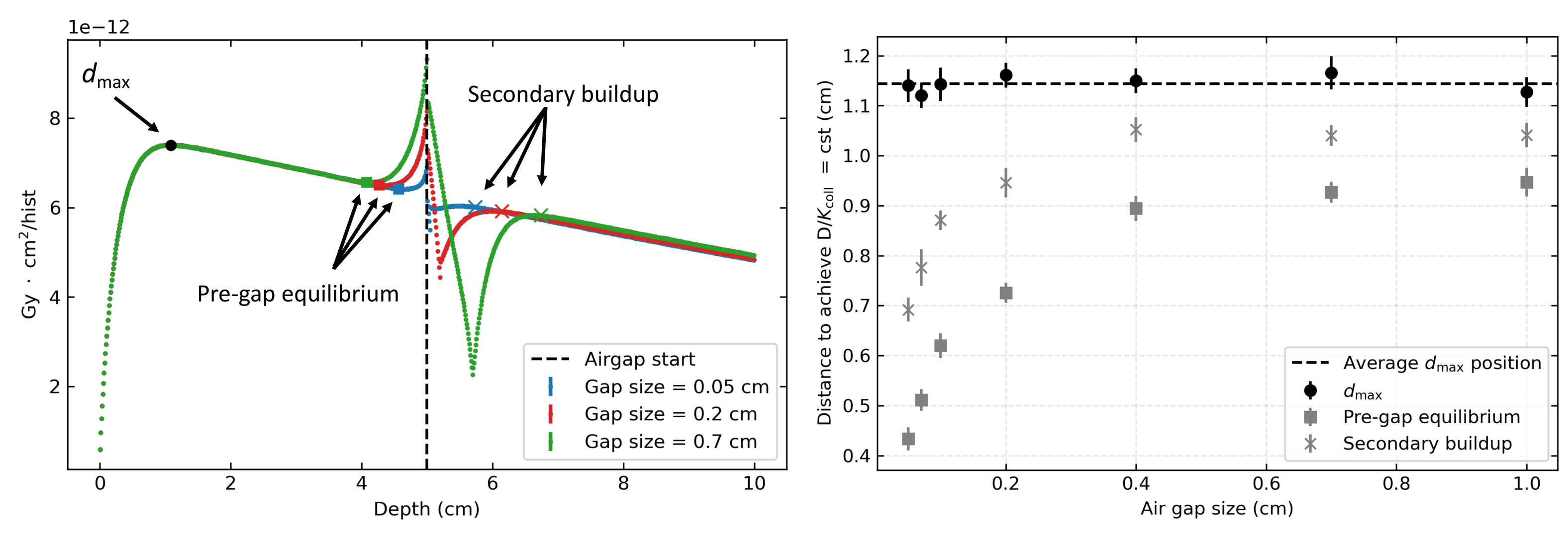

Figure 3. Dose perturbations for various gap sizes (left) and distance to achieve D/K_{coll} = cst as a function of air gap size (right). (B = 1.5 T)

DISCUSSION

These results demonstrate that the breakdown of cavity theory in MRgRT is not caused by the magnetic field itself, but by the violation of the conditions required for Fano's theorem to hold. This is consistent with the work of Bouchard *et al.* (2015) [5], who showed that, in the presence of an external irradiation beam, Fano conditions are only satisfied when the magnetic field scales with the electron density of the media.

A common misconception is to assume the dosimetric impact of small upstream air gaps to be negligible because the low-energy electrons affected by the ERE would not reach the region of interest according to their CSDA range. For a 0.2 cm air gap, only electrons with energies below approximately 0.52 MeV are expected to undergo ERE, suggesting that perturbations should be confined to within their CSDA range, which is around 0.1766 cm for an electron of this energy in water [6]. However, the present results show that the perturbation extends well beyond the CSDA range of the affected electrons, altering CPE over a much larger distance than previously thought.

CONCLUSIONS

A re-examination of the fundamentals of dosimetry in the presence of a magnetic field shows that Fano's theorem provides a valuable framework for understanding dosimetric perturbations in MRgRT. These results demonstrate that conventional dosimetric intuition must be revisited when magnetic fields are present. These findings complement the new CoPs by providing a stronger theoretical foundation for understanding the challenges of clinical dosimetry in MRgRT.

REFERENCES

1. Sarfehnia A, Alvarez PE, Bellon MR, et al. AAPM task group report 351: Protocol for clinical reference dosimetry in external beam MR-guided radiotherapy. Med Phys. 2025; 52:e17884.
2. Billas I, Budgell G, George B, Thomas RAS, Duane S, Eaton DJ. Reference dosimetry for MRI-Linacs: an addendum to the 2020 IPEM code of practice for high-energy photon therapy dosimetry. Phys Med Biol. 2025 Apr 14;70(8).
3. Malkov, V.N. and Rogers, D.W.O. (2016), Charged particle transport in magnetic fields in EGSnrc. Med. Phys., 43: 4447-4458
4. Mohan, R., Chui, C. and Lidofsky, L. (1985), Energy and angular distributions of photons from medical linear accelerators. Med. Phys., 12: 592-597.
5. Bouchard H, de Pooter J, Bielajew A, et al. Reference dosimetry in the presence of magnetic fields: conditions to validate Monte Carlo simulations. Phys Med Biol. 2015;60(17):6639–6654.
6. Berger MJ, Coursey JS, Zucker MA, Chang J. ESTAR, PSTAR, and ASTAR: Stopping-Power & Range Tables for Electrons, Protons, and Helium Ions. NIST Standard Reference Database 124. 2017.