Dosimetric assessment of photon, proton, and carbon ion beams in a magnetic field; a Monte Carlo simulation study

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ABSTRACT

Background: The advent of Magnetic Resonance-guided (MR-guided) radiotherapy, facilitated by MR-guided linear accelerators (MR-LINACs), has significantly enhanced the availability of online adaptive radiotherapy treatments. Research indicates that a static magnetic field influences the amount of radiation absorbed by patients undergoing MR-guided radiotherapy. This study employed Monte Carlo simulations to assess the dose distribution of Photon, Proton, and Carbon ion beams in the absence and presence of magnetic fields. ***Materials and Methods:*** All simulations were performed using version 9.1 of the GATE software. The experimental configuration consisted of a water phantom equipped with a one mm-thick air slit oriented parallel to the x-y plane. Energy and dose measurements from both the primary beam and secondary electrons were conducted using DoseActor. ***Results:*** The observed magnetic field shifted the Bragg peak for both proton and carbon ion beams, with an increasing displacement correlating to higher primary beam energy levels. Furthermore, there was a positive correlation between secondary electron doses and magnetic field intensity; in scenarios involving a 7 Tesla magnetic field, photon doses at the water-air interface increased considerably. Additionally, at the air slit location, doses from photon-induced secondary electrons markedly increased at this interface. ***Conclusion:*** The Electron Return Effect (ERE) influences dose distribution at water-air boundaries. Increased initial energies and more robust magnetic fields exacerbate these phenomena, emphasizing the critical importance of rigorous deliberation in the treatment planning process.

INTRODUCTION

Particle therapy, encompassing proton and carbon -ion beams, represents a significant advancement in contemporary radiation oncology. Unlike conventional photon therapy, particle therapy utilizes charged particles' unique physical and radiobiological properties [(1)]. This approach enables the delivery of highly localized doses to tumors while sparing adjacent healthy tissues. A notable feature of particle beams is the Bragg peak, where most of the dose is deposited at a specific tissue depth, corresponding to the end of the particle's range [(2)]. This characteristic allows for precise tumor targeting while minimizing exposure to critical structures beyond the treatment site [(3)]. Additionally, carbon-ion therapy offers further advantages due to its higher linear energy transfer (LET) and increased relative biological effectiveness (RBE), making it a preferred modality for treating radioresistant tumors or those situated in anatomically complex regions [(4)]. These attributes have established particle therapy as a standard of care for certain malignancies and a promising alternative for others under investigation.

Despite its advantages, particle therapy presents several challenges [(5)]. Issues such as motion management, anatomical changes during treatment, and the steep dose gradients associated with particle beams necessitate advanced imaging and treatment planning strategies. Recent technological advancements have revolutionized radiation oncology, particularly integrating magnetic resonance imaging (MRI) into radiotherapy systems. MR-guided radiotherapy (MRgRT) enables real-time tumor tracking, adaptive treatment planning, and superior soft tissue visualization without ionizing radiation, making it particularly advantageous for particle therapy [(6)]. However, applying magnetic fields in MR-guided systems introduces complexities that must be addressed [(7)]. Charged particles experience Lorentz force effects within magnetic fields, leading to altered trajectories and dose distortions, such as Bragg peak displacement and the electron return effect (ERE). The ERE is a phenomenon where secondary electrons, produced during particle interactions with tissue, are deflected by the magnetic field and return to their origin along curved paths [(8)]. This effect is especially pronounced at tissue-air interfaces, where the density gradient causes the secondary electrons to loop back and deposit additional doses near the interface. These dose perturbations are particularly significant at tissue-air or tissue-bone interfaces, where abrupt changes in density amplify the effects of the magnetic field [9].

Proton therapy, recognized for its well-defined physical characteristics and widespread clinical implementation, has been the principal subject of most MR-guided particle therapy research. Investigations demonstrate that magnetic fields can induce significant lateral displacement of proton beams and resultant dose dispersion, mandating rigorous optimization of beam energies and trajectories [10]. For example, Fuchs *et al*. highlighted the need for treatment plan adaptation within high magnetic field environments to minimize dose deformation [11]. Similarly, Pham et al. stressed the importance of optimizing beam energies to ensure precise dose delivery in the presence of magnetic fields [12].

Carbon-ion therapy, while exhibiting reduced susceptibility to magnetic field influence due to the increased mass of carbon ions, demands precise treatment planning to minimize potential dose discrepancies. The superior linear energy transfer (LET) and relative biological effectiveness (RBE) of carbon ions compared to protons establish their suitability for intricate clinical scenarios [13]. Further investigation into the interaction between magnetic fields and dose deposition is warranted. Wang *et al.* have offered valuable insights into magnetic field-induced dose distortions in carbon-ion therapy, underscoring the need for sophisticated treatment planning methodologies [14]. Furthermore, published research has demonstrated the effectiveness of carbon-ion therapy in managing complex and radioresistant neoplasms, reinforcing its crucial role within heavy-ion therapy research [15].

Monte Carlo simulations are essential for investigating the interactions between magnetic fields and particle beams. These simulations enable high-fidelity modeling of particle trajectories, energy deposition, and dose distributions, accounting for complex phenomena such as scattering, secondary electron production, and tissue inhomogeneities [16]. Mesbahi *et al*. demonstrated the effectiveness of Monte Carlo methods in assessing secondary radiation doses in high-energy photon beams, an approach readily adaptable to the study of magnetic field effects in particle therapy [17]. Through these computational techniques, researchers can comprehensively understand the influence of beam energy, magnetic field strength, and tissue composition on dose distribution patterns [18].

This study employs Monte Carlo simulations to conduct a comprehensive dosimetric analysis of the effects of magnetic fields on photon, proton, and carbon-ion beams. This study concurrently examines all three modalities within a unified framework, enabling direct comparisons. Specifically, we investigate dose distribution profiles, Bragg peak shifts, and the correlation between beam energy and magnetic field strength. The research provides valuable insights into the combined influence of beam type, energy, and magnetic field strength on dose deposition profiles, offering a holistic perspective on optimizing MR-guided radiotherapy systems. This work advances adaptive treatment strategies in MR-guided particle therapy and establishes a foundation for improved clinical outcomes in complex oncological cases.

MATERIALS AND METHODS

GATE Monte Carlo code

The Geant4 Application for Tomographic Emission (GATE) is a sophisticated, open-source software toolkit developed by the OpenGATE Collaboration (France). It offers broad accessibility for both research and clinical applications [19]. The OpenGATE Collaboration comprises 25 academic and industrial institutions dedicated to developing, maintaining, and distributing the GATE software under the guidance of its steering committee [20]. This study employed GATE version 9.1 for all simulations.

Settings of particle transport physics

For proton and carbon ion beams, the QGSP-BIC-EMZ (Quark-Gluon String Precompound-Binary Cascade-Electromagnetic) physics list was employed to model hadronic and electromagnetic interactions [21]. Nuclear interactions were simulated using the QGSP model and the BIC approach. Multiple Coulomb scattering was modeled using the WentzelIV, option 4, EMZ [22]. Electromagnetic interactions of the photon beam were simulated using the EMLivermore physics list.

Specifications of geometries studied

In this study, a water phantom containing a 1 mm air slit oriented in the X-Z plane was used (figure 1). Rectangular cuboid phantoms, with dimensions ranging from 10×10×10 cm^3 to 10×50×10 cm^3 and filled with water, were employed. The thickness of the phantom's superior section was adjusted to accommodate the primary beam energy and type. The primary beam was collimated along the negative Y-axis, while the magnetic field was applied along the negative Z-axis. Magnetic field strengths of 0 T, 1.5 T, 3 T, and 7 T were investigated. The air gap was positioned proximate to the Bragg peak to coincide with the region of maximum dose deposition. As illustrated in figure 1, the water-air interface was considered in the investigation of the ERE.

Performing simulation

To assess the energy deposition and radiation dose from the primary beam and secondary electrons, we utilized DoseActors, specialized tools within the simulation framework designed for precise data collection, such as measuring energy deposition and particle count during simulations.

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This study employed these actors to calculate the dose distribution along the Y-axis with a spatial resolution of 0.1 mm. Simulations were performed for carbon ion beams with energies of 100, 220, and 310 MeV/n, proton beams of 80, 120, and 180 MV, and photon beams at 6, 10, and 25 MV. Each simulation involved tracking 1 billion particles to ensure statistical uncertainties remained below 1%, thereby enhancing the reliability of the results. This methodology enables a detailed and accurate evaluation of dose deposition patterns for different beam types and energy levels.

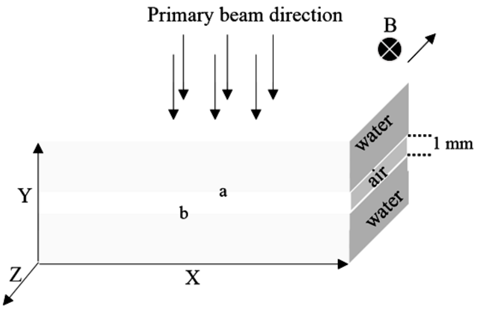

Figure 1. A schematic diagram of the water phantom, incorporating an air slit for spatial dose distribution calculations within a magnetic field. The phantom consists of water that is oriented perpendicular to the radiation beam. A homogeneous magnetic field is applied perpendicular to the XY plane in the -Z direction. The figure does not represent actual dimensions.

Validation of simulation results

The simulation results underwent a thorough validation process to confirm the precision and dependability of the dose distributions and energy depositions derived through the Monte Carlo method. Multiple approaches were employed, including benchmarking against experimental data, cross-verification with alternative computational techniques, and rigorous statistical analysis to assess uncertainties. Additionally, sensitivity analyses were conducted to evaluate the impact of key parameters on the outcomes, ensuring robustness under varying conditions. These measures collectively reinforced confidence in the accuracy of the results, providing a solid foundation for their application in research and clinical settings.

The proton and photon dose distribution simulations were evaluated against the guidelines in ICRU Reports 78 (23) and 89 (24). These serve as benchmarks for standard dose profiles of therapeutic beams in the absence of magnetic fields. These reports outline critical parameters and reference data to ensure accuracy and consistency in dose delivery for clinical applications. By comparing the simulation results to these established standards, the study aimed to validate the reliability and precision of the modeled dose distributions under controlled conditions. This comparison is essential for ensuring the therapeutic beams meet the required safety and efficacy criteria in clinical practice.

The depth-dose characteristics and Bragg peak profiles for carbon ion beams were thoroughly validated by comparing them with established experimental data. Specifically, the results were benchmarked against the findings of Akbari and Karimian (25) and Fuchs *et al.* (11), providing detailed analyses of depth-dose distributions under comparable beam and phantom conditions. This validation ensures the accuracy and reliability of the dose profiles, supporting their applicability in clinical and research settings.

Comparison with experimental results

Simulated dose distributions for photon and proton beams were evaluated against experimental data obtained under non-magnetic conditions and within a 1.5 T magnetic field (9). These experiments serve as valuable benchmarks, offering detailed insights into the behavior of secondary electrons at water-air interfaces. Additionally, they provide critical information on the displacement of the Bragg peak induced by the presence of a magnetic field. Such findings contribute to a deeper understanding of dose deposition processes and the impact of magnetic fields on therapeutic beam delivery, facilitating advancements in precision radiotherapy techniques.

Energy deposition and dose profiles

DoseActor modules were utilized to obtain high-resolution dose distributions, enabling precise analysis of radiation behavior. These distributions were systematically compared to theoretical models predicting Bragg peak displacement and secondary electron energy deposition under different magnetic field strengths. This approach ensured a robust evaluation of the interplay between magnetic fields and dose delivery, contributing to a deeper understanding of the effects on particle trajectories and energy transfer mechanisms.

The generated profiles were systematically compared against existing theoretical frameworks, including the models proposed by Raaijmakers *et al.*, which detail the behavior of proton beam deflection within magnetic fields. These established models served as a benchmark to validate the accuracy and reliability of the results, ensuring consistency with recognized scientific principles (9).

Integrating experimental benchmarks with theoretical analyses established a comprehensive and reliable framework for validating simulation outcomes. This approach enhanced the credibility of the results and ensured their relevance and applicability to clinical practices and research environments. By leveraging this dual-method validation, the simulations were rigorously tested against real-world data and theoretical predictions, minimizing discrepancies and reinforcing their utility in addressing complex biomedical challenges. Such a

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robust methodology underscores the importance of combining empirical evidence with computational modeling to drive advancements in medical and scientific fields.

Statistical analysis

Statistical analyses were conducted to validate the Monte Carlo simulation outcomes. Data processing and analysis were performed using licensed software, including IBM SPSS Statistics (version 26, IBM Corporation, USA), OriginLab (version 2022b, OriginLab Corporation, USA), and Microsoft Excel 2021 (Microsoft Corporation, USA). Key statistical metrics such as mean, standard deviation, and standard error were calculated for dose distributions and Bragg peak displacements across varying magnetic field directions and beam energies. Statistical uncertainties were assessed for each simulation to ensure reliability. OriginLab facilitated the creation of depth-dose distribution graphs and dose profile visualizations. At the same time, Excel was utilized for preliminary data processing and generating comparative bar and line graphs to illustrate trends effectively. These tools collectively enhanced the precision and clarity of the analysis.

RESULTS

The summarized findings in table 1 highlight the effects of magnetic fields on Bragg peak displacement and electron dose enhancement (EDE) ratios for proton, carbon-ion, and photon beams. For proton and carbon-ion beams, the Bragg peak shifts to shallower depths with increasing magnetic field strength, larger incredible shifts observed at higher beam energies. These shifts result from the Lorentz force acting on charged particles. Additionally, the dose at the Bragg peak increases with stronger magnetic fields and higher energies, indicating a positive correlation between magnetic field strength, beam energy, and dose enhancement. Photon beams, in contrast, exhibit no Bragg peak displacement as their primary beam path remains unaffected by magnetic fields. However, photon beams show notable changes in EDE ratios with increasing magnetic field strength and photon energy attributed to the interaction of secondary electrons with the magnetic field. Overall, these results demonstrate the significant impact of magnetic fields on dose distribution and beam behavior, particularly for charged particle therapies, emphasizing the importance of accounting for these effects in treatment planning and optimization.

The data illustrated in figure 2 demonstrates a positive correlation between the secondary electron dose's magnitude and the magnetic field's intensity across various radiation types and energies. The presence of a magnetic field induces a leftward shift in the location of the maximum dose, which is influenced by the energy of the primary beam. This phenomenon is attributed to the Lorentz force, which causes the return of electrons. Furthermore, as the energy of the primary beam increases, there is a notable decrease in the maximum dose of secondary electrons. These observations are relevant for advancements in charged particle therapy, particularly in MRI-guided radiotherapy, where magnetic fields are crucial in dose distribution and treatment precision.

Table 1. Summary of Bragg peak displacement and electron dose enhancement (EDE) ratios for proton, carbon-ion, and photon beams in the presence of magnetic fields.

Beam type	Proton								
Energy (MeV)	80			120			180		
Magnetic Field (T)	1.5	3	7	1.5	3	7	1.5	3	7
Bragg Peak shift (mm)	0.1±0.05	0.5±0.08	2.5±0.9	0.2±0.03	4±1.03	13.3±2.11	2±0.18	8.5±1.42	37±4.2
EDE at Water-Air boundary	1.11±0.02	1.12±0.04	1.33±0.16	1.08±0.03	1.13±0.09	2.00±0.19	1.19±0.06	1.22±0.17	1.36±0.21
Beam type	Carbon-Ion								
Energy (MeV/n)	100			220			310		
Magnetic Field (T)	1.5	3	7	1.5	3	7	1.5	3	7
Bragg Peak shift (mm)	0±0.0	0.8±0.03	1.7±0.21	0.1±.02	0.4±0.05	1.3±0.6	0.5±0.02	1±0.31	3.5±1.02
EDE at Water-Air boundary	1.10±.03	1.14±.05	1.2±0.11	1.06±0.04	1.23±0.14	1.16±0.07	1.07±0.02	1.25±0.12	1.21±0.09
Beam type	Photon								
Energy (MV)	6			10			25		
Magnetic Field (T)	1.5	3	7	1.5	3	7	1.5	3	7
EDE at Water-Air boundary	1.60±0.18	3.60±1.02	4.10±1.16	1.56±0.12	4.42±1.08	5.80±1.12	1.25±0.07	5.21±0.63	8.26±1.61

Proton beam: For proton beams, in figure 2 panels (a), (b), and (c)... depict dose distributions corresponding to energies of 80 MeV, 120 MeV, and 180 MeV, respectively. The analysis reveals that higher magnetic field strengths increase peak dose while slightly narrowing the dose profile, particularly at elevated energy levels. This behavior is attributed to the enhanced confinement of secondary electrons caused by the magnetic field, which improves dose localization. These findings underscore the influence of magnetic fields on dose shaping and their potential implications in optimizing particle therapy.

Carbon-ion beams: Panels (d), (e), and (f) in figure 2 illustrate dose profiles for carbon-ion beams with energies of 100 MeV/n, 220 MeV/n, and 310 MeV/n,

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respectively. Similar to proton beams, the peak dose height of carbon-ion beams increases with field strength; however, this effect diminishes at higher energy levels. Due to their greater mass and lower sensitivity to deflection, the Bragg peak of carbon-ion beams remains relatively stable under the influence of magnetic fields, demonstrating reduced susceptibility to perturbations compared to lighter particles.

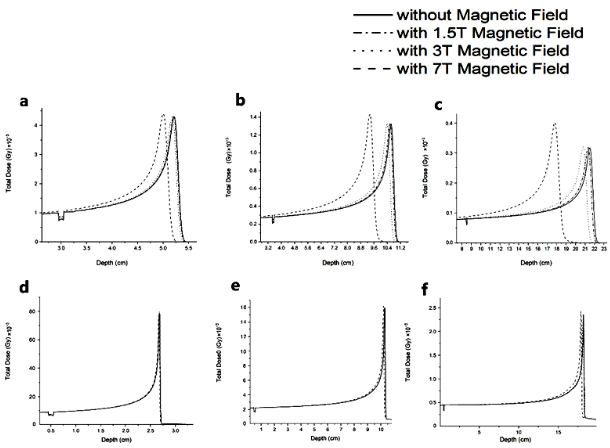

Figure 2. The depth-dose distributions of proton and carbon-ion beams under various magnetic field strengths. Proton beams with energies of 80 MeV **(a)**, 120 MeV **(b)**, and 180 MeV **(c)** and carbon-ion beams with energies of 100 MeV/n **(d)**, 220 MeV/n **(e)**, and 310 MeV/n **(f)** were simulated in the absence of a magnetic field (solid line) and in the presence of 1.5 T (dash-dot line), 3 T (dotted line), and 7 T (dashed line) magnetic fields. The results indicate that magnetic fields can significantly alter the dose distribution, leading to increased lateral scattering and reduced penetration depth, particularly for higher energy beams.

Photon Beams: Panels (g), (h), and (i) in figure 3 illustrate the dose distributions for secondary electron induced by photon beams with energies of 6 MV, 10 MV, and 25 MV, respectively, under the influence of a magnetic field. The interaction of photons induces secondary electrons with the water-air interface, resulting in a significant dose enhancement. It intensifies with increased photon energy and magnetic field strength. This phenomenon, driven by the electron return effect (ERE), distinctly shapes the dose profiles for each beam energy. The findings highlight that stronger magnetic fields lead to enhanced confinement of secondary electrons and more significant dose deposition. These effects vary based on beam type and energy, underscoring the importance of understanding the interplay between beam energy, particle interactions, and magnetic field strength. Such insights are critical for optimizing dose delivery and addressing dose perturbations in MRI-guided radiotherapy and hadron therapy systems.

The data reveals an asymmetry in absorbed dose distribution, with an enhancement on the left side and a reduction on the right. This effect is caused by the electron return effect (ERE), where the applied magnetic field influences the trajectory of secondary electrons, redirecting them back toward the left side. Consequently, this increases the energy deposition in that region while decreasing the electron flux and associated dose on the right side. This phenomenon highlights the significant impact of magnetic fields on dose distribution, which is critical for optimizing radiation therapy and understanding its implications in clinical applications.

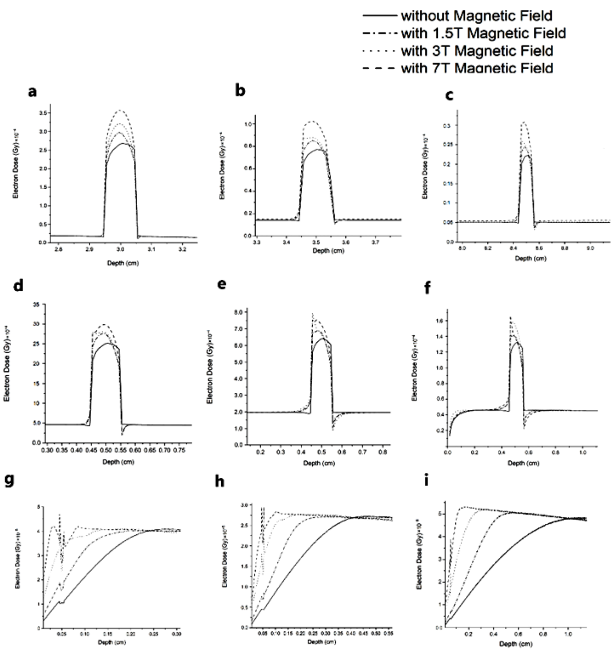

Figure 3. Secondary electron dose profiles generated by proton, carbon-ion, and photon beams at the air slit under varying magnetic field strengths (0, 1.5, 3, and 7 T), highlighting the magnetic field's influence on dose distribution. For further explanation, please refer to the text. In the existence of a magnetic field, the energy deposition distribution by the primary beam is altered. This displacement is proportional to the magnetic field strength and the primary beam energy.

Increasing the magnetic field strength significantly influences the energy deposition patterns of secondary electrons in proton and carbon -ion beams, primarily due to the Lorentz force acting on charged particles. This effect becomes more pronounced at higher beam energies, leading to noticeable shifts in the Bragg peak position. The extent of these shifts increases with beam energy and magnetic field intensity for proton beams. In a 7 T magnetic field, Bragg peak shifts of 2.5±0.9 mm, 13.3±2.11 mm, and 37±4.2 mm were observed for proton energies of 80 MeV, 120 MeV, and 180 MeV, respectively. Minimal displacement was noted for the 80 MeV beam across all tested magnetic fields (≤2.5 mm). However, at 120 MeV, shifts of 0.2±0.03 mm, 4±1.03 mm, and 13.3±2.11 mm were recorded under 1.5 T, 3 T, and 7 T fields, respectively. Similarly, for the 180 MeV beam, corresponding displacements of 2±0.18 mm, 8.5±1.42 mm, and 37±4.2 mm were

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observed under the same field conditions. These findings highlight the critical impact of magnetic fields on dose distribution in particle therapy, particularly at higher beam energies.

The Bragg peak of carbon-ion beams, similar to proton beams, shifts under the influence of a magnetic field, and this displacement increases as both the magnetic field strength and beam energy rise. However, the displacement observed in carbon-ion beams is consistently smaller than in proton beams, suggesting a reduced sensitivity to magnetic fields. Even in an intense 7 T magnetic field, the displacement for carbon-ion beams remained lower than that of protons, with measured values of 1.7±0.21 mm, 1.3±0.6 mm, and 3.5±1.02 mm for beam energies of 100 MeV/n, 220 MeV/n, and 310 MeV/n, respectively. Notably, the maximum dose delivered by carbon-ion beams was unaffected by the presence of magnetic fields, showing no significant variation from the dose at 0 T. These findings indicate that carbon-ion beams maintain their dose delivery precision even under high magnetic field conditions, making them a robust option for therapeutic applications in environments where magnetic fields are present.

The dose of secondary electrons generated by the carbon ion beam shows a clear positive correlation with increasing magnetic field strength (figure 3). Notably, within the magnetic field, the peak dose of these secondary electrons shifts toward shallower depths, with this displacement being more pronounced than the behavior observed in secondary electrons produced by proton beams. Additionally, the energy deposition profile of carbon-ion beams demonstrates a progressive shift toward smaller depths as the energy of the primary beam increases. These findings highlight the intricate interplay between magnetic fields, beam properties, and energy deposition patterns, which are critical for optimizing therapeutic applications of carbon-ion beams in radiation therapy.

The presence of a magnetic field influenced the behavior of electron energy deposition at the water-air interface. An increase in the relative energy deposition by electrons was observed within the air gap region. This effect can be attributed to the magnetic field's impact on electron trajectories, enhancing their interaction within this region. Conversely, on the distal side of the air gap, beyond the air slit, a reduction in energy deposition was noted. This decrease is likely due to fewer electrons successfully reaching this area, as the magnetic field altered their paths. These findings highlight the complex interplay between magnetic fields and electron transport and underscore the importance of considering such effects in applications involving magnetic fields and energy deposition.

Applying a magnetic field influences the dose deposition patterns of photon beams, particularly at the air-water interface. Under the magnetic field, the depth-dose curve exhibits a steeper gradient before the build-up region, with the degree of slope enhancement directly proportional to the field strength. This phenomenon arises from the magnetic field's impact on the trajectories of secondary charged particles produced during photon interactions, effectively altering their spatial distribution and energy deposition. These findings underscore the importance of understanding magnetic field effects in optimizing radiation therapy techniques, as they can enhance dose conformity and potentially improve therapeutic outcomes.

The dose contribution from photon-induced secondary electrons showed a notable increase at the water-air interface in a magnetic field. The peak dose of these secondary electrons amplified with stronger magnetic fields, an effect that became more pronounced at higher primary photon beam energies. Beyond the peak, the secondary electron dose declined as the magnetic field strength rose. The energy deposition profile of photons shifted toward lower values with increasing magnetic field intensity, with this shift being more significant at elevated beam energies. A similar trend was observed in the relative energy distribution of secondary electrons, reflecting the primary photon energy deposition behavior. Due to the differing interactions of particles with magnetic fields, the impact on secondary electron dose distribution is substantial for photon beams, less significant for proton beams, and minimal for carbon-ion beams. These findings highlight the importance of considering magnetic field effects when evaluating dose distributions in radiotherapy involving photon beams.

DISCUSSION

This study investigates the impact of magnetic fields on the photon, proton, and carbon-ion beams, emphasizing Bragg peak displacement, secondary electron dose enhancement (EDE), and dose variations at water-air interfaces. The results reveal the significant role of the Lorentz force in modifying beam behavior and secondary electron trajectories, particularly in MRI-guided particle therapy. Magnetic fields notably influence photon beams at tissue-air interfaces due to the electron return effect (ERE), leading to substantial dose enhancements. Consistent with Raajmakers *et al.,* who reported a five-fold dose increase at such interfaces under a 1.5 T magnetic field, our findings confirm these effects and their clinical relevance. These insights provide valuable contributions to understanding magnetic field interactions in advanced radiotherapy techniques and highlight the need for careful dosimetric considerations in treatment planning [9].

Our research builds upon previous studies by

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demonstrating significant dose amplification at 7 T, particularly with higher photon energies, where the EDE ratios surpassed eightfold for 25 MV photons. Additionally, the impact of magnetic fields on proton therapy was further explored, focusing on Bragg peak displacement and dose distribution in MRI-guided systems. Our study, consistent with earlier findings by Oborn *et al*., who observed an 11 mm Bragg peak shift for 150 MeV protons in a 3 T field, revealed a notable displacement of 13.3 mm for 120 MeV protons under a 7 T magnetic field. These results underscore strong magnetic fields' critical influence on photon and proton beam behavior, highlighting their implications for optimizing dose delivery in advanced radiotherapy techniques [26].

This research provides a detailed quantification of increased displacements at higher proton beam energies, with a maximum observed shift of 37 mm for 180 MeV protons, underscoring the relationship between beam energy and magnetic field strength. The findings emphasize the significant influence of magnetic fields on dose distribution, mainly through the enhancement of secondary electron dose at water -air interfaces. Moreover, the electron dose enhancement (EDE) ratios obtained in this study are consistent with those reported by Raaymakers et al., reinforcing the reproducibility and reliability of these observations. These results contribute to a deeper understanding of the interplay between magnetic fields and proton therapy, offering valuable insights for optimizing treatment planning and improving therapeutic outcomes [9].

Carbon ion beams demonstrate superior resistance to magnetic field distortions compared to protons and photons, as indicated by their reduced Bragg peak displacements and more consistent dose profiles. This behavior supports the observations of Akbari and Karimian, who reported minimal deflection of carbon ion beams under a 3 T magnetic field. Such stability under magnetic influence enhances the precision and reliability of carbon ion therapy, making it a promising modality for treating tumors in environments with magnetic fields, such as MRI-guided radiotherapy systems. This characteristic further underscores the advantages of carbon ions in advanced radiation therapy applications [25].

In our research, carbon ion beams demonstrated a maximum Bragg peak displacement of merely 3.5 mm at 310 MeV/n, even under a strong 7 T magnetic field. This limited displacement highlights their reduced sensitivity to the Lorentz force, attributed to their higher mass and charge than other particles. These properties make carbon ions particularly advantageous for MRI-guided particle therapy, as they allow for more precise targeting of tumors with minimal deviation in their trajectory. This precision is critical for enhancing treatment efficacy while reducing damage to surrounding healthy tissues. Consequently, carbon ions emerge as a promising choice for advancing the integration of MRI in particle therapy applications.

A detailed comparative study has demonstrated that photon beams exhibit the highest sensitivity to magnetic field-induced dose enhancements, especially at tissue-air interfaces. These findings align closely with the observations reported by Raaymakers *et al*., further validating their conclusions. This sensitivity is particularly significant in advanced radiotherapy techniques, where precise dose delivery is critical. The interaction between magnetic fields and photon beams at these interfaces underscores the importance of accounting for such effects during treatment planning to ensure accuracy and efficacy. These results contribute to a deeper understanding of the interplay between magnetic fields and radiation, offering valuable insights for optimizing therapeutic approaches in clinical settings [9]. Proton beams exhibit moderate sensitivity to external factors, with dose variations and Bragg peak shifts influenced by energy levels and magnetic field strength, as observed by Oborn *et al*. [25]. In contrast, carbon ion beams display excellent stability under similar conditions, highlighting their potential advantages in clinical applications. This stability minimizes unintended dose deviations, making carbon ion therapy a more reliable option for precision treatment in scenarios where consistent dose delivery is critical.

Advanced treatment planning algorithms are crucial for optimizing MRI-guided radiotherapy, mainly high-energy photon and proton beams. The notable dose enhancements observed with photon beams necessitate precise modeling to prevent unintended dose spikes that could compromise treatment safety. Similarly, proton therapy demands careful adjustments to account for Bragg peak displacement caused by strong magnetic fields, ensuring accurate dose delivery to the target tissue. In contrast, carbon ion therapy demonstrates greater resilience to magnetic field effects, making it a promising modality for integrating MRI systems. Its stability and precision highlight its potential for applications where accurate dosing is paramount, reinforcing the need for continued research and innovation in this field.

In conclusion, this study provides critical quantitative data on how magnetic fields influence the dosimetric properties of different therapeutic beams, paving the way for advancements in MRI-guided radiotherapy and particle therapy. The findings underscore the interplay between beam type, energy levels, and magnetic field strength, emphasizing the necessity for tailored treatment planning to enhance precision and efficacy. By addressing these interactions, this research contributes to the development of optimized strategies for therapeutic delivery, ensuring improved patient outcomes in modern radiation

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oncology.

Conflict of Interest: The authors confirm that there are no conflicts of interest associated with the content or findings presented in this work. All efforts have been made to ensure the integrity and objectivity of the research, and no financial, personal, or professional affiliations have influenced the outcomes. This statement reflects the authors' commitment to maintaining transparency and upholding the highest ethical standards in scholarly communication.

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Authors' Contributions: H.R., conceptualized the study; S.B., collected data and drafted the manuscript.

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