Calculation of Magnetic Field Effects on Dose Distribution, Inside a Heterogeneous Phantom, in MR-Guided Helium Ion-Therapy Using FLUKA Monte Carlo Simulation Code

Nahid Hajiloo
Radiation Application Research School, Nuclear Science and Technology Research Institute, P.O. Box 31485-498, Karaj, Iran.
Email: nhajiloo@aeoi.org.ir

Abstract
Helium-ion therapy, is being developed because of its advantages such as less lateral scattering than protons and fewer nuclear fragments than carbon beams. The idea of using magnetic resonance imaging to guide helium-ion therapy raises challenges, including dose disturbances in the patient's body that occurs due to the deviation of the initial beam under a magnetic field. In this work, the impact of magnetic field presence on the central axis depth-dose curves of helium ion beams inside a heterogeneous phantom with air and bone layers was investigated. According to the calculations, presence of the magnetic field has an important impact on dose distribution of helium beams depending on the field strength and beam energy. As a 32.3% abrupt increase and 92.5% reduction in dose were observed at the boundary between the water-air and the water-bone layer insert, respectively. The accuracy of the simulation evaluated by experimental data.
Keywords: Helium ion therapy, Transverse magnetic fields, Dose distribution

Introduction
Because of the physical and radiobiological properties of helium ions compared to the most clinically available ion beams (i. e., proton and carbon), such as beam sharpness and less fragment, currently in the Heidelberg Ion-Beam Therapy (HIT) Center, alongside other ions, research on the use of helium ions in treatment is conducted [1]. Advances in image-guided radiotherapy (RT) have allowed for dose escalation and more precise radiation treatment delivery. Each decade brings new imaging technologies to help improve RT patient setup. Currently, the most frequently used method of three-dimensional pre-treatment image verification is performed with cone beam CT. However, more recent developments have provided RT with the ability to have on-board MRI coupled to the radiotherapy unit. This latest tool for treating cancer is known as MR-guided RT. Several varieties of these units have been designed and installed in centers across the globe. MR-gRT has an array of advantages over traditional types of IGRT platforms, but it does have some limitations that must be addressed. Although attempts have been made to create a suitable shield for the magnetic field around the MRI systems, the magnetic field of the MRI system has an effect on the particle accelerator, and the magnetic field is not negligible, especially in the patient's position, and its presence causes changes in dose distribution. By investigation of these changes and accurately estimating them, changes in dose distribution can be compensated in some way. In order to identify such effects, in this study, using the Monte Carlo FLUKA code, the changes in the dose distribution of helium ions beam, used in a heterogeneous phantom, including water, bone and air in the presence of a uniform magnetic field, were calculated.

Materials and method
In this research, FLUKA Monte Carlo code has been used for simulation. A water phantom with dimensions of 30 × 30 × 50 cm^3 was simulated. A single-energy, mono-directional helium ion beam perpendicular to the water phantom was simulated. The spatial distribution of the particles was considered to be a rectangular distribution function with dimensions of 6.3 mm. The magnetic field perpendicular to the direction of the beam along the +X axis was simulated inside the phantom.
To investigate, the impact of the magnetic field presence on the central axis depth-dose curves inside a heterogeneous phantom (Fig. 1) with 3 cm thick air and bone layers was investigated. The location of the air and bone layers was ranging 25 to 28 cm in depth. Bone and air densities were considered to be 1.85 and 0.001 g/cm^3, respectively. The incident helium beam energy and the magnetic field studied in this scenario was 250 MeV/n was 3.0 T, respectively. The bin size was considered to be 1 mm in the non-Bragg region and 0.25 mm in the Bragg area. Also the accuracy of the simulation was evaluated by verifying the depth-dose curves of helium ion beams in a water phantom with experimental data without the magnetic field influence [2]. Moreover, to achieve a statistical error of less than 1% in the Monte Carlo simulation, minimum and maximum histories of 4.5 × 10^6 and 10^8 particles was tracked depending on particle energy studied in this article.

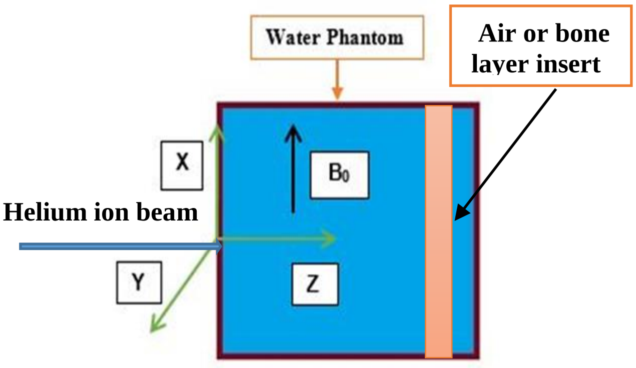


Figure 1. Homogeneous phantom consisting of a 3 cm thick heterogeneous layer of air or bone insert.

Results and discussion

Figure 2 shows the one-dimensional depth-dose distribution of helium ion beams with the energy of 220.5 MeV/n inside a heterogeneous phantom with 3 cm thick layers of bone and air. In the case of the presence of an air layer inside the phantom, as can be seen in Fig. 3, at the boundary between water and air, an increase in dose occurs due to the Electron Return effect (ERE) phenomenon [3], in which the deflection of the secondary electrons in backward direction leads to overdose the first layer between two interfaces. The reason for the important changes at the depth-dose in the presence of a magnetic field and the heterogeneity of the air is the increase in the deflection of the helium beam inside the air layer, which leads to a sharp decrease in the dose at the Bragg peak. In the case of the presence of a bone layer, an important impact on the depth-dose curve compared to the case without a magnetic field was observed.

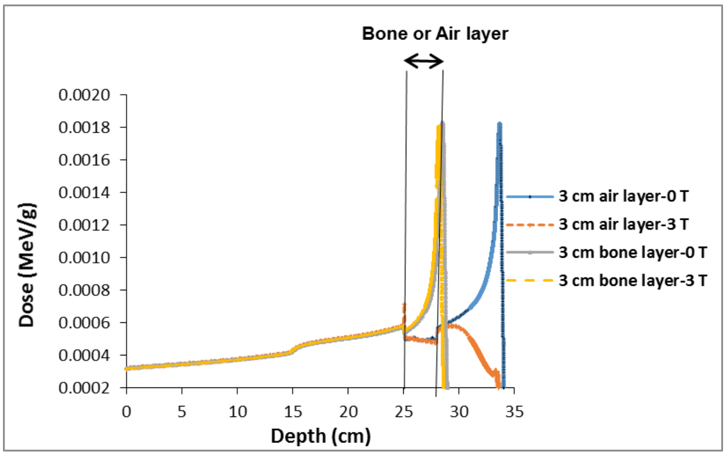
To better display the dose changes in the central axis direction in the presence of the 3.0 T magnetic field applied to heterogeneous phantoms, including the air and bone layers, the percentage of dose changes in the direction of the central axis after applying the field is displayed in Fig. 3. The formula for calculating dose difference is as follows (formula 1):

$$\text{Percentage of decrease in dose } (\%) = \frac{D_{3.0T} - D_{0.0T}}{D_{0.0T}} \times (100)$$

In this equation, $D_{0.0T}$ and $D_{3.0T}$ are the dose in the presence of 0.0 and 3.0 T fields, respectively.

In the presence of the air layer, a 32.3% abrupt increase in dose due to magnetic field application at the boundary between the water and air, which is due to the ERE phenomenon. In the presence of the bone layer, a 92.5% reduction in dose occurs compared to the absence of a field at the boundary between bone and water.

For validation of calculation results, the Bragg peak depth values of the helium ion beams calculated in this study were compared with the experimental values published in the literature [2]. The maximum difference between the simulated and the measured values[2] was 0.96 mm, which indicates the accuracy of the Monte Carlo calculations without the magnetic field.



(a)

Figure 2. One-dimensional depth-dose distribution of helium ion beams with the energy of 220.5 MeV/n inside a heterogeneous phantom containing bone or air layer.

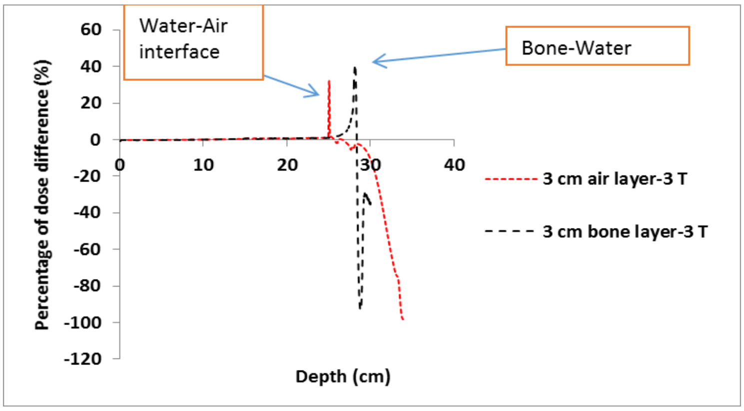


Figure 3. Percentage of dose changes along the central axis after applying a 3.0 T magnetic field inside heterogeneous phantoms, including air or bone layers.

Conclusions

The presence of heterogeneous layers of air and bone leads to important variation in the boundary of these layers with water due to the presence of a magnetic field. The amount of dose changes might depend on the location of these inhomogeneous layers relative to the Bragg depth, thickness, and the energy of the incident beam, which could be topics of interest for future research.

References

[1] B. Knäusl et al., *Can particle beam therapy be improved using helium ions? - a planning study focusing on pediatric patients*, Acta oncol. 55, 751 (2016).

[2] T. Tessonnier et al., *Helium ions at the heidelberg ion beam therapy center: comparisons between FLUKA Monte Carlo code predictions and dosimetric measurements*, Phys. Med. Biol. 62, 6784 (2017b).

[3] B. W. Raaymakers et al., *Feasibility of MRI guided proton therapy: magnetic field dose effects*, Phys. Med. Biol. 53, 5615 (2008).