Technical Note: Experimental verification of EGSnrc calculated depth dose within a parallel magnetic field in a lung phantom

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Purpose: The calculation of depth doses from a 6 MV photon beam in polystyrene using EGSnrc Monte Carlo, within a parallel magnetic field, has been previously verified against measured data. The current work experimentally investigates the accuracy of EGSnrc calculated depth doses in lung within the same parallel magnetic field.

Methods: Two cylindrical bore electromagnets produced a magnetic field parallel to the central axis of a Varian Silhouette beam. A Gammex lung phantom was used, along with a parallel plate ion chamber, for the depth dose measurements. Two experimental setups were investigated: top of phantom coinciding with the top of the magnet’s bore, and top of phantom coinciding with the center of the bore. EGSnrc was modified to read the 3D magnetic field distribution and then used to simulate the depth dose in lung.

Results: The parallel magnetic field caused measurable increases in dose at the surface and in the buildup region for both setups. For the setup where the top of the lung phantom coincides with the top of the magnet, the surface dose increased by ~11% compared to the no magnetic field case but the depth of maximum dose remained unchanged. When the phantom’s top surface coincided with the center of the magnet, the surface dose increased by 32% and dose maximum occurred at a shallower depth. EGSnrc was able to calculate these dose increases due to the magnetic field accurately for both setups. All the simulated depth dose values were within 2% (with respect to $D_{\text{max}}$) of the measured ones, and most of the investigated points were within 1.5%.

Conclusions: Surface and dose increases due to a parallel magnetic field have been measured in a lung phantom at two separate locations within the magnetic field. EGSnrc has been shown to match these measurements to within 2%. © 2018 American Association of Physicists in Medicine [https://doi.org/10.1002/mp.13215]

Key words: dose, EGSnrc, linac-MR, lung, magnetic field, Monte Carlo

1. INTRODUCTION

Integrating a clinical linear accelerator (linac) with a magnetic resonance imager (MRI) has the potential of delivering radiation to a tumor with unprecedented accuracy, by allowing health care professionals to visualize the tumor during irradiation. However, such an integrated linac-MR unit will deliver a modified dose when compared to a conventional radiation treatment due to the presence of the MRI’s strong magnetic field. Under the influence of the MRI’s main magnetic field the charged particles, produced by the primary photons, will experience the Lorentz force. For systems in which the main magnetic field is transverse to the radiation beam central axis, the Lorentz force causes electrons transitioning from a higher to a lower density medium to return to the interface. This can cause a substantial dose increase at tissue — air or tissue — lung interfaces, that has been termed as the electron return effect (ERE). Systems with the radiation beam central axis parallel to the main magnetic field have a minimal dose increase at tissue — air surfaces. However, the parallel magnetic field is preventing the contaminant electrons accompanying the photon beam from scattering laterally, causing an entrance surface dose increase that can be substantial, measurable, or minimal depending on the MRI’s fringe magnetic field and design.

All these dose modifications have previously been investigated using several Monte Carlo (MC) packages: Geant4, EGSnrc, and PENELOPE. While Geant4 dose calculations in the presence of a magnetic field have been previously verified experimentally for multiple materials, to date, EGSnrc MC has only been recently experimentally verified in polystyrene. The current study aims to
extend the experimental verification of EGSnrc with a magnetic field parallel to the radiation beam central axis to lung-like materials as well.

2. MATERIALS AND METHODS

The experimental setup, shown in Fig. 1, consisted of two GMW electromagnets (3472-70, GMW Associates, San Carlos, CA) stacked, one on top of the other, and an in-house built wooden stand that supported the two electromagnets. This electromagnet configuration provided a magnetic field parallel to the central axis of a Varian Silhouette linac. Using a three-axis Hall magnetometer (Model THM1176, Metrolab Technology SA, Switzerland), the maximum magnetic field strength was measured to be 0.207 T at the center of the common bore. While not exactly the same as any of the existing parallel configuration linac-MR clinical designs, this experimental setup can be used to test the dose effects of magnetic fields between several Gauss (6 Gauss measured at linac head), and 0.207 T, parallel to the radiation beam central axis. The depth dose measurements were acquired using a specially designed phantom that consisted of 1.0, and 1.5 cm thick sheets of lung material (GAMMEX RMI, Middleton, WI). The two thicknesses of Gammex lung material were cut into 13 × 13 cm² sheets, and were replaced from above to below the ion chamber insert in such a way as to provide a depth dose measurement at every 0.5 cm depth interval. Polystyrene rails attached to 10 cm of polystyrene backscatter held the lung (18 cm total thickness) in place, while allowing for a reproducible placement of the ion chamber insert at each depth.

The ion chamber insert was built using one of the 1.5 cm thick Gammex lung sheets, machined to tightly fit a Markus phantom (PTW, Freiburg, Germany) parallel plate ion chamber (ppic). This ppic was chosen for its small size, and has a thin 0.03 mm polyethylene entrance window, 5.3 mm diameter collecting electrode, and a 2 mm electrode separation with the sensitive volume vented to the atmosphere. The air cavity and entrance window are embedded in a 30.0 mm diameter acrylic body that goes around and below the sensitive air volume, leaving the entrance window flush with the top. This design eliminates most potential air gaps around the sensitive volume of the chamber. Submillimeter air gaps, in close proximity to the sensitive volume, may only be present between the front entrance window and the phantom insert(s) above it. The error induced by these air gaps was considered negligible, since the parallel magnetic field has been previously shown to maintain the dose fairly constant over small air gaps. The ion chamber and sheet combination were stepped down through the stack of lung material measuring the depth dose from the surface of the phantom to a depth of 10 cm.

The measurements in the Gammex lung phantom were performed with the entire phantom placed at two separate locations within the electromagnets’ bore: top surface of the phantom coinciding with the top of the electromagnet [Fig. 1(a)], and top surface of the phantom coinciding with the center of the electromagnet bore [Fig. 1(b)]. A 6 MV beam with 5 × 5 cm² field size at the isocenter was used for both setups, which became 8.5 × 8.5 cm² on the surface of the phantom at a source to surface distance (SSD) of 170 cm [Fig. 1(a) setup], and 9.2 × 9.2 cm² on the surface of the phantom at an SSD of 183 cm [Fig. 1(b) setup].

For the Monte Carlo simulations, DOSXYZnrc was slightly modified to read the 3D magnetic field. The standard magnetic field implementation, based on the work by A. F. Bielajew, already present in the macro package “emf_macros”, was used but with a shorter particle step size. The particle step size was shortened by reducing the parameter responsible for controlling the amount of deflection in the electromagnetic field (EMULMT) from the default 0.02 to 0.001. With the reduced step size and using the default condensed history technique, this implementation is expected to pass the Fano cavity test as it is similar to one of the cases investigated by Malkov and Rogers. Shortening the step size in this manner has also been shown to result in magnetic field dose simulations more accurately matching our polystyrene measurements. A previously benchmarked phase space

![Image](https://example.com/image.png)

**Fig. 1.** The measurement setup with the two GMW electromagnets (shown in cross section) placed on a wooden stand. The Gammex lung phantom with the polystyrene bottom (indicated in the figure) was positioned with its top surface coinciding with the top of the electromagnet (a), then with its top surface coinciding with the center of the electromagnet (b). [Color figure can be viewed at wileyonlinelibrary.com]
file represented the 6 MV beam of the Varian Silhouette unit and was used as the source in the DOSXYZnrc simulations. COMSOL Multiphysics V4.4 (Burlington, MA) calculated the 3D magnetic field map that was benchmarked against measurements as previously described.\textsuperscript{10}

The standard EGSnrc lung material (LUNG521ICRU) was used to simulate the Gammex lung slabs. The simulated phantom was composed of lung (13 × 13 × 18 cm$^3$) followed by 10 cm of polystyrene (between 18 and 28 cm depth). However, running the simulations in a phantom composed entirely of lung did not have any noticeable effect on the simulated depth dose between 0 cm (surface) and 10 cm depth. The simulations were run similarly to the ones in polystyrene\textsuperscript{10} with an air cavity and polyethylene entrance window (0.53 × 0.53 × 0.2 cm$^3$ and 0.53 × 0.53 × 0.003 cm$^3$ respectively) approximating the Markus parallel plate chamber dimensions, and scoring the dose to the air cavity. The circular dimensions of the ion chamber components were approximated in the lateral (x and y) directions since DOSXYZnrc can only model rectangular geometry. The chamber dimensions in the depth (z) direction however were modeled exactly. This method of approximating the cylindrical geometry of the ion chamber with a cubical one has yielded excellent results for our previous work\textsuperscript{10} and implies that the depth dose is not very sensitive to the exact dimensions of the ion chamber components in the lateral direction. The air cavity and polyethylene entrance window were stepped down through the simulated lung phantom much the same way as the ion chamber insert was stepped for the measurements.

3. RESULTS AND DISCUSSION

For each setup, both the magnetic field and no magnetic field curves were normalized to the no magnetic field maximum dose ($D_{\text{max}}$) to determine the PDD, and the differences between the measured and simulated PDDs are presented in Fig. 2. At the surface the simulated dose is lower than the measured one, particularly without the magnetic field, for both experimental setups. However, when the magnetic field is present, as we move deeper in the phantom, the simulated dose is higher than the measurement by up to 2.5%.

Therefore, when the ion chamber is at the surface, there are fewer electrons traversing the air cavity in the EGSnrc simulation, compared to the measurements, both with and without the magnetic field. However, at deeper locations within the phantom, more electrons traverse the air cavity in the simulations compared to measurements when the magnetic field is present. This may be caused by not explicitly simulating the integral acrylic body of the ion chamber. For simulating the depth dose in polystyrene, modeling the air cavity and entrance window was enough to match measurements and simulations,\textsuperscript{10} since the electron density of polystyrene and acrylic are close to each other.

Thus, all our subsequent lung simulations included the acrylic body of the ion chamber as a 2.7 × 2.7 × 1.4 cm$^3$ volume around and below the air cavity. The comparison between the manufacturer schematic of the Markus ion chamber and the ion chamber model used in our Monte Carlo simulations is presented in Fig. 3. Since acrylic is not a standard material in EGSnrc, the 521icru.pegs4.dat file was appended to include the cross sectional data for acrylic.\textsuperscript{22}

Figure 4 shows the comparison between the measured (solid lines) and the simulated (points) depth dose for the setup presented in Fig. 1(a), where the surface of the lung phantom coincides with the top of the electromagnet. With a mean statistical uncertainty of 0.5%, the data markers are larger than the uncertainty for all the simulated points. The maximum uncertainty in the measured PDDs is 0.3%.

With the acrylic body of the ion chamber included, the EGSnrc Monte Carlo is able to accurately calculate the dose in lung material in the presence of a parallel magnetic field.
with the most simulated points falling within 1.5% of the measurements. The largest difference is 1.8% for the depth dose with the magnetic field turned on. Both measurements and simulations show a surface dose increase of ~11% in the lung material due to the parallel magnetic field. This increase in the surface dose is due in part to contaminant electrons originating in the linac head and the irradiated air column having their lateral spread confined by the parallel magnetic field. For our particular setup the fringe magnetic field lines converge toward the central axis of the electromagnet bore, thus the contaminant electrons are also concentrated toward the center of the beam that was aligned with the central axis of the magnet. Past the first centimeter of the buildup region, these contaminant electrons have mostly been absorbed in the lung material and the two depth dose curves, with and without the magnetic field, are within <2% of each other for both measurements and simulations. There is also no significant difference in the depth of maximum dose, caused by the magnetic field, for this setup.

The measurements and simulations for the setup presented in Fig. 1(b), where the surface of the lung phantom coincides with the center of the magnet, are compared in Fig. 5. Similar to the setup in Fig. 1(a), for both the measured and the simulated PDDs, the uncertainties are smaller than the data markers. EGSnrc is able to accurately calculate the dose in lung with a parallel magnetic field for this setup as well, with all the simulated points agreeing with the measurements to within <1.5%. The highest percent difference between measurements and simulations is at the surface irrespective of magnetic field presence. Both the measurements and the simulations show a surface dose increase of ~32% (with respect to no magnetic field D_{max}) caused by the presence of the parallel magnetic field.

The higher surface dose increase, compared to the previous setup, is caused by the additional air column being irradiated in relatively high (>0.13 T) magnetic field and by the converging magnetic field lines further concentrating contaminant electrons toward the center of the beam. For this setup the entire buildup region is affected by the magnetic field, with the two depth dose curves becoming indistinguishable only past the depth of maximum dose. Additionally, for this setup, the magnetic field makes the depth of maximum dose shallower in both the measurements and the simulations.

Figure 6 summarizes the percent difference between measurements and simulations for both setups, with and without magnetic field. As can be seen by comparing Fig. 6 to 2, adding the acrylic body of the ion chamber around the air cavity in the Monte Carlo Simulations drastically improves the agreement between the measured and the simulated surface dose. Past the buildup region, the PDD simulated with a magnetic field is, on average, lower than the measured one. The average difference
between measurements and simulations with the magnetic field past the buildup region is 1.5% for the Fig. 1(a) setup and 0.6% for the Fig. 1(b) setup, while the average uncertainty in the difference is 0.7% and 0.8%, respectively. This difference may be due to a slightly different density of the acrylic used for the actual ion chamber compared to the simulated one. As stated above, acrylic is not a standard material present in the cross sectional files of EGSnrc, and we needed to add it. We used the most common density for acrylic, namely 1.18 g/cm³. However acrylic can have a range of densities (between 1.17 and 1.20 g/cm³). Using the exact density of the physical ion chamber’s acrylic for the simulations may yield a slightly better match between measurements and simulations.

To investigate the influence of simulated ion chamber component size on the calculated depth doses, a few points (d = 0.0 cm, D$_{max}$ = 4.5 cm, 7.0 cm) were simulated with a 10% smaller air cavity volume (by reducing the dimensions from 0.53 × 0.53 × 0.2 to 0.5 × 0.5 × 0.2 cm³). This setup was simulated both with and without the magnetic field present. The calculated points were again normalized to D$_{max}$, recalculated with the smaller volume, without the magnetic field. The PDDs at 7.0 cm depth with the 0.5 × 0.5 × 0.2 and 0.53 × 0.53 × 0.2 cm³ cavities were within 0.6% for both cases. The PDDs with the two cavity sizes calculated at the surface were within 0.3% and 0.7%, respectively with and without the magnetic field. These differences are comparable to the previously mentioned mean statistical uncertainty in our Monte Carlo simulations (~0.5%). Thus the PDD calculations are fairly insensitive to the lateral ion chamber component size, while being sensitive to the ion chamber materials when the ion chamber wall has a considerably different density compared to the medium.

4. CONCLUSION

The dose in the Gammex lung-like material has been measured in the presence of a magnetic field parallel to the central axis of the radiation beam using a PTW Markus parallel plate ion chamber. The measurements were compared to EGSnrc Monte Carlo simulations performed in regular lung. It was found that the simulations needed to include a rough model of all the ion chamber components (polyethylene entrance window, air cavity, as well as the acrylic ion chamber body) for a better match with the measurements, due to the considerable difference in the density of the chamber wall compared to lung. The approximations in the lateral shape of the Monte Carlo ion chamber model may have a minimal impact on the final percent depth dose results as evidenced by very small changes due to a 10% reduction in the chamber’s sensitive volume.

EGSnrc was able to accurately calculate the dose in lung in the presence of a realistic parallel magnetic field at two different locations within the electromagnet bore. All the simulated points were within 2% (with respect to no magnetic field D$_{max}$) of the measurements, with the majority falling within less than 1.5%.

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CONFLICTS OF INTEREST

One of the authors, Dr. Fallone, is a co-founder and CEO of MagnetTx Oncology Solutions.

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