Technical Note: Ion chamber angular dependence in a magnetic field

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(Received 20 December 2016; revised 19 May 2017; accepted for publication 2 June 2017; published 10 July 2017)

Purpose: There have been several studies investigating dose deposition effects within radiation detectors in the presence of a magnetic field. However, to date there has only been a passing investigation which explicitly investigates detector dose–response as a function of detector orientation. Herein we will investigate the dose–response as a function angular orientation of a PR06C ionization chamber. We will also benchmark the Monte Carlo code PENELOPE with the newly developed magnetic field Fano test.

Methods: The PENELOPE Monte Carlo package was used to simulate a PR06C ionization chamber in 0.35 T through 1.5 T magnetic fields oriented either parallel or orthogonal to an incident 6 MV radiation beam. The ionization chamber was rotated through a number of polar and azimuthal angles. The dose deposited within the chamber at each angular position and magnetic field strength was scored then normalized to that deposited in the same orientation with no magnetic field. The simulation was also benchmarked via a Fano test in magnetic field.

Results: The Fano test yielded a 0.4% difference between simulation and expected result, which is similar to previous findings and sufficient for the purposes of this study. The angular dose–response map in all cases where the magnetic field is oriented orthogonal to the radiation beam is quite varied and can range from 0.89 to 1.08. Angular deviations as small as 3° can lead to dose–response changes in excess of 1%. When the magnetic field is parallel to the photon beam, the angular dose–response map is homogeneous and less than 1% below 1.0 T.

Conclusions: Within a magnetic field-oriented orthogonal to the radiation beam, the ionization chamber dose–response fluctuates greatly as a function of polar and azimuthal angle, where a parallel field yields a more homogeneous dose–response. © 2017 American Association of Physicists in Medicine [https://doi.org/10.1002/mp.12405]

Key words: angular dependence, ion chamber, Linac-MR, magnetic field, Monte Carlo, setup inaccuracies

1. INTRODUCTION

There are currently a number of groups developing hybrid linear accelerator MR imaging devices (Linac-MR) with the purpose of real-time imaging during the treatment of cancers.1–4 The strong static magnetic field of the MR imaging device will not directly affect the primary photon fields used to treat; however, the secondary electron field — and hence radiation dose deposition — will experience a deflection owing to the action of the Lorentz force.5–12

The actions of the Lorentz force on the secondary electron fluence has been found to modify the measured dose deposition in selected ionization chambers inconsistent with the changes in the dose to the medium.13–15 The dose–response in these studies is heavily geometry dependent and was found to be a combination of the altered path length of electrons within the detection volume, and electron fluence alterations for those electrons immediately surrounding the chamber. These previous studies have primarily investigated the effect of magnetic field strength on the dose–response of the considered detectors at specific relative orientations of radiation beam, magnetic field, and detector axis. The exception being Smit et al.14 who have measured in phantom the effect of rotating an NE2571 ionization chamber through 180° in a plane orthogonal to the incident radiation beam and containing a 1.5 T static magnetic field.

The work herein will investigate, via Monte Carlo simulation, the PR06C dose–response as a function of polar and azimuthal angle with respect to the radiation beam in the presence of a homogeneous magnetic field oriented either longitudinally or transversely to the radiation beam. The complete angular mapping of the dose–response as a function
of chamber angle will allow for the analysis of errors that may arise due to the incorrect angular positioning of radiation detectors in various radiation measurement situations. These kinds of errors have arisen in the past for estimated photon beam angular deviations of $3^\circ$.\textsuperscript{13} when measuring the dose–response as a function of magnetic field strength.

Furthermore, there are several current studies which examine the efficacy of various Monte Carlo codes.\textsuperscript{16–18} in light of the recent work on the addition of magnetic fields to the Boltzmann radiation transport equation\textsuperscript{19,20} and the development of a magnetic field compatible Fano test.\textsuperscript{21} These studies have found varying levels of congruence between simulation and expected values, ranging from 0.1% to 1% depending on magnetic field strength, particle energy, and simulation parameters. Within this study, we will benchmark the Monte Carlo code PENELOPE\textsuperscript{22} by employing the conditions outlined by Bouchard et al.\textsuperscript{21} to run our own Fano test with identical simulation parameters to those used in the angular mapping geometry.

2. MATERIALS AND METHODS

2.1. Monte Carlo model

PENELOPE was employed in the simulation of a PR06 ionization chamber in various angular configurations within a photon beam in the presence of a static magnetic field.\textsuperscript{22–24} The PENELOPE code system was chosen due to its use in the previous simulation of the PR06C chamber,\textsuperscript{15} which will allow for a more direct comparison to previous results. The PENELOPE main program penmain.f and the associated magnetic field file pm-field.f were used as provided by the OECD/NEA databank with the lines writing electron tracks to file commented out. The WCC and WCR input parameters were set to 1 keV. These parameters define the energy thresholds for hard inelastic and radiative events, respectively. The $E_{\text{abs}}$ parameters were set to 10 keV, these parameters define the particle absorption energies in the material, particles below this threshold deposit their energy in place and the simulation proceeds to the next particle in the stack. The C1 and C2 parameters can range from 0 to 0.2, with 0 being a full non-mixed type simulation, and were each set to 0.01, which favors simulation accuracy over speed. These parameters define the average deflection angle between hard elastic events and maximal fractional energy loss between hard elastic events, respectively. Finally, the maximum step length between events was limited to 1 $\mu$m to ensure that sufficient interaction sampling occurs in the volume of interest so as to accurately represent the dose deposited. All simulations were run with the above parameters in all materials until the uncertainty in the dose–response ratio was < 1% on average as determined by common uncertainty propagation in ratios (fractional uncertainties are added in quadrature).

The ionization chamber was defined in PENELOPE using an identical geometry to the previous study (shown in Fig. 1),\textsuperscript{15} with materials from the PENELOPE code system. The detection volume was modeled as a cylindrical air cavity (with density of 0.0012 g/cm$^3$) 6.4 mm in diameter, and 20.2 mm in length, with a spherical tip extending a further 1.8 mm. The walls of the ionization chamber are 0.28 mm in thickness, and the central electrode has a diameter of 1.6 mm and length of 21.1 mm. The detector stem extends a further 24 mm opposite the collection volume and has a diameter equal to that of the outer wall of the collection volume. All non-air ionization chamber materials were modeled as C-552, a synthetic air-equivalent conducting plastic with density 1.76 g/cm$^3$. The entirety of the ionization chamber was encased in a snug fit PMMA (density 1.19 g/cm$^3$) buildup cap 12.7 mm in thickness, and the entire system was simulated in vacuum. The centroid of the detection volume was located at 0, 0, 0 in x, y, z in every simulation performed, and the average dose deposited per simulated shower was scored in the detection volume.

In order to model the pertinent angles required to map the angular dependence of the dose–response of the PR06C ionization chamber, the chamber (with buildup) was rotated through various points about the origin. Each rotation will henceforth be defined with the common polar ($\theta$) and azimuthal ($\phi$) angles representing the directionality of the tip of the chamber, i.e., angles of ($0^\circ$, $0^\circ$), ($90^\circ$, $0^\circ$), ($90^\circ$, $90^\circ$) correspond to the tip of the chamber pointing in the positive Z, X, and Y axis, respectively. Small angular deviations about standard chamber orientations are of interest, and hence, the densest accumulation of simulation points occurs around the standard directions of ($0^\circ$, $0^\circ$), ($90^\circ$, $0^\circ$), ($90^\circ$, $90^\circ$), and ($90^\circ$, $180^\circ$). Specifically, deviations of $3^\circ$, $5^\circ$, and $10^\circ$ outward along 8 equally spaced lines from the aforementioned standard directional axes were simulated, and additional polar and azimuthal angles were simulated sparsely between these regions. These simulated points are visualized for the reader in Fig. 2.

![Fig. 1. PR06C ionization chamber as simulated, pictured in the ($90^\circ$, $0^\circ$) orientation. The central black region represents the collection volume (air), the dotted region represents the C552 plastic central collector electrode and the wall, and the outer gray region is the PMMA buildup cap. The chamber is in vacuum for the purposes of the simulation.](image-url)
As per prior studies, a Varian 6 MV photon beam with a spectrum described by Sheikh-Bagheri and Rogers (2002) was employed as the source of radiation. The source was located 100 cm from the center of the collection volume of the ionization chamber in the +z direction. The beam shape was modeled as a cone with aperture 3.205°, which yields a circular field size of 5.6 cm in radius at the location of the ionization chamber centroid. The main magnetic field was simulated as static and homogeneous as per prior studies. Separate angular dose–response maps were created with the magnetic field simulated in the +z and +y directions with strengths of 0.5 T, 1.0 T, or 1.5 T, and 0.35 T in the +y direction only.

The ionization chamber dose–response as a function of angle is defined as the ratio of the average dose deposited per shower with magnetic field to that without magnetic field in a particular angular orientation (θ, φ). The simulated dose–response for each magnetic field strength as a function of angular orientation were compiled into a sparse matrix in MATLAB (MathWorks Inc., Natick, MA, USA), where a 2D cubic spline interpolation between points using the function “griddata” was performed and the resulting full matrix plotted. It should be noted that symmetry in (90°, 90°) and (90°, 270°) was forced, i.e., the dose–responses of (90°, 270°) were set to be equal to (90°, 90°)] as their equality is expected geometrically. This is because for a magnetic field along the +y direction, the primarily −z directed electrons would curve either clockwise or counter clockwise with respect to a circular cross-sectional plane of the ionization chamber; this directionality difference is expected to have no bearing on dose deposition. Similar arguments can be made for z-directed magnetic fields.

2.B. Fano cavity test

To validate our magnetic field simulations, a Fano test benchmark simulation was performed, using a similar approach to that outlined by Sempau and Andreo (2006) and identical to that employed by De Pooter et al. (2015) for the same code system. The simulation was performed with identical input parameters to the simulations above, and employed 2 MeV isotropic electrons (representing the secondary radiation field) in a 1.5-T magnetic field perpendicular to the detector axis. This magnetic field direction is expected to have the greatest effect on the accuracy of the PENELOPE algorithm in this geometry. Two of the input parameters differ slightly from those used by De Pooter et al. (2015) to benchmark the PENELOPE code system; they used an Eabs value of 1 keV (as opposed to 10 keV) and a maximum step length of 0.1 mm (as opposed to 1 μm). It is anticipated that the small step size utilized should drive the Fano test toward a favorable result.

3. RESULTS AND DISCUSSION

3.A. Fano cavity test

The Fano test result was 0.4% ± 0.5% (k = 3, i.e., 3 standard deviations) for 2-MeV electrons in a 1.5-T field perpendicular to the long axis of the detector for the PENELOPE simulation parameters considered. This result compares well to the results obtained by De Pooter et al. (2015) for a 1.5-T magnetic field with similar simulation parameters, where an overall result of 0.3% — and in some cases 1.0% — was found. In addition, it is the ratio of dose deposited within a magnetic field environment to that without magnetic field that is of interest in this study. These ratios were found to behave in a more stable and favorable manner with regard to the Fano test. The 0.4% level of equivalence should thus be suitable for simulation of these ratios to assess general trends and identify promising orientations.

3.B. Magnetic field directional dependence

The angular dependence maps as a function of polar and azimuthal angle of the ionization chamber with respect to the radiation beam within 0.35 T, 0.5 T, 1.0 T, and 1.5 T transverse and longitudinal fields are presented in Figs. 3 and 4. All simulated ratios have statistical uncertainties of 0.8–1.0% and an average of 0.9% (k = 3). Each simulated angle was run for approximately 370 core hours on a 2.3 Ghz AMD Opteron processor. It should finally be noted that the dose to the ionization chamber without magnetic field changes negligibly within 10° rotations, and thus changes in dose–response can represent errors in angular positioning normalized to a local standard position.

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Fig. 2. Polar plot of simulated ionization chamber angles. The radius represents the polar angle (θ) and the plot angle represents the azimuthal angle (φ) of the tip of the chamber. The radiation direction is straight into the page, and the magnetic field is either toward the reader (longitudinal orientation) or oriented top to bottom in the figure (transverse orientation).
As is evident from Fig. 3 and shown in Table I, there appears to be a relatively stable measurement orientation at polar and azimuthal angles of 90° and 90° with respect to the radiation beam when the magnetic field is oriented along the line of the detector axis. The largest deviation from a 1.0 ratio for a 10° rotation in any direction around this point is 1.0 ± 0.9% for any magnetic field strength investigated, with a mean variation on the order of 0.5 ± 0.9% for all field strengths. Although the uncertainty (k = 3) in these values are comparable to the values themselves, it is clear that there is little if any overall angular variation around this point. It is important to note that this level of error is more stringent than...
what is generally presented in comparable literature, where typically 1 standard deviation, and less often 2 standard deviations are quoted. This is unsurprising due to the cylindrical symmetry of the ionization chamber active volume in the direction of the Lorentz Force. It is also clear from this figure that any other detector orientations that would yield a null detector response of 1.0 in transverse magnetic fields are at non-conventional angles, and in areas of varying intensities of slope as a function of both magnetic field strength and angular position. The dose–response changes are most severe with polar angle changes in all cases, with the maximal deviations coming from changes in polar angles as opposed to azimuthal angle changes. Table I also examines the maximal and average dose–response behavior of small angular deviations in any direction about standard detector positions where the ionization chamber would not be aligned with the main transverse magnetic field. In these positions, at 1.5 T, we see up to a 2 ± 0.8% change in dose–response for a 5° rotation and a 1 ± 0.8% change in dose–response for a 3° rotation. The average change in response is expectedly lower than these values, but does increase past 1% at 10°. Similarly, at lower magnetic field strengths we see maximal changes in response at or near 1% even for a 3° rotation, and the average change in response remains under 1% for up to 10° rotations.

At 90° polar and 0° azimuthal angles, the simulated dose–response in 1.5-T transverse magnetic fields was found to be 1.054 ± 0.009. This would yield a theoretical correction factor of 0.949 compared to no magnetic field, which agrees with the 0.953 value found by Smit et al. (2013) for the NE2571 chamber, and is comparable to the change of 0.958–0.962 in kQ values found by O’Brien et al. (2016) for a number of farmer chambers. For this comparison, it is important to note that the kQ value includes a correction for dose to water, whereas our correction factor does not. When the detector is aligned with the 1.5-T transverse magnetic field, 90° polar and 90° azimuthal angles, we have found a theoretical correction factor of 0.996 (dose–response of 1.0039 ± 0.0008), which again is very similar to the 0.992–1.005 values found previously for a range of farmer chambers. This yields an overall 5% variation in dose–response between these two orientations at 1.5 T, which differs from the 8.8% variation found previously by Smit et al. (2013), although similar trends along azimuthal rotation were observed. Finally, Smit et al. (2013) had previously found no more than a 0.2% deviation in dose–response for azimuthal only rotations of 10° in the (90°, 0°) orientation at 1.5 T. As shown in Table I, a much larger change in dose–response can be expected when also accounting for polar angle rotations. Overall, this work more closely agrees to the work of O’Brien et al. (2016), both of which present some findings different from those of Smit et al. (2013).

It is also worth noting that the polar and azimuthal angular positions of maximal and minimal response are unstable as a function of the magnetic field strength as shown in Fig. 3. The minimum and maximum ratio pairs and their locations are summarized in Table II. The values themselves are similar but not identical in all cases to the maximum and minimum values found previously for the PR06C. Deviations from these previous values appear to be partially explained by a shift in the angular directions of the minimum and maximum values which were unaccounted for in previous studies.

Table I. Maximal and average dose–response variations for 3°, 5°, and 10° rotations in any direction, expressed as a percent change in normalized dose–response, about each of the associated standard detector angular orientations (θ, φ). Tabulated for each magnetic field strength in the +y direction (90°, 90°). Each value has an average ± 0.9% uncertainty (k = 3).

<table>
<thead>
<tr>
<th>Variation from reference axis (%)</th>
<th>0.35 T (3°, 5°, 10°)</th>
<th>0.5 T (3°, 5°, 10°)</th>
<th>1.0 T (3°, 5°, 10°)</th>
<th>1.5 T (3°, 5°, 10°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max variation (0°, 0°)</td>
<td>1.3, 1.3, 2.3</td>
<td>0.6, 1.1, 1.5</td>
<td>0.7, 0.8, 2.0</td>
<td>1.0, 1.7, 3.4</td>
</tr>
<tr>
<td>Average variation (0°, 0°)</td>
<td>0.5, 0.6, 0.9</td>
<td>0.3, 0.4, 0.6</td>
<td>0.3, 0.4, 0.6</td>
<td>0.5, 0.7, 1.0</td>
</tr>
<tr>
<td>Max variation (90°, 0°)</td>
<td>0.5, 0.9, 1.1</td>
<td>0.7, 0.7, 1.2</td>
<td>0.5, 0.9, 1.2</td>
<td>0.9, 2.0, 2.8</td>
</tr>
<tr>
<td>Average variation (90°, 0°)</td>
<td>0.3, 0.5, 0.5</td>
<td>0.4, 0.4, 0.5</td>
<td>0.3, 0.5, 0.8</td>
<td>0.4, 0.7, 1.0</td>
</tr>
<tr>
<td>Max variation (90°, 90°)</td>
<td>0.8, 0.8, 1.0</td>
<td>0.8, 0.8, 0.8</td>
<td>0.9, 0.9, 0.9</td>
<td>0.8, 0.8, 0.8</td>
</tr>
<tr>
<td>Average variation (90°, 90°)</td>
<td>0.3, 0.3, 0.4</td>
<td>0.3, 0.4, 0.5</td>
<td>0.4, 0.4, 0.5</td>
<td>0.4, 0.5, 0.5</td>
</tr>
<tr>
<td>Max variation (90°, 180°)</td>
<td>0.7, 0.9, 1.5</td>
<td>1.0, 1.1, 1.6</td>
<td>0.7, 0.9, 0.9</td>
<td>1.0, 1.5, 2.8</td>
</tr>
<tr>
<td>Average variation (90°, 180°)</td>
<td>0.4, 0.5, 0.6</td>
<td>0.4, 0.5, 0.6</td>
<td>0.4, 0.6, 0.7</td>
<td>0.5, 0.7, 1.2</td>
</tr>
</tbody>
</table>

Table II. Maximum and minimum dose–response ratios and their polar and azimuthal locations (θ, φ) for transverse magnetic fields of 0.35–1.5 T. Each value has an average ± 0.9% uncertainty (k = 3).

<table>
<thead>
<tr>
<th></th>
<th>0.35 T</th>
<th>0.5 T</th>
<th>1.0 T</th>
<th>1.5 T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum dose ratio</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dose ratio</td>
<td>1.05</td>
<td>1.06</td>
<td>1.09</td>
<td>1.08</td>
</tr>
<tr>
<td>Position (θ, φ)</td>
<td>(60°, 0°)</td>
<td>(60°, 0°)</td>
<td>(95°, 0°)</td>
<td>(60°, 180°)</td>
</tr>
<tr>
<td>Minimum dose ratio</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dose ratio</td>
<td>0.94</td>
<td>0.92</td>
<td>0.90</td>
<td>0.89</td>
</tr>
<tr>
<td>Position (θ, φ)</td>
<td>(10°, 135°)</td>
<td>(3°, 180°)</td>
<td>(10°, 45°)</td>
<td>(30°, 0°)</td>
</tr>
</tbody>
</table>
As shown in Fig. 4, the PR06C chamber has a uniform and small (≤ 1%) response behavior as a function of detector polar and azimuthal angle, at or below longitudinal magnetic fields of 1.0 T. The response of the ionization chamber at 1.5 T in magnetic fields parallel to the radiation beam is worst at low polar angles — near 1.5 ± 0.8° — but is still overall quite uniform with an average variation of 0.3 ± 0.8% from the mean. This behavior is unsurprising given previous work investigating dose–response as a function of longitudinal magnetic field strength yielded near uniform responses regardless of the limited angles investigated.15

4. CONCLUSION

This article represents a comprehensive study of the angular orientation dependency of the magnetic field dose–response of an ionization chamber. To the authors’ knowledge, it is also only the second study to include the magnetic field adapted Fano cavity test for the Monte Carlo code PENLEOPE. The simulation parameters employed for this specific study passed the Fano cavity test to the 0.4% level, which is supportive of the other PENLEOPE Fano test results. Further, this level of congruence between simulation and theory is still sufficient to analyze gross trends and identify possible ideal detector orientations, especially when taking the ratio of dose deposition values, which has been shown to yield better performance in Fano test results.

Regarding farmer chamber setup, when a strong magnetic field exists in an orientation perpendicular to that of the radiation beam, it may be best to orient a farmer style chamber along the direction of the magnetic field. Here, the expected magnetic field response is 1.0 regardless of field strength, and small angular deviations in positioning do not have a strong effect on dose–response. Other standard orientations of ionization chamber can yield dose–response errors of 1–2% ± 0.9% with small 5° errors in angular positioning dependent on magnetic field strength, and can yield further errors if the incorrect magnetic field is used to determine the dose–response. Resultantly, care must be exercised when positioning such chambers so as not to introduce avoidable errors in measurement. When using farmer style ionization chambers similar to the PR06C in magnetic fields parallel to the radiation beam, only one small magnetic field correction, near or below about 1% depending on field strength, is required regardless of detector angular orientation with respect to the photon beam.

ACKNOWLEDGMENTS

This work is supported by the Alberta Innovates: Health Solutions, CRI0 Team grant.

CONFLICT OF INTEREST

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

REFERENCES


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