Dose response of selected ion chambers in applied homogeneous transverse and longitudinal magnetic fields

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Purpose: The magnetic fields of an integrated MR-Linac system will alter the paths of electrons that produce ions in the ionization chambers. The dose response of selected ion chambers is evaluated in the presence of varying transverse and longitudinal magnetic fields. The investigation is useful in calibration of therapeutic x-ray beams associated with MR-Linac systems.

Methods: The Monte Carlo code PENELOPE was used to model the irradiation of NE2571, and PR06C ionization chambers in the presence of a transverse and longitudinal (with respect to the photon beam) magnetic fields of varying magnitude. The long axis of each chamber was simulated both parallel and perpendicular to the incident photon beam for each magnetic field case. The dose deposited in each chamber for each case was compared to the case with zero magnetic field by means of a ratio. The PR06C chamber’s response was measured in the presence of a transverse magnetic field with field strengths ranging from 0.0 to 0.2 T to compare to simulated results.

Results: The simulations and measured data show that in the presence of a transverse magnetic field there is a considerable dose response (maximum of 11% near 1.0 T in the ion chambers investigated, which depends on the magnitude of magnetic field, and relative orientation of the magnetic field, radiation beam, and ion chamber. Measurements made with the PR06C chamber verify these results in the region of measurement. In contrast, a longitudinal magnetic field produces only a slight increase in dose response (2% at 1.5 T) that rises slowly with increasing magnetic field and is seemingly independent of chamber orientation. Response trends were similar for the two ion chambers and relative orientations considered, but slight variations are present from chamber to chamber.

Conclusions: Care must be taken when making ion chamber measurements in a transverse magnetic field. Ion chamber responses vary not only with transverse field strength, but with chamber orientation and type, and can be considerable. Longitudinal magnetic fields influence ion chamber responses relatively little (2% at 1.5 T), and only at field strengths in excess of 1.0 T. © 2013 American Association of Physicists in Medicine. [http://dx.doi.org/10.1118/1.4794496]

Key words: Monte Carlo, Monte Carlo methods, linac-MR, longitudinal and transverse linac-MR, linear accelerators, biomedical MRI, magnetic field, dosimetry, ionization chambers

I. INTRODUCTION

At present, a few research groups are pursuing the integration of a magnetic resonance imaging (MRI) system with a linear accelerator (linac) and have achieved irradiation and imaging of a volume simultaneously.1, 2 Our group at the Cross Cancer Institute (CCI) in Edmonton, Canada uses a biplanar magnet for the MRI that rotates in unison with the linac as outlined in previous work.1, 3 This biplanar design is capable of both the transverse and longitudinal orientations. In the longitudinal orientation, the magnetic field of MRI is oriented parallel to the direction of the photon beam, and in the transverse orientation, the magnetic field is oriented perpendicular to the direction of the photon beam. The group at the UMC Utrecht in the Netherlands is combining a solenoidal magnet with a rotating megavoltage linac that is used in the transverse configuration.2

Currently, there is a geometric margin included around the clinical target volume to account for inter- and intrafractional patient setup variability and tumor motion.4 The goal is to use the imaging capabilities of the MRI devices in real time to track the motion of the tumor, and control the radiation beam to account for this motion. This added control will reduce the healthy tissue exposed to unnecessary radiation by reducing the geometric margin, and allow for increased dose to the target volume yielding an improved therapeutic outcome.
Several investigations have studied the influence of the Lorentz force by the magnetic field of the MRI on the path of the electrons released in geometries irradiated with therapeutic photon beams\(^3\).\(^5\).\(^6\) The resultant change in dose in a homogeneous medium has been shown to be small to negligible in both transverse\(^6\) and longitudinal magnetic configurations.\(^7\) However, tissue air interfaces in the presence of a transverse magnetic field can exhibit large changes in dose distribution due to the electron return effect (ERE)\(^3\).\(^8\).\(^9\) whereby electrons are curved under the influence of the magnetic field while traveling in lower density tissue such as lung and/or air cavities.

Air cavity ionization chambers are generally used for the reference dosimetry calibration of the clinical radiation beams. It can therefore be expected, and has been previously shown\(^10\).\(^11\) that ion chamber response per unit fluence will be different in the presence of a transverse magnetic field due to the change in the trajectories of the secondary electrons within the air cavity. Therefore, the measurements made with the ion chamber cannot be easily converted to the dose in the medium, as done in reference dosimetry protocols (e.g., TG51), since the magnetic field affects the electron paths much more in the air cavity than the medium. For the case of longitudinal geometry, dose deposition in the air cavity of the ion chamber will be altered in a manner similar to that of lung tissue investigated previously\(^12\), but on a smaller scale. Although, the dose response of ion chambers in the presence of a longitudinal magnetic field also needs to be investigated, it is expected that there will be a relatively smaller change in response when compared to the transverse magnetic field case.

In this study, we examine the dose response of two ionization chambers (NE2571, PR06C) in a magnetic field, in order to examine the practicability of their use in calibrating the photon beams in a hybrid MR-Linac system. In addition to investigating various ion chambers, we further extend this work beyond similar works\(^5\).\(^10\).\(^11\) by including the effect of longitudinal magnetic field on the response of ion chambers in photon beams. Monte Carlo simulations are carried out in various relative orientations of magnetic field, radiation beam, and long axis of the ion chamber. Experimental measurements are made in a subset of these configurations in order to validate the simulations wherever possible.

II. MATERIALS AND METHODS

II.A. Description of geometry

While studying the magnetic field dose response of various radiation detectors, there are a few geometrical orientations to consider. The strength of the magnetic field itself is varied in the investigation, and the orientation of the magnetic field is considered either parallel (longitudinal magnetic field orientations III and IV of Fig. 1) or perpendicular (transverse magnetic field orientations I and II of Fig. 1) to the direction of radiation beam. In each of the two orientations of the magnetic field, the long axis of the radiation detector can be further oriented in two different ways. In orientations I and III of Fig. 1, the long axis of the chamber is oriented parallel to the radiation beam direction for both magnetic field orientations, while in orientations II and IV of Fig. 1 the long axis of the chamber is perpendicular to the radiation beam.

The NE2571 chamber was selected for this study to compare directly to the Meijsing group measurements.\(^10\) The PR06C was selected because it is widely used for relative dose and quality assurance measurements, and its central electrode is made of C-552 compared to aluminum used in the NE2571.

II.B. Simulation setup

The Monte Carlo code PENELOPE (Refs. 13 and 14) has been used for the simulation of the ion chambers. This code was chosen due to its treatment of electromagnetic fields as outlined in the user manual,\(^13\) which has been previously determined to match EGS results.\(^3\) The geometry package included with PENELOPE allows for easy modeling of the chamber and associated irradiation setup. Additionally, PENELOPE allows lower cutoff energies for particle transport. This is of importance in ion chamber simulation because the chamber is small, and even the lower energy electrons may leave the scoring volume in some cases instead of depositing their whole dose within the scoring volume. Thus, transport cutoff needs to ensure that the electrons at the cutoff energy do not escape the scoring volume. The code itself has been thoroughly benchmarked without the introduction of a magnetic field.\(^14\).\(^15\).\(^16\) The code is provided with a subroutine, pm-field.f, containing the electromagnetic implementations that are described in the user manual.\(^13\) The main program pm-field.f provided with the code was used in a series of experiments with a small modification to eliminate the recording of electron tracks to a file. The energy per shower deposited in...
the air cavity of each chamber as a function of magnetic field strength was scored. The data are then presented as the ratio of energy deposited in the presence of magnetic field to that without any magnetic field.

The user selectable transport parameters in PENELOPE are outlined in Table I. The parameters WCC and WCR are energy thresholds for hard inelastic collision and radiative events, respectively. Both of these parameters were set to 1 keV so as to accurately model lower energy events. Eabs is the absorption energy for particles, when the energy of a particle drops below this value it is no longer tracked and is assumed to deposit the remaining of its energy in place. A value of 1 keV was chosen to accurately model the transport of lower energy electrons. The C1 and C2 parameters in Table I are related to the random hinge mixed simulation algorithm in PENELOPE. C1 determines the mean free path between hard elastic events, and C2 is the maximum average fractional energy loss between hard elastic events. These define the degree of mixed simulation, and can be varied from 0 (full simulation) to 0.2 (maximum allowed mixed simulation value). The C1 and C2 parameters were varied to obtain a balance between simulation speed and accuracy, the results of simulations were found to vary little when decreasing the C values below 0.1. Simulations in each case were run for \(2 \times 10^9\) histories or a number that yielded an error with standard deviation on the order of 0.5%, whichever came first.

All four orientations outlined in Fig. 1 were simulated for each of the ion chambers. Since the NE2571 ion chamber was simulated partly to match the data measured by Meijsing et al., the 6 MV photon beam spectrum for the Elekta system was used in this simulation. The PR06C was simulated using the Varian 600C 6 MV photon beam spectrum as this unit was available for experimental investigations. The 6 MV spectra for the Varian 600C and Elekta systems were taken as those published by Sheikh-Bagheri and Rogers. To match measured data and for a degree of consistency within chamber simulations, both chambers were simulated at 100 cm from the radiation source at the isocenter, the field sizes varied between chambers to match experimental limitations due to the magnets used, these parameters are outlined in Table I.

The NE2571 chamber was simulated as a series of cylinders corresponding to the cross sectional layout of the chamber. The air cavity was cylinder of 6.4 mm diameter and 21.8 mm length. The air cavity was surrounded by a graphite wall of 0.35 mm annular thickness. The central, solid electrode with 1 mm diameter and 20.6 mm length was made from aluminum. This chamber was placed in water phantom (30 \(\times\) 30 \(\times\) 30 cm\(^3\)) at a depth of 4 cm in order to match the simulation geometry to previous work done with the same chamber by Meijsing et al.

The PR06C chamber had a simulation geometry that matched the readily available data from manufacturers and distributors. The PR06C chamber was modeled as a central cylindrical air cavity of 6.4 mm diameter and 20.2 mm length with a spherical tip extending a further 1.8 mm. The central C-552 electrode has a diameter of 1.6 mm and length of 21.1 mm where C-552 refers to a synthetic, conducting plastic that is considered to be air equivalent. The C-552 annular wall had a constant radial thickness of 0.28 mm that surrounded the air cavity. A 24 mm long solid C-552 cylindrical stem with a diameter matching the outer diameter of the wall was also included in the simulation. The PR06C chamber was simulated in air with a PMMA buildup cap that fits snugly, as per the experimental conditions. The buildup cap was simulated with a cylindrical body and spherical tip with an inner surface matching the chamber; it extends through the length of the stem, and is of uniform thickness of 12.7 mm.

To ensure the accuracy of the simulations, the simulated chamber data were benchmarked without a magnetic field in addition to being compared to the measured relative data in a magnetic field. Benchmarking simulations were performed for both chambers in the absence of magnetic field. For each chamber model, the values of the factor \(k_0\) as used in the TG-51 protocol were determined by using the formalism outlined by Muir and Rogers, and the PENELOPE Monte Carlo parameters outlined previously. To ensure validity of the chamber models, the results of these simulations were compared to the previous Monte Carlo study of \(k_0\) values, and published values in TG-51.

II.C. Measurement setup

A NE2571 chamber is unavailable for use in our laboratory. For the PR06C, all experiments were conducted in 6 MV beam from a Varian 600C linac (Varian Medical Systems, Palo Alto, CA). Measurements were made in air with a PMMA buildup cap of thickness 1.3 cm fitted onto the chamber which ensures electronic equilibrium in the absence of magnetic field. The current experimental MRI-Linac system uses permanent magnet, thus, an electromagnet was used in the experiments to obtain variable field strength. The chamber and buildup cap combination was placed between the poles of a small electromagnet (EEV M4261, Chelmsford, England) at the approximate center of the magnet in configurations I and II. The poles of the magnet measure 7.5 cm in diameter and are separated by a distance of 7.5 cm. The magnetic field strength at the center of magnet was varied from 0 to 0.21 T. Although, the maximum field strength of the electromagnet was limited to 0.21 T, this field strength was previously found to be useful for the autocontouring of simulated tumor in lung background. It should be noted that our previous

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Source to chamber distance (cm)</th>
<th>Field size (cm × cm)</th>
<th>Spectrum</th>
<th>PENELOPE parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE Technology Ltd NE2571</td>
<td>100</td>
<td>4 × 10</td>
<td>6 MV Elekta</td>
<td>WCR = WCC = E_{abs} = 1 eV C1 = C2 = 0.1</td>
</tr>
<tr>
<td>Capintec PR06C</td>
<td>100</td>
<td>3.6 × 7</td>
<td>6 MV Varian 600C</td>
<td>WCR = WCC = E_{abs} = 1 eV C1 = C2 = 0.1</td>
</tr>
</tbody>
</table>
The prototype Linac-MR system uses 0.21 T permanent magnet, and the currently available commercial MR-simulation and proposed system from ViewRay also use a similar magnetic field strength. The magnetic field strength between the poles was measured with a three-dimensional hall probe (SENIS GmbH C-H3A-2m_E3D-2.5kHz-1%-0.2T), the probe has an accuracy of 1% as claimed by the manufacturer. Configurations III and IV were not investigated experimentally in this study since the physical structure of the electromagnet did not allow the magnetic field to be parallel to the radiation beam. The ion chamber was set at the isocentre at a distance of 100 cm from the radiation source. The physical size of the electromagnet limited the radiation field size to 4 × 7 cm² but it was sufficiently large to cover the buildup cap and the active volume (0.65 cm³, 24 mm length) of the chamber in both orientations.

The ratio of the charge measured by the ion chamber in the magnetic field (as per the electrometer reading) to the charge measured with zero magnetic field is calculated as a function of the magnetic field strength. A similar ratio was also calculated using the Monte Carlo simulations and compared with the measured one. A multiplicative correction factor can be calculated as the reciprocal of this ratio, to be included in the TG51 formalism correcting for the response of the ion chamber in a magnetic field. In each measurement 100 MUs were delivered and the electrometer reading recorded. This was repeated three times per magnetic field strength, the average of these three was used as the data point associated with the magnetic field. After the measurement set was complete the baseline (no magnetic field) measurement and three intermediate field strengths were verified again.

To investigate the individual contributions of a select few specific TG51 parameters to the change in chamber response due to a magnetic field, measurements of \( P_{\text{ion}} \) and \( P_{\text{pol}} \) were also made at magnetic field strengths of 0.0, 0.09, and 0.14 T. The chamber was set at isocentre (100 cm) in orientation II and irradiated with 100 MUs at 6 MV using a field size of 4 × 7 cm². \( P_{\text{ion}} \) and \( P_{\text{pol}} \) values were calculated according to well-known methods using chamber readings at varying bias voltages and polarity.

The relative nature of the simulation data makes it unnecessary to study the consequences of changing field sizes, resulting in variable head or phantom scatter, provided the field size remains the same in simulations with and without the magnetic field. To ensure the change in chamber response remains constant with field size, the response is measured for a variety of field sizes and two nonzero magnetic field strengths using the measurement setup above (with exception to field size) and orientation II. The resultant ratios are compared from field size to field size and to the expected simulation values.

### III. RESULTS AND DISCUSSION

The results of the \( k_Q \) simulations are provided in Table II along with the previously determined values. The simulated \( k_Q \) values for both chamber models matched the literature values closely. These results, in addition to the measurement verifications of presented data, confirm the accuracy of the chamber models employed. Additionally, the change in dose response as a function of magnetic field strength remains unchanged through the investigated field sizes, and matches the simulated results within 1%, as presented in Table III below, giving credence to the use of the Sheikh-Bagheri and Rogers square field spectra in this instance.

It was found that \( P_{\text{ion}} \) and \( P_{\text{pol}} \) values remained unchanged within error from 0.0 to 0.09 T and 0.14 T. The magnetic field appears not to have any effect on ion collection efficiency at these lower field strengths. The numerical results of the \( P_{\text{ion}} \) and \( P_{\text{pol}} \) measurements are presented in Table IV below. Unsurprisingly, the vast majority of the gross chamber response comes from factors outside \( P_{\text{ion}} \) and \( P_{\text{pol}} \), most likely from \( k_Q \) itself.

The NE2571 ion chamber response in the transverse magnetic field orientations I and II (Fig. 1) obeyed the trends that were measured in previous work. Moreover, the responses among the two chambers were similar which was to be expected considering the similarities in chamber design. Longitudinal field simulations show very little change in response until higher field strengths. At higher fields, the chamber response increases by a few percent depending on the chamber in question.

#### III.A. NE2571

Figure 2 shows the dose response of the NE2571 chamber as a function of magnetic field strength. The results from

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**TABLE II.** Chamber \( k_Q \) values without the magnetic field are compared with the previously published results. Errors quoted are 1 standard deviation.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>TG-51 ( k_Q ) values (Ref. 18)</th>
<th>Previous ( k_Q ) MC study (Ref. 19)</th>
<th>Simulated ( k_Q ) values</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE Technology ltd NE2571</td>
<td>0.995</td>
<td>0.992</td>
<td>0.990 (±0.04)</td>
</tr>
<tr>
<td>Capintec PR06C</td>
<td>0.994</td>
<td>0.994</td>
<td>0.991 (±0.02)</td>
</tr>
</tbody>
</table>

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**TABLE III.** Ratio of readings with the magnetic field indicated to no magnetic field as a function of field size. All measured values are ±0.0015.

<table>
<thead>
<tr>
<th>Field strength (T)</th>
<th>2 × 2 cm ratio</th>
<th>3 × 3 cm ratio</th>
<th>4 × 4 cm ratio</th>
<th>5 × 5 cm ratio</th>
<th>7 × 5 cm ratio</th>
<th>10 × 5 cm ratio</th>
<th>Simulated ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08</td>
<td>1.0030</td>
<td>1.0024</td>
<td>1.0029</td>
<td>1.0025</td>
<td>1.0030</td>
<td>1.0025</td>
<td>1.0033</td>
</tr>
<tr>
<td>0.14</td>
<td>1.0060</td>
<td>1.0056</td>
<td>1.0058</td>
<td>1.0053</td>
<td>1.0059</td>
<td>1.0060</td>
<td>1.0057</td>
</tr>
</tbody>
</table>
TABLE IV. $P_{\text{pol}}$ and $P_{\text{ion}}$ values as a function of magnetic field. Calculation formalism used as per column reference. All values are ±0.002.

<table>
<thead>
<tr>
<th>Field strength (T)</th>
<th>$P_{\text{ion}}$ (Ref. 23)</th>
<th>$P_{\text{ion}}$ (Ref. 18)</th>
<th>$P_{\text{pol}}$ (Ref. 18)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0021</td>
<td>1.0023</td>
<td>1.004</td>
</tr>
<tr>
<td>0.09</td>
<td>1.0021</td>
<td>1.0023</td>
<td>1.004</td>
</tr>
<tr>
<td>0.14</td>
<td>1.0027</td>
<td>1.0029</td>
<td>1.005</td>
</tr>
</tbody>
</table>

the Monte Carlo simulations in orientations I–IV and from the measurements made by Meijsing et al.\textsuperscript{10} in orientations I and II are shown. In orientation I, the simulated response first decreases to a minimum of 0.89 at 0.8 T and climbs slowly back toward 1.0 at higher magnetic field strengths. In orientation II the simulations response shows the opposite trend increasing slowly to a maximum of 1.07 at 1.0 T before decreasing toward 1.0 at higher magnetic field strengths. There is good agreement between measurement and simulation in orientation II at the field strengths where measurements are available, simulations and measurements differ on average by 0.45%. The simulations in orientation I agree within 1% up to field strengths of 0.45 T, but the simulated data is slightly higher than the measurements at higher field strengths. Simulations and measurements at field strengths over 0.45 T in orientation I differ an average of 2.1%. These differences are most likely due to the leniencies allotted to the simulation geometry in the interest of simulation speed, namely the lack of a conical tip or stem on the ion chamber. Deviations in this orientation have also been discussed by the Meijsing group with respect to measurement setup. The simulated histories in orientations I and II were run until the error bars would match previously simulated results.\textsuperscript{10} No data were available to match for orientations III and IV, so histories were run until the standard deviation of the error in the simulation was near 0.5%.

The dose response of the chamber in magnetic field has been previously related to the nature of electron tracks within the chamber cavity. The response can be associated with the number and track length of the dose depositing electrons within the air cavity of the chamber itself, as discussed previously.\textsuperscript{10}

Orientations III and IV show little change in response with increasing magnetic fields. There is less than 1% change in dose response up to field strength of 1.0 T for both orientations. After this point the response slowly increases to near 1.02 at the highest field strength simulated (1.5 T). This relatively small response was expected, since electrons are being focused along the magnetic field lines in orientations III and IV, but are deflected outside of the chamber in orientations I and II.

III.B. PRO6C

Figure 3 shows the Monte Carlo simulation results of the PR06C chamber in orientations I–IV, and measurement results in orientations I and II. The results exhibit nearly identical response to the NE2571 chamber as expected. The simulated response for orientation I was found to decrease to a minimum of 0.91 at 0.8 T before increasing slowly toward 1.0 with increasing magnetic field strengths. The simulated results for orientation II showed an increase to a maximum of 1.08 at 1.0 T before decreasing toward 1.0 at higher magnetic field strengths. This behavior was expected because similarities in chamber design. The measurements made with this chamber match the simulated results very closely (0.2% average difference), and verify the simulations of orientations
I and II to a field strength of 0.21 T. We expect that if measurements could be made at higher field strengths they would follow the simulations closely, which is suggested by the NE2571 measurement trends.

Figure 3 also shows that orientations III and IV have a nearly identical response to the NE2571 chamber. This result was also expected due to similarities in chamber design. The data for orientations III and IV both show relative responses of less than 1.01 up to 1.0 T, before increasing slowly to 1.02 at 1.5 T.

IV. CONCLUSION

Ion chamber measurements within the magnetic field of a hybrid MRI-Linac have been found to require a multiplicative correction factor akin to $C_{TP}$, $P_{ion}$, etc. This correction factor is the reciprocal of the chamber response (i.e., 0.935 for a response of 1.07), and is dependent on the type of chamber used, the magnetic field strength, and the relative orientations of the magnetic field, radiation beam, and the chamber itself. The measured values found for the chambers investigated match closely to the simulated values, and are similar from chamber to chamber.

Transverse field orientations I and II (Fig. 1) exhibit the same behavior as the previous study, and the longitudinal orientations III and IV (Fig. 1) show little response as a function of magnetic field at all. A correction factor was found not to be required for field strengths less than 1.0 T in the presence of a longitudinal magnetic field, regardless of ion chamber orientation. In a transverse geometry a correction factor is required, and is dependent on magnetic field strength and chamber orientation.

Mechanisms of dose response in radiation detectors are known, and can in the future be applied to other detectors which may be better suited for measurements in a magnetic field environment.

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